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Rice Production Worldwide

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Preface

Rice is among the three most important grain crops in the world, and it has a major contribution to fulfill the food needs across the globe. The role of rice crop is inevitable in the current and future global food security. Rice is grown in Asia, Americas, Australia, Europe, and Africa following diverse production practices. Pests and other problems, genotypes, and management practices in rice vary greatly in different parts of the world. Such difference are needed to be highlighted in order to understand and improve the global rice production. Our book 'Rice Production Worldwide' will help the readers to understand the past trends in global rice production, the current cultures of rice production in a global perspective, and the changes that are required to improve and sustain the rice productivity in different regions. In this book, we have addressed the rice origin, history, role in global food security, rice physiology, major rice producing areas of world (their importance, characteristics of rice cropping systems, management practices; salient technologies involved, merits and demerits of the particular systems), major rice production systems (conventional flooded system, aerobic rice system. etc.), rice cultivars, fertilizer management, and pest management in rice. Further, we have highlighted the harvesting, threshing, and processing of rice as well as the role of biotechnology in improving the rice production, quality, and nutrition. The book is equally advantageous for academicians, researchers, students, and farming community.

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Current Status, Challenges, and Opportunities in Rice Production

Rajendra Prasad, Yashbir Singh Shivay, and Dinesh Kumar

1.1 Introduction

Rice is grown in all the six continents of the world (Asia, Africa, Australia, Europe, North America, South America) where field crop production is practiced leaving only the icy continent of Antarctica, where no crops are grown. Rice is the staple food for nearly half of the world's population. Rice has been a part of the cultural identities of several countries, and a number of festivals are related to the rich harvest of rice, e.g., Pongal, Onam, and Bihu in India, Rub Kwan Khao in central Thailand (www.ricewisom.com), Harvest Moon in China and Chu Suk in Korea (everything ESL.net), Dewi Sri in Indonesia, Santabary festival in Madagascar, and Amu festival in Ghana. In these festivals, the first grains of rice are offered to veneration God. Rice harvest festivals are also organized in southern states of the USA, namely, Arkansas and Louisiana, as a fair with lots of fun, food, and merrymaking. Rice is mentioned in Rig Veda and Mahabharata (Nene 2012; Prasad et al. 2016) and in the Bible (Rubin 2004).

Rice has now become a foreign exchange earner for several countries and is playing a role in their economies. Top ten rice exporting countries in 2014 were India, Thailand, Pakistan, the USA, SR Vietnam, Italy, Uruguay, Brazil, China, and Australia, respectively (Table 1.1) (Workman 2015). The largest rice importing regions are Middle East and sub-Saharan and Western Africa (Adjao and Staatz 2015).

In recent years, there have been three major studies on probable trends in the rice markets over the coming decades, namely, USDA (2013) for the period 2011–2022, University of Arkansas, USA (Wailes and Chavez 2012), and OECD/FAO (2013).

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Table 1.1 Global rice export during 2014

Country	*D* value (million US$)	Share (% of the world)
India	7906	32.1
Thailand	5439	22.1
Pakistan	2200	8.9
USA	2047	8.3
SR Vietnam	1713	6.9
Italy	699	2.8
Uruguay	524	2.1
Brazil	397	1.6
China	378	1.5
Australia	353	1.4

(Workman 2015)

The general conclusions are as follows: (1) Asia will continue to dominate the world rice economy, and (2) likely increase in world rice consumption is expected at 1 % per annum (pa); the rates may be higher in the Middle East and sub-Saharan Africa. According to OECD/FAO projections, rice–coarse grain price ratio may fall from 2.5 in recent years to 1.9 by 2022, and the rice–wheat price ratio may fall marginally from 1.8 to 1.7. This indicates some disadvantage to rice over coarse grains.

Success of the Green Revolution in the late 1960s witnessed a steady rise in Asia's per capita rice consumption, where it increased from 85 kg per year in the early 1960s to nearly 103 kg in the early 1990s. During the same period, global per capita rice consumption increased from 50 to 65 kg per annum. During this period (1960s–1990s), the global rice consumption increased from 150 to 350 million metric tons (MMT) due to two factors: (1) increased per capita rice consumption and (2) more than twofold increase in Asia's population. However, since the early 1990s, strong economic growth in many Asian countries, particularly in China and India, halted the upward trend in global per capita rice consumption as consumers diversified their diet from rice to high-value products such as meat, dairy products, fruits, and vegetables. A recent analysis has shown a declining trend in the contribution of rice toward total calorie intake by humans in Asian countries; the contribution of rice toward total calorie intake by humans changed from 30.2 % in 1961 to 26.8 % in 2007 in China, while it changed from 79.1 % in 1961 to 69.8 % in 2007 in Bangladesh (Timmer 2010). In 1961, the contribution of rice toward total calorie intake was 30.2 % in China and 79.1 % in Bangladesh, and in 2007 it was declined to 26.8 % in China and 69.8 % in Bangladesh. It is predicted that this trend will provide a check and limit the demand for rice to 501 MMT as against a production of 502.7 MMT in 2021–22 (Wailes and Chavez 2012).

