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An Overview of Nitrogen, Phosphorus and Potassium: Key Players of Nutrition Process in Plants

5

Dwaipayan Sinha and Pramod Kumar Tandon

Abstract

Elements play an important role in the physiology and overall growth of the plant. Depending upon the amount required by the plants for their growth, they can be broadly divided into macro- and microelement. Plants generally absorb these elements through the root system from the soil. Humans have been dependent on plants since the advent of civilization for food and medicine. With the increase in population there has been an increase in demand for the food and which resulted in the intensification of agriculture. Needless to mention, this often results in scarcity of available nutrients from the soil, thereby stressing the necessity adding excess nutrients from outside. Thus the relevance of fertilization comes into the picture and its importance has been gradually felt by the scientists since the last 200 years. Various types of fertilizers containing essential elements are now being added to agricultural lands for betterment of yield. This chapter is an attempt to highlight the various aspects of three essential macroelements required by the plants, namely nitrogen (N), phosphorus (P) and potassium (K). The chapter deals with the requirement of these three elements from the agronomic point of view and the present status of the fertilization process involving the mentioned elements.

Keywords

Nitrogen · Phosphorus · Potassium · Fertilizer · Agriculture

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5.1 Introduction

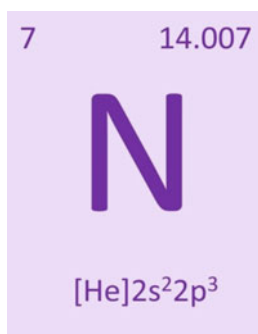
Elements play a pivotal role in the overall physiology of the plant. The plant acquires elements from the soil largely through their root system which are then transported and translocated in their desired destination inside the plant body (Paez-Garcia et al. 2015). This uptake of elements from the soil is facilitated by various transporters present in the cells of root and root hairs of the plants (Nussaume et al. 2011; Kimura et al. 2019). Once inside the plant body the elements play their individual role all of which are related to overall growth and productivity of the plant. Plants require 17 elements for their growth and depending upon the amount of requirement they can be classified into macro- and micronutrients. The macronutrients of the plants are those which are present at greater than 1000 mg per kg of the dry weight of the plant. These elements include carbon, hydrogen, oxygen, calcium, potassium, magnesium, nitrogen, sulphur and phosphorus out of which carbon, hydrogen and oxygen constitute roughly 95% of plant dry matter. Other elements which are present at less than 100 mg per kg of dry weight are called micronutrient. They include chlorine, boron, copper, iron, manganese, molybdenum, nickel and zinc (Pilon-Smits et al. 2009). The mineral nutrient elements play some vital role in plant and may be broadly classified into (1) constituent of plant cell wall, (2) aids in osmotic relation and maintenance of turgor pressure of the cell, (3) process of energy transfer, (4) participation in enzyme catalysed reactions, (5) participation in reproduction (Pandey 2018). This chapter is an attempt to overview the different aspects of three essential macroelements, namely nitrogen (N), phosphorus (P) and potassium (K) and their relationship with the plants.

5.2 Elemental Nutrition in Plants-Historical Aspects

There has been a long history of the nutritional aspect of plants and constant investigation by humans on the nutritional processes. The practices of plant nutrition are mentioned in the *Odyssey* (eighth century BC) by Homer where the use of manure, compost, straw, animal residues, river and pond silt, green manure, ash, bones, marl, lime and gypsum has been mentioned as agents of soil fertilization (Antonokiewicz and Labetowicz 2016). Marcus Porcius Cato (234-149 BCE) also mentioned strategies of soil fertilization through composting in his book “*De AgriCultura*”, while CaisPliniusSecundus (CE 23-79) described the process of manuring and recommended the use of green manures (Blakemore 2018). However efforts to decipher the secret of plant nutrition gained pace from the late medieval age onwards. It was Flemish physician and chemist Van Helmont (1577–1644) who had concluded that water provided plants the elements required for growth. Further extension of the concepts was provided by Claude Perrault (1613–1688) towards the end of seventeenth century. He proposed that the roots were the functional organs responsible for sequestering “juices” from the earth for their nutritive purpose. The eighteenth century proved to be a breakthrough in the field of plant nutrition. At that time a couple of theories were proposed by two German scientists namely “The

humus theory for plant nutrition” by Albrecht Daniel von Thaer (1752–1828) and the “Theory of mineral plant nutrition” by Justus von Liebig (1803–1873) (Métoui et al. 2016). The humus theory was presented by Albrecht Daniel von Thaer in his work “The Principles of Agriculture”. He proposed that the plants mainly draw their nutrients from the humus or the soil organic matter. It was further postulated that the driest matter of the plants is derived from soil nutritive juices containing fractions of soil organic matter (Feller et al. 2012). “Theory of mineral plant nutrition” was proposed by Justus von Liebig. He proposed the “law of minimum” which directly indicated the relevance of mineral in growth and yield of plants (Van der Pleog et al. 1999). Throughout the nineteenth century and the early twentieth century experienced the import of guano and nitrate fertilizers from South America and this was considered to be one of the driving force for the growth of fertilizer industry (Clark and Foster 2009; Espie and Ridgway 2020). One of the greatest achievement in the early twentieth century is the discovery of industrial production of ammonia from atmospheric nitrogen which was the first basic product of the fertilizer industry (Galloway et al. 2013). These discoveries eventually paved the path of chemicalization and stressed the need for chemical fertilizers which can bring about fertility to the soil and increase crop productivity.

5.3 Nitrogen as an Essential Macronutrient Source



Nitrogen is the main component of earth’s atmosphere (Luo et al. 2018). Existing as a diatomic molecule having one of the strongest known triple bonds which results in its unreactivity in normal atmospheric condition (Howie et al. 2016). Thus only a few organisms can pick up molecular nitrogen due to its stability (Galembeck and Dos Santos 2019). The formation of nitrogen compounds in the atmosphere occurs spontaneously during lightning when nitrogen reacts with oxygen to form various oxides. These nitrogen oxides (NO_x) react with the moisture in the atmosphere to form various acids of nitrogen and come down on the earth crust with rains. The acids rapidly react with minerals present in the earth crust to form various nitrates

and nitrite salts and thus get integrated into the soil (Wong et al. 2017). These contribute to overall nitrogen input in the earth crust. In addition to it, nitrogen is also fixed from the atmosphere by microbes in the form of ammonium ion which is then sequentially oxidized into nitrate. This oxidized nitrogen forms an important source of nitrogen for eukaryotic primary producers (Zerkle and Mikhail 2017). The microbiota of guts of animals are also responsible for adding up nitrogen and for this reason animal faeces have been regarded as an important source of nitrogen and fertilizing agent (Aiysha and Latif 2019). An important source of nitrate is the saltpeter (Clements et al. 2014) which played crucial role during world war in Europe and triggered the production of soluble nitrate compounds that can act as fertilizers (DiNicolantonio and O'Keefe 2017). The most important source of nitrogenous compounds for agriculture is the Haber–Bosch process of ammonia production (Vicente and Dean 2017). Ammonia is used as an ingredient of fertilizer to promote growth of agricultural crops (Wendeborn 2020).

Nitrogen is absorbed by plants in a combination of two forms, namely the nitrate form (NO_3^-) and ammoniacal form (NH_4^+) (Abbasi et al. 2017). Most of the crops prefer nitrogen in the form of nitrate (Liu et al. 2014; Hu et al. 2014). However paddy and few other higher plants prefer nitrogen in the form of ammonia (Duan et al. 2007; Yang et al. 2017a). Most of the fertilizers contain nitrogen either in ammoniacal form or in nitrate form. The urea fertilizers contain an amide which is swiftly converted by soil microorganisms into ammoniacal form and finally into nitrate (Staley et al. 2018). Based on the forms of nitrogen, nitrogenous fertilizers may be classified into: (a) nitrate fertilizers, (b) ammoniacal fertilizers, (c) ammoniacal-nitrate fertilizers and (d) amide fertilizers. The various forms of nitrogen fertilizers are tabulated in Table 5.1.

