Chapter 10
Fertilizer Management in Rice

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10.1 Introduction

Rice (*Oryza sativa* L.), with global production of more than 740 M t in 2014 (FAOSTAT 2016), is the staple food for nearly half the world population. Rice can be grown both in dry and wet conditions over a wide range of latitudes and across a wide range of soil, climatic, and hydrological conditions; primarily, it is grown in the humid and subhumid tropics and subtropics. Global average yield of irrigated rice is 5 t ha^{-1}, but national, regional, and seasonal yield averages vary widely. In the tropics, skilled rice farmers achieve rice yields of 7–8 t ha^{-1} in the dry season, and 5–6 t ha^{-1} in the wet season when cloud cover reduces the amount of solar radiation and hence the yield. The productivity of rainfed upland and flood prone deep water rice, however, continues to be low and is static around 1.0 t ha^{-1} (Dobermann and Fairhurst 2000). To produce high grain yield levels, modern rice cultivars require adequate amount of essential nutrients. Of the total 172.2 Mt fertilizer ($N+P_2O_5+K_2O$) consumed globally during 2010–2011, 14.3 % (24.7 Mt) was used in rice. Percentages for nitrogen (N), phosphorus (P), and potassium (K) were 15.4, 12.8, and 12.6, respectively (Heffer 2013). Intensive rice production and future rice demands will require knowledge-intensive strategies for the efficient use of all inputs, including fertilizer nutrients. As irrigated and rainfed lowland rice systems account for about 80 % of the worldwide harvested rice area and 92 % of total rice production (Dobermann and Fairhurst 2000), the discussions in this chapter will be focused more toward these production systems.

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In lowland rice ecosystems, the crop is flooded for all or part of the growing season. Rice is unique among cereal crops because its root system is adapted to largely anaerobic soil conditions. The aquatic environment also alters the availability of several essential nutrients, affects nutrient uptake and use efficiency and fertilization practices. Although some issues still require more research, knowledge of nutrient management under flooded soil conditions to produce lowland rice has progressed rapidly over the past several decades. Average recovery efficiencies of N, P, and K from mineral fertilizers in field trials with rice at 179 farmers' fields ($n = 314$) in five countries (China, India, Vietnam, Indonesia, and the Philippines) were 33, 24, and 38 %, respectively (Witt and Dobermann 2004). However, data compiled from research trials from all over the globe revealed that average recovery efficiency for N was calculated as 46 % (Ladha et al. 2005). Better nutrient management practices at research stations compared to those followed by farmers was the reason. Similarly, optimization of factors that cause low P- and K-use efficiency in rice is important. In a long-term experiment with rice in China (Zhang et al. 2006), with no P application (NK treatment), rice had a high internal P efficiency of 590 kg grain kg^{-1}, indicating P deficiency. Adding P but skipping K (NP treatment) alleviated the P deficiency, but because the system was K-deficient, this resulted in suboptimal yield increase and an uneconomical soil P accumulation. With balanced fertilization (NPK), yield was increased primarily due to an increase in recovery and agronomic efficiency. Imbalanced use of fertilizers not only aggravates the deficiency of K as well as micronutrients in the soils (Ladha et al. 2003), but also proves to be uneconomic and environmentally unsafe. In about 50 M ha of rice land in Asia, deficiency of phosphorus (P), zinc (Zn), or iron (Fe) or excess of salts like iron or aluminum limits rice yields.

A large potential exists for increasing rice yield but inefficient nutrient use is one of the most limiting factors. To ensure higher rice productivity, appropriate nutrient management practices have become an essential component of the modern rice production technology. Nutrient use efficiency in rice can be improved by using proper inorganic and organic nutrient sources, need-based rate of fertilizer application, appropriate methods, and application timing of fertilizers, water management, soil pH management, and the use of high yielding cultivars adapted to a given environment. Efficient nutrient management in rice has paramount significance for improving yield and profitability in short term and better ecological management services in the long-term perspective.

10.2 Nitrogen

Nitrogen is a constituent of amino acids, proteins (enzymes), nucleic acids, and chlorophyll in plants and is usually the most yield limiting nutrient in rice production except in soils containing high organic matter content, which can supply enough N during the crop season. It is a mobile element inside the plant so that its deficiency symptoms appear first on the older leaves. Lower leaves of N deficient rice plant turn yellow later but if the deficiency is not corrected, whole plant may become chlorotic. Deficiency of N in rice leads to reduced plant height, tillering, leaf area index, and crop photosynthetic rate.

Irrigated lowland rice is one of the most inefficient crops with respect to fertilizer N-use efficiency. Different management options can be followed to supply adequate amount of N to rice crop for optimum production and minimal losses into the environment. However, successful adoption of a set of practices for lowland rice requires an understanding of the relationships among rice growth and development, the biological and chemical transformations of fertilizer and native soil N, soil chemical and physical properties, and management of irrigation water.

10.2.1 Nitrogen Transformations in Flooded Rice Soils

Rice is grown in variable, complex, and dynamic soil moisture regimes during a crop season. The soil is generally flooded either immediately before rice is seeded (as in direct water-seeded culture) or transplanted. In case seedlings are established by direct dry-seeded methods as in broadcast or drill-seeded rice, soil is flooded when the crop reaches the five-leaf stage and begins to tiller. In typical rice soils (heavy textured with low permeability), the flood water is generally maintained until physiological maturity. In permeable light textured soils, fields are flooded every 1 or 2 days after the flood water is drained. In some instances, the flood water is intentionally drained to allow the soil to completely dry for specific management reasons or it is lost due to lack of short-term water availability. Most of the irrigated rice production systems are subjected to alternate wetting and drying (aerobic and anaerobic cycles) within the crop season or between the crop seasons.

Flooding an oxidized soil affects utilization of both the soil N and the fertilizer N by rice. Under aerobic conditions, NH_4^+ is very rapidly oxidized to NO_3^-. Flooding of the soil accentuates the loss of almost all NO_2^- and NO_3^- present in the soil through denitrification and leaching (Buresh et al. 2008). Thus, most of N mineralized under aerobic soil conditions is lost before its uptake by the rice crop. On the other hand, under flooded conditions, organic N continues to be mineralized and remains available as NH_4^+ for plant use rather than being nitrified and lost via denitrification (Fig. 10.1). To produce optimum rice yields, amount and time of application of fertilizer N should be governed by the amount and pattern of organic N mineralized after flooding. The rice production systems that lack controlled water management and undergo several alternate aerobic and anaerobic shifts during a crop season show inefficient N use because substantial amounts of applied as well as native soil N are preferentially lost via denitrification. The most fundamental N recommendation for lowland rice is to use ammonical or NH_4^+ forming fertilizers such as urea. Ammonium N may be lost through volatilization, fixed by clay minerals, or immobilized by soil organic matter (Fig. 10.1). The NO_3^- containing fertilizer sources should not be applied prior to soil submergence as NO_3^--N may get denitrified or lost via leaching, particularly on permeable sandy soils or may possibly be transported in the general direction of water movement across a field (Buresh et al. 2008). As NH_4^+, a cation, attaches to the soils cation exchange complex and is held by the soil very close to its point of placement, NH_4^+ fixation capacity of a soil should be taken into account when strategies for N fertilization are developed to maximize N-use efficiency.

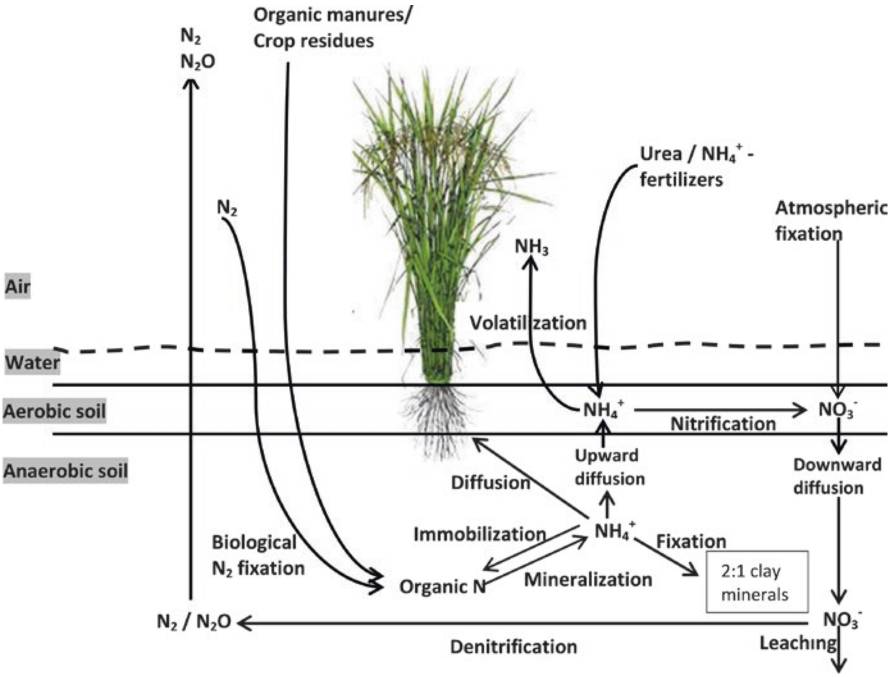

Fig. 10.1 Nitrogen transformations in a submerged soil under lowland rice

10.2.2 Critical Levels and Uptake of Nitrogen by Rice

Nitrogen is a highly mobile element inside the plant and when N is deficient in plant body it is readily translocated from stems and older leaves to the younger leaves or developing panicles at the heading stage. Critical N concentration in the rice plant generally increases quadratically with increasing N application rate and decreases with an increase in plant age due to the dilution effect (Fageria and Baligar 2001). Yoshida (1981) found that tiller development was stopped when leaf blade N concentration was <20 g N kg^{-1} of plant dry matter; tillering rate was increased linearly as leaf blade N concentration increased up to 50 g N kg^{-1} of plant dry matter. De Datta (1981) concluded that 25 g N kg^{-1} in the leaf blade of rice plants at the active tillering stage was the critical value. Because a concentration gradient can be observed among the leaf positions from top to bottom, the youngest leaves have a higher N concentration than older leaves (Westfall et al. 1973). The N status of the first fully opened leaf from the top of rice plants at any given time has been found to be a reliable indicator of the N availability in the soil. Technological developments during last decades have made it possible to quickly and nondestructively quantify chlorophyll content related spectral characteristics of leaves. It can be used to diagnose plant N deficiency and efficiently manage fertilizer N in rice (Bijay-Singh 2014).