1.2 Origin of Rice and Taxonomy

The cultivated rice belongs to the family Poaceae (Gramineae), subfamily Bambusoideae, tribe Oryzeae, and genus *Oryza*. The genus *Oryza* has been divided into four species complexes: (1) *sativa* complex, (2) *officinalis* complex, (3) *meyeriana* complex, and (4) *ridley* complex (Khush 2005). Only *Oryza sativa* complex has two cultivated species, namely, *O. sativa* and *O. glaberrima* Steud. *Oryza sativa*, the Asian rice, is grown worldwide, while *O. glaberrima* is grown on a limited acreage in a few African countries. The species in other *Oryza* complexes are wild types. The major problem with the wild types was lodging and shattering of grain and domestication selection focused on plants that had less lodging and shattering (Callaway 2014).

The two major subspecies of *O. sativa*, namely, *japonica* and *indica*, are more closely related to distinct wild varieties than they are to each other, pointing to two separate regions of domestication: *japonica* in China and *indica* in India (Gross and Zhao 2014). *Japonica* and *indica* share identical non-shatter mutations in gene sh4. However, it is suggested (Sang and Ge 2013) that the mutation arose in an ancestor of *japonica* rice first and then found its way to *indica*. In China, the domestication may have taken place in the lower end of Yangtze River Valley (Vughan et al. 2008; Fuller et al. 2009) or in the Pearl River Valley (Huang et al. 2012). It is certain that the origin of rice lies in the region of Asia covering Assam-Meghalaya area of India and river valley regions of southeast China (Swaminathan 1984; Fuller 2011). *Indicas* are grown throughout the tropics and subtropics. Traditional *indicas* are characterized by tall stature, weak stem, droopy leaves, high tillering capacity, long grains, and poor response to high nutrient input conditions. *Japonicas* have stiff, short stalk, and erect type with round grains and are highly responsive to nutrient inputs. These are limited to the temperate zones. A third subspecies, which is broad grained and thrives under tropical conditions, was identified based on morphology and initially called *javanica*, but is now known as *tropical japonica*. Examples of this subspecies include the medium grain "Tinawon" and "Unoy" cultivars, which are grown in the high-elevation rice terraces of the Cordillera Mountains of northern Luzon, Philippines. Because of high yields and economic returns, International Rice Research Institute (IRRI), Philippines, developed two cultivars of *japonica* suitable for tropics, which are NSIC Rc170 or IRRI 142 (now called MS11) and NSCIC Rc220 or IRRI 152 for large-scale cultivation in the Philippines (Kang 2010).

1.3 Area, Production, and Consumption

Although rice yields are still growing, the rate of growth has been declining; compound growth rate was 2.5 % per annum (pa) during 1962–1979 and declined to 1.4 % pa during 1980–2011 (Adjao and Staatz 2015). The cereal production forecast by Food and Agriculture Organization (FAO) in April–June 2015 indicated that out of the total cereal production of 2524.3 MMT, the contribution of rice (milled), wheat, and coarse grains is likely to be 500.5 MMT, 723.4 MMT, and 1300.3 MMT, respectively. At the global level, the share of rice in total cereal production did not change significantly between 1961 and 2007, starting from 24.6 % and gradually reaching to 28.1 % (Timmer 2010); thus, about 20 % of cereal production in the world is going to be rice.

Table 1.2 Predictions of area, production, consumption, and yield of rice

Item	2010/11	2015/16	2021/22
Area (M ha)	157.3	160.2	160.5
Production (MMT)	451.4	481.5	502.7
Consumption (MMT)	446.2	478.5	501.0
Average yield (MT ha^{-1})	2.87	3.01	3.13

Source: Wailes and Chavez (2012)
Mha million hectares, *MMT* million metric tons of milled rice, *MT ha^{-1}* metric tons of milled rice per hectare

According to world rice outlook, rice-harvested area in the year 2015–2016 is likely to be 160 million hectares (M ha), and it is not going to change much by the year 2021–2022 (Table 1.2). About 80 % of the total global area under rice is in eight Asian countries, namely, China, India, Indonesia, Bangladesh, the Philippines, Vietnam, Thailand, and Myanmar, which are not just any eight countries of over 200 countries of the United Nations; they hold 46.6 % of the world's population. Asia as a whole has 90 % of the world's rice area. Comparatively, Africa has only 8 M ha (5 %) (IRRI 2006), Latin America and the Caribbean have about 5.5 M ha (Pulver et al. 2010), and Brazil has about 2.8 M ha (Lafranco 2010). However, the growth rate in rice area during 1980–2011 has been 3.1 % pa in Africa as compared to only 0.4 % pa in Asia (Adjao and Staatz 2015). Considering the total rice production, China had the largest share of 30.1 % in 2010, which is likely to decrease to 27.3 % by 2021–2022, while India's share may slightly increase from 21.5 % in 2010 to 22.4 % in 2021–2022 (Wailes and Chavez 2012). Asia's share of world's rice production may slightly decline from 89.9 to 89.3 % over 2010–2021, while Africa's share may increase from 3.4 to 4.2 % (Wailes and Chavez 2012).