So far as global production is concerned, the USA tops the list of the countries producing ammonium sulphate in 2017 producing 2.96 million tonnes which accounted for 25.71% of the world's ammonium sulphate production. Other countries including Russia, Japan, Canada, Indonesia account for 60.93% of the total production. World's total ammonium sulphate production in 2017 was estimated to be 11.5 million tonnes (Knoema website[®] 2017a). The production of ammonium sulphate by the top eight countries is depicted in Fig. 5.1. Russia is the leading country in terms of ammonium nitrate production with a production of 9.86 million tonnes in the year 2017 accounting for 45.46% of the world's ammonium nitrate production. The total ammonium nitrate production in the world was estimated to be 21.6 million tonnes in 2017 (Knoema website[®] 2017b). Figure 5.2 describes the quantity of ammonium nitrate produced by the top eight countries in the world. The USA is the leading producer of monoammonium phosphate. In the year 2017, the total production of monoammonium phosphate by the USA was 5.18 million tonnes which accounted for 69.38% of the world's total production, while the total production of the world was 7.47 million tonnes (Knoema website[®] 2017c). Production of monoammonium phosphate by the top eight countries is depicted in Fig. 5.3.

Table 5.1 Various forms of nitrogen fertilizers

Fertilizer form	Compound	Formula	Percentage of nitrogen
Ammoniacal form	Ammonium sulphate	$(\text{HH}_4)_2\text{SO}_4$	20.5
	Ammonium chloride	NH_4Cl	26
	Monoammonium phosphate	$(\text{HH}_4)\text{H}_2\text{PO}_4$	11–20
	Diammonium phosphate	$(\text{NH}_4)_2\text{HPO}_4$	18
	Anhydrous ammonia	NH_3	82
	Aqua ammonia	$\text{NH}_3 + \text{H}_2\text{O}$	20–24.6
Nitrate form	Calcium nitrate	$\text{Ca}(\text{NO}_3)_2$	15.5
	Sodium nitrate	NaNO_3	16
	Potassium nitrate	KNO_3	13
Ammoniacal nitrate forms	Ammonium nitrate	NH_4NO_3	33.5
	Cal Nitro (ammonium nitrate + limestone)	$\text{NH}_4\text{NO}_3 + \text{Ca}(\text{CO}_3)_2$	26
	Ammonium sulphate nitrate (ASN)	$((\text{NH}_4)_3(\text{NO}_3)(\text{SO}_4))$	26
Amide forms	Urea	$\text{CO}(\text{NH}_2)_2$	45
	Calcium cyanamide	CaCN_2	19.8

Adapted from: Kumar et al. (2013), Agropedia; Mengel (2020), Nitrogenous Fertilizers and Agronomy guide, Purdue University Cooperative Extension Service

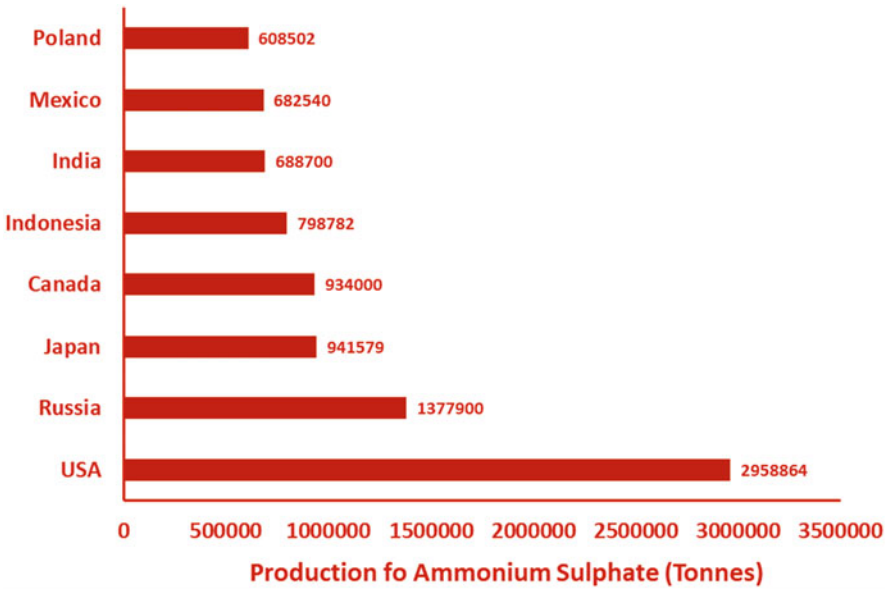


Fig. 5.1 Production of ammonium sulphate by top 8 countries in the year 2018 (Adapted from: Knoema® website 2017a)

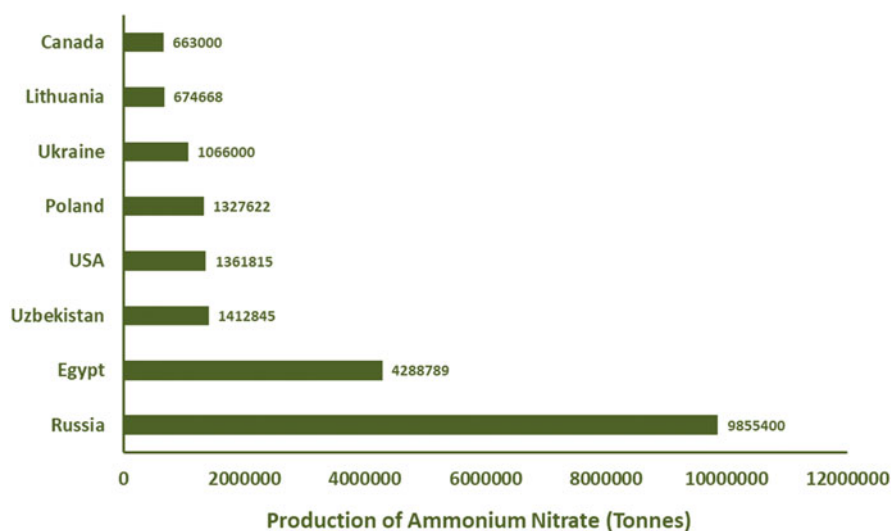


Fig. 5.2 Production of ammonium nitrate by top 8 countries in the year 2018 (Adapted from: Knoema® website [2017b](#))

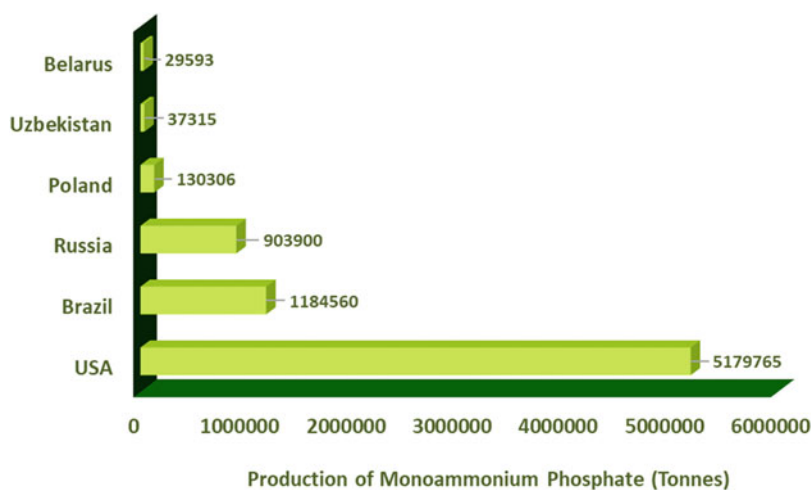


Fig. 5.3 Production of monoammonium phosphate by top 6 countries in the year 2018 (Adapted from: Knoema® website [2017c](#))

5.3.1 Nitrogen Requirement by Agricultural Crops

Nitrogen is the most abundant mineral required by the plant and acts as an important determinant of plant growth (Prinsi and Espen [2015](#)). The element is the key component of cellular biomolecules such as nucleic acids, proteins, chlorophyll and plant growth regulators (Nguyen et al. [2015](#)). Nitrate is absorbed from the soil

by the plants mainly in the form of nitrate (NO_3^-) or ammonium (NH_4^+) by the root system of the plant (Hu et al. 2014). However the nitrogen supply in the soil often becomes limited prompting the farmers to use nitrogenous fertilizers to adjust the deficiency (Muñoz-Huerta et al. 2013). All plants require a balanced amount of nitrogen for their optimum growth and development (Gastal and Lemaire 2002). This requirement often varies in different plants and is often supplemented by the use of nitrogenous fertilizers if required. In addition to it, symbiotic microbes are also capable of fixing nitrogen in the nodules of leguminous plants, thereby incorporating nitrogen into the biological system (Sulieman and Tran 2014; Mus et al. 2016). In this section, the requirement of nitrogen by selected crops will be discussed.

