Fertilizers and Environment: Issues and Challenges

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Abstract About 50 % of the increase in agricultural produce during the twentieth century was achieved by application of inorganic fertilizers to crop plants. Fertilizer application is still an important farm input that is required to achieve challenging yield targets of the twenty-first century. However, fertilizer application is known to deteriorate the environment around us. Therefore, better fertilizer use efficiency (FUE) is suggested for economical yields and a safer environment. This chapter first introduces the concept of FUE for a safer environment and then, subsequent topics detail factors affecting FUE and known management practices to enhance FUE at agricultural farms. Future research challenges relating to FUE and the environment are identified. The chapter, as a whole, summarizes important literature for farmers, policy makers, and scientists.

Keywords Fertilizer use efficiency • Environmental pollution • Soil Fertility • Crop productivity

1 Introduction

In spite of decreased growth rate of the world's average population from 1.26 to 1.10 % since 2006, absolute annual increase is continuing to be large. According to a recent estimate by the Population Division of the United Nations, about 80 million people will be added annually to the world population until the mid-2030s.

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K.R. Hakeem (ed.), *Crop Production and Global Environmental Issues*,
DOI 10.1007/978-3-319-23162-4_21

The major share of this increase is expected to take place in the developing countries. More food, feed, and cloth are required for these additional people (Evans 2009). It has been estimated that the world will need twice as much food within 30 years (Glenn et al. 2008).

Over the previous few decades, dietary patterns around the globe have changed due to income growth, urbanization, awareness, and consumer preferences. Diets have shifted away from staples such as cereals, roots, and tubers and pulses towards more livestock products, vegetable oils, and fruits and vegetables (FAO 2008). Total meat production in developing countries has increased from 27 million tonnes to 147 million tonnes between 1970 and 2005, and global meat demand is expected to increase by more than 50 % by 2030 (FAO 2011). This will further increase the pressure on agricultural land, especially in Asia, which has the world's highest population density per hectare of arable land. Nonetheless, biofuel production would also require more land replacing the food crops. As per estimates, if biofuel use grows by 50 % over the next 10 years then 21 million hectares of food crops would be displaced by bioenergy crops. This would imply greater intensification of agriculture to meet food demand.

Cultivated soils do not usually contain sufficient amounts of plant nutrients for high and sustained crop yields. Therefore, agricultural yield depends upon availability of nutrients applied through fertilization and yield of most crops has been reported to increase linearly with the amount of absorbing nutrients (Kaur et al. 2007). Plant nutrition is one of the major factors that control soil productivity and quality (Jaga and Patel 2012). Fertilizers maintain soil fertility and productivity through supplying essential plant nutrients and therefore make a vital contribution to economic crop production.

Intensive agriculture can have negative effects on the environment: it can upset the balance of the food chain, pollute ecosystems, and cause harm to flora and fauna. To keep food production at the same level as population growth, without using up or destroying the resources and environment, is a major task. The main challenges include increasing the area of productive land, increasing the yield per unit area of land, maintaining soil productivity and reversing the nutrient mining of soil, and breeding new crop varieties with higher yield potential and improved tolerance to biotic and abiotic stresses. One of the sources of pollution from intensive agriculture is the excessive use of fertilizers (Ju et al. 2014). Typically a crop plant uses less than half of the applied fertilizers (Connor et al. 2011). Remaining nutrients attach to soil particles, leach into ground or surface water, or cause air pollution such as oxides of N (Ongley 1996; Hietz et al. 2011).

Recovery of applied inorganic fertilizer by plants is low in many soils of the world and increased fertilizer use efficiency (FUE) or nutrient use efficiency (NUE) is the only option for sustainable agriculture (Fixen 2009). Plants use only about 50 % of applied N; the remaining 15–25 % reacts with organic compounds in soil, 2–20 % is lost through volatilization, and 2–10 % is reported to interfere with surface and groundwaters (Raun and Johnson 1999; Sonmez et al. 2007; Chien et al. 2009). Average FUE is reported up to 65 % for corn, 57 % for wheat, and 46 % for rice (Ladha et al. 2005; Chien et al. 2009). The recovery of applied P is even lower and on an average only 25 % or less of the applied P is taken up by crop plants in a growing season. Moreover, precipitation of applied P with Ca and Mg in calcareous soils (Rahmatullah et al. 1994) and with Fe and Al oxides in acidic soils further reduces P use efficiency (Vance et al. 2003).