1.4 Milestones in the Development of Modern Rice Varieties

1.4.1 Indica–Japonica Crosses

As a sequel to the recommendations of the International Rice Commission (IRC) Working Group, an *indica* × *japonica* hybridization program was initiated in 1951 under the auspices of FAO, United Nations. All the countries of tropical Asia participated in the project by sending the seeds of their best *indica* varieties for crossing with japonicas at the Central Rice Research Institute (CRRI), Cuttack, India. India and Malaysia distributed early-maturing, nonseasonal commercial varieties derived from this project. In India, ADT 27, which was suitable for the early monsoonal season, replaced the earlier varieties ADT 3 and ADT 4 in the Thanjavur delta. In Malaysia, Malinja and Mahsuri had the preferred grain quality and were recommended for the irrigated areas in Wellesley province (Parthasarathy 1972). Even today, Mahsuri is widely grown in many parts of tropical Asia, where there is poor soil and poor water control in the monsoonal season (DeDatta 1981).

1.4.2 High-Yielding Fertilizer Responsive Varieties

In 1949, Dee-geo-woo-gen, a semidwarf rice variety, was crossed with Tsai-yuan-chung, a tall disease-resistant variety, and Taichung Native 1 was selected from this cross and released for cultivation in 1956. This was the first semidwarf, non-lodging, high-yielding variety which had a yield potential of 6 t ha^{-1}. Later IRRI released IR-8 (Dee-geo-woo-gen × Peta, an Indonesian variety) in 1966, which also yielded 6 t ha^{-1} or more. These high-yielding *indica* varieties spread in Southeast Asia and brought the Rice Revolution. Since then, IRRI has released a number of high-yielding varieties.

1.4.2.1 Hybrid Rice

Chinese rice breeder Yuan Longping, who is known as the father of hybrid rice, successfully transferred the male sterility gene from wild rice to create the cytoplasmic genetic male sterile (CMS) line and developed hybrid rice (Virmani et al. 1997). Hybrid rice yield is reported to be as high as 13.9 t ha^{-1} (Anonymous 2011). Hybrid rice is now grown in many South Asian countries, and in China it covers more than 50 % area under rice (FAO 2004).

1.4.2.2 Basmati Rice

Basmati is an aromatic rice variety. The earliest mention of basmati rice was done by a poet Waris Shah in his authored poetic love story Heer Ranjha in 1766 (Singh 2000; Robinson 2010). Basmati rice is famous for making pulao, a delicacy in India, Pakistan, and the Middle East and even in parts of the UK, the USA, and Canada, where large Indian and Pakistani communities reside. The aroma in basmati rice is due to a compound named 2-acetyl-1-pyrroline (Wongpornchai et al. 2003). The region for origin of basmati rice is Punjab (both in India and Pakistan), and the earliest basmati rice variety Basmati 370 was released for commercial cultivation from Rice Research Station, Kala Shah Kaku (now in Pakistan), in 1933 (Singh 2000). Since yields of traditional basmati varieties were low (1 to 2.5 t ha^{-1}) and the crop used to get lodged on heavy fertilization, plant breeders at the Indian Agricultural Research Institute, New Delhi, India, crossed traditional basmati varieties with semidwarf high-yielding varieties and developed high-yielding (4–6 t ha^{-1}) basmati varieties. The first such variety was Pusa Basmati 1. One of the most popular basmati varieties is Pusa Basmati 1121, which has a kernel length of 8.2 mm and an elongation ratio of 2.0 to 2.5 on cooking (Anonymous 2007). It was released for commercial cultivation in 2003, and by 2013 it covered 84 % of the total basmati area in Punjab, 78 % in Uttar Pradesh, 68 % in Haryana, and 38 % in Uttarakhand states. One of the latest additions is Pusa Basmati 1509. Work on the development of high-yielding varieties of basmati rice has also been conducted in Pakistan. The basmati rice varieties released in Pakistan include C-622, Basmati Pak (or Kernal

Basmati), Basmati 198, Basmati 370, Pak 177, Basmati 385, Shaheen Basmati, Basmati 2000, Super Basmati and Basmati 515, and PK-386 (Zafar 2015). Shaheen Basmati is more tolerant to salt-affected soils than other varieties, Basmati 2000 has better threshing characteristics, and Basmati 515 has a higher-yield potential than other varieties. Despite being released in 1996, Super Basmati is still widely grown in Pakistan (nearly 80–90 % of area under rice). In the USA, aromatic rice variety Texmati was developed by Rice Tec Inc., Alvin, Texas.

1.4.2.3 Genetically Modified Rice

One of the genetically modified (GM) rice is "golden rice." Golden rice has been engineered to express beta-carotene by introducing a combination of genes that code for biosynthesis pathway for the production of provitamin A in the endosperm (Ye et al. 2000). Enhancement of Fe content in rice has also been achieved by improving the uptake from soil and by increasing the absorption and storage of Fe (Murray-Kolb et al. 2002; Takahashi et al. 2001). Further, GM rice has been developed that produces both beta-carotene and ferritin (Potrykus et al. 1996). However, golden rice has been a point of controversy. There are problems in the acceptance of GM crops in several countries (Jaffe 2005).