Reports from China indicate that the rice plant requires 21.10 kg of nitrogen to yield one ton of rice. Moreover, it has been reported in Huai River basin, the consumption of nitrogen by dryland rice varied from 60 to 100 kg per hectare for a yield of 3.2 to 4.1 tonnes per hectare. In Southern China, a yield of 7.5 tonnes per hectare of irrigated rice was achieved by the addition of nitrogen at rates of 60–120 kg per hectare (Che et al. 2016). It is also reported that for irrigated rice in Sahelian West Africa, the internal efficiency ranges from 48 and 112 kg grain per kg of nitrogen (Haefele et al. 2003). In another study it is reported that basmati rice of India requires 40 kg of nitrogen per hectare of cultivable (Aulakh et al. 2016). Another report states that Pakistan achieved maximum yield of super basmati of 4.2 ton per hectare of land through the application of 157 kg per hectare of nitrogen (Manzoor et al. 2006). Report from Myanmar indicates that input of nitrogenous nutrient at rate of 5 and 36 kg per hectare resulted in a production of 1.2–2.3 tonnes of rice in the rainfed lowland area, while application of 76–110 kg nitrogenous fertilizer per hectare resulted in an average production of 2.8 to 3.5 tons (Matsuda 2011). Another study from Bangladesh indicated that application of nitrogen at 60 kg per hectare resulted in the highest yield of grain (5.36 tonnes per hectare) of rice variety Budhan1 (Haque and Haque 2016). Another study revealed that application of nitrogen at 60 kg per hectare resulted in highest panicle length, filled grain per panicle and grain yield in Morichsail variety of rice (Jahan et al. 2014).

Wheat is another important food crop extensively cultivated in India. It has been reported in a study from Haryana, India that the recommended dose of nitrogen for optimum yield and chapatti quality of wheat is 130 kg per hectare with an equal application of 50 kg per hectare at seedling and early tillering stage and the lesser rate at the first node stage (Coventry et al. 2011). In another study done in Nadia district of West Bengal, It was reported that to obtain 1 ton of grain, the nitrogen requirement varies from 8.3 to 29.6 kg (Maiti et al. 2006). Another report from Punjab province in Pakistan states that application of nitrogen at 120 kg per hectare increased the yield of wheat up to 5.12 tonnes per hectare (Majeed et al. 2015). A study from China reported the effect of irrigation and nitrogen application on Yumai 49–198, a winter wheat cultivar from Huanghai area of China. It was observed that the highest grain yield was observed with nitrogen application at 300 kg per hectare. This was accompanied by a significant increase in grain protein and the total essential and non-essential amino acid content (Zhang et al. 2017). Another study reported the

use of nitrogen fertilizer in the management of dryland wheat in the USA. In the study, using hard red spring wheat (cv. Choteau), it was observed that application of 90 kg of nitrogen per hectare of land significantly increased grain yield, protein content and nitrogen uptake (Walsh et al. 2018).

Next to wheat, maize is another cereal that is popularized in a large number of regions across the globe. Several studies have been done to evaluate the nitrogen requirement of maize. A report from a field experiment from Peshawar valley of Pakistan states that application of nitrogen at rate of 200 kg per hectare to hybrid maize was found to be most beneficial in terms of productivity and cost effectivity of the farmer. Application of nitrogen at 150 kg per hectare was most beneficial for the local varieties of maize (Amanullah et al. 2016a). In another study from China, using spring maize (Zhengdan 958), it was found that application of 304 kg per hectare of nitrogen leads to maximum yield of 10506 kg per hectare (Yin et al. 2014). A study from Ethiopia using hybrid long maturing variety (BH661) of maize, it was found that application of 92 kg of nitrogen per hectare of land resulted in highest yield (Abebe and Feyisa 2017). Another report from Bangladesh states that application of 180 kg of nitrogen per hectare resulted in a higher amount of grain and maximum yield (Tajul et al. 2013).

Soybean is one of the important legume contributing to 25% of global edible oil and two-thirds of world's protein concentrate for feeding livestock (Agarwal et al. 2013). A study from China estimated the nitrogen requirement of Soybean using quantitative evaluation of the fertility of tropical soils (QUEFTS) model. It was found that to produce 1000 g of soybean seeds, 55.4 kg of nitrogen is required for the aboveground parts which corresponded to internal efficiency of 18.1 per kg of nitrogen (Yang et al. 2017b). Another report from China indicates that application of nitrogen at 50 kg per hectare resulted in optimum grain yield, pod number per plant and grain number per plant (Gai et al. 2017). In a recent report from Brazil, it was stated that soybean plants can be inoculated with bacterial strains SEMIA 587 and 5019 (*Bradyrhizobium elkanii*), 5079 (*Bradyrhizobium japonicum*) and 5080 (*Bradyrhizobium diazoefficiens*) for a more efficient nitrogen fixation and improvement in yield (De Souza et al. 2019). There are also reports of microbial inoculation to enhance nitrogen uptake in Soybean plant in Ghana. A study reported that treatment of soybean plants with rhizobial inoculants, namely Legumefix and Biofix as well as 100 kg nitrogen per hectare resulted in increase in shoot dry weight, grain yield and nodule dry weight of soybean plant (Ulzen et al. 2016). Another report from Siaya County of western Kenya also states that inoculation rhizobial inoculant legume fix resulted in an increase in grain yield of up to 4000 kg per hectare (Thuita et al. 2018).

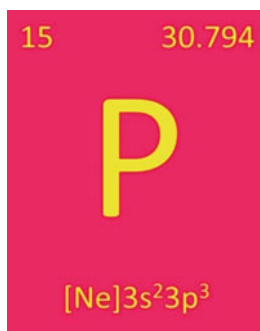
5.3.2 Nitrogen Deficiency

Nitrogen input through nitrogenous fertilizer forms the single largest input of the mineral in croplands (Liu et al. 2010). Deficiency of nitrogen results in reduced photosynthesis, reduction in contents of chlorophyll and accessory pigments (Cetner

et al. 2017), stunted growth and chlorosis (Sett and Soni 2013). In addition to it, nitrogen deficiency results in reduced cell size (Yanagida et al. 2011), volume and protein content (Ding et al. 2005) and reduces the number and size of chloroplasts (Makino and Ueno 2018; Omondi et al. 2019). In rice, nitrogen deficiency results in paling of old leaves and sometimes all leaves along with chlorosis in the tip. The leaf colouration becomes light green (Chen et al. 2014). In addition to it, rice plants suffering from nitrogen deficiency also results in small leaves and leaf etiolation from the tip (Sun et al. 2018). This is accompanied by dwarfing of plants and lowering of grain yields (Zhang et al. 2015). In wheat, the specific symptoms of nitrogen deficiency symptoms first appear on the oldest leaves with the new leaves appearing comparatively green. Consequently older leaves become paler than the new ones due to chlorosis with the symptoms initially beginning at the tip and then extending down the leaves to the base (Snowball and Robson 1991). A study reported that deficiency of nitrogen resulted in decreased activity of superoxide dismutase, guaiacol peroxidase and catalase as well as a higher concentration of reactive oxygen species in the peduncles (Kong et al. 2013). Another study indicates that nitrogen deficiency results in higher phenolic content and high degree of cross-linking in cell walls of wheat roots which results in thickening of cell walls (Meychik et al. 2017). In maize, deficiency of nitrogen results in stunted growth and reduction in leaf photosynthesis. In addition to it, in the harvest time, the plant height, leaf area and shoot biomass were less than that of the control plants which received nitrogen enriched nutrient solution throughout the study (Zhao et al. 2003). Another study reports that nitrogen deficiency resulted in reduction of grain yields and plant weight in maize (Ding et al. 2005). A study also reports that nitrogen deficiency results in strong metabolic shifts and metabolite profiles. Deprivation of nitrogen resulted in selective downregulation of processes involved in nitrate reduction and amino acid assimilation. Decrease in nitrogen availability also resulted in accumulation of phosphorus along with downregulation of genes usually involved in phosphate starvation response (Schlüter et al. 2012). Another report states that nitrogen deficiency in maize resulted in greater starch concentrations in leaves due to more and larger starch granules in bundle sheath cells (Ning et al. 2018). In soybean, a study reports that nitrogen deficiency resulted in a drastic decrease in the content of galactolipids, monogalactosyldiacylglycerol and digalactosyldiacylglycerol in leaves (Narasimhan et al. 2013). In another study, it was indicated that nitrogen

deficiency resulted in n 8- and 15-fold increases in the secretion of daidzein and genistein, respectively, in soybean (Sugiyama et al. 2016).