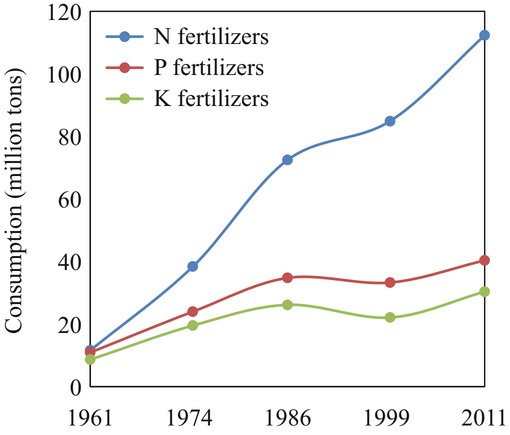
Overreliance and imbalanced use of mineral fertilizers is reported to pose serious public and environmental hazards (Savci 2012). The impact of fertilizer on the environment must be scrutinized as public influence over production is increasing. Overuse of N fertilizers contributes several harmful effects on the environment. In soil, by the process of microbial nitrification, ammonium ion is converted into nitrate and thus a negative charge on nitrate favours its downward movement into groundwater. However, the time taken by nitrates to move from the root zone to groundwater varies significantly depending upon soil texture and climate. According to the World Health Organization (WHO), concentration of NO_3-N should not exceed 10 mg L^{-1} in drinking water. The main alleged health hazard due to nitrate ingestion in food and water is a blue baby disease of young babies. Nitrogen loss as gaseous substances generally occurs through volatilization and denitrification, and this leads to environmental pollution. Another negative aspect of increased fertilization is eutrophication of water bodies. Increased concentration of P promotes luxurious growth of higher aquatic plants and algae that degrade water quality (Conley et al. 2009). Eutrophication leads towards depletion in oxygen and proliferation of unwanted species. As a consequence, it reduces the number of living species such as fish in the aquatic environment (Ansari et al. 2011).

Decreased fertilizer recovery not only has heavy costs but also has serious environmental concerns. Thus, judicious application of fertilizers to soils and their use by plants is needed for sustainable and safer agriculture. Nutrient use efficiency accounts for the acquisition of nutrients from the soil, biomass generation from nutrients, and remobilization of nutrients to organs of agronomic interest (Baligar et al. 2001; Aziz et al. 2011a, b). Nutrient use efficiency can be described by four agronomic indices: partial factor productivity (PFP), that is, crop yield in kg per nutrient applied in kg; agronomic efficiency (AE), that is, a kg crop yield increase per kg nutrient applied; apparent recovery efficiency (RE), that is, nutrient taken up in kg per nutrient applied in kg; and physiological efficiency (PE), that refers to kg yield increase per kg nutrient taken up (Mosier et al. 2004). Fertilizer use efficiency can be enhanced by adopting best management practices that refer to application of nutrient at the right time, from the right source, at the right rate, and at the right place (Roberts 2008; Epstein 1972; Fageria 1992).

2 Fertilizer Use Efficiency and Environment

Agriculture in the world is dependent on manufactured fertilizers and demand of fertilizers for crop production is increasing in most of the countries due to cultivation of modern varieties and intensive cropping systems. Consumption of N, P, and K fertilizers for crop production increased from 31 million tons in 1961 to 183

Fig. 1 Use of N, P, and K fertilizers. (*Source*: FAO 2014)



million tons in 2011 (FAO 2014). The greatest increase of consumption during the period was in N fertilizers (Fig. 1). The sharp increase in fertilizer consumption during the 1960s and 1970s can be attributed to the introduction of fertilizer-responsive cultivars of cereals, the Green Revolution cultivars. Even in the twenty-first century, the focus of plant breeders seems to be development of hybrids and varieties for greater yields. The new cultivars introduced have higher demands for nutrients as compared to old cultivars.

Energy and raw material, utilized for fertilizer manufacturing, often come from limited resources. A substantial amount of energy is consumed in the manufacture of fertilizers at industries and in transport of manufactured fertilizers to agricultural fields. From mining to manufacturing, various hazardous chemicals are introduced in the soil, water, and atmosphere. A detailed description of environmental hazards of the fertilizer industry is given in a technical report of United Nations Environment Programmme (UNEP 2000). Fertilizer manufacturing plants emit ammonia, fluorine (as SiF_4 and HF), oxides of N (NO_x and N_2O), oxides of S (SO_x), fertilizer dust, acid mists, and radiation in the atmosphere. Effluents of the industry also have these pollutants in toxic concentrations. Moreover, most of the solid wastes and by-products of the industry are pollutants. Therefore, manufactured fertilizers are a major cause of environmental pollution (Li et al. 2013; Ju et al. 2014).

Based on composition and purity of the raw material, fertilizers may be a source of pollutants in soils. As compared with N and K fertilizers, heavy metal contaminations were greater in rock phosphate and P fertilizers (Raven and Loeppert 1997). Toxic soil Cd concentrations in potato and sugar beet fields were related to long-term overuse of P fertilizers (Cheraghi et al. 2012).

Not all of the applied quantity of mineral nutrients is taken up by crop plants. More than 90 % of applied fertilizers may be lost in the environment leading to increased pollution of soil, water, and atmosphere. The situation gets worse when the applied nutrients, such as N and P, end up in water bodies causing eutrophication. Apart from runoff, N can also leach to groundwater and volatilize to atmosphere.

About 50 % applied N can be lost through ammonia volatilization and 25 % as nitrate leaching beyond the root zone (Zhao et al. 2011). Leaching of nitrate and contamination of drinking water resources increases health risks for humans and animals and volatilized ammonia is itself toxic and it also acts as a greenhouse gas and results in acid rains.