Herbicide-resistant (HR) rice is another group among GM rice. So far three types of HR rice have been developed. Glyphosate- and glufosinate-resistant ones are GM rice, whereas imidazolinone-resistant rice was developed through chemically induced seed mutagenesis and conventional breeding (Gealy et al. 2003). HR rice are widely grown in the USA. However, there is a potential risk of transfer of the genes conferring HR traits to wild and weedy species (Kumar et al. 2008). Recently, Burgos et al. (2014) from the USA have reported that continuous growing of HR Clearfield (nontransgenic HR) rice has led to the evolution of HR weeds, which tend to possess crop halophytes in the portion of chromosome 2 containing the acetolactate synthase gene which confers herbicide resistance to Clearfield rice.

1.4.2.4 NERICA Rice

Oryza glaberrima was domesticated in Africa about 3500 years ago. It was prone to lodging and its panicles had shattering problem. To overcome these problems, *O. sativa* was introduced in Africa some 450 years ago. *Oryza sativa* gave higher yields and has spread steadily in Africa. However, some *O. glaberrima* varieties, such as CG 14, are more weed competitive and resistant to iron toxicity, drought, nematodes, waterlogging, and major African rice diseases and pests. They also adapt better to acid soils and to soils low in phosphorus (P). Efforts are therefore underway to develop crosses between *O. glaberrima* and *O. sativa* since the 1990s. These new rice types are known as NERICA (New Rice for Africa). The best NERICA varieties combine the stress tolerance of *O. glaberrima* and high-yield potential of *O. sativa* (Mohapatra, 2010).

1.4.2.5 Aerobic Rice

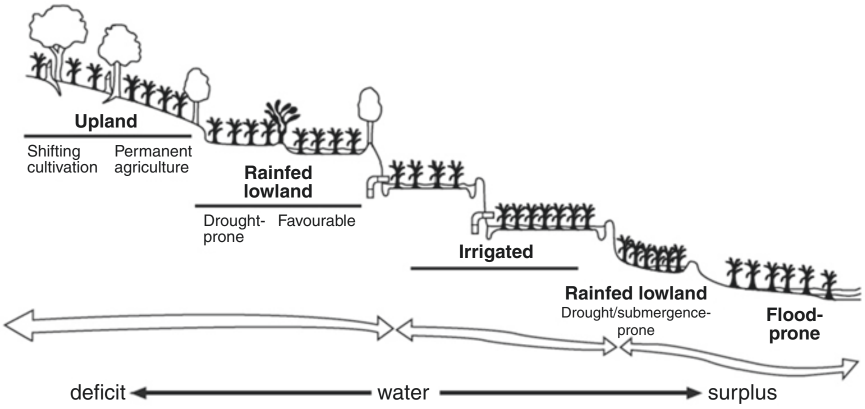
Aerobic rice varieties (ARVs) were developed to permit growing of rice as an upland crop, such as wheat (Prasad 2011). In China, the breeding program for aerobic rice was initiated in the 1980s at the China Agricultural University (CAU), the China Academy of Agricultural Sciences (CAAS), the Liaoning Province Academy of Agricultural Sciences (LPAAS), and the Dandong Academy of Agricultural Sciences (DAAS). This led to the development of Han Dao (HD)297, HD277, and HD502. In addition, LPAA released Han 58 and DAAS released Danjing 5. These new varieties have more drought tolerance, reduced plant height, higher lodging resistance, erect upper leaves, and increased resistance to blast, higher grain yield, and better grain quality. The HD277 and H58 are currently the most extensively grown ARVs in China (Huaqi et al. 2002).

In Brazil, the National Research Center for Rice and Beans has developed many ARVs. Maravilha and Primavera were the first upland rice varieties, released in 1996, that combined the grain quality and desirable aerobic rice characteristics (Pinheiro 1999). Recently released ARVs are Talento and Soberana (Pinheiro et al. 2006) and AN Cambara (Santana 2010).

IRRI initiated its own program for developing ARVs with a focus on tropical and subtropical regions and developed IR55423-01 (named Apo) and UPLRI-5 from the Philippines, B6144-MR-6-0-0 from Indonesia, and CT6510-24-1-2 from Columbia. Yields obtained with ARVs vary from 4.5 to 6.5 tha^{-1}, which is about the double or triple of that obtained with traditional upland varieties and 20–30 % less than that obtained with lowland varieties grown under flooded conditions (Farooq et al. 2009). Aerobic rice helps in doubling the water use efficiency, and there is 50 % water saving relative to the conventional lowland rice (Zhao et al. 2010).