5.4 Phosphorus as an Essential Macronutrient Source



In most of the living systems, phosphorus is represented by phosphates (Razzaque 2011). The main source used by fertilizer company for industrial production of phosphates is hydroxyapatite, a member of the apatite group (Xiong et al. 2018). In nature, phosphorus are generally present in various forms of calcium phosphate minerals and are produced through a wide range of environmental procedures namely geological (igneous apatite), geochemical and/or geomicrobiological (phosphorite) and biological (biological apatite). The igneous apatites nucleate and crystallize from molten, phosphate-rich rock resulting in the formation of fluorapatite ($\text{Ca}_5\text{F}_2[\text{PO}_4]_3$), chlorapatite ($\text{Ca}_5\text{Cl}_2[\text{PO}_4]_3$) or hydroxyapatite ($\text{Ca}_5[\text{OH}]_2[\text{PO}_4]_3$) (Omelon et al. 2013). The most commonly used phosphatic fertilizers include diammonium phosphate (DAP), monoammonium phosphate (MAP), NPKs and single super phosphate (SSP) (Indorama Corporation website 2017). As per reports of Knoema®, India is the largest producer diammonium phosphate in the world. As of 2017, the total DAP production by India was 4.65 million tonnes that accounts for 44.90% of the world's DAP production. The total world's DAP production was estimated to be at 10.4 million tonnes in 2017 (Knoema® website 2017d). The amount of DAP production by top 8 countries of the world is depicted in Fig. 5.4.

As per a report from Global Industry Analysts, Inc, amid the COVID-19 crisis and looming economic recession, the worldwide phosphate market will grow by a projected 12.5 million metric tonnes propelled by a CAGR OF 2.4% (Global Industry Analysts, Inc report 2020). China tops the list of mine production of phosphate in the year 2018 with a whopping 140 million metric tonnes (Williams 2019). The top phosphate producers of the world are depicted in Fig. 5.5.

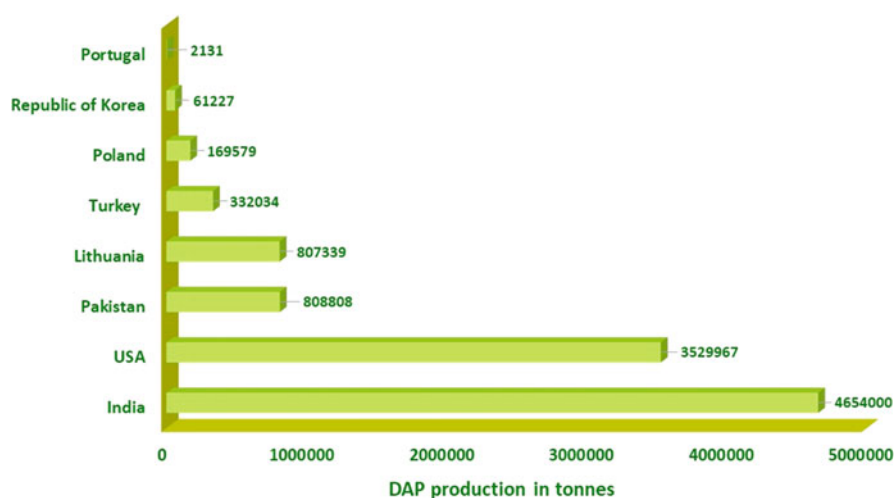


Fig. 5.4 Quantity of DAP produced by top 8 countries (Adapted from Knoema® website 2017d)

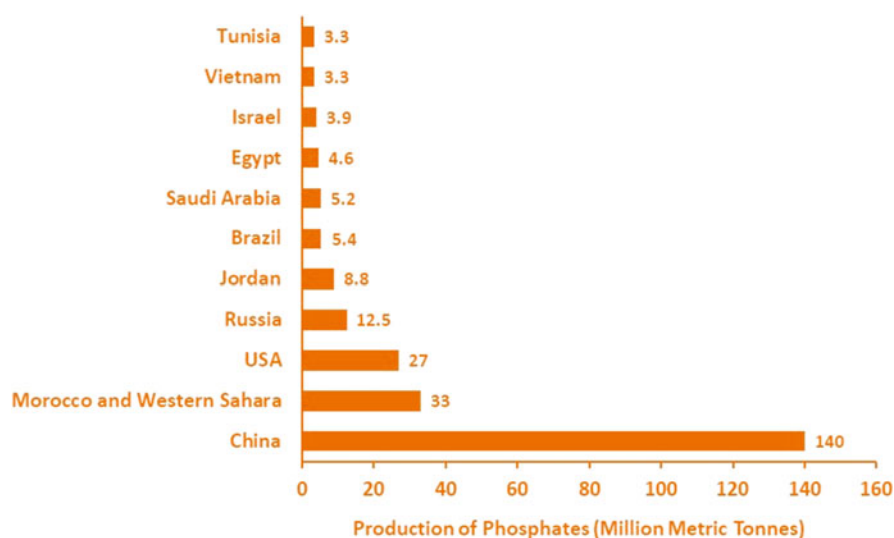


Fig. 5.5 Production of phosphates by top 10 countries. Tunisia and Vietnam are tied at 3.3 million metric tonnes. (Adapted from: Investing news website 2013)

5.4.1 Phosphorus Requirement by Agricultural Crops

Phosphorus is another essential element required for the development and growth of plants and constitutes up to 0.2% of dry weight in plants (Alori et al. 2017). It is one of the essential macronutrient required for the synthesis of nucleic acid, membrane build up and stability, energy metabolism and many other critical physiological and biological processes during plant growth and development (Hasan et al. 2016).

Phosphorus is poorly available to the soil due to its extremely low diffusion rate (10^{-12} to 10^{-15} m²/s) (Shen et al. 2011). It has been reported by IRRI that for optimum nutrition, rice plants take up 6.4 kg P₂O₅ (2.8 kg P) per ton of grain yield (4.4 kg P₂O₅ in grain and 2.0 kg P₂O₅ in straw) (Rice Knowledge Bank website 2020a). A study from Japan recommended that for rice, phosphorus fertilization requires to be restricted to 20 kg per hectare per year which corresponds to 46 kg per hectare per year as P₂O₅ (Nagumo et al. 2013). In a study from Malaysia, it was found that the optimum yield of red rice was obtained when phosphorus in the form of triple phosphate was applied at a rate of 35 kg per hectare. The yield was not significantly affected by any further increase in the application of fertilizer (Masni and Wasli 2019). A study from the small fields of Khyber Pakhtunkhwa of Pakistan revealed that application of phosphorus at the rate of 90 kg per hectare of land in combination with animal manure resulted in increased productivity of rice (Amanullah et al. 2016b). In another study in Nizamabad district of Telangana, India, it was shown that the highest grain yield of 6.41 tonnes per hectare was achieved in kharif rice when P₂O₅ is applied at a rate 85 kg per hectare (Archana et al. 2017). In another study from Bangladesh it is reported that application of phosphorus in the form of triple phosphate at the rate of 10 kg per hectare resulted in the yield of 4850 kg per hectare and straw yield of 5125 kg per hectare in demonstration plots. It was also found that the yield was higher in demonstration plots than in non-demonstration plots (Razzaque and Rafiquzzaman 2007). In another experiment from Japan, it was found that application of superphosphate at the rate of 60 kg per hectare of land along with poultry manure resulted in a yield of 6.90 and 7.42 tons per hectare of land in consecutive years of 2017 and 2018 (Moe et al. 2019).