Like most other plants, rice can absorb N from the soil solution both as NO_3^- and NH_4^+, and the preferential form of N uptake is mainly determined by its abundance and accessibility. A large body of published literature, in general, suggests that rice prefers NH_4^+ compared to NO_3^-; however, Takenaga (1995) observed that rice absorbed NH_4^+-N more effectively during vegetative stage and NO_3^--N during reproductive stage. Rice does not absorb large amounts of NO_3^- because generally NH_4^+ containing fertilizers are applied and management practices largely prevent nitrification (Buresh et al. 2008). Urea undergoes hydrolysis after it is added to soil, and forms NH_4^+, hence, both ammonium sulfate $[(NH_4)_2SO_4]$ and urea are equally effective N sources for rice. Ammonium sulfate is a better source of N than urea on alkaline soils or when it is not possible to incorporate fertilizer immediately by flooding. Ammonia volatilization, i.e., the loss of N as NH_3 gas, may be a pathway of significant importance when urea is applied to rice in alkaline soils. According to De Datta (1981), N should be applied as NH_4^+ at the planting of rice. Once rice crop reaches the panicle initiation stage, it rapidly takes up the NO_3^- form of N. The NH_4^+ and NO_3^- forms are equally effective when N is used as topdressing to rice (Wilson et al. 1994).

Total N uptake and dry matter accumulation of rice with age follow similar trends. Adequate N availability during the beginning of rapid growth (tillering) plays an important role for optimum growth and yield. With an increase of dry matter of rice crop, plant tissue N content decreases due to dilution effect, whereas total N uptake increases with increased dry matter. Almost half of the total dry matter is produced by the start of panicle initiation/booting stage and accordingly half of the total N uptake occurs by this stage. When the supply of fertilizer N to rice is optimum, 50 % of the total N is absorbed before half of the total dry matter is produced. Remaining 30–50 % of the total N uptake occurs after the start of panicle initiation. About 60–70 % of the above-ground N is located in rice panicle at maturity. Most of the N in rice grain at harvest is absorbed between rice panicle emergence and heading. It is initially stored in plant tissue and eventually translocated to the panicle. Modern high yielding varieties producing around 5 t ha^{-1} of grain, in general, can remove about 110 kg N from the soil. Uptake of native soil N plays a crucial role in the N nutrition of rice crop. The total N content of rice straw and grain at maturity usually contains 20–40 % more N than that supplied by fertilizer and this extra (other than fertilizer) N is supplied by native soil N (Moore et al. 1981).

10.2.3 Nitrogen Use Efficiency and Fertilizer N Management in Rice

Fertilizer N is used efficiently when a large proportion of the applied fertilizer is taken up by the crop (termed recovery efficiency), and there is a reasonable increase in yield for each kilogram of fertilizer N applied (termed agronomic efficiency). In the case of rice, N fertilizer use efficiency varies widely depending upon the fertilizer source, the N application time, or both. The recovery efficiency of N fertilizer by rice generally ranges from 20 to 80 % (Fageria et al. 2003) with an average of about 30–40 % (Cassman et al. 1993). However, the amount of N not accounted for N recovery efficiency should not be interpreted as N that is lost without utilization from the soil–plant system. A portion of the unaccounted N may certainly be lost by denitrification, leaching, and ammonia volatilization, but a significant portion of this N may be incorporated into the microbial biomass or reside in the rice root system and become a part of the soil organic matter. Between 16 and 25 % of the total applied N fertilizer has been recovered in the soil organic fraction between panicle differentiation and maturity of rice (Bollich et al. 1994).

The rate, source, time of application, and method or placement of N fertilizer determine N recovery efficiency in the above-ground biomass of lowland rice. Many of the principles that govern N-use efficiency are the same for transplanted, dry direct seeded, or direct-water-seeded rice cultures (Fageria et al. 2003). The time of application of split doses of fertilizer N varies because critical growth stages of rice under different systems occur at different times. Nitrogen fertilizer is typically applied in at least two or more split doses in most of the rice production systems. The first application is often termed as basal dose. Sometimes the basal application represents the largest portion (50–75 % of the total N requirement) of N fertilizer applied in any single application during the growing season. In transplanted rice systems, N fertilizer is applied to the soil surface and mechanically incorporated before the field is flooded, applied to the soil surface and incorporated by the flood water, or injected into the soil. In the dry seeded, delayed flood system, the basal dose of N is applied during early vegetative growth and followed by application of irrigation. Regardless of the cultural system, the most fundamental components of basal N management are the use of an ammonium-forming N fertilizer source, the N fertilizer application on a dry soil surface, and the immediate flooding of the soil (Kamprath and Watson 1980). Split doses of fertilizer N applied as top dressings after the basal dose are utilized more efficiently than basal application (Westcott et al. 1986). Recovery efficiency of top dressed N doses is, however, determined by rice growth stage and time of application. Due to low rates of fertilizer N (around one-third of the total fertilizer N), a highly developed rice root system, and the high plant N requirement around panicle initiation stage, recovery efficiency of top dressed N dose is very high and may range between 45 (Westcott et al. 1986) and 82 % (Wilson et al. 1994).

Proper management of the floodwater is critical for efficient utilization of N fertilizer applied to rice. If flood water is drained before uptake of N by rice, nitrification of NH_4^+-N may lead to production of NO_3^--N, which may get leached or denitrified in case soil is reflooded. The recovery efficiency of the basal application of urea-N in the dry-seeded, delayed flood system may approach to 70 % under optimum conditions (Wilson et al. 1994). When basal N is applied to a wet soil or the flood water is mismanaged, the recovery efficiency declines. In several regions in the Indo-Gangetic plains in South Asia, generally continuous flooding of rice cannot be maintained either due to shortage of water or due to high water percolation rates in the soil and it leads to alternating flooded (reduced or anaerobic) and drained (oxidized or aerobic) conditions. Therefore, nitrification occurs during “dry spells” and nitrates thus produced are subsequently reduced to N_2 and N_2O through denitrification when soils are reflooded. Although there is much variation in the data on nitrification rates estimated at different locations in the Indo-Gangetic plain, a trend with respect to soil temperature and pH is easily discernible (Aulakh and Bijay-Singh 1997).

A lot of research on N fertilization of rice in different regions has focused on developing management practices for the production of high yields while minimizing N losses and costs associated with N fertilization. Optimum fertilizer N rates, improved methods, and timings of application and placement, use of specially formulated forms of fertilizer including those with urease and nitrification inhibitors, integrated use of fertilizer, manures, and/or crop residues have been standardized to achieve better synchronization between the supply and requirement of N by rice. Nevertheless, best management practices for fertilizer N in rice do not simply consist of a universal set of recommendations. These are designed to achieve the four main objectives of cropping systems management: productivity, profitability, sustainability, and environmental health. The phrase "right source at the right rate, right time, and right place" implies that each fertilizer N management practice is right in terms of the goals of sustainable production. A balance among the four "rights" is essential as it helps to avoid too much emphasis on one at the expense of overlooking the others. Fertilizer N rate may sometimes be overemphasized, owing to its direct relation to cost. Source, time, and method of placement are sometimes overlooked. For example, urea super granules (1 g size granules of urea) were developed for easy application of urea in the reduced zone of puddled rice soils and for minimizing N loss through NH_3 volatilization (Savant et al. 1982). This combination of source modification and method of placement is very successful and becoming popular with farmers, particularly in Bangladesh (Bowen et al. 2005). However, Bijay-Singh and Katyal (1987) revealed that urea super granules applied in the reduced zone of coarse textured soils prove to be very inefficient source of N for rice. In highly permeable soils, N applied as urea super granules was readily leached as urea beyond root zone of rice (Katyal et al. 1985). The four aspects of fertilizer N management, i.e., source, rate, time, and place are completely interconnected and are also linked to the full set of management practices for the cropping system. None of the four can be right when any one of them is wrong. For a given situation, there can be more than one right combination of source, rate, timing, or placement, but when one of the four changes, the others may also change. Some general guidelines for efficient N management in rice are listed in Table 10.1.

In a majority of the rice-growing regions in Asia and in the developing countries, blanket recommendations for N management are practiced. These consist of fixed rates and timing for large tracts having similar climate and land forms, and cannot help to increase N-use efficiency beyond a limit. Due to large field-to-field variability of soil N supply, efficient use of N fertilizer is not possible when broad-based blanket recommendations for N fertilizer are used (Adhikari et al. 1999). Optimum crop yields can be obtained with the fixed-rate method provided the nutrient application level is high enough to compensate for a possible low supply of the nutrient from the soil in any field in the region. Obviously, a wide range in blanket recommendations for N fertilizer application rates is expected for different countries (Table 10.2) and within each country. Advantages of the fixed nutrient rate method are its simplicity and no costs involved for soil analysis. The uniform adoption of blanket recommendations does not ensure economy and efficiency of N fertilizer use since the variation in soil fertility is not taken into account, and there will be

Table 10.1 Some general guidelines for efficient nitrogen management in rice

Situation	Strategy
Upland (dryland)	Broadcast and mix basal dressing in top 5 cm of surface soil.
	Incorporate top-dressed fertilizer by hoeing-in between plant rows and then apply light irrigation, if available.
Rainfed deep water	Apply full amount as basal dressing.
Lowland (submerged)	Use nonnitrate sources for basal and topdressing.
Soil is very poor in N	Give relatively more N at planting.
Assured water supply	N can be top-dressed every 3 weeks up to panicle initiation. Drain field before topdressing and reflood 2 days later.
Permeable soils	Increase the number of split applications.
	Do not apply N fertilizer in the flood water.
Short duration varieties	More basal N and early topdressing should be preferred.
Long duration varieties	Increased number of topdressings.
Colder growing season	Less basal N and more as topdressing should be given.
Over aged seedlings used	More N at planting be applied.
Alkali soils	Apply more (about 25 %) N than in a normal soil.