1.5 Rice Ecosystems

Rice is grown under a wide variety of environments. The IRRI (IRRI 1993) has categorized rice field ecosystems (RFES) into four types: upland, irrigated, rainfed lowland, and flood-prone rice ecosystems (Fig. 1.1). The upland RFES varies from low-lying valleys to undulating and steep sloping land with high runoff and lateral water movement and covers less than 13 % of the world's rice land. In the irrigated RFES, the rice fields have assured water supply for one or more crops a year. Irrigated lands cover about half of the world's rice lands and produce about 75 % of the world's rice. The rainfed lowland RFES has both flooding and drought problems. About one quarter of the world's rice fields are rainfed lowlands. The remaining rice fields are classified as flood-prone RFES and cover about 8 % of the world rice area. This RFES is subjected to uncontrolled flooding. The land may remain submerged for as long as 5 months at a time with water depth from 0.5 to 4.0 m or more, and in some areas there could be even intermittent flooding with brackish



Upland	Rainfed lowland	Irrigated	Flood-prone
Level to steeply sloping fields; rarely flooded, aerobic soil; rice direct seeded on plowed dry soil or dibbled in wet, non-puddled soil	Level to slightly sloping, bunded fields; non-continuous flooding of variable depth and duration; submergence not exceeding 50 cm for more than 10 consecutive days; rice transplanted in puddle soil or direct seeded on puddle or plowed dry soil; alternating aerobic to anaerobic soil of variable frequency and duration	Leveled, bunded fields with water control; rice transplanted or direct seeded in puddle soil; shallow flooded with anaerobic soil during crop growth	Level to slightly sloping or depressed fields; more than 10 consecutive days of medium to very deep flooding (50 to more than 300 cm) during crop growth; rice transplanted in puddle soil or direct seeded on plowed dry soil; aerobic or anaerobic soil; soil salinity or toxicity in tidal areas

Fig. 1.1 Rice land ecosystems (after Greenland 1997 as adapted from IRRI 1993) (Reproduced with the kind permission from IRRI)

water caused by tidal fluctuations. These different RFESs have varying plant nutrient problems, weed species, and pest problems and demand different rice crop management strategies.

1.6 Rice Soils

The wide ranges of environmental conditions lead to an equally wide variety of rice soils. Moorman (1978) observed that the most important soil suborders on which rice is grown are Aquents, Aquepts, Orchepts, Tropepts, Aqualfs, and Aqults. As regards texture, rice is grown on loamy sands to heavy clay loams or clays. It is grown on acid soils below pH 5 to sodic soils having pH above 9. Again the rice soils may have organic matter contents of less than 1 % in loamy sands to peat soils having organic matter content as high as 95 %. Flooding changes the entire chemistry of soils. The submergence leads to gradual depletion of oxygen in the soil, and this causes reduction of a number of nutrient ions such as nitrates, sulfates, iron, manganese, etc. (Patrick and Mahapatra 1968). A number of chemical reactions follow submergence, which affect rice plant growth. Some of these are briefly discussed here.

1.6.1 Redox Potential

The single electrochemical property that serves to distinguish a submerged soil from a well-drained soil is the reduction of oxygen, which is measured by its redox potential. The low potentials (0.2 to −0.4 V) of submerged soils reflect this reduced state as a contrast to the high potentials (0.8 to 0.3 V) of aerobic soils (Ponnamperuma 1972). Iron, manganese, and sulfur availability is most affected by the changes in redox potential.

1.6.2 Soil pH

The overall effect of soil submergence is to increase the pH of acid soils and to depress the pH of sodic and calcareous soils, the ultimate result being convergence to pH 7.0 (Ponnamperuma 1972) (Fig. 1.2). This permits the rice plants to grow well on acid as well as alkaline soils too. You may consult Ponnamperuma (1972) for further information regarding the characteristics of submerged soils.

1.6.3 Iron

Under submerged conditions Fe^{3+} is reduced to Fe^{2+}. The relationship between Fe^{2+} and pH is given by the expression (Ponnamperuma 1972)

$$\mathrm{pFe}^{2+} = 2\mathrm{pH} - 10.8$$

According to the above expression, the activity of Fe^{2+} is likely to be 3.5 ppm at pH 7.5, 35 ppm at pH 7.0, 350 ppm at pH 6.5, and 3500 ppm at pH 6.0. Thus, a pH change of 0.5 units above or below pH 7.0 can spell the difference between deficiency and toxicity of iron in submerged soils. Iron toxicity leads to bronzing disease indicated by brown spots on the leaves, which may coalesce to cover the entire leaf (Becker and Asch 2005). This is due to accumulation of oxidized polyphenols (Dobermann and Fairhurst 2000). Such leaves contain 300 to 1000 $\mu g\ Fe^{2+}\ g^{-1}$ dry matter (Ottow et al. 1983). Iron toxicity prone areas include poorly drained Acquents, Acquepts, and Acquults in Indonesia, the Philippines, and Sri Lanka

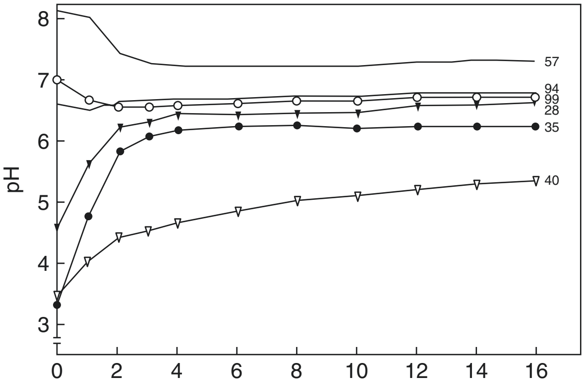


Fig. 1.2 Changes in soil pH due to submergence (numbers for different curves refer to soil sample numbers; soils were clay or clay loam having 2.2 to 7.2 % organic matter, 0.08 to 4.7 % iron, and 0.0 to 0.8 % manganese) (From: Ponnamperuma, F.N. (1972) Advances in Agronomy 24:29–96) (Reproduced with the kind permission from Elsevier Limited, Kidlington, Oxford, UK)

(Jagsujinda and Patrick 1993); acid sulfate and peat soils of Brundi, Senegl, and Madagascar (Genon et al. 1994); lowlands of Western Africa (Audebert et al. 2006); and flooded soils of Assam and northeast region of India (Singh et al. 2003). Drainage and liming help in overcoming iron deficiency (Prasad 2000).