Due to pollution hazards of fertilizers during mining, manufacturing, and application, manufactured fertilizers are not safe for our environment (Table 1). Organic farming is suggested by some scientists as a sustainable and safer agricultural technology (Gabriel et al. 2010; Koohafkan et al. 2012; Strandberg et al. 2013). As desired yield levels are not achieved in organic farming, scientists have focused on integrated nutrient management strategies to improve fertilizer use efficiency (Bruulsema et al. 2008). Such strategies are not only good for better farm income, but also help us partially to decrease our dependence on manufactured fertilizers.

Table 1 Some fertilizer pollution reports from various world locations

Source	Location	Observations	Reference
N fertilizers	China	Aquifer have nitrate contamination about 20-100 mg L^{-1}	Zhao et al. (2011)
N fertilizers	India	Eutrophication, $NO_3 = 350$ mg L^{-1}	Pathak (1999)
N fertilizers	Poland	NH_4 concentration in pine tree bark 1699 mg kg^{-1}	Seniczak et al. (1998)
Rock phosphate	Pakistan	Contamination of Cr upto 105 μg g^{-1}	Javied et al. (2009)
Rock phosphate	North Africa	Concentration of Zn about 420 μg g^{-1}	Kongshaug (1992)
N fertilizers	Nigeria	$NO_3 = 20$–100 (mg L^{-1})	Uma (1993)
Phosphate fertilizer	China	Arsenic-contaminated soil with concentration about 1.6 to 20.3 mg kg^{-1}	Hartley et al. (2013)
Phosphate fertilizer industry	Lebanon	Zn = 92 (mg kg^{-1} soil)	Aoun et al. (2010)
Fertilizer N	China	Total N_2O emissions 980 (Gg N per year)	Liu and Zhang (2011)
Phosphatic fertilizer	China	Ar, Cd, and Pb contamination of 13.5, 2.6, and 300 mg kg^{-1}, respectively	Feng et al. (2009)
Single super phosphate	North Carolina	Contamination of Cd about 79.0 μg g^{-1}	Chien et al. (2009)
NPK fertilizer contain	China	Benzoanthracene 35.6 g kg^{-1}, Chrysene 33.9 μg kg^{-1}	Mo et al. (2008)
Fertilizer	Belgium	Polychlorinated dibenzo-p-dioxins 0.17 ng TEQ/k	Elsken et al. (2013)
Multinutrient fertilizer	Brazil	Contamination of Cr and Pb about 244 and 273 mg kg^{-1} soil	Nunes et al. (2010)
Rock phosphate	New Zealand	Contamination of Cd about 41 mg kg^{-1}	Loganathan and Hedley (1997)

Less fertilizer consumption at agricultural farms means less mining and manufacturing while there are still additional profits from crop production. By this, several issues of environmental pollution can be minimized. Therefore, increased FUE is a milestone towards a safer environment and greater agricultural profit.

3 Factors Affecting Fertilizer Use Efficiency

A fertilizer is considered efficient when maximum economical yield is obtained with the minimum amount of fertilizer application. Various soil, plant, fertilizer, and environmental factors that affect FUE are described below.

3.1 Leaching Losses

Nitrate (NO_3) fertilizers are susceptible to leaching losses (Almasri and Kaluarachchi 2004a, b). The extent of leaching is more in sandy soil compared to clayey soils. The situation is further aggravated when soil is bare than cropped soil. The main problems related to NO_3^- leaching are eutrophication of surface waters, increased production of nitrous oxide from receiving water bodies, and a higher concentration of NO_3^- in drinking water (WHO recommends <50 mg NO_3^- L^{-1} of drinking water).

According to Lehmann and Schroth (2003), nitrate leaching is lower in subsoil due to the increase in net positive charge, and the nitrate held in subsoil can be taken up by deep-rooted crops. Therefore, it is important to distinguish between nitrate movement within the soil profile (i.e., topsoil to subsoil), and leaching beyond the root zone, into the groundwater. Losses from ammonical fertilizers are higher during the summer season because of rapid oxidization by nitrifying organisms. The activity of the nitrifying organism can be reduced to minimize leaching losses. Various chemical compounds inhibit microbial nitrification of N fertilizers and reduce the leaching loss.

Phosphorus losses by subsurface leaching are negligible compared to losses by erosion and surface runoff. Subsurface leaching increases when P is in soluble organic form, as manure; the soil's capacity to bind inorganic P is saturated; preferential flow of water through channels and cracks in the soil prevents soluble P from getting in contact with the soil's adsorption sites. Furthermore, drained soils have a higher rate of subsurface leaching compared to undrained soils. Compared to inorganic P, dissolved organic P is more mobile in soil (Havlin et al. 1999; For detailed reading see Tunney et al. 1997).

Potassium can be lost in drainage water in sandy and acid soils and in high rainfall areas (Malavolta 1985; Havlin et al. 1999). Losses can be minimized by modifying the time of application with crop growth stage to maximum plant uptake period and also applying the fertilizer in split doses. However, in clayey soils, there are no leaching losses. Moreover, recently developed slow-release K fertilizers are not subject to leaching losses, for example, potash frits, potassium metaphosphate, and fused potassium phosphate.

Sulfate, added to soil as a secondary nutrient along with N and K fertilizers, is susceptible to leaching from the topsoil and accumulating in the subsoil. In the subsoil SO_4^{2-} is only available later in the season to deep-rooted crops. Leaching can also result in SO_4^{2-} losses to groundwater. Sulphate is also readily leached from surface soils; maximum losses are in soils dominated by monovalent cations such as K and Na and minimal in soils with high amounts of Al (Havlin et al. 1999).