Wheat is considered to be one of the most productive and important crops of the twenty-first century (Curtis and Halford 2014). A very interesting study was performed in northwestern Pakistan to assess the influence of residual phosphorus on wheat productivity under rice-wheat cropping system. It was found that heavier grains (40.54 g/1000 grains) were recorded when wheat plants were grown in plots that had received phosphorus at the rate of 120 kg per hectare during its previous rice cultivation. A study from China reported that wheat plants require phosphorus at 100 kg per hectare of land for optimal growth (Deng et al. 2018). It was also observed that the yields were greater when wheat were grown in plots which had received higher levels of phosphorus (120 and 80 kg per hectare, respectively) (Amanullah and Inamullah 2016). In a study from Toba Tek Singh district of Pakistan, it was observed that application of 81 kg of P₂O₅ per hectare of land resulted in a yield of 3.94 mega grams (Mg) per hectare of wheat crop cultivar Inquilab-91 (Rahim et al. 2010). In another study it was reported that 90 kg per hectare of P₂O₅ is optimum for maximal yield of wheat in the agroclimatic condition of Sindh, Pakistan (Khan et al. 2008). Similar results were also obtained from a pot experiment study of wheat. It was shown that application of 80 kg per hectare of single super phosphate resulted in the highest number of tillers per plant, plant height, spike length, number of grains per spike, grain yield and straw yield (Khan et al. 2010). In another experiment conducted in Bahauddin Zakariya University, Multan, Pakistan reported that application of 60–120 kg of phosphorus in the form of P₂O₅ resulted in

maximal improvement of growth parameters as well as the yield of wheat crop (Hussain et al. 2008).

The phosphorus requirement of maize has also been elaborately investigated. For maize diammonium phosphate and triple phosphates are used for fertilization. Depending upon the soil phosphorus index, maize plants require 0–185 kg per hectare of diammonium phosphate or 0–85 kg per hectare of triple phosphate (P_2O_5). Soil with high phosphorus index does not require any additional phosphorus fertilization (Potash Development Association website 2008). In an experiment in the agronomy research farm of The University of Agriculture Peshawar-Pakistan, it was observed that application of phosphorus at higher rates resulted in a significant increase in yield and yield components of maize under semi-arid conditions (Amanullah and Khan 2015). In another experiment conducted in China Agricultural University, it was found that optimum grain yield of 7.12 Mg per hectare was observed on the application of phosphorus at a rate of 75 kg per hectare (Deng et al. 2014). In another study from Maharashtra, India it was found that the application of phosphorus at 100 kg per hectare resulted in higher growth attributes including yields (Kwadzo et al. 2016). In an experiment conducted by Department of Soil Science and Land Management, Federal University of Agriculture Abeokuta (FUNAAB), Ogun State, Nigeria, it was reported that application rate of 30–45 kg of phosphorus per hectare of land resulted in a maximum dry yield of maize (Ogunsola and Adetunji 2016).

The effect of phosphorus on the yields of soybean has also been studied by various groups of researchers. In one study conducted by University for Development Studies, Nyankpala in the Guinea Savannah agro-ecological zone, it was found that application of phosphorus at 45 kg per hectare along with rhizobium inoculant resulted in maximal plant height, canopy spread, number and weight of nodules, number of pods and total grain yield (Ahiabor et al. 2014). Another study from Indonesia reported that maximal grain yield of soybean was obtained upon application of 125 kg per hectare of P_2O_5 (Kuntyastuti and Suryantini 2015). A study conducted at Main Agricultural Research Station, Dharwad, India reported that optimal yield of soybean was obtained upon treatment of 80 kg per hectare of phosphorus in conjugation with 60 kg per hectare of nitrogen (Raghuveer et al. 2017).

5.4.2 Phosphorus Deficiency

Phosphorus deficiency is a very common nutritional factor that limits agricultural production worldwide (Wissuwa 2003). It is reported that suboptimal levels of phosphorus in soils may result in a reduction in crop yields by 5–15%. Phosphorus deficiency is more critical in highly withered soil and in calcareous-alkaline soil (Shenoy and Kalagudi 2005). A typical phenotypic response of phosphorus deficiency in plants are stunted shoot growth and branching, dark to blue green colouration of leaves, weaker and thin stems, reduced tillering, imperfect pollination, fewer flowers, delayed maturity, poor grain quality and low yield (Ajmera et al. 2019). The general morphological symptoms related to phosphorus deficiency in

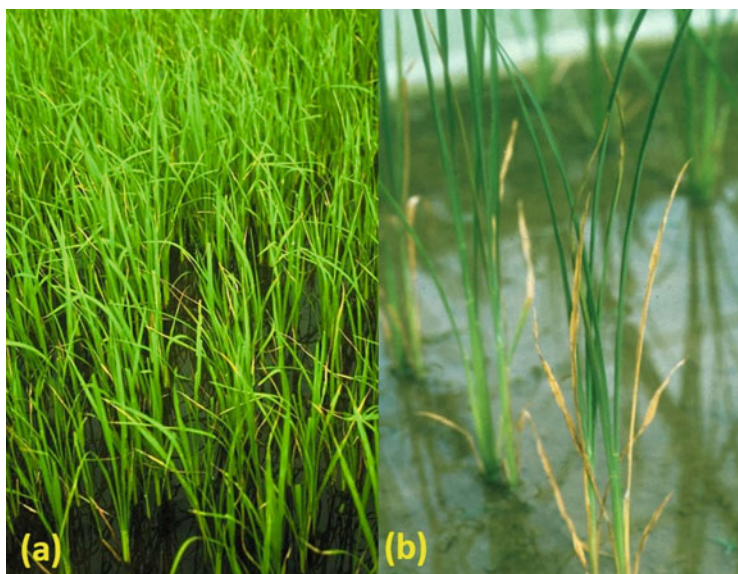


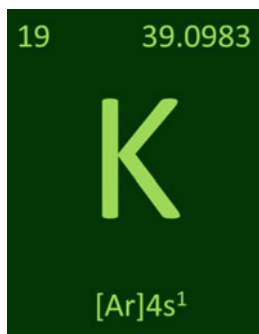
Fig. 5.6 Deficiency symptoms of phosphorus in rice plants (a) in rice fields, (b) close up of individual plant (source: Rice Knowledge Bank Website [2020b](#))

rice are stunted growth, reduced tillering, narrowing and shortening of older leaves, erect having dirty green colouration. The stems are thin and spindly with retarded development (Rice knowledge Bank Website [2020b](#)) (Fig. 5.6).

A study with rice reported that deficiency of phosphorus resulted in a reduction in lateral root density, length of small and large lateral roots. In addition to it, there is an increase in root hair length and density along with a reduction in nodal cross-sectional area (Vejchasarn et al. [2016](#)). In another study it was reported that phosphorus deficiency resulted in reduced accumulation of all nutrients except sulphur and copper in the aboveground biomass of the plants and also results in a reduction in biomass accumulation by as much as 30% (Rose et al. [2016](#)). It was also reported that phosphorus deficiency results in the initiation of root aerenchyma in rice (Pujol and Wissuwa [2018](#)). In case of wheat, the phosphorus deficiency results in pale and olive green wilted seedlings. In matured leaves, chlorosis initiates at the tip and migrates down the leaf on a front, while the base of the leaf and the rest of the plant remains dark green. The necrosis of this chlorotic area is rapid with tips turning orange and dark brown and shrivelling while the rest part turns yellow (Department of Primary Industries and Regional Development, Government of Australia [2017a](#)). Maize is another crop which is widely cultivated throughout the globe but is frequently subjected to phosphorus deprivation (Lin et al. [2013](#)). In maize, phosphorus deficiency has a negative impact on leaf area index along with the reduction in absorbance of photosynthetically active radiation (PAR) by the canopy. In addition to it, the plants deprived of phosphorus exhibits reduction in growth accompanied by a delay in the emergence of adventitious roots (Pellerin et al. [2000](#)). Phosphorus

deprivation also resulted in reduction of elongation rates of leaf (Plénet et al. 2000). A recent study reports the impairment of root and shoot growth in the case of phosphorus deficiency. This is accompanied by a decline in phosphorus concentration (Klamer et al. 2019). Another recent study states the upregulation of gibberellic acid synthesis genes such as AN1, GA20ox1 and GA20ox2 and downregulation of gibberellic acid inactive genes such as GA2ox1 and GA2ox2 in maize plants subjected to low phosphate concentration (Zhang et al. 2019a). In soybean, phosphorus deficiency results in yellowing of leaves, while some veins still remained green. The yellow leaves progressively turned red and then violet finally resulting in collapse (Rosolem and Tavares 2006). Deficiency of phosphorus also results in reduced biomass and phosphorus content in seedlings (Zhou et al. 2016; Singh et al. 2018) and alteration in the balance of diurnal starch accumulation and utilization (Qiu and Israel 1992). A study reported that phosphorus deficiency in soybean resulted in impairment of symbiotic nitrogen fixation by delaying the onset of nodule function and decreasing nodule development (Qiao et al. 2007).