1.6.4 Manganese

Reduced conditions in submerged rice fields also lead to reduction of Mn^{4+} to Mn^{2+}. In the soils which are rich in manganese and organic carbon, Mn^{2+} concentration can go as high as 90 ppm within a week or two after submergence followed by subsequent decline to a stable level of 10 ppm (Ponnamperuma 1972). This leads to manganese toxicity in rice, which generally occurs in concurrence with iron deficiency (Prasad 2007). Potassium (K) fertilization (Alam et al. 2003) and Si application (Li et al. 2012) can ameliorate manganese deficiency in rice.

1.6.5 Sulfur

Under submergence, sulfate is reduced to sulfide (S^{2-}), and in iron-deficient soils, H_2S (hydrogen sulfide) is produced, which is toxic to rice (Tanaka et al. 1968; Joshi et al. 1975; Armstrong and Armstrong 2005). It damages rice roots, which become sparse, have reduced laterals, and turn black, and the disease is known as "Akiochi" in Japan. Hydrogen sulfide production under submerged conditions adversely affects not only rice but also acts as a host of other plant species and organisms (Lamers et al. 2013). When sufficient iron is present, FeS is formed and gets precipitated. Submergence can therefore lead to sulfur deficiency in rice (Yamaguchi 1999).

Effects of submergence on N, P, K, and Zn are discussed under nutrient management.

1.7 Cropping Systems (CS)

In tropical regions, one, two, or three crops of rice are taken depending upon the rainfall and availability of irrigation water. In subtropical, subtemperate, and temperate regions, upland crops, such as beans, corn, wheat, and vegetables, are grown before or after rice. Beans and fodder legumes, such as clovers, and legume green manures such as *Sesbania aculeata* improve soil fertility (George and Prasad 1989; John et al. 1989; Sharma and Prasad 1999). Of great interest is the rice–wheat (*Triticum aestivum*) cropping system (RWCS) practiced over 18.5 million hectares in South Asia and Southeast Asia (Prasad 2005; Ladha et al. 2009). In the Indian subcontinent, rice is grown during rainy season (July to November) when 700–1000 mm rainfall is received, while wheat is grown during the winter season (November to May) on stored soil moisture with supportive irrigation. In China, rice and wheat have several common months, and quite a bit of rain is received during the wheat growing season. Many farmers in India and Pakistan take a third crop of potato (*Solanum tuberosum*) or toria (*Brassica campestris*) in between rice and wheat. Also, many farmers cultivate mung bean (*Vigna radiata*)/cowpea (*Vigna unguiculata*)/green manure in between wheat and rice. Some of the rice-based cropping systems are rice–wheat, rice–potato–wheat, rice–toria–wheat, rice–wheat–mung bean, rice–wheat–cowpea, rice–wheat–green manure (*Sesbania* spp., *Crotalaria* spp.), rice–potato–wheat–green manure, rice–wheat–sunflower (*Helianthus annuus*), rice–wheat–rice, rice–vegetable peas (*Pisum sativum*)–wheat, rice–vegetable peas–wheat–green manure, and rice–wheat–maize (*Zea mays*). There could be many more variants involving vegetables and other short-duration crops.

The major problem of the RWCS is that rice is transplanted on a puddled soil in the rice production system called “conventional tillage with typical puddled transplanted rice” (CTTPR), which has to be dried and given primary tillage for a soft seedbed for wheat. This delays seeding of wheat resulting in serious yield losses. Also repeated puddling adversely affects soil physical properties by destroying soil aggregates, reducing permeability in subsurface layers, and forming hardpans at shallow depths (Sharma et al. 2003, 2004), all of which can negatively affect the following wheat crop (Tripathi et al. 2005). To avoid the delay in sowing wheat, no-till direct seeding technology has been developed, which has been very successful (Kumar and Ladha 2011).

1.8 Constraints to Sustained Rice Production

The productivity and sustainability of rice and rice-based systems are threatened because of (1) increasing scarcity of resources (land, water, and labor and machines), (2) inefficient use of inputs (fertilizer, water, herbicides, insecticides, etc.), and (3) the rising cost of cultivation.

1.8.1 Natural Resources

1.8.1.1 Land

Rice farm holdings in Asia are quite small, and arable land available per person is already too little compared to developed countries like the USA (Table 1.3). Further, more and more land is being diverted to roads, railways, and dwellings indicating a decline in arable land. Thus, the only hope for continued sustainable rice production is in increasing productivity per hectare.