Adapted from Pillai (1992)

Table 10.2 Recommended/optimum levels of NPK for lowland rice in some countries

		Recommended fertilizer level (kg ha^{-1})		
Country	Region/Season	N	P	K
Bangladesh	Hathazari	80	12.2	14.1
Bhutan	Wangdipho-drang	75	21.8	0.0
Egypt	–	100	16.2	0.0
India	Haryana	125	11.4	41.5
	Pattambi, Kerala	90	19.6	37.3
Indonesia	Dry season	140	15.3	24.9
	Wet season	80	7.9	24.9
	West Java	115	10.9	33.2
Japan	Hyogo Prefecture	170	53.3	141.1
Malaysia	MUDA	80	13.1	24.9
Pakistan	Muridke	120	11.4	0.0
	Dera Ismail Khan	135	17.5	30.7
Philippines	Nueva Ecija	90	12.2	23.2
	Guadalupe, Laguna	100	13.1	0.0
	Tarlac	80	21.8	24.9
Sri Lanka	–	73	25.3	48.1

Adapted from Pillai (1992)

wastage of fertilizers in some fields. As efficient N use is central to eco-efficiency in agriculture, it is important to work out N fertilizer doses that will produce not only high yields of rice per unit area and remain economically attractive to farmers but also result in minimal environmental impacts.

Farmers in many developing countries in Asia have developed a tendency to rely primarily on N fertilizers to maximize rice yields. High levels of N fertilizer without appropriate balance with P and K result in negative effects on rice yields, the soil, and the environment in addition to increased incidence of crop lodging, weed competition, and pest attacks. As intensive cereal systems remove large quantities of N, P, and K, an imbalanced application of nutrients leads to mining from the soil for the nutrients that are not supplied in adequate amounts, or yield levels are determined by the amount of nutrient supplied in the least amount. In a long-term experiment on rice–wheat cropping system in India, Kumar and Yadav (2001) found that 20 years after continuously applying different combinations of N, P, and K rates to both the crops, the highest rate of yield decline in rice and wheat was found when 120 kg ha^{-1} N was applied with no P and K. The lowest rate of decline was observed when N, P, and K were applied at 40, 35, and 33 kg ha^{-1}, respectively.

10.2.3.1 Controlled-N Release Fertilizers

Many times low N-use efficiency in rice is observed due to lack of synchronization between crop demand and release of N from water-soluble sources like urea. Application of soluble N fertilizers to rice in split doses is an attempt to increase the degree of synchronization between supply and demand of N, but there is a limit to achieve it. In recent decades, controlled-release N fertilizers have been developed that consist of highly soluble urea prills or granules coated with water-insoluble materials like sulfur or polyolefin that control the rate, pattern, and duration of N release (Shaviv 2001). Besides the advantages of controlled-released fertilizers in reducing N losses to the environment and increasing fertilizer N-use efficiency in rice (Chalk et al. 2015; Pandey and Singh 1987; Patil et al. 2010; Wang et al. 2015; Yan et al. 2008; Ye et al. 2013), the rate of N application and the number of applications during the growing season can often be reduced, which has the added advantage of saving labor costs. In recent years, different variants of polymer-coated controlled-release urea have been designed to synchronize N release and crop N uptake with minimal leakage of N to the environment. These have already been tested for obtaining high yields of rice along with high N-use efficiency (Kondo et al. 2005; Patil et al. 2010; Singh et al. 2007; Wang et al. 2015; Yan et al. 2008; Ye et al. 2013; Zhang et al. 2012).

10.2.3.2 Urease and Nitrification Inhibitors

In flooded rice systems, NH_4^+-N originating from hydrolyzed urea accumulates in floodwater and is prone to NH_3 volatilization due to elevated pH of flood water during daylight hours and increased temperatures. Even when urea is applied during non-flooded periods, applied N can be lost via NH_3 volatilization in substantial amounts. In flooded rice systems, N losses via NH_3 volatilization have been recorded in the range of 20–56 % of applied N (De Datta et al. 1989; Fillery and De Datta 1986). The use of urease inhibitors to reduce NH_3 volatilization from urea hydrolysis has emerged as an effective strategy to increase N-use efficiency of urea-based N products in rice. Urease inhibitor NBPT [N-(*n*-butyl) thiophosphorictriamide] has been reported to significantly reduce NH_3 volatilization losses due to urea application to rice (Buresh et al. 1988; Norman et al. 2009). Besides use of hydroquinone in China, NBPT is the only urease inhibitor of commercial and practical importance in agriculture (Trenkel 2010). Several researchers have recorded significant increase in grain yield of rice due to combined application of NBPT + urea over application of urea alone (Dillon et al. 2012; Liu et al. 2014; Norman et al. 2009; Pang and Peng 2010; Rogers et al. 2015). In China, hydroquinone is being extensively used as a urease inhibitor in rice because of its lower price (Yeomans and Bremner 1986). Malla et al. (2005) and Xu et al. (2005) observed that urea amended with hydroquinone can improve crop growth of rice.

Losses via nitrification–denitrification in rice soils can be substantial when an aerobic period is followed by an anaerobic period. Such conditions in rice systems are encountered in a drying and wetting cycle as in permeable soils or in intermittent wet and dry rice systems (Belder et al. 2004). In flooded rice fields, there exist adjoining aerobic zones where nitrification can occur and anaerobic zones where denitrification occurs (Fig. 10.1). The transport of NO_3^- between aerobic and anaerobic zones couples nitrification with denitrification (Buresh et al. 2008). Losses via denitrification have been recorded in the range of 12–33 % (Aulakh et al. 2001; Buresh et al. 1993). Nitrification inhibitors are chemicals that when added to N fertilizers and applied to soil, delay the transformation of NH_4^+ to NO_2^- by inhibiting or at least by slowing the action of *Nitrosomonas* spp. bacteria. Many compounds that can inhibit nitrification have been identified (Trenkel 2010), but three products are available on commercial scale. These are: (i) 2-chloro-6-(trichloromethyl) pyridine (Nitrapyrin) with the trade name “N Serve”, (ii) dicyandiamide (DCD, $H_4C_2N_4$), and (iii) 3,4-dimethylpyrazole phosphate (DMPP). In a meta-analysis based on 10 studies in which urea was the N source, Linquist et al. (2013) observed that application of DCD resulted in 16.5 % overall increase in yield of rice. Norman et al. (1989) and Wilson et al. (1990) used ^{15}N-labeled fertilizers and observed N uptake efficiency in rice by applying DCD along with urea. It has been observed that DCD in combination with hydroquinone could substantially reduce N_2O emissions during rice growth season (Xu et al. 2000, 2002). Li et al. (2009) found that application of DMPP nitrification inhibitor with urea increased the rice grain yield by 6–18 %. In India, oil extracted from the seeds of neem (*Azadirachta indica* A. Juss) is used as nitrification inhibitor; all urea sold in the country is now treated with neem oil.

10.2.4 Site-Specific Nitrogen Management in Rice

Among many factors that influence N-use efficiency, one potentially important factor is the uncertainty faced by farmers in deciding the amount of N fertilizer to be applied (Lobell 2007). This uncertainty can be reduced by knowing the N supplying capacity of the soil. Applying quantity of fertilizer N calculated by considering soil N supply rather than following traditional farming practices resulted in an increase in N-use efficiency by 30–40 % and grain yield by 7 % in 179 irrigated rice fields in Asia (Dobermann et al. 2002). Another reason for low N-use efficiency is the inefficient splitting of N applications and use of excess N than the required. In addition to field-to-field variability, the strategies for N fertilizer management must be responsive to temporal variations in crop N demand to achieve supply–demand synchrony and minimize N losses. Cassman et al. (2002) found that N recovery by irrigated rice at on-farm locations in Asia averaged 31 % compared to 40 % for rice grown under field-specific management. Peng and Cassman (1998) demonstrated that recovery efficiency of top-dressed urea during panicle initiation stage could be as high as 78 %. Thus, improvement in the synchrony between crop-N demand and N supply from soil and/or the applied N fertilizer is likely to be the most promising strategy to increase N-use efficiency in rice.

Number of split doses, the amount of N applied per split, and the time of application vary considerably even within small recommendation domains. However, on the positive side, flexibility of the farmers in adjusting the timing and amount of fertilizer N applied offers great potential to synchronize the site-specific N application with the demand of the rice in real time. It was in mid-1980s and 1990s that the emphasis was shifted from reducing N losses to feeding needs of rice crop for increasing N-use efficiency (Buresh 2007). The research was oriented toward finding means and ways to apply N in real-time using crop and site-specific needs. Methods based on soil tests and analysis of tissue samples did not work because these were time consuming, cumbersome, and expensive. Also, N prescriptions based on soil tests done before planting of rice cannot account for variations in the weather during the rice season. Because rice farmers often use leaf color as a visual and subjective indicator of the need for N fertilizer in rice, the breakthrough in the diagnostic tools that can assess N need of crop plants in real time came from spectral characteristics of rice leaves. Chlorophyll content and/or biomass of rice leaves can be estimated through the development of some noninvasive optical methods based on leaf greenness, absorbance, and/or reflectance of light by the intact leaf. These include chlorophyll meters, leaf color charts (LCC), optical sensors, ground-based remote sensors, and digital, aerial, and satellite imageries. Over more than a decade, chlorophyll meter, LCC, and Green Seeker optical sensor have been extensively tried to improve N-use efficiency in rice grown in different agroecosystems and regions.