3.2 Gaseous Losses

Gaseous losses of N from soils may be through (1) ammonia volatilization under high pH conditions in alkaline soils and (2) loss as N_2, N_2O, and NO due to denitrification. These losses are influenced by soil pH, fresh organic matter, moisture, temperature, and soil microbial diversity. Ammonia volatilization at high pH can be minimized by proper placement of urea. Cantarella et al. (2005) reported volatilization losses ranging 37–64 % of urea applied to maize crop at various locations. It is recommended to apply ammonical fertilizers at least 4–6 inches below the soil surface. Alternatively, urea should be used instead of nitrate fertilizer wherever there are high chances of losses of N by denitrification processes.

3.3 Immobilization

Immobilization is a major cause of reduced FUE as nutrients released from fertilizer become unavailable for growing crops over a certain period of time via chemical, physicochemical, and microbiological immobilization (Keeney and Sahrawat 1986; FAO 1972; Zhang et al. 2013). Ammonium and K ions are immobilized by strong adsorption by 2:1 type clay minerals such as vermiculite (Allison et al. 1953; Barshad and Kishk 1970). High soil pH further enhances this type of fixation. Practical soil fixation can be reduced by timely and proper placement of fertilizer. Fertilizer should be carefully selected so that it will have minimum interaction with the soil. Furthermore, the time and mode of application should be selected to ensure minimum immobilization of nutrients, such as preferable use of nitrate fertilizer may improve availability.

At low pH, the efficiency of water soluble P is very low. In acidic soils, P is known to react with Fe/Al oxides to form insoluble complexes (Vance et al. 2003). However, rock phosphate has shown increased solubility and availability under acidic conditions. In calcareous soils, applied P is invariably converted into tri-calcium phosphate, an insoluble P compound (Rahmatullah et al. 1994). Under such conditions water soluble P are relatively more efficient than water insoluble P such as rock phosphate.

Microbiological fixation of fertilizer N may be of concern when undecomposed organic matter of wider C/N ratio is present in the soil. However, this is a temporary type of immobilization. Application of a starter dose of N fertilizer to organic matter or by allowing enough time for complete decomposition of undecomposed organic matter may improve the N availability for the crop. Sulfate can bind to clays, and it is less mobile than nitrate but has higher mobility than phosphate.

3.4 Soil Compaction and Fertilizer Use Efficiency

Soil compaction is a common observation under mechanized farming and is one of the major problems facing modern agriculture. Soil compaction increases soil strength and decreases soil physical fertility through decreasing storage and supply of water and nutrients, which leads to additional fertilizer requirement and increasing production cost (Hamza and Anderson 2005). Numerous physical changes in soils due to compaction result in a poor response for N and P fertilizers. Soil compaction results in the soil particles coming closer resultantly decreasing soil bulk density and soil porosity. Because the points of contact between soil particles are increased, compaction also results in an increase of soil strength. In fine-textured soil, compaction reduces the available water capacity of soil, resulting in decreasing nutrient availability.

3.5 Soil Temperature

Soil temperature is one of the important environmental factors affecting plant growth and fertilizer response of crops (Mackay and Barber 1984; Pregitzer and King 2005). Temperature affects most physical processes occurring in the soil and the rate of chemical reactions increases with rise in temperature that controls nutrient availability. Soil temperature affects fertilizer efficiency by changing solubility of fertilizers, cation exchange, and ability of the plants to absorb and use nutrients (Pregitzer and King 2005; Hussain et al. 2010; Hussain and Maqsood 2011). Volatilization losses of N are related to high soil and atmospheric temperature. Soils in warm regions generally fix higher amounts of P compared to temperate regions. Soil temperature can be managed to an extent by common management practices including tillage, mulching, and irrigation. Moreover, root growth is severely affected by either too cold or hot soil temperature ultimately affecting nutrient uptake (Marschner 1995).

3.6 Soil Moisture

Soil moisture regulates nutrient movement within soil and their uptake by plants. Drought conditions can limit nutrient uptake because of decreased nutrient movement as well as decreased root growth (Marschner 1995).

Excessive moisture leads to leaching loss of added fertilizers whereas lack of moisture results in poor availability of the added fertilizer and high osmotic pressure of the soil solution due to concentration effect fertilizers (Taylor et al. 1983). Thus, efficient water management is complementary to efficient fertilizer management. Maximum efficiency of fertilizers can be obtained only in the presence of adequate soil moisture and vice versa. Mengel and Haeder (1973) demonstrated that increasing soil moisture from 10 to 28 % increased K transport by up to 175 %.

3.7 Soil pH

Soil pH is one of the major edaphic factors that regulate nutrient availability (Marschner 1995). Most plant nutrients are available at soil pH 6 to 7.5. If soil pH is lower or higher than the range, nutrient availability reduces sharply and even 1 unit pH increase or decrease can decrease/increase 100 times nutrient availability. At low pH, most micronutrients except molybdenum are available and even can be present in toxic concentrations because of their increased solubility (Tan 2011). In contrast, their availability reduces at alkaline pH particularly of Zn, Fe, Cu, and Mn.