1.8.1.2 Water

Rice growers in Asia are small holder farmers who are always on the mercy of nature. Tuong and Bouman (2003) reported that seasonal water input for TPR varies from 660 to 5280 mm depending on growing season, climatic conditions, soil type, and hydrological conditions. This consists of (1) 160–1580 mm for land preparation (puddling), 400–700 mm for evapotranspiration (ET), and 1500–3000 mm (for loamy/sandy soils) or 100–500 mm (for heavy soils) of unavoidable losses due to percolation and seepage. Gupta et al. (2002) estimated that water use for rice in the Indo-Gangetic Plains varied from 1144 mm in Bihar (wetter region) to 1560 mm in Haryana (drier region). In the Philippines, water use has been reported as 790–1430 mm (aerobic fields) or 1240–1880 mm (flooded fields) (Bouman et al. 2005). In Pakistan, water input was 2190–2445 mm for flooded rice, 1793–1935 mm for alternate wetting and drying, and 1573–1635 mm for direct-seeded rice (Jabran et al. 2015a, b). The higher water application in rice as compared to other cereals is mostly due to water requirements for puddling and losses associated with continuous flooding such as seepage and deep percolation losses to groundwater (Hafeez et al. 2007). Seepage and percolation losses vary from 25 % to 85 % of total water input depending on soil type and water table and 25–50 % in heavy soils with shallow water tables and 50–85 % in coarse-textured soil.

Total seasonal water input to rice fields varies from as little as 400 mm in heavy clay soils with shallow groundwater tables to more than 2000 mm in coarse-textured (sandy or loamy) soils with deep groundwater tables. Thus, on average about 1300–1500 mm of water is needed for irrigated rice in Asia. On an average, it takes 1432

Table 1.3 Arable land (ha person^{-1}) in Asian countries as compared to that in the USA

Country	2000–2004	2010–2014
Bangladesh	0.05	0.05
Cambodia	0.28	0.028
China	0.08	0.08
India	0.13	0.13
Indonesia	0.10	0.10
Japan	0.03	0.03
Korea, Democratic Republic	0.09	0.09
Korea Republic	0.03	0.03
Malaysia	0.06	0.03
Myanmar	0.21	0.20
Nepal	0.09	0.08
Pakistan	0.12	0.12
Philippines	0.06	0.06
Sri Lanka	0.06	0.06
Vietnam	0.07	0.07
USA	0.52	0.49

Source: World Bank-IDA (2015) (via the Internet)

liters of water to produce 1 kg of rice in an irrigated lowland production system (http://www.knowledgebank.irri.org/step-by-step-production/growth/water-management).

Irrigated rice receives an estimated 34–43 % of the total world's irrigation water or about 24–30 % of the entire world's developed freshwater resources (RKB 2015). Due to increase in area under irrigated rice, the use of groundwater structures (mostly irrigation pumps) and use of groundwater in Asia have considerably increased (Table 1.4). Thus, irrigated rice has resulted in lowering the water table, and in some regions this has reached an alarming situation. For example, in North China Plain (NCP), water table is declining by 1–3 m each year (Shah et al. 2000), while in the Indo-Gangetic Plain (IGP) of India, it is declining by 0.5–0.7 m each year (Carriger and Vallee 2007; Tuong and Bouman 2003).

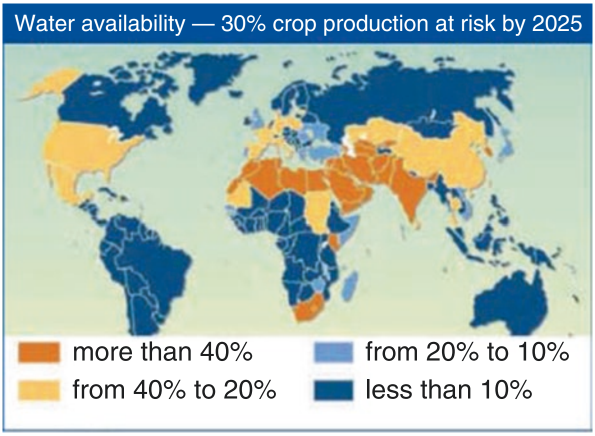
Increasing water scarcity has threatened the productivity and sustainability of the irrigated rice system in Asia (Tuong et al. 2004). Irrigation water is becoming scarce each day, and according to World Economic Forum (WEF 2011) of UNEP, several rice-growing Asian countries are likely to face 20–40 % (average 30 %) shortage in water availability by 2025 (Fig. 1.3).

In response to water shortage, researchers have made efforts to grow rice with less water inputs. These include the technologies such as alternate wetting and drying, aerobic rice cultivation, dry direct-seeded rice, and rice cultivation using drip irrigation. For details, please see the chapter “Rice Production Methods.”