5.5 Potassium as an Essential Macronutrient Source



The necessity of potassium for the growth of plants was first indicated by Justus Leibig in 1840 (Galembeck and Dos Santos 2019). Though the reserves of potassium in soil are large but most of them are in unavailable form resulting in the requirement of potassium fertilizers (Zörb et al. 2014). This results in a high demand of potassium by agricultural crops. This led to search of potassium deposits in the soil which was eventually discovered during the 1850s at Stassfurt in Germany. Two most important minerals unearthed were hydrated double salts carnallite, $\text{KCl} \cdot \text{MgCl}_2 \cdot 6\text{H}_2\text{O}$, and kainite, $\text{MgSO}_4 \cdot \text{KCl} \cdot 3\text{H}_2\text{O}$. Consequently in 1861, a factory was set up in Stassfurt to produce potash salts from these deposits which produced 20,000 tonnes of the salts the following year. By 1909, annual production of potassium fertilizer in Germany soared to more than seven million tonnes (Freemantle 2016). Another potash deposit was accidentally discovered in

Table 5.2 Different types of potassium fertilizers

S.No.	Name of fertilizer	Chemical formula	Percentage of potassium
1.	Muriate of potash	KCl	50
		KCl	41
		KCl	33
2.	Potassium sulphate	K_2SO_4	43
3.	Potassium nitrate	KNO_3	18
4.	Sulphate potash magnesia	$K_2SO_4 \cdot MgSO_4$	18
5.	Kainite	$KCl + NaCl + MgSO_4$	10

Adapted from: Scherer 2005

Saskatchewan, Canada in the process of drilling oil in the 1940s. In 1958, the Potash Company of America became the first potash producer in Canada with the establishment of a conventional potash mine at Patience Lake which is still operational. At present Canada exports 95% of its potash to over 50 countries around the world (Western Potash Corporation Website 2020). The reserves of potash in Ural mountains amounts to 210 billion tonnes and are owned by Uralkali (Investing News website 2013). The company produced 11.1 million tonnes of potassium chloride with a sales volume of 9.8 million tonnes in the year 2019 (Uralkali website 2020). The main constituents of potash include sylvite (KCl), carnallite [$KCl \cdot MgCl_2 \cdot 6 (H_2O)$], kainite ($MgSO_4 \cdot KCl \cdot 3H_2O$) and langbeinite ($2MgSO_4 \cdot K_2SO_4$) (Garrett 1996). The deposit formation of potash is of two types, namely the underground deposits naturally protected from underground waters and the salt beds or lakes in the arid regions of the world (Sun and Ma 2018; Zhang et al. 2019b). The potassium fertilizers are of two main categories in which the K^+ ions are combined either with chloride (muriate of potash) or sulphate (sulphate of potash). Potassium chloride is available in three different grades, namely 50% K, 41% K and 33% K. The last two variants contain substantial quantities of sodium chloride (NaCl) and are recommended as K^+ fertilizers for natrophilic crops (Scherer 2005). The different types of potassium fertilizers are tabulated in Table 5.2.

Canada tops the list among the country in the production of muriate of potash. As per the report of Knoema[®], Canada produced 20.3 million tonnes of potassium chloride in the year 2017 and accounted for 44.98% of the world's potassium chloride production (Knoema website 2017e). The production of muriate of potash (potassium chloride) by the top eight countries of the world is depicted in Fig. 5.7.

5.5.1 Potassium Requirement by Agricultural Crops

Potassium is an essential element that affects most of the biochemical and physiological processes related to plant growth and metabolism (Wang et al. 2013). Potassium is of great importance in physiology of plants. It performs critical functions related to activation of enzyme, osmotic adjustment, turgor generation, cell expansion, regulation of membrane electric potential and pH homeostasis (Ragel

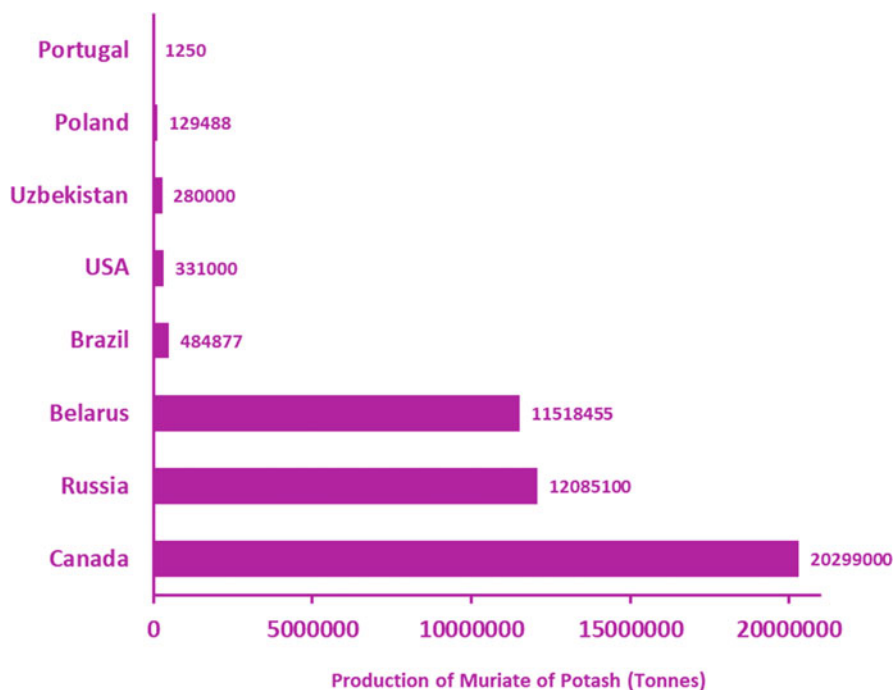


Fig. 5.7 Production of muriate of potash by top 8 countries in the yield 2017 (Adapted from Knoema website [2017e](#))

et al. 2019). A study on the hybrid rice growing in coastal saline soils of West Bengal, India recommended a dose of 101.5 kg of potassium oxide (K_2O) per hectare for achieving higher productivity during the wet season (Banerjee et al. 2018). A report from a pot experiment study indicated the combined application of nitrogen and potassium at the rate of 23 and 30 kg per hectare, respectively, resulted in maximum grain yield (Kumar et al. 2013). In another study, it was reported that potassium fertilizer applied at the rate of 37.5 muriate of potash per hectare of land during the heading time resulted in best head rice yield (HRY) when harvested between 25 and 30 days after 50% flowering (DAFF) (Atapattu et al. 2018). A report from Pakistan states that application of potassium fertilizer at the rate of 375 kg per hectare resulted in improvement of growth and yield parameters in wheat (Arif et al. 2017). A study from Bangladesh also reported that application of potassium at 60 kg per hectare resulted in a maximal yield of wheat subjected to irrigation by municipal wastewater (Mojid et al. 2012). A report from Bangladesh recommends 72 kg of potassium oxide (K_2O) for the production of wheat in light soil (Hossain et al. 2015). In a study carried out in Tigray Region, northern Ethiopia, it was found that application of 30 kg of K_2O per hectare of land resulted in highest apparent potassium recovery and agronomic efficiency in wheat (Brhane et al. 2017). One recent study reported that application rate of potassium (K_2O) at 150 mg and 250 mg