Plant nutrient availability depends on the prevalent soil pH. In highly acidic or alkali soils, efficiency of P fertilizers is low. In such situations, efficiency of fertilizers can be increased by correcting the soil condition, using suitable amendments. Physiologically alkaline fertilizers such as calcium carbonate and the like should receive priority on acid soils and physiologically acid fertilizers, or alternatively use of acidic fertilizers such as ammonium sulphate on alkaline soils. At pH higher than 7, Ca and Mg ions, as well as the presence of carbonates of these metals result in precipitation of P fertilizers, decreasing their availability (Cole and Olsen 1959; Shen et al. 2011).

3.8 Soil Organic Matter

The organic matter in soil not only supplies different nutrient elements, but also improves physical conditions of soils, stimulates microbial activity, protects the soil from erosion, retards the fixation of nutrients, increases mobility of nutrients in soils, increases the buffering capacity, and helps in many other ways (Tan 2011; Osman 2013a, b). Potential benefits of organic matter in soil in turn increase the efficiency of applied inorganic fertilizers. However, a high amount of organic matter may not prevent P losses as a result of leaching. This may be due to the absence of Al and Fe compounds, which are mainly responsible for P retention under low pH conditions (Vance et al. 2003).

3.9 Plant Characteristics

Crop species vary in their ability to remove nutrients form soil. Furthermore, there is significant variation within cultivars of the same crop species (Aziz et al. 2006, 2011a, b, 2014; Gill et al. 2002). Numerous researchers have revealed varietal variations for K uptake in ryegrass, maize, soybean, and barley (Dunlop et al. 1979; Terman 1977; Glass and Perley 1980). Because the roots are the principal organs through which plants take up nutrients, the rooting pattern and habit have an important bearing on nutrient removal. Crops with shallow extensive fibrous roots are able to uptake a greater amount of fertilizer applied per unit area (Lynch 1995). The fertilizer needs of deep-rooted crops are generally lower than shallow-rooted crops. Munson (1985) identified five plant root factors that significantly influence nutrient uptake from soil. These include ion flux, root radius, rate of water uptake, root length, and rate of root growth.

3.10 Fertilizer Characteristics

Nutrient mobility, type of fertilizer, and the time and method of application significantly influence the FUE (Sadras and Lemaire 2014). Nitrogenous fertilizers are highly mobile and subjected to both downward and lateral mobility. In contrast, P is highly immobile (Smeck 1985). Potassium is also mobile but compared to N its mobility is lower (Nastri et al. 2000). To get maximum efficiency N and K fertilizer should be applied in frequent split doses and P as basal dressing or near the root zone (Munson 1985; Sowers et al. 1994; Awan et al. 2007). The type of fertilizer also determines the efficiency (Zaman et al. 2005). Ammonium and urea fertilizers are more efficient than nitrate fertilizers for paddy soils (Datta 1986). Water-soluble P materials are more efficient for short duration crops and in soils that are neutral to alkaline in reaction. There is also a certain amount of interaction noticed among crops and fertilizers. For example, paddy performs better when ammonium sulphate is applied as N carrier and for tobacco when potassium sulphate is applied as K carrier (Craswell et al. 1981; Vann et al. 2013).

4 Possible Ways to Improve Fertilizer Use Efficiency

Increase in FUE aims at obtaining more yield while adding a small amount of fertilizer materials. This will not only result in minimizing the production cost for a certain crop but it will also reduce the risk of environmental contamination. Hence, it improves the overall economy of a region/country. The FUE can be improved by managing soil and plant factors coupled with improvement in fertilizer materials.

4.1 Site-Specific Nutrient Management

Soil is an ultimate reservoir of plant nutrients and their availability depends upon a number of soil properties including physical, chemical, and biological (Havlin et al. 1999). As the soil system is dynamic, hence both temporal and special variability exist resulting in a huge variation in nutrient concentrations even in similar soil types. Fertilizer recommendations are general for any region or area. This may lead to over- or underapplication of applied fertilizer materials, resulting in a decreased FUE. Moreover, a plant's nutrient requirement varies with growth stages. This demands site-specific fertilization depending upon soil physicochemical properties and crop species/varieties. Fertilization according to the need of the crop is one of the management options to improve FUE and reduce the risk of environmental contamination. Precision farming technology is a valuable tool to identify and correct site-specific crop nutrient deficiencies (Roberts 2008). In addition to crop monitoring, modern technologies such as leaf color charts, chlorophyll meters, and remote sensing are useful techniques to manage nutrient requirements by crops.