Hand-held chlorophyll meters provide a fast, easy, on-site, precise, and scientific way to appraise the N needs of rice. The chlorophyll meter quantifies green color of the leaf by measuring the relative quantity of chlorophyll. Most of the research directly evaluating the effectiveness of chlorophyll meters in improving N-use efficiency has been conducted with the rice crop across different regions in Asia. In the majority of the transplanted or direct-seeded rice farms across Vietnam (Son et al. 2004), China (Wang et al. 2001), Indonesia (Abdulrachman et al. 2004), Philippines (Gines et al. 2004), Thailand (Satawathananont et al. 2004), and India (Bijay-Singh et al. 2002; Khurana 2005; Maiti et al. 2004), chlorophyll meter-based N management led to significant increases in N-use efficiency when compared with the farmers' fertilizer practices. At some places, increase in N-use efficiency was moderate thereby suggesting the need to integrate chlorophyll meter with other site-specific factors to make it a more effective in N management tool. To use chlorophyll meter, there is a need to determine a critical value that is unique to an environment and below which N-use efficiency and/or crop yields are likely to be adversely affected. Critical chlorophyll meter values can be fixed for different regions or varietal groups or these can be dynamic. The dynamic threshold chlorophyll value or sufficiency index approach ensures maintaining intensity of the color of leaves at 90 % or more of the intensity in the overfertilized reference plot (Bijay-Singh et al. 2006; Hussain et al. 2000). It has the advantage of being self-calibrating for different soils, seasons, and cultivars. In different regions across the Asia, critical chlorophyll meter values for rice ranged between 32 and 37.5. A difference of even 2 units in these critical values can decrease N-use efficiency and/or reduce yields as evidenced in some of these studies. In Texas, Turner and Jund (1994) reported the need for N in rice when chlorophyll meter values of the most recently matured leaves are less than the critical value of 40.

Leaf color chart consists of a panel of green plastic chips ranging with colors based on the wavelength characteristics of leaves and ranging from yellowish green to dark green that, respectively, cover a continuum from leaf N deficiency to excessive leaf N content (Pasuquin et al. 2004). Thus, unlike chlorophyll meter that measures light absorption, LCCs measure leaf greenness and the associated leaf N by visually comparing light reflection from the surface of leaves and the LCC (Yang et al. 2003). These are simple, easy-to-use, and inexpensive alternatives to chlorophyll meters and are particularly beneficial for individual income-poor farmers in Asian countries (Bijay-Singh et al. 2002). There are two major approaches in the use of the LCC (Fairhurst et al. 2007; Witt et al. 2005). In the *real-time* approach, a prescribed amount of fertilizer N is applied whenever the color of rice leaves falls below a critical LCC value. The *fixed splitting pattern* approach provides a recommendation for the total N fertilizer requirement (kg ha^{-1}) and a plan for splitting and timing of applications in accordance with crop growth stage, cropping season, variety used, and crop establishment method. The LCC is used at critical growth stages to decide whether the recommended standard N rate will be needed to adjust up or down based on leaf color (Bijay-Singh et al. 2012; Fairhurst et al. 2007). Leaf color chart-based N management has been evaluated mostly following the "real-time" approach rather than "fixed time adjustable dose" method. We have listed (Table 10.3) two categories of comparisons between LCC method and farmers' fertilizer practice (FFP) for managing fertilizer N in rice in Asia. In the first category, the most commonly observed effect of following LCC-based N management is the production of rice yield similar to that with FFP but with less N fertilizer application. It suggests that farmer's N management practice is inadequate. In another scenario, an increase in grain yield with a reduction in N fertilizer use was observed by following LCC method (Table 10.3). Increase in partial factor productivity (PFP) in all the comparisons listed in Table 10.3 may also occur due to retention of increasing proportion of N inputs in soil organic and inorganic N pools. Adoption of LCC method for managing N by farmers is likely to be driven by economic returns. With small-

Table 10.3 Comparison of leaf color chart (LCC) method with farmers fertilizer practice (FFP) for nitrogen management in rice in Asia

Country, region, year, critical LCC value, type of rice, number of farms	N used, kg N ha^{-1}		Grain yield, t ha^{-1}		AE_N[a]		PFP_N[a]		References
	FFP[b]	LCC	FFP	LCC	FFP	LCC	FFP	LCC	
Same grain yield with reduced N fertilizer application following LCC									
Philippines, Maligaya, 1998, LCC-4, TPR, 11	78	33	3.97a	3.87a	9b	20a	51	117	Balasubramanian et al. (2003)
Philippines, Maligaya, 1999, LCC-4, TPR, 11	74	46	4.49a	4.68a	12b	19a	91	102	
Vietnam, Cai Lay District, 1998, LCC-3, B-WSR, 28	120	82	5.24a	5.26a	–	–	44	64	
Vietnam, Cai Lay District, 1999, LCC-3, B-WSR, 7	99	70	6.34a	6.31a	–	–	64	90	
India, Haryana, 2001, LCC-4, TPR, 165	149	124	6.36a	6.37a	–	–	43	51	
Bangladesh, Gazipur, 2002, LCC-4, TPR, 9	72	46	4.46a	4.56a	–	–	62	102	Haque et al. (2003)
India, Punjab, 2003, LCC-4, TPR, 48	115	91	6.5a	6.5a	–	–	57	71	Varinderpal-Singh et al. (2007)
India, Punjab, 2004, LCC-4, TPR, 53	134	100	8.1a	8.2a	–	–	61	82	
India, Punjab, 2000, LCC-4, TPR, 8	120	91	6.53a	6.61a	20.8	27.8	57	85	Yadvinder-Singh et al. (2007)
India, Punjab, 2002, LCC-4, TPR, 11	126	78	6.93a	7.12a	11.3	17.8	52	83	

(continued)

Table 10.3 (continued)

Country, region, year, critical LCC value, type of rice, number of farms	N used, kg N ha^{-1}		Grain yield, t ha^{-1}		AE_N[a]		PFP_N[a]		References
	FFP[b]	LCC	FFP	LCC	FFP	LCC	FFP	LCC	
Increase in grain yield with reduced N fertilizer application following LCC									
Philippines, Maligaya, 1998, LCC-3, B-WSR, 6	151	125	4.53b	5.15a	6b	14a	30	41	Balasubramanian et al. (2003)
Vietnam, Huyen District, 1999, LCC-3, B-WSR, 18	98	80	4.63b	4.92a	–	–	47	62	
India, Uttar Pradesh, 2002, LCC-4, TPR, 1	150	135	6.9b	7.6a	20.7b	28.1a	46	56	Shukla et al. (2004)
Bangladesh, LCC-4, TPR, 33	149	100	3.8b	4.1a	10b	16a	25	41	Alam et al. (2006)

[a] AE_N, agronomic efficiency of applied N; RE_N, apparent recovery efficiency of applied N; PFP_N, partial factor productivity of applied N

[b] FFP, farmers' fertilizer practice in which all nutrient management was done by the farmer without any interference by the researcher. However, in some studies conducted only on research farms and not in actual farmers' fields, FFP denotes fixed-schedule N application

[c] For grain yield and NUE indices of AE_N, and PFP_N at different sites, values with different letters are significantly different at the 0.05 probability level

to-medium farm size in developing countries, the use of a simple and inexpensive leaf color chart is assisting farmers in applying N when the plant needs it.

Several researchers have used mid-season spectral reflectance measurements with optical/crop canopy sensors to estimate rice growth and N status (Ali et al. 2014; Bajwa et al. 2010; Nguyen et al. 2006; Xue et al. 2004). Based on target yield approach and split fertilization approach, Xue et al. (2014) used Green Seeker optical sensor for top-dressing N at panicle initiation stage of rice. Tubaña et al. (2011) also used canopy reflectance to top-dress N fertilizer at panicle initiation stage of rice. Recently, Bijay-Singh et al. (2015) found that high N-use efficiency and optimum yield of transplanted rice can be achieved by applying a moderate amount of N fertilizer at transplanting, enough N fertilizer at active tillering, and an optical sensor-guided N fertilizer dose at panicle initiation stage of rice.

Site-specific nitrogen management for rice as developed in Asia by International Rice Research Institute (IRRI) and described by Witt et al. (2007) advocates estimation of N fertilizer requirement of rice from the difference between a yield target and the yield without N fertilizer. The N-limited yield can be determined with the nutrient omission plot technique (IRRI (International Rice Research Institute) 2007) as the grain yield of a crop not fertilized with N but supplied with enough quantity of other nutrients. As only a fraction of the N fertilizer applied to rice is taken up by the crop, total amount of N fertilizer required for each ton of increase in grain yield is estimated by using agronomic efficiency factor; an efficiency of N use of 18–20 should be achievable by good crop management in tropical Asia. To ensure that supply of N matches the crop need at critical growth stages, the estimated total fertilizer N requirement by rice crop is then apportioned among multiple times of application during the growing season. The site-specific nitrogen management approach as developed by IRRI advocates the use of LCC for monitoring the relative greenness of a rice leaf as an indicator of the leaf N status (Witt et al. 2005) and guide the application of N fertilizer doses to rice at appropriate stages.

10.2.5 Nitrogen Management for Rice Hybrids

An ideal rice genotype is able to absorb a relatively large quantity of N from soil and is capable of producing a high grain yield per unit of absorbed N besides storing relatively a small amount of N in straw. Different lowland rice genotypes vary significantly with respect to N-use efficiency and the differences may be related to many physiological processes such as absorption, nitrate reduction efficiency, N remobilization, translocation, assimilation, and storage (Isfan 1993). Nitrogen harvest index is a measure of N portioning in rice among genotypes; high N harvest index is associated with efficient utilization of N (Rattunde and Frey 1986). Rice hybrids have 10–15 % yield advantage over conventional rice cultivars (Yang and Sun 1988) and it is presumably related to a greater total N uptake and internal N-use efficiency. Yang (1987) reported that total N uptake by hybrid rice was greater than that of conventional rice cultivars, especially from transplanting to tillering and from panicle emergence to grain filling stages. Hybrid rice takes about 15–20 % of its total N uptake after heading and provide consistently higher response to N fertilizer application at flowering compared to only 6–7 % for the conventional cultivars. Therefore, hybrid rice has greater agronomic efficiency compared to conventional rice (Lin and Yuan 1980). The primary factors contributing to the high N-use efficiency in hybrid rice are high N recovery efficiency, more root N absorption potential, high shoot N-use capacity, and high N remobilization efficiency.