per kg of soil helped in achieving higher yield of winter wheat under shading at early filling stage (SE) by alleviating the damage done on the photosynthetic apparatus by SE (Wang et al. 2020). Studies on the requirement of potassium by maize plants have also been undertaken by a number of researchers. In one recent study it was reported that potassium application at the rate of 75 kg per hectare resulted in maximum performance of maize plants from yield point of view under water stress condition (Ul-Allah et al. 2020). In another study, it was found that application of 100 kg per hectare of potassium resulted in maximum plant height, leaf area index, thousand grains weight, grains per year and grain yield in maize crops (Liaquat et al. 2018). In case of soybean, a study reported that combined treatment of phosphorus at 175 kg per hectare and potassium (in form of muriate of potash) at 120 kg per hectare resulted in highest number of filled pods per plant, length of the pods, number of seeds per pods and highest number of seeds and this constitutes the recommended dose for optimum yield of soybean (Khanam et al. 2016). In an experiment with intercropping system using maize and soybean in China it was found that joint application of phosphorus at 17 kg per hectare and potassium at 112.5 kg per hectare resulted in higher seed yields of soybean (Xiang et al. 2012). In mixed cropping system where maize is intercropped with soybean, it was found that application of potassium at 80 kg per hectare for maize and 60 kg per hectare for soybeans resulted in an accelerated biomass accumulation and distribution of other essential nutrients in the plant parts (Ahmed et al. 2020).

5.5.2 Potassium Deficiency

The visual symptoms of potassium deficiency are stunted growth of plants accompanied by yellowing of leaf margins (Hasanuzzaman et al. 2018). In addition to it, the older leaves of plants suffering from potassium deficiency undergo necrosis due to evacuation of potassium ions to the younger leaves (Cochrane and Cochrane 2009). In rice potassium deficiency results in decrease in concentration of potassium in shoots and roots. In addition to it, there is an increase in activities of antioxidant enzymes, namely superoxide dismutase, ascorbate peroxidase, glutathione reductase and catalase (Liu et al. 2013). Another study reveals that potassium deficiency results in decrease in growth of the roots. Both roots volume, roots surface area and numbers of laterals were decreased in plants growing under potassium deprivation. Moreover, potassium deficiency also resulted in damage of cellular organelles and membranes along with precipitation of dark particles in root cell walls (Jia et al. 2008). In wheat, potassium deficiency results in paler and weaker plants. In this case, the older leaves are first affected starting with necrosis and death of leaf tip followed by progressive yellowing and death downwards. There is a contrast in colouration of leaf margins (yellow) and green centre. The yellowing leaf tip and leaf margins often generate a green “arrow” like design towards leaf tip (Department of Primary Industries and Regional Development, Government of Australia 2017b).

In maize, potassium deficiency first appears on the lower leaves. The leaf symptoms include yellowing to necrosis ultimately leading to tissue death in the



Fig. 5.8 Picture of potassium deficient maize plant (Source: Sawyer, Iowa State University, Integrated crop management [2018](#))

outer margins but located from the leaf tip to midrib in a v shape. The yellowing consequently covers the entire leaf. Upon persistence of potassium deficiency, the lower leaves die back and the leaf symptoms proceed towards the apex of the plant and accompanied by reduction in growth (Sawyer, Iowa State University, Integrated Crop Management [2018](#)) (Fig. 5.8).

A study reported that potassium deficiency results in reduction of total length, root surface area, the root diameter and root volume of root system in maize (Du et al. [2017](#)). Another experiment reported that content of chlorophyll a, b and a + b decreased due to deficiency of potassium in maize (Zhao et al. [2016](#)). Another recent report states that potassium deficiency resulted in damage of chloroplast and photosynthetic reaction centres (PSII) along with increased superoxide and hydrogen peroxide levels. The anatomical structures of the leaves were also affected due to deficiency of potassium and the manifestations included smaller thickness of leaf, lower epidermis cells and vascular bundle area. Other physiological parameters including chlorophyll content, net photosynthetic rate, stomatal conductance, photochemical quenching and electron transport rate of PSII were also reduced due to potassium deficiency (Du et al. [2019](#)).

In soybean, the potassium deficiency symptom can be observed in the leaves involving yellowing of leaflet margins with mild deficiency which may turn brown and necrotic with extreme deficiency (Mallarino, Iowa State University, Integrated Crop Management [2018](#)) (Fig. 5.9). A study reported that potassium deficiency resulted in reduction in net photosynthetic rate, transpiration rate and stomatal conductance. This was accompanied by reduction in RUBISCO activity and dry weight of soybean plants (Wang et al. [2015](#)).



Fig. 5.9 Picture of potassium deficient soybean plant (a) young plants, (b) matured plants (Source: Mallarino, Iowa State University, Integrated crop management 2018)

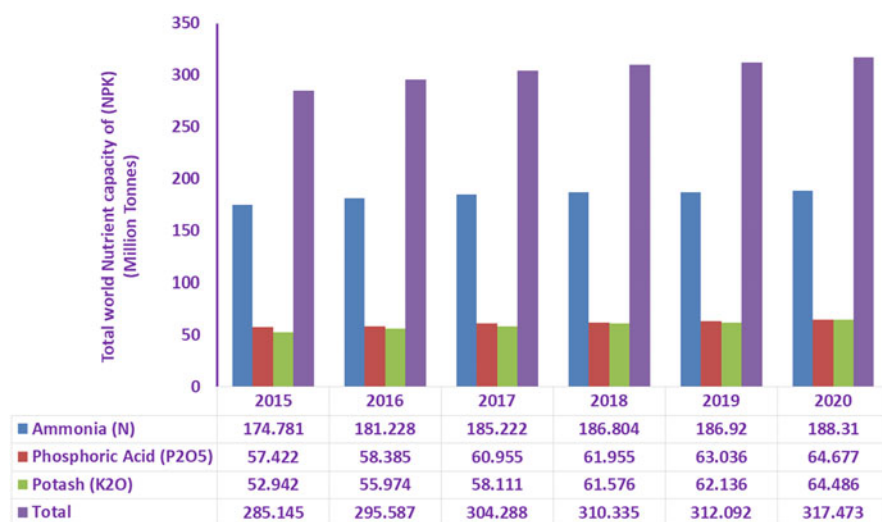


Fig. 5.10 Total world nutrient capacity of nitrogen, phosphorus and potassium, 2015–2020 (thousand tonnes) (Source: FAO, United Nations, Rome 2017)

5.6 Nitrogen(p), Phosphorus (p) and Potassium-Demand and Supply

As per the FAO bulletin, the consumption of three main fertilizer across the world, namely nitrogen (N), phosphorus (P₂O₅) and potassium (K₂O) was estimated to reach 186.67 million metric tons in 2016. In addition to it, the demand of N, P₂O₅ and K₂O is likely to grow annually on average by 1.5, 2.2 and 2.4%, respectively, from 2015 to 2020. It is also expected that over the next 5 years, the capacity of production of fertilizers, intermediates and raw materials is expected to increase (FAO 2017).

The FAO bulletin states that the global total nutrient capacity including N, P₂O₅ and K₂O was 285.15 million tonnes in 2015 with a total supply of 245.77 million tons. The detailed estimated nutrient capacity of ammonia (NH₃), phosphoric acid (H₃PO₄) and potash (K₂O) from 2015 to 2020 is illustrated in Fig. 5.10, while the world supply is illustrated in Fig. 5.11.