4.2 Crop-Specific Nutrient Management

Crop responses to applied fertilizers vary from specie to specie; variability even exists among different cultivars of the same species. For example, cereals demand more K compared to vegetables and other crops (Greenwood et al. 1980), whereas dicotyledons require more B than monocots (Neales 1960). Thus, application of these nutrients to such crops according to their requirement will result in more efficient utilization and reduced losses to the environment. A number of studies have been reported on genotypic variation among wheat, maize, cotton, brassica, and rice cultivars for different nutrients (Kanwal et al. 2009; Maqsood et al. 2009; Aziz et al. 2011a, b, 2014). Hence, application of fertilizers to crop cultivars that are not responsive and inefficient utilizers leads towards environmental pollution. Moreover, as a plant goes through different growth stages during its life cycle, certain stages are high-demanding compared to others. Hence, FUE can be improved by applying the nutrients at the right time and in the right amount, when there is actual need for that nutrient by the growing crop. Split application of N is also one of the management options to match the nutrient requirement with the crop demand. Ortiz-Monasterio et al. (1996) found about 50 % reduction in nitrous oxide emission from irrigated wheat crop while applying only 33 % of N fertilizer at planting and the remainder after 1 month.

Nature has bestowed an excellent mechanism in plants by which certain crop species/genotypes are more efficient utilizers of applied as well as indigenous soil nutrients. This may be attributed either to more efficient nutrient uptake or its rapid assimilation during metabolic processes. Roots play an important role in this regard. However, root growth is also restricted under high nutrient concentration (Shen et al. 2012). As FUE aims at obtaining more yield with the application of less fertilizer material, therefore nutrient application should be at the optimal rate at which root growth is maximum. However, under high input systems, FUE can also be improved by maximizing root proliferation in subsurface soils either through breeding or agronomic nutrient management practices (Mi et al. 2010; Lynch 2007, 2011). More root proliferation leads to more exploration of soil nutrient reserves, hence more nutrient uptake. Farmers can achieve better FUE by growing those cultivars that are efficient utilizers of applied as well as indigenous plant nutrients.

4.3 Fertilizer Materials

Fertilizer use efficiency can also be improved by changing the morphology of the fertilizer material either by coating or by increasing the size of the granule. Fertilizers vary in nutrient solubility, availability, and recovery. Fertilizers applied to one crop may have residual effects for subsequent crops. Only less than half of the applied P may be recovered by the first crop (Sattari et al. 2012), whereas most of N fertilizers are readily available to plants and mobile in the soil system. This leads to higher losses of applied N. Coated N fertilizers with controlled release of N can ensure a continuous supply of N to plants for longer periods (Mulder et al. 2011; Ni et al. 2011a, b; Xie et al. 2011; Yang et al. 2011).

Controlled/slow-release fertilizers for improving NUE from urea have also been practiced in many parts of the world. In addition, urease inhibitors were also introduced to minimize N losses from urea. A number of inorganic and organic urease inhibitors were tried in the past (readers are referred to the review by Chien et al. 2009). However, *N*-(*n*-butyl)thiophosphorictriamide (NBTPT) was found to be most effective compared to others such as phenylphosphorodiamidate (PPDA) (Byrnes 1988; Lu et al. 1989). NBTPT addition to soil resulted in 60 % reduction in ammonia volatilization losses compared to control where no urease inhibitor was applied (Cantarella et al. 2005). In addition, some other laboratory and field studies (Chien et al. 1988; Christianson et al. 1990; Freney et al. 1995) revealed that cyclohexylphosphorictriamide (CHPT) was even more effective than NBTPT. Combined nitrate and urease inhibitors were also tried to see their impact on improving FUE (Nastri et al. 2000; Radel et al. 1992; Zaman et al. 2005). However, until now urease inhibitors can delay NH_3 losses for only 1–2 weeks in the case of surface application of urea (Chien et al. 2009). Moreover, it also depends upon soil physicochemical properties coupled with moisture and temperature. Nevertheless, coating of urea with natural biodegradable polymers and micronutrients can also reduce N losses from 30 to 67 % (Junejo et al. 2011). In addition, the concept of urea supergranules has also been reported with some advantages over the routine application of normal granules. This will act as a slow-release fertilizer.

These controlled released fertilizers only partially reduce nutrient losses and further research is required to check nutrient losses by applying the right type of fertilizer. Therefore, research efforts must be directed towards cheaper and environmentally friendly fertilizers that have minimal nutrient losses and greater FUE. A number of new fertilizer products are now available to improve fertilizer use efficiency including sulphur-coated urea, slow-release fertilizers, smart fertilizers, and nitrification inhibitors.

4.4 Integrated Nutrient Management

Integrated nutrient management (INM) (i.e., combined use of organic and inorganic sources of nutrients) is also an important key to achieve higher FUE (Yamoah et al. 2002). Organic amendments not only improve soil fertility status but also result in improvement of soil physicochemical properties such as structure and nutrient and moisture retention, as well as porosity/aeration. However, while adding organic amendments to soil, their C:N ratio and mineralization rate should also be kept in mind (Treadweell et al. 2007).

Incorporation of legumes in crop rotation is also an integral component of INM. Legumes not only improve soil nutrient reserves but also improve soil physical properties helpful in root proliferation, hence more efficient nutrient uptake. Rahman et al. (2009) observed a significant increase in N use efficiency while incorporating broadbean and hairy vetch legume crops in a rice-based cropping system. INM by using green manures, animal manures, and crop residues reduces the fertilizer application rate along with reduced emission of N_2O (Aulakh 2010), hence more FUE. Long-term studies on INM in China were conducted in multilocation field trials for rice by Zhang et al. (2011). They observed 20–30 % reduction in fertilizer use coupled with 20–80 % increase in agronomic FUE. However, success of this INM system demands a comprehensive training of the farmers. Otherwise imbalanced use of nutrients will not only waste the resources but lead towards environmental contamination.