10.3 Phosphorus

Phosphorus is one of the major essential nutrients for plants. It is a component of high energy compounds like adenosine triphosphate and genetic materials required for seed production. It is also involved in the synthesis of compounds like phospholipids, nucleotides, glycophosphates and its deficiency can dramatically reduce growth and yield of plants. In rice, deficiency of P appears when tillering starts and plant begins to accumulate dry matter. Symptoms include severe stunting and erect leaves with dark green color. Deficiency of P retards cell elongation and leaf expansion (Marschner 1995). Fageria (1980) observed a delay by as much as 10–12 days in rice maturity due to P deficiency. Application of P to rice on P-deficient soils increased rice root growth, number of panicles and grain weight of rice (Fageria and Gheyi 1999). Under P deficient conditions, rice does not respond to application of N, K, and other nutrients.

Phosphorus nutrition of rice crop depends upon the ability of a soil to supply P to plant roots and desorption characteristics of the soil (Roy and De Datta 1985). Concentration of inorganic P in the soil solution and the capacity of the soil to maintain this concentration determine the supply of P to rice roots. Plants rarely absorb more than 20 % of the total fertilizer P applied (Friesen et al. 1997). Reduced soil conditions under lowland rice normally increase the P availability to rice, and in many soils, P availability is not a yield-limiting factor for rice. However, on the same soil, upland crops like wheat and maize might show dramatic responses to P fertilization. Both P sorption capacity of the soil and bonding energy of P increase under alternate anaerobic–aerobic conditions (Sanyal and De Datta 1991). On the other hand, flooding decreases the crystallinity of ferrous hydroxides, which increases their sorption capacity, increases the insoluble Fe–P fraction, and reduces P desorption.

10.3.1 Critical P Level in Plant and Uptake of P by Rice

Phosphorus is a mobile element inside the plant. Therefore, P concentration of individual leaf decreases with advancement of leaf age. Top leaves have the highest P concentration and the bottom leaves have the lowest P concentration, especially when available P in the soil is limited. During early vegetative growth, P concentration in rice tissue increases with increasing P rates. Tissue P concentration remains nearly constant from panicle initiation until flowering. After flowering, the filling of rice grain starts and becomes a strong sink for P and straw P concentration declines.

Critical tissue P concentrations for rice during vegetative growth range from 1.0 to 2.0 g P kg^{-1}. According to Yoshida (1981), 2.0 g P kg^{-1} in the first fully opened leaf from the top was needed to realize the maximum tillering rate. De Datta (1981) suggested that 1.0 g P kg^{-1} in the rice leaf blades at active tillering was the critical concentration. In general, whole plant P concentrations during vegetative growth at >2.0 g P kg^{-1} are sufficient for optimum rice growth and yield production.

The above-ground P uptake by high-yielding rice varieties may approach 60 kg P ha^{-1}, but more commonly it ranges from 25 to 50 kg P ha^{-1} with 60–75 % of the total plant P contained in the panicles at maturity (Fageria et al. 2003). Seasonal P uptake and dry matter accumulation tend to follow similar patterns and accumulation of P is closely related to plant age. The average P harvest index [Grain P/(Grain P + Straw P)] generally ranges from 0.60 to 0.75. The rice grains remove a significantly large proportion of total P uptake during the crop growth period. Therefore, recycling of rice straw to the field cannot contribute much P for succeeding crop in the rotation.

10.3.2 Phosphorus Management Strategies in Rice

Phosphorus management in rice aims at preventing P deficiency rather than treating P-deficiency symptoms. Significant response of modern rice varieties to P fertilizer may be observed after several years of intensive cropping, particularly when both N and K were applied or when the P-supplying capacity of the soil is low (De Datta et al. 1988). Therefore, P management must focus on the buildup and maintenance of adequate available P levels in the soil to ensure that P supply does not limit crop growth and N-use efficiency (Fairhurst et al. 2007). Inputs of P from sources such as irrigation water and straw are small but P is not easily lost from the system. As P fertilizer applications exhibit residual effects that can last several years maintenance of soil P supply requires long-term strategies tailored to site-specific conditions that consider P inputs from all sources (Fairhurst et al. 2007). Unbalanced P input/output can lead to either depletion or excessive enrichment of soil P in intensive irrigated rice systems. For example, in a survey of farmers' fields carried out by Oberthuer et al. (1995), 64 % of a 20,000-ha area of irrigated rice in Central Luzon, Philippines, was classified as low in available soil P reserves. In contrast, 85 % of the total lowland rice area in Java, Indonesia, was found to be having high soil P status and rice yields no longer responded to applied P (Sri Adiningsih et al. 1991).

Use of calibrated soil test values is still the best criteria for making P fertilizer recommendations for rice, although routine soil test methods may not provide a reliable estimate of the P available to lowland rice. For example, soils used for growing lowland rice commonly have low soil test P values but may or may not respond to P fertilization (Shahandeh et al. 1994; Wilson et al. 1999). Different extractants tend to under- or overestimate P availability even to upland crops (Kamprath and Watson 1980). Their ability to accurately predict the P fertilizer requirement of flood-irrigated rice is further compromised by the anaerobic soil conditions used for production of rice. Although no single extractant has shown a significant advantage for making P recommendations on lowland rice, Sanyal and De Datta (1991) suggested that Olsen P is perhaps the best routine method for predicting rice response to P as it is better correlated with the extraction of Fe–P.

Classical empirical approach for making P recommendations based on critical soil test levels and P fertilizer response curves requires a large number of site-specific field calibration studies. It does not take into account crop P requirements based on a target yield and interactions with other nutrients. Another approach to work out P recommendations for rice is based on estimates of the potential soil P supply and crop P uptake (Fageria and Gheyi 1999). Potential P supply can be estimated as P uptake by a rice crop from indigenous soil resources measured under field conditions, when all other nutrients are amply supplied (Janssen et al. 1990). Fairhurst et al. (2007) have described a practical version of using this strategy for calculating P rates for lowland rice. Blanket recommendations for large regions (Table 10.2) are still widely used for applying P to rice in many developing countries in Asia because currently available soil P maps do not provide a satisfactory basis for specifying soil type-specific fertilizer recommendations. In fact, management-induced variation between farmers is much larger than differences among soil types.

Sustainable P management requires the replenishment of soil P reserves, especially at high yield levels in double and triple rice-cropping systems, even if a direct yield response to P application is not expected. According to Fairhurst et al. (2007), the rule of thumb is: where the soil P supply is small, apply 8.7 kg P ha^{-1} for each tonne of target grain yield increase (difference between yield target and yield in no-P plot). According to Dobermann et al. (2000), 26 kg P ha^{-1} is normally applied to obtain maximum yield of flooded rice in Asia. To produce maximum rice yields, recommendation for P fertilizer in the United States ranges between 10 and 40 kg P ha^{-1} (Norman et al. 2003). Soils with high P fixing capacities may require as high as 97–175 kg P ha^{-1} (Chen 1997) to produce optimum yields. Using appropriate method of P application is critical to reduce the P input and increase P fertilizer use efficiency. For example, high P rates cited by Fageria (1980) for high P fixing in Brazilian acidic lowland soils were reduced from 97–175 to 22–44 kg P ha^{-1} if the fertilizer was banded rather than broadcast. Phosphorus fertilizer is generally applied to rice at planting, but late application can be made provided it is not later than the time of active tillering (De Datta 1981). Early application of P is essential for root elongation. According to Patrick et al. (1974), broadcast preplant incorporated P application is equally effective as P drilled with the seed. However, due to rapid fixation of P in alkaline soils, McGee et al. (2002) observed that broadcast application of P at the five-leaf stage increased tissue P concentration, P uptake, and grain yield more than P broadcast applied to the soil surface at seeding. When P is

Table 10.4 Effect of P application on crop yields (t ha^{-1}) in rice–wheat system in northwestern India

Rate of P (kg ha^{-1})		Punjab[a] (7 years average)		Haryana[b] (4 years average)	
Rice	Wheat	Rice	Wheat	Rice	Wheat
Yields (t ha^{-1})					
0	0	4.0	2.3	5.0	3.0
0	26	6.6	4.1	5.9	4.3
26	0	6.5	2.4	5.8	3.8
13	26	6.6	4.2	6.2	4.4
26	26	6.6	4.2	6.3	4.6

[a] Yadvinder-Singh et al. (2000)
[b] Faroda (1992)

deficient, rice yield response to P fertilizer declines as the time of P fertilization is delayed (Patrick et al. 1974; Slaton et al. 1998). Patrick et al. (1974) showed that P placed with the rice seed during drilling was superior to broadcast application 2 weeks after seeding. Dipping rice seedlings into P slurry before transplanting has also been reported to be useful (De Datta 1981). Most commonly used fertilizers to supply P to rice are the highly water-soluble single and triple-super phosphates, diammonium phosphate, and sometimes monoammonium phosphate. There is no evidence of differences in rice responses to different sources of water-soluble P.

When lowland rice is grown in rotation with an upland crop like wheat (as in the vast Indo-Gangetic plains in South Asia), P is managed in cropping system rather than in individual crops. General recommendation is that P should be applied to wheat and rice can use the residual P from the soil (Meelu et al. 1982; Palmer et al. 1990; Run-Kun et al. 1982). The availability of soil P and residual fertilizer P increases under submergence and high temperatures prevailing during rice growth. Also, rice has a greater ability to utilize the residual P from Fe–P and Al–P fractions than wheat (Gill and Meelu 1983). For the rice–wheat system, when 26 kg P ha^{-1} was applied to wheat, rice did not respond to P (Table 10.4). However, from a 7-year study, Yadvinder-Singh et al. (2000) suggested that P should also be applied to rice at rates of >15 kg P ha^{-1} if rice yields greater than 6 t ha^{-1} are targeted. Similar conclusions could be drawn from a 4-year study on a clay loam soil (Faroda 1992) (Table 10.4).