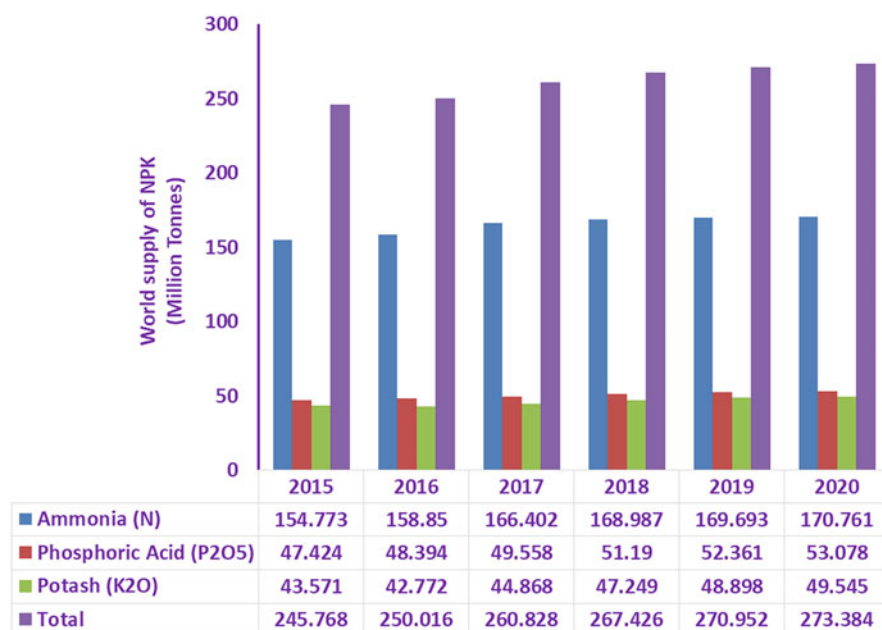


Fig. 5.11 World supply of nitrogen, phosphorus and potassium, 2015–2020 (thousand tonnes) (Source: FAO, United Nations, Rome 2017)

5.7 NPK Fertilizer: A Brief Overview

NPK fertilizer is the combination of three macronutrients required by plants, namely nitrogen (N), phosphorus (P) and potassium (K). It is used as a fertilizer in agriculture industry to make plants healthy from nutritional point of view and meet the demand of healthy crops (Databridge Market Research website 2019). The NPK fertilizers are composed of nitrogen, phosphorus (in form of P_2O_5) and potassium (in form of K_2O) and these constituents may vary in their ratios. As, for example, a 12-32-16 grade of NPK complex fertilizer indicates the presence of 12 % nitrogen (N), 32 % phosphorous (P_2O_5) and 16 % potash (K_2O) (FAO website 2020). The individual constituent of selected NPK formulations is tabulated in Table 5.3.

So far as production is concerned, Russia tops the list of among NPK producers followed by India, Indonesia, Vietnam and Poland. In the year 2017, the production of NPK fertilizer by Russia was 8.41 million tons which accounts for 32% of total NPK production of the world. The other countries include India, Indonesia, Vietnam and Poland account for 76.72% of the production (Knoema website 2017f). The year wise production of NPK fertilizers for selected countries from 2010 to 2017 is tabulated in Table 5.4.

Table 5.3 Constituents of selected NPK formulations (Source: FAO website [2020](#))

	NPK complex 15-15-15	NPK complex 17-17-17	NPK complex 19-19-19
Moisture content by weight	1.5% (Max)	1.5% (Max)	1.5% (Max)
Total nitrogen content by weight (on dry basis)	Minimum 15%	Minimum 17%	Minimum 19%
Neutral ammonium citrate soluble phosphate (as P_2O_5) content by weight	Minimum 12%	Minimum 17%	Minimum 19%
Water soluble potash (as K_2O) content by weight	Minimum 15%	Minimum 13.6%	Minimum 19%
Particle size	Not less than 90% of the material shall pass through 4 mm IS sieve and be retained on 1 mm IS sieve. Not more than 5% shall be below 1 mm size.	Not less than 90% of the material shall pass through 4 mm IS sieve and be retained on 1 mm IS sieve. Not more than 5% shall be below 1 mm size.	Not less than 90% of the material shall pass through 4 mm IS sieve and be retained on 1 mm IS sieve. Not more than 5% shall be below 1 mm size.

According to a leading market research report, the global NPK fertilizer (food-grade) market was valued at 2.31 billion US dollars in the year 2017 and is projected to reach 2.90 billion US dollars by the year 2023 growing at compound annual growth rate (CAGR) of 4.0% from the year 2018 (Research and Markets website [2019](#)). The same organization also reported that this market is likely to reach a value of 3.92 billion US dollars with a 6.1% CAGR (CISION PR Newswire [2019](#)). Another report states that the NPK fertilizer (feed-grade) was estimated to be valued around 5.4 billion US dollars in the year 2018 and is projected to reach 6.6 billion US dollars by the year 2023 growing at CAGR of 4.1% from 2018 (Markets and Markets website [2019a](#)). The key players in the production of NPK fertilizers include Borealis AG (Austria), AkzoNobel (Netherlands), Yara International ASA (Norway), Petróleo Brasileiro S.A. (Brazil) and Agrium Inc. (Canada). In addition to it, The Mosaic Company (US), Israel Chemicals Ltd. (Israel), EuroChem (Switzerland), PotashCorp (Canada), K+S AKTIENGESSELLSCHAFT (Germany), Alltech (US), PhosAgro (Russia), Haifa Chemicals (Israel), Aditya Birla Chemicals (India) and SKW Stickstoffwerke Piesteritz (Germany) are the other players that hold a significant share in the NPK fertilizers (feed-grade and food-grade) market (Markets and Markets website [2019b](#)). A report from Ken Research Private limited states that the complex fertilizer production in Asia is likely to grow at a CAGR of 3.1% during the span of 2018–2022 whereas the consumption of complex fertilizers is likely to incline at a CAGR of 1.9% during the same period (Ken Research Website [2018](#)). Study done by the same organization also suggests that Kingenta,

Table 5.4 Detailed of the production of NPK fertilizers in selected countries from 2010 to 2017 (tonnes) (Source: Knoema website, f)

	2017	2016	2015	2014	2013	2012	2011	2010
Russia	8407500	6310000	6080600	5641700	44700	3115000	3253800	3205600
India	3846100	3655000	3744700	3754100	3104500	480300	506000	494000
Indonesia	3282957	2764687	3001087	2716098		2893868	2213491	1853172
Vietnam	3276100	3081000	3304000	3387100	3372300			
Poland	1343362	1407953	1376489	1217933				
Republic of Korea	1339597	1273238	1410913	1560501	1409707	1639316	1248324	1288861
Japan	1182693	1163715	1097430	1141338	1207014	1207634	1212210	1220684
Belarus	877806	819079	779816	630561	426726	385122	342639	314654

Table 5.5 Year wise consumption of NPK fertilizer in India (Source: CEIC website [2019](#))

S.No.	Year	Consumption of NPK fertilizer (kg per hectare)
1.	2008	115.27
2.	2009	127.21
3.	2010	135.27
4.	2011	146.32
5.	2012	130.79
6.	2013	131.36
7.	2014	118.49
8.	2015	127.45
9.	2016	130.66
10.	2017	123.41
11.	2018	128.02

Coromandel International, Binh Dien Fertilizer, Petrokimia Gresik and Thai Central Chemicals will continue to be major producers of NPK fertilizers in China, India, Vietnam, Indonesia and Thailand, respectively (Open PR website [2020](#)). In India, the consumption of NPK fertilizer was reported to be 128.020 kg per hectare of land in March 2018 which is an increase with respect to the consumption in 2017. The year wise consumption of NPK fertilizer from 2008 to 2018 is tabulated in Table 5.5.

5.8 Conclusive Remarks

According to the reports of UN population prospects, the population of world is projected to be 34% from 6.8 billion to 9.1 billion by 2050 (FAO). This increase in population will automatically increase the demand for food. It is projected that the global demand for cereals for both food and animal feed is likely to reach 3 billion tonnes by 2050 (FAO). In order to satisfy the demand of food by 2050, the world's food production should increase by 70% which implies an extension of farmed land or an intensification of the production on the currently farmed land (Aznar-Sánchez et al. [2020](#)). This intensification can be obtained by applying high levels of fertilizers for increasing the yield of crops (Withers et al. [2018](#)). Thus the fertilizer production is likely to have an uptrend in the coming years. Though the nitrogen present in the nitrogenous fertilizers is ultimately recycled back to the environment in gaseous form through the action of biogeochemical cycle, however, phosphate and potash are exhaustible. Thus judicious use of phosphate and potash is very important in the coming years. Efforts should be taken to recycle the phosphate and potash fertilizer post-application in the agricultural fields which can be a topic of future research. In addition to it, the focus should also be given to use of biofertilizers which can very well fix, solubilize and transport essential nutrients from the atmosphere and deliver to the crops. Thus an overall balance is required in the application of fertilizers and recycling the same. A multidisciplinary approach towards the fertilizer management

coupled with the promotion of green manures seems to be the most optimal approach towards sustainable development for the overall benefit of mankind.

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