4.5 Method of Fertilizer Application

Nutrient losses can also be minimized by following proper application methods. Conventional fertilizer application methods such as broadcasting and side dressing are less efficient compared to fertigation and foliar fertilization techniques (Rehman et al. 2012). Nevertheless, it also depends upon specific mineral nutrient, crop species, and soil properties. For example, banded application of P to crops results in more P uptake compared to broadcast application. This improved P uptake might be attributed to reduced soil contact, hence less fixation of applied P fertilizers. Sitthaphanit et al. (2009) observed reduced leaching losses of N, P, and K by split application and delaying the basal application in a tropical sandy soil. N losses from urea and other fertilizers can also be minimized by its deep placement into the soil. Deep placement of urea supergranules is one of the best management options to improve FUE in flooded rice in Bangladesh and Vietnam (Roy and Hammond 2004). However, its application is laborious and costly, hence impracticable for developed countries of the world.

Unconventional methods of fertilizer application are also in practice in many parts of the world. Nutrients are applied directly to the leaves (foliar fertilization) or to the roots (drip fertigation) where they are actually required. It also involves reduced fertilizer and labor cost. Moreover, it will result in improved water use efficiency in arid and semiarid regions of the world. Liang et al. (2014) found that optimal daily fertigation is a better approach to improve cucumber yield and FUE under greenhouse conditions. Alam et al. (2005) conducted a study on wheat crop employing different N and P application methods and found 74 % increase in P fertilizer efficiency over top-dressed N and P. Fertigation results in improved N use efficiency as more NO_3 are present in the upper soil surface and NO_3 leaching losses to the groundwater decrease (Hebbar et al. 2004; Hou et al. 2007; Hassan et al. 2010). However, there are certain limitations that should be addressed before following these practices. In the case of fertigation, fertilizer material should not be corrosive and also not react with other chemicals in water. In addition, good quality water should also be used otherwise precipitation of salts will result in clogging the entire irrigation system. Therefore, generally fertigation is practiced for vegetable and fruit plants.

Foliar feeding of nutrients to plants is also a promising management strategy to improve FUE. With micronutrients that are generally required in small quantities, their uniform application to growing plants can also be carried out by foliar application. Dixon (2003) reported that foliar application of N and P is about 7 and 20 % more efficient compared to soil application of these nutrients. Foliar application of urea resulted in 80 % recovery of applied N in wheat crop (Smith et al. 1991). Foliar application along with the bed planting method resulted in improved agronomic efficiency, that is, about 93.82 % compared to conventional methods where it was only 43.67 % (Bhuyan et al. 2012). However, foliar fertilization of plants should be done at very low rates of fertilizer material otherwise leaf burning will result in crop damage. In addition, nutrient feeding through foliar application also demands a comprehensive knowledge of crop growth stage and nutrient demand.

4.6 Balanced Fertilization

Balanced nutrition is an important key to improve FUE. The major reason for low N use efficiency in many agricultural soils of the world is either high N input or low N input. In the case of high input agricultural systems, it leads towards the contamination of natural resources. Indeed N deficiency is ubiquitous throughout the world but in addition, certain other essential elements such as P, S, K, Zn, and B are also deficient. According to an estimate about half of the world's cereal-growing soils are Zn deficient (Cakmak 2002). Boron deficiency has also been reported in more than 80 countries worldwide (Shorrocks 1997). However, in many parts of the world mostly farmers apply N coupled with a nominal quantity of P fertilizer while ignoring the use of K and other macro- and micronutrients. This imbalanced fertilization results in a wider N:P ratio of about 7:1 to 6:1 (Vitousek et al. 2009). Furthermore, a very wide N:K ratio (i.e., 1:0.23 to 1:0.36) exists throughout the world (Krauss 2004). This practice is more common in developing countries and is one the major constraints to improve nutrient utilization efficiency in the existing cropping systems. As plants need 17 essential elements for their growth and development, so overuse of only one nutrient creates a strong imbalance and results in reduced NUE by plants. A number of studies reveal that addition of S, K, P, and Zn along with N results in enhanced N recovery from the applied fertilizer source, hence more FUE (Aulakh and Malhi 2004; Gordon 2005; Salvagiotti et al. 2009; Liu et al. 2012a, b, c). Dobermann et al. (2002) observed 30–40 % increases in N recovery efficiency of rice from balanced fertilization. More efficient recovery of nutrients from applied fertilizers will lead towards reducing the burden of contaminants on the environment.

5 Moisture Conservation and Water Management

Moisture conservation in rainfed areas by mulching and deep ploughing will enhance fertilizer efficiency. Similarly management of irrigation water at critical crop stages is also important to improve fertilizer efficiency.