10.4 Potassium

Potassium is a major plant nutrient that improves root growth and plant vigor, helps prevent lodging, and enhances crop resistance to pests and diseases. It is often the most limiting nutrient after N in high yielding rice systems. It plays an important role in lignification of vascular bundles, a factor that contributes to susceptibility to lodging and diseases in K-deficient plants. The deficient symptoms of K in rice can be easily confused with that of N because onset of K deficiency is visible as a color change of lower leaves. Typical symptoms of K deficiency in rice include stunted plants with little or no reduction in tillering, droopy and dark green upper leaves, and chlorosis of the interveinal areas and margins of the lower leaves starting at the leaf tip (Fageria et al. 2003). Leaf symptoms of K deficiency can be confused with that of tungro disease, but tungro occurs in patches in a field and usually has more pronounced yellow and orange leaves and plant stunting. Potassium deficiency leads to direct yield loss due to reduced size and weight of rice grains.

Potassium increases the number of spikelets per panicle, percentage of filled grains, and 1000-grain weight but does not have a pronounced effect on tillering of rice. Incidence of diseases such as brown leaf spot, cercospora leafspot, bacterial leaf blight, sheath blight, sheath rot, stem rot, and blast is greater where excessive N fertilizer and insufficient K fertilizer have been applied. Deficiency of K in rice occurs due to excessive use of N or N + P fertilizers with insufficient K application in direct-sown rice during early growth stages when the plant population is large and root system is shallow, and in hybrid rice because of greater demand for K (Fairhurst et al. 2007). The extent of rice response to K application is less than that observed for N and P, although above-ground K content of rice is equal to or greater than the plant N content and greater than all other essential nutrients. As rice, because of its fibrous root system, is highly efficient in scavenging plant available soil K, many soils can support the production of continuous rice or rice–wheat rotations for extended periods without a need to apply K to maintain high yield levels (Dobermann et al. 1996b). However, in some soils, regular applications of K fertilizer to rice are needed to avoid K deficiency. Yield responses of 0–10 % to direct K fertilization of rice are normally observed (Dobermann et al. 1996b). Prior to 1990s, K was rarely applied to rice in United States and South Asia. But due to production of high yields of rice and other crops for many years in these regions, soils have been mined of K so that regular applications of K fertilizer have become necessity to produce optimum yields of rice (Bijay-Singh et al. 2004; Slaton et al. 1995; Williams and Smith 2001).

Weathering of soil minerals—primary alumino silicates that include K feldspars and micas and secondary alumino silicates like illite—releases K in the soil. Potassium exists in four distinct pools in the soil—soil solution K (0.1–0.2 %), exchangeable K (1–2 %), nonexchangeable K (1–10 %), and mineral K (90–98 %). K ions move from one pool to another whenever the removal or addition of K disturbs the equilibrium between these pools (Barber 1995). Equilibration between the soil solution and exchangeable K pools is rapid and is usually completed within hours. Although considered immobile, a significant amount of K can be lost via leaching on some soils following displacement from the exchange complex after flooding. Leaching is a significant problem in soils with low cation exchange capacities (Bijay-Singh et al. 2004; Fageria et al. 1990). Yadvinder-Singh et al. (2005) found that leaching losses of K were 22 and 16 % of the applied K, respectively, in sandy loam and loamy soils maintained at submerged moisture regimes. Increased amount of K in the soil solution is absorbed by rice plants or leached to depths below the rice root system in permeable soils (Wells et al. 1993). If adequate amount of K is not absorbed by rice during vegetative stage and significant amount of soil K gets lost via leaching, K deficiency may occur later in the growing season unless K is not supplemented shortly before the onset of reproductive growth.

10.4.1 Critical Levels of K in Rice and Uptake of K

According to Yoshida (1981), during the vegetative growth phase of rice, tillering stops when the K concentration in the leaf blade is <5.0 g kg^{-1} of leaf dry weight. For maximum number of grains per panicle and reduced spikelet sterility, mature leaves should contain more than 20 g K kg^{-1} at booting stage of rice (Kiuchi and Ishizaka 1961). According to De Datta (1981), straw K concentration <10 g K kg^{-1} at maturity certainly indicated K deficiency.

Luxury consumption of K by rice may occur but the K concentration of rice seed remains relatively constant between 2.5 and 3.0 kg K kg^{-1} regardless of K fertilization (Dobermann et al. 1998). Rice absorbs most of its K during the vegetative and early reproductive growth stages and a major portion of the K absorbed before anthesis remains in the stems and leaves (Hirata 1995). Around 80–90 % of the above-ground K content of rice remains in leaves and stems at maturity (Dobermann et al. 1996a). Thus, if the rice straw is not physically removed from the field, the majority of K is recycled back into the soil. Otherwise K fertilization practices must be modified to prevent depletion of soil K.

10.4.2 Potassium Management Strategies in Rice

Where soil K supply is small, the general strategy for K management for rice is to apply 25 kg K ha^{-1} for each tonne of target grain yield increase over the yield of rice in the plots receiving no fertilizer K (Fairhurst et al. 2007). According to Dobermann et al. (2000), 50 kg K ha^{-1} should normally be applied to obtain maximum yields of flooded rice and this rate is representative of K fertilizer rates used to fertilize rice in other parts of the world. Since more than 80 % of K taken up by rice remains in the straw after harvest, straw should be considered as an important input source when calculating K requirements. Many times significant responses of rice to K application are not observed because of high seasonal K inputs (7–60 kg K ha^{-1} $year^{-1}$) via irrigation water and release of nonexchangeable K (Forno et al. 1975). The standard approach for the identification of K-deficient soils or plant K deficiency revolves around rapid chemical tests with empirical critical threshold ranges. This approach requires conducting large number of field experiments to establish calibrations between a given soil K test value and the probability of a response to applied K (McLean and Watson 1985; Sekhon 1995). Most of these calibrations provide reliable measures of the soil K-supplying power only for specific soil types such as those with relatively high native fertility and little K fixation character, and provide reasonable recommendations for fertilizer K application to rice. However, this approach is inadequate for intensive irrigated rice systems in the tropics and subtropics, which are extremely K demanding with two and sometimes three rice crops each year grown in submerged soil with soil drying in fallow periods or when rice is grown in rotation with an upland crop like wheat. Extractable soil K levels can fluctuate enormously under alternating aerobic–anaerobic soil conditions or when soils have strong K-fixation properties. Extractable soil K^+ is still considered as the most important indicator of available K in rice soils, but its suitability as a measure of plant available K remains controversial, especially when soils with different textures and clay mineralogy are considered (Kemmler 1980; Sekhon 1995). Generally accepted critical level of 1 N ammonium acetate extractable K in rice soils is 0.17–0.21 cmol K kg^{-1}. In the United States, K fertilizer is usually recommended for rice when exchangeable soil K is <60 mg K kg^{-1}, regardless of the soil texture or the extractant (Williams and Smith 2001). Fageria (1999) observed that rice did not respond to K fertilization when soil test concentrations were >50 mg K dm^{-3} (Mehlich 1 or 0.05 N HCl + 0.025 N H_2SO_4 extractable K). Dobermann et al. (1996b) found that mixed-bed exchange resins incubated for 2 weeks under flooded soil conditions were superior to K extracted by 1 N ammonium acetate for prediction of K uptake by rice.

In more than 25 M ha area in China and Indo-Gangetic plains in South Asia, rice is grown in an annual rotation with wheat. In a number of long-term experiments on rice–wheat systems located all over the Indo-Gangetic plain, average grain yield response to application of 33 kg K ha^{-1} to rice ranged from 0 to 0.5 t ha^{-1}; the low response to fertilizer K in these alluvial soils suggests that release of K from illitic minerals could meet the K needs of these crops (Bijay-Singh et al. 2004). In a long-term experiment in Hubei province in China, Chen (1997) observed that the direct response of wheat to K application was larger than that of rice, while the residual response of rice was larger than that of wheat. In a large number of balanced fertilization demonstration trials carried out during more than a decade in southern China, application of 48–75 kg K ha^{-1} to rice resulted in grain yield response of 7.9–61.3 % (Scientific Technology Department of Ministry of Agriculture 1991). In general, K application showed larger yield responses on wheat than on rice. Thus, when fertilizer K is not available in sufficient quantity, it should be preferably applied to wheat rather than rice.

Fertilizer K is applied to rice by broadcast method immediately before or after seeding/transplanting, or split into multiple applications. In general, a major portion, and sometimes all, of the K fertilizer should be applied at or near the time of seeding/transplanting of rice (Bijay-Singh et al. 2004; Fageria et al. 2003). A smaller portion of the total K fertilizer requirement should be top-dressed on soils where leaching losses of K are of concern. In the humid tropical soils with low cation exchange capacity and clay content, fertilizer K is commonly broadcast applied as a top-dressing along with N. Fageria (1991) reported that lowland rice yields were higher when the total K fertilizer requirement was applied in split top-dressed applications. In a silt loam, a single application of K fertilizer applied at five-leaf stage, or at the panicle initiation stage was sufficient to maximize grain yield of rice;

K fertilizer applied during the boot stage did not increase yields above the untreated control (Slaton et al. 2001). Foliar sprays may also be considered as beneficial methods of K application (Bijay-Singh et al. 2004). Due to low cost and high K analysis, KCl is the most common source of K. However, its use in salt-affected areas is discouraged. Potassium sulfate can supply both K and S, but it is more expensive than KCl. In South Asia, 99 % of the total fertilizer K applied is KCl and no significant difference in rice response has been observed between KCl and potassium sulfate (Tandon and Sekhon 1988).