Table 1.4 Number of groundwater structures (mostly irrigation pumps) and annual groundwater use

Country	Groundwater structures (million)	Groundwater use (km^3 yr.$^{-1}$)
Bangladesh	0.80	31
India	19	150
Nepal Terai	0.06	<1
Pakistan (Punjab province)	45	45
China	3.5	75
Iran	0.5	29
Mexico	0.07	29
USA	0.2	100

Source: Shah (2005, 2007)



Source: UNEP

Fig. 1.3 Water shortage in different parts of the world (Reproduced with the kind permission from UNEP)

1.8.1.3 Labor

In Asia, where most rice cultivation operations such as nursery raising, transplanting, weeding, and even harvesting are still done manually, the labor requirements are very high for CTTPR and are reported to be 237 person-days ha^{-1} in Malaysia (Wong and Moorka 1996), 229 person-days ha^{-1} in India (Thakur et al. 2004), and 139 person-days ha^{-1} in Bangladesh (Rahman et al. (2008). Labor availability for agriculture is declining globally, and rice, which is a very labor-intensive crop, is going to suffer the most. Worldwide 60 % of all child labor in the age group of 5 to 17 works in agriculture including farming, fisheries, aquaculture, forestry, and livestock, mostly as unpaid family members (ILO 2010). Further, wages for farm workers in South and Southeast Asia have increased; the average wage in the 2010s is five times higher than that in the 1970s, and an increase of 100 to 200 % in the current labor wages is a realistic expectation within the next 5–10 years

(Beltran et al. 2012). The mass rural-to-urban movement of young working class and resulting high wages of farm labor will eventually lead to mechanization of rice cultivation in Asia.

1.8.2 Inputs

1.8.2.1 Energy: Mechanization of Rice Cultivation

Energy is required for all field operations in rice culture. The major advantage with machines is precision and saving of time. For each ton of rice produced, more than 7000 mega joules (MJ) of energy are needed, whether provided by humans, animals, or machines (Rickman 2012). For instance, manual plowing of a hectare requires 150 person-days, 12 days when animals are used, a day with a two-wheel tractor, and only 1–2 hours with a four-wheel tractor; the same amount of energy of about 1500 mega joules is required to do the job. The major difference is the time saved (Rickman 2012). Similar is the situation with transplanting. In one study, the mechanical transplanting of rice proved beneficial in saving of 66 % cost of transplanting and required only 7 % of time as compared with manual transplanting (Sharma et al. 2002a, b). Moreover, it is seen that population of the plants in the farmers' field is generally low (18–20 plants m^{-2}) because the hired labor tends to transplant more area in a limited time for higher earnings, but it results in reduced grain yields. Aggarwal and Singh (2015) opined that mechanical transplanting is a promising solution to avoid yield reduction, as it helps in avoiding delay in transplanting under labor-scarce conditions particularly in Indo-Gangetic plains. Similarly, the cost of rice cultivation by drum seeding was reduced by 26 % because of mechanized paddy cultivation, and net return per acre also increased by 34 % (Malleswara Rao et al. 2014). As regards harvesting, manual harvesting and threshing cost $100–120 per hectare, while manual harvesting with mechanical threshing costs about $80 per hectare, which is similar to combine harvesting that costs $80–100 per hectare (Rickman 2012). Moreover, grain losses due to shattering are much less from rice combine harvesters compared with the manual harvesting. Rice combine harvesters are expensive and relatively sophisticated machines. Small holder farmers obviously cannot afford to buy or maintain these machines. Availability of combine harvesters and other farm machinery on custom-hiring basis is the only solution and is already being practiced in some countries.

In countries like the USA, Brazil, and Japan, rice cultivation is completely mechanized, while in developing countries it is fully manual or partially mechanized. The majority of US rice is typically planted with seed drills after preparatory cultivation involving several tillage and smoothing operations and basal fertilizer application. After or before seeding, levees are established using levee disks or squeezers, and gates and spills are established using vinyl and/or metal frames to permit maintenance of shallow 5–10 cm standing water throughout the growing season, and the fields are drained 15–25 days after heading (Synder and Slaton 2001). In Sacramento Valley in California, rice seeding is done by airplanes in standing water (Souza 2005)**.** Using GPS (global positioning system) equipment, pilots are able to lay the seed exactly on target. Fertilizer and pesticide application all over the USA is done by airplanes, and harvesting is done by combine harvesters. In Brazil, all operations are done using tractor and other necessary equipment, while harvesting is done by combine harvesters (Fageria et al. 2014). In Japan, paddy rice production has been mechanized since the 1970s, and 90 % of rice transplanting is mechanized (Li et al. 2005). Also in South Korea, 100 % of the tillage, 98 % of the transplanting, 100 % of the spraying, and 99 % of the harvesting of paddy rice production have been mechanized (Park and Kim 2005). In Japan, again most operations are done by especially designed equipment including transplanters, hand-operated harvesters, or combine harvesters (Oshino 1985). In China, mechanization of rice cultivation is in progress (Xu et al. 2011).

1.8.2.2 Fertilizer

Nitrogen

Rice crop uses about 21–25 % of the total N fertilizer consumed globally. However, the N use efficiency in rice is very low. Agronomic efficiency of N in rice was reported to be 13 kg grain kg^{-1} N from India (Prasad et al. 2000) and 10.4 kg grain kg^{-1} N from China (Zhang et al. 2007a). The low nitrogen use efficiency in rice and even in other crops is due to four N loss mechanisms, namely, surface runoff on sloping lands, ammonia volatilization, leaching, and denitrification (Zou et al. 2005; Towprayoon et al. 2005; Pathak et al. 2006; Ussiri and Lal 2012; Prasad et al. 2014; Prasad and Shivay 2015). The agronomic techniques employed to reduce these