6 Future Challenges

6.1 Limiting Resources of Rock Phosphate

Limiting raw material for fertilizer manufacturing further increases the importance of FUE. Rock phosphate is the only raw material for most P fertilizers. According to Global Phosphorus Research Initiative, reservoirs of rock phosphate are estimated to deplete completely in the next 100 years (GPRI 2014). This demands wise use of available rock phosphate and higher FUE (Cordell et al. 2011). Moreover, the only option when rock phosphate will not be available will be managing the P cycle while adding the required P rates in the form of organic matter (Dawson and Hilton 2011). Then this organic matter must be mineralized at a rate of crop P demand. Related strategies are already known and often listed under organic farming. However, organic farming is uneconomical in most developing countries due to lower crop yields and greater expense. A great number of scientists are working to find a suitable alternative technology for the days when rock phosphate will no longer be available. Plant breeding for better P uptake and use efficiency for a P-deficient environment is being advocated and efforts are underway; however, newly developed cultivars of agronomic crops actually require greater inputs of P fertilizer as increase in yield is often related to greater fertilizer demand.

6.2 Depleting Soil Fertility

Exhausting cropping systems are depleting nutrients from the soils (Foster and Magdoff 1998) and heavy fertilizer applications can damage the environment due to losses of nutrients. Also, higher fertilizer rates decrease FUE and may result in uneconomical yield if applied more than the crop demands. Restoration, maintenance, and buildup of soil fertility status require knowledge about various soil aspects (Palm et al. 1997; Sanchez et al. 1997; Lahmar et al. 2012). Due to imbalanced application of fertilizers, soil is more depleted in micronutrients as compared to macronutrients (Fan et al. 2008). For many cropping systems, workable strategies are still not known to maintain soil fertility and produce greater yield by taking into consideration soil and environmental health.

6.3 Soil-Specific Recommendations

It is recommended that fertilizers should be applied according to crop requirement and soil characteristics (Pierce and Sadler 1997). Soil- and crop-specific fertilizer recommendations take into account soil, crop, and environmental factors for greater nutrient recovery and yields (Swinton and Lowenberg-DeBoer 1998). The right type of fertilizer applied in the right amount, with the right method, and at the right time are important considerations of FUE (Bruulsema et al. 2008). However, there is a need for developing kits for determining site-specific crop nutrient deficiencies. This will be a great breakthrough in improving FUE and reducing the risk of environmental contamination of land, air, and water resources.

Soils differ greatly in physical, chemical, and biological characteristics. Therefore, plant-available pools of nutrients in soils also vary (Hussain et al. 2011). The native status of a particular nutrient in the soil is the most important factor controlling the required rate of fertilizer. Based on this approach, scientists have formulated critical concentrations of plant-available nutrients in soils. These critical limits are (in mg kg^{-1} soil): nitrate-N (extraction with AB-DTPA) >20, P (extraction with $NaHCO_3$) >15, K (extraction with NH4OAc) >150, Zn (extraction with DTPA) >1.0, Cu (extraction with DTPA) >0.5, Fe (extraction with DTPA) >4.5, Mn (extraction with DTPA) >2.0, and B (extraction with hot water) >1.0 (Watanabe and Olsen 1965; Mahler et al. 1984; Soltanpour 1985; Quevauviller et al. 1996). Depletion of nutrients from soil solution by plant uptake is restored from various other nutrient pools in soils (Viets 1962; Barber 1995). However, soil buffering capacity is partially ignored when recommending fertilizers on the concentration of plant-available nutrients in the soil. Therefore, FUE would differ if soil buffering capacity is sufficient to supply nutrients over a longer period of time.

Only soil P and K are investigated in detail by different adsorption and release models for soils. Reports suggest recommending fertilizer rates based on adsorption isotherms: however, this is limited to P and K only (Zhengli et al. 1988; Mehadi et al. 1990; Dobermann et al. 1996). However, recommendations based on adsorption isotherms are often too complex to be understood by farmers. Moreover, there are site-to-site variations among the fields of a farm and even within a single field. There is a demand for a more farmer-friendly and dynamic system of fertilizer recommendations that consider all soil characteristics. Efforts are underway to estimate site-specific fertilizer requirements by use of advanced technology (Mueller et al. 2001; Franzen et al. 2002; Mallarino and Wittry 2004). However, the desired success is still awaited.

6.4 Biofortification, Environment, and FUE

Biofortification of edible plant parts through genetic and agronomic means is being advocated on a large scale (Bouis et al. 2011). Biofortification strategies currently focus on seven mineral elements (Fe, Zn, Cu, Ca, Mg, I, and Se) that are most commonly deficient in human diets (White and Broadley 2009). Agronomic biofortification strategies require higher rates of fertilizer application to increase food quality (Hussain et al. 2013). However, the greater the nutrient applied, the lesser will be FUE and there will more environmental hazard.

Computations for FUE include amount of fertilizer applied, amount of nutrients uptaken by plants, and yield of the crop (Jat and Gerard 2014). Environmental considerations, food quality parameters, and actual farm profits are not considered in FUE. Nevertheless, these factors play a key role in suitability and profitability of fertilization (Prasad 2008). In future, new computations of FUE are required to include these factors. Farm profit can easily be calculated. However, the most challenging task is to quantify environmental hazards of fertilization in a given soil-crop-environment and management combination. Probably, the amount of nutrient lost in the atmosphere or water bodies is more hazardous for the environment as compared to the amount of fertilizer temporarily retained in the soil.

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