10.5 Zinc

Zinc (Zn) deficiency in rice occurs after transplanting and is a widespread phenomenon limiting productivity under lowland conditions (Quijano-Guerta et al. 2002). Zinc is a cofactor for enzymes such as glutamate dehydrogenase and alcohol dehydrogenase that are involved in N metabolism. Deficiency of Zn depresses the activity of alcohol dehydrogenase, decreases anaerobic root metabolism, and reduces the ability of rice seedlings to withstand anaerobic soil conditions (Moore and Patrick 1988). Rice plants in early growth stages are more susceptible to Zn deficiency. If the deficiency is not corrected, it can also affect plants in the reproductive growth phase. As Zn is not very mobile within the plant, its deficiency symptoms are first observed in the youngest leaves, which usually become chlorotic at the leaf base during early stages of Zn deficiency. The midribs and base of older leaves may also turn yellow or pale green with brown blotches and streaks when Zn deficiency progresses (Yoshida 1981). According to Mueller (1974), Zn deficiency tends to be more severe when high rates of N and P are applied. Application of high rates of P fertilizers may aggravate Zn deficiency due to formation of Zn phosphate in soil solution and/or inhibitory effect of excessive P on the metabolic functions of Zn within the plant (Shimada 1995). Rice is considered susceptible to Zn deficiency because inadequate Zn levels in the soil limit tillering and, consequently, the number of panicles per unit area (Fageria 2001). Zinc deficiency is becoming one of the major public health problems in many countries, especially where people rely on cereal-based food (Cakmak 2008).

Rice yield losses due to Zn deficiency range from 10 to 60 % (Slaton et al. 2002). Nevertheless, yield losses are small if Zn deficiency is recognized quickly and the appropriate corrective actions are taken. Data generated in different parts of the world support that seedling Zn concentrations <15–20 mg Zn kg^{-1} are low or deficient and require Zn fertilization for optimum rice growth (Fageria et al. 2003). According to Adriano (1986), Zn deficiency of rice seedlings is likely when leaf or whole plant concentrations are <15 mg Zn kg^{-1}. Concentrations of Ca, Cu, Fe, Mg, and Mn tend to be higher in Zn-deficient rice. However, tissue concentrations of N and K are reduced indicating inhibition in their uptake (Moore and Patrick 1988).

Zinc concentration in the soil solution decreases after flooding, though it may temporarily increase immediately, but equilibrates around 0.3–0.5 μM

(Forno et al. 1975). Zinc uptake by rice depends not only on the concentration of Zn in the soil solution, but also on the concentrations of Fe^{2+} and Mn^{2+} in the soil solution that increases with flooding of the soil. A decrease in available Zn concentration in the soil is also associated with high P availability, precipitation of $Zn(OH)_2$ with an increase in pH, formation of insoluble franklinite ($ZnFe_2O_4$) and ZnS in acidic soils and $ZnCO_3$ in calcareous soils. Leached, old acid-sulfate, sodic, saline-neutral, calcareous, peat, sandy, highly weathered, acid, and coarse-textured soils and those with high available P and Si status are particularly prone to Zn deficiency. In alkaline soils and those rich in organic matter, Zn and P availability may be decreased by adsorption to amorphous Fe hydroxides and carbonates, particularly under fluctuating water regimes (Kirk and Bajita 1995).

Application of suitable Zn fertilizers at the proper rates based on soil testing and at appropriate crop growth stages is the best method to ensure that Zn nutrition is not a yield-limiting factor for rice production. Some critical soil levels for occurrence of Zn deficiency are (i) 0.6 mg Zn kg^{-1}extractable with 1 N NH_4-acetate, pH 4.8, (ii) 1.0 mg Zn kg^{-1} extractable with 0.05 N HCl, and (iii) 2.0 mg Zn kg^{-1} extractable with 0.1 N HCl (Fairhurst et al. 2007). Critical DTPA extractable soil Zn concentration of 0.8 mg Zn kg^{-1} has been reported for Indian soils for lowland rice (Tiwari and Dwivedi 1994). According to Sims and Johnson (1991), critical soil Zn concentration range for most crops is between 0.5 and 2.0 mg Zn kg^{-1} for DTPA and 0.5–3.0 mg Zn kg^{-1} for Mehlich 1 (0.05 N HCl + 0.025 N H_2SO_4 extractable). As reviewed by Fageria et al. (2003), this range is true for rice as well. When soil test for available Zn is not available but Zn deficiency symptoms are observed in the field, broadcasting 10–25 kg $ZnSO_4{\cdot}H_2O$ or 20–40 kg $ZnSO_4{\cdot}7H_2O$ per ha over the soil surface is recommended. Apply 0.5–1.5 kg Zn ha^{-1} as a foliar spray (a 0.5 % $ZnSO_4$ solution at about 200 L water per ha) for emergency treatment of Zn deficiency in growing plants (Fairhurst et al. 2007). Fertilizer Zn should be applied immediately at the onset of symptoms. The commercially manufactured granular Zn fertilizers are Zn sulfates, oxides, oxysulfates, lignosulfonates, and a number of organic chelated materials like ZnEDTA and ZnHEDTA, but highly water-soluble $ZnSO_4$ is the most commonly used Zn fertilizer. Liscano et al. (2001) suggested that 40–50 % Zn in the fertilizer should be water soluble to optimize Zn uptake by rice seedlings. The recommended rates of soil applied Zn are about 20 times higher than the total crop uptake of Zn. Thus, a single Zn fertilizer application should provide adequate Zn for several years before additional Zn fertilizer is needed. Relatively high rates of Zn fertilizers are applied to the soil before seeding. On high pH soils, surface application of Zn fertilizers has been more effective than soil incorporation. Yoshida (1981) observed that dipping rice seedling roots in a 1 % ZnO suspension before transplanting could prevent Zn deficiency. Fairhurst et al. (2007) recommended dipping of rice seedlings or presoak seeds in a 2–4 % ZnO suspension. Lowering the pH of alkaline or calcareous soils by application of acid forming fertilizers and amendments like elemental S has shown improvement in Zn availability and uptake by rice (Slaton 1998).

10.6 Sulfur

Sulfur (S) as an essential plant nutrient is a constituent of amino acids like cysteine and methionine, several coenzymes like biotin, and lipoic acid, thioredoxins, and sulfolipids (Zhao et al. 1997). Deficiency symptoms of S are similar to those for N but due to limited mobility of S in the plant, chlorosis of the plant is rather uniform. Sulfur deficiency is initially expressed as chlorosis of the younger leaves while N deficiency results in chlorosis of older leaves. Reduction in the dry weight of leaf blades is larger than in stems and roots when there is S deficiency. In rice, number of panicles and panicle length may be adversely affected by S deficiency (Fageria et al. 2003). Critical concentration of S in rice varies from 2.5 g S kg^{-1} at tillering stage to 1.0 g S kg^{-1} at heading (Wells et al. 1993). According to Wang (1976), critical concentration of S in straw should be 0.5 g S kg^{-1} for optimum grain yield. De Datta (1981) reported that S concentration in rice grain varies between 0.34 g S kg^{-1} for S-deficient plants and 1.6 g S kg^{-1} in plants that show no response to S application.

Deficiency of S has been reported from nearly all rice-producing regions of the Asia (Khurana et al. 2008). Low S content of most tropical soils, use of S-free fertilizers (urea substituted for $(NH_4)_2SO_4$, triple superphosphate substituted for single superphosphate, and KCl substituted for K_2SO_4), depletion of soil S due to intensive cropping, and low inputs of atmospheric S due to reduced industrial emissions are the possible reasons. Plant available S decreases rapidly when soil reduction proceeds under lowland rice. Besides uptake of S by plants, SO_4^{2-} may get leached and reduced to S^{2-}, which can be toxic to plants and may also be lost from the soil as H_2S gas. According to Ponnamperuma (1972), S concentrations as high as 15,000 mg SO_4^{2-} kg^{-1} may be reduced to zero within 6 weeks of submergence of neutral and alkaline soils.

According to Fairhurst et al. (2007), soil tests for S are not reliable unless these include inorganic S as well as some of the mineralizable organic S fraction (ester sulfates). The critical levels for S deficiency in soils are: <5 mg S kg^{-1} extractable with 0.05 M HCl, or <6 mg S kg^{-1} extractable with 0.25 M KCl heated at 40 °C for 3 hours, or <9 mg S kg^{-1}: 0.01 M extractable with 0.04 M $Ca(H_2PO_4)_2$. The critical S concentration in rice tissue varies from 2.5 g S kg^{-1} at tillering to 1.0 g S kg^{-1} at heading (Wells et al. 1993). Pillai and Singh (1975) reported 0.16 % S as the critical concentration at tillering stage of rice grown in calcareous soils. Yoshida (1981) observed that the critical S concentrations in straw needed for maximum dry weight production varied from 1.6 g S kg^{-1} at tillering to 0.7 g S kg^{-1} at maturity. Wang (1976) reported a critical concentration of S in rice straw as 0.5 g S kg^{-1}. For lowland rice grain yields of 5–7 t ha^{-1}, S uptake was between 5 and 9 kg S ha^{-1}.

Soils particularly prone to S deficiency are (i) those containing allophane (Andisols), (ii) those with low organic matter status, (iii) highly weathered and containing large amounts of Fe oxides, (iv) light textured, which are easily leached, and (v) highly reduced clay soils that are continuously cropped with rice. Hoque and Hobbs (1980) reported that in Bangladesh, an average application of 34 kg S ha^{-1} as $(NH_4)_2SO_4$ increased the yield of rice by 100 to 1300 kg ha^{-1} and on farmers' fields by 300 to 2200 kg ha^{-1} over and above the yield obtained due to application of

60 kg N ha^{-1}. Irrigation water frequently contains adequate amounts of SO_4^{2-} to supply seasonal crop requirements. If S deficiency is identified during early growth, the response to S fertilizer is rapid and recovery from S deficiency symptoms can occur within 5 days of S fertilizer application. Where moderate S deficiency is observed, 10 kg S ha^{-1} may be applied. On soils with severe S deficiency, 20–40 kg S ha^{-1} may be applied (Fairhurst et al. 2007). According to Wang (1976), at least 10 kg S ha^{-1} is required from fertilizer for rice production and $(NH_4)_2SO_4$ or single superphosphate are good sources of S. Also, 27 kg S ha^{-1} applied once supported two crops of rice. Yamaguchi (1997) reported that a mixture of $(NH_4)_2SO_4$ and urea increased rice dry matter production when the proportion of $(NH_4)_2SO_4$ supplied more than 25 % of the total N application. Elemental S can also be used as a source of S provided an adequate time interval is allowed for the oxidation of S into a plant available form. When the availability of S is initially low, SO_4^{2-} containing fertilizers should be applied at seeding or by the five-leaf stage when rapid plant growth and tillering begin. The application of S containing fertilizers may also be necessary during the reproductive growth phase to prevent late-season S deficiency on highly permeable or reduced soils. Some preventive strategies for S management in rice could be (i) application of S to the rice nursery, (ii) incorporation of rice straw instead of removing or burning it because 40–60 % of the S contained in straw is lost due to straw burning, (iii) maintaining sufficient percolation (about 5 mm day^{-1}) to avoid excessive soil reduction, and (iv) carrying out dry tillage after harvesting to increase the rate of sulfide oxidation during the fallow period.

10.7 Iron

Iron (Fe) is required for photosynthesis. Its deficiency may inhibit K absorption. Iron is not highly mobile within the plant and the youngest leaves are the first to show its deficiency symptoms. Interveinal yellowing and chlorosis of emerging leaves are observed at the onset of Fe deficiency. Further progression of Fe deficiency results in uniform pale yellow to bleached appearance (Snyder and Jones 1988).

Iron deficiency occurs commonly in rainfed upland rice, rainfed dry nurseries, or when rice is grown under upland conditions. Rice seedlings before flooding are the most susceptible to Fe deficiency (Yoshida 1981) because rice roots produce comparatively low amounts of iron-chelating phytosiderophores compared to other grass species (Mori et al. 1991). Deficiency of Fe most often occurs when rice is grown on neutral, calcareous, and alkaline upland soils, alkaline and calcareous lowland soils with low organic matter content, lowland soils irrigated with alkaline irrigation water, and coarse-textured soils derived from granite. Major causes of Fe deficiency in rice are low concentration of soluble Fe^{2+} in upland soils, insufficient soil reduction under submerged conditions (low organic matter status of soils), high pH of alkaline or calcareous soils following submergence (decreased solubility and uptake of Fe because of large bicarbonate concentrations), and wide P:Fe ratio in the soil (Fe bound in Fe phosphates, possibly because of the excessive application of P) (Fairhurst et al. 2007). Thus, Fe deficiency does not commonly occur in flooded rice due to the increase in Fe availability associated with the anaerobic soil conditions. As solubility of Fe increases during organic matter decomposition in flooded soils, Fe deficiency may occur when organic matter decomposition is insufficient.

Iron has a relatively wide sufficiency concentration range in plants. Sufficient Fe concentration range in the youngest mature leaf blade during vegetative growth has been reported to be 75–150 mg Fe kg^{-1} (Dobermann and Fairhurst 2000). The sufficient Fe concentration of the whole shoots was somewhat lower at 60–100 mg Fe kg^{-1}. As for other nonmobile elements, Fe concentration in rice leaves increases with age. Soil analysis is not an effective means of identifying Fe-deficient soils.

Applications of inorganic Fe sources such as $FeSO_4$ to soil are often ineffective in controlling Fe deficiency unless large amounts are applied. According to Fairhurst et al. (2007), Fe deficiency can best be treated by applying solid $FeSO_4$ (about 30 kg Fe ha^{-1}) next to rice rows, or broadcast (larger application rate required) along with organic matter through crop residues, green manures, or animal manures. Foliar applications of $FeSO_4$ (2–3 % solution) or Fe chelates can also be used to cure Fe deficiency. Due to low Fe mobility in the plant, two to three applications at 2-week intervals (starting at tillering) are necessary to support new plant growth. Use of acidifying fertilizers such as $(NH_4)_2SO_4$ instead of urea on high-pH soils can also be helpful. In coarse textured soils, incorporation of 10 t ha^{-1} of a green manure plus submergence for 10 days followed by raising upland rice nursery checked Fe chlorosis (Sharma and Katyal 1982).

10.8 Manganese

Manganese (Mn) is found in chloroplast and along with Fe and Cu performs vital role in the electron transport system (Obata 1995). It is involved in photosynthetic oxygen evolution and functions as a co-factor to activate enzymes such as dehydrogenases. The protease enzyme contained in rice seeds is also activated by Mn. Manganese is immobile in plants so that its deficiency symptoms appear initially in the younger leaves. Chlorosis and development of an irregular yellow mottling between the leaf veins are the typical symptoms of Mn deficiency in rice.

The role of Mn is closely associated with that of Fe as it supports the movement of Fe in the plant. Manganese is also required for photosynthesis. Manganese deficiency is more often observed in upland rice, alkaline and calcareous soils with low organic matter status and small amounts of reducible Mn, degraded paddy soils high in Fe content, acid upland (Oxisols, Ultisols), leached old acid sulfate soils with low base content, leached sandy soils containing small amounts of Mn, or in excessively limed acid soils. Uptake of Mn is also reduced because of hydrogen sulfide accumulation or large concentrations of Ca^{2+}, Mg^{2+}, Zn^{2+}, or NH_4^+ in the soil solution. The adequate Mn concentration for rice growth in water culture experiments has been reported as 0.1–0.5 mg L^{-1} (Shimada 1995).

Critical soil levels for occurrence of Mn deficiency in the soil are 1.0 mg Mn kg^{-1} extractable with terephthalic acid + $CaCl_2$, pH 7.3 or 2.0 mg Mn kg^{-1}, extractable with 1 N NH_4-acetate + 0.2 % hydroquinone, pH 7 (Fairhurst et al. 2007). Manganese deficiency in rice occurs when the Mn concentration in the plant tissue is less than 20 mg Mn kg^{-1} (Wells et al. 1993). Deficiency of Mn can be corrected by foliar application of Mn or by banding Mn with an acidifying starter fertilizer. Manganese sulfate or finely ground MnO (5–20 kg Mn ha^{-1}) can be applied in bands along rice rows. For rapid treatment of Mn deficiency, foliar spray with $MnSO_4$ solution (1–5 kg Mn ha^{-1} in 200 L water ha^{-1}) can be effectively adopted. Chelates are less effective because Fe and Cu displace Mn. Application of farmyard manure and acid forming fertilizer such as $(NH_4)_2SO_4$ can prevent Mn deficiency in rice (Fairhurst et al. 2007).

10.9 Boron

Boron (B) is an important constituent of cell walls and its deficiency results in reduced pollen viability. As B is not retranslocated to new growth, deficiency symptoms usually appear as white, rolled leaf tips of young leaves. Boron deficiency in rice may be expressed solely in the form of reduced grain yield from floret sterility. Okuda et al. (1961) observed that panicles of B-deficient rice plants failed to come out from the boot. The critical soil level for occurrence of B deficiency is 0.5 mg B kg^{-1} hot water extraction (Fairhurst et al. 2007). While Fageria et al. (1997) suggested a critical concentration of 8 mg B kg^{-1} in rice leaves at maturity, Yu and Bell (1998) reported that 18.5 mg B kg^{-1} in rice leaves and 8.9 mg B kg^{-1} in rice stems were associated with optimum rice yields. Boron deficiency in rice may be corrected by applying B in soluble forms as borax (0.5–3 kg B ha^{-1}) (Fairhurst et al. 2007). Borax should be broadcast and incorporated before planting, top-dressed, or as foliar spray during vegetative rice growth.

10.10 Integrated Plant Nutrient Management in Rice

The integrated plant nutrient management (IPNM) aims to judiciously manipulate the nutrient stocks and flows to maintain and improve fertility and health of the soil for sustained crop productivity on long-term basis and use fertilizer nutrients as supplement to nutrients supplied by different organic sources available at the farm. The IPNM in rice has great impact in terms of maintaining health of soils that are low in organic matter content as are commonly found in South Asia (Katyal et al. 2001). In recent years, a large number of long-term experiments on rice-based cropping systems in South Asia have shown that integrated management of different organic materials and mineral fertilizers resulted in positive impact on the yield of rice along with build-up of soil organic matter. Ladha et al. (2003) analyzed 12 rice–wheat long-term experiments and concluded that annual rate of yield change in rice was significantly higher with integrated management of organic manures and fertilizers as compared with the NPK treatment.

10.11 Conclusions

Fertilizers account for 20–25 % of total production costs in lowland rice systems. Therefore, increasing the yield of rice per unit area through the use of appropriate nutrient management practices has become an essential component of modern rice production technology. It has been endeavored to manage nutrients in the form of recommendations consisting of optimum fertilizer N rates, improved methods and timings of application and placement and new forms of fertilizers. Development of efficient practices for managing different nutrients in rice has been possible by integrating basic knowledge of soil properties, nutrient cycles, chemical and biochemical transformation processes, and rice growth and nutrient uptake under flooded soil conditions. These agronomically and environmentally efficient nutrient management strategies are already recommended in many rice-producing regions.

To achieve high recovery efficiency of nutrient applied as fertilizers, agronomic efficiency and rice yield levels through better synchronization between the supply and the uptake of nutrients by the crop, a shift from blanket fertilizer recommendations to site-specific need-based fertilizer management scenarios is being made. New innovations in the management of N, P, K, and micronutrients in rice are evolving as our understanding increases about the fate of these elements under the emerging soil–water–crop scenarios based on salt- and drought-tolerant rice cultivars or new plant types for irrigated rice ecosystems, enhanced nutritional quality of rice grain through breeding, biotechnological approaches, integrated rice crop management with fine tuning of production technologies to reduce the cost of production and enhance productivity, production of rice under climate change adaptive technologies, mechanization of rice farming to sustain rice productivity, and conservation of natural resources like land, water, and labor. The challenge ahead is to continue incorporating new and emerging technologies into practical management recommendations so that all rice farmers, even those with limited resources, can adopt the efficient nutrient management practices to produce enough rice for everyone and with minimal damage to the environment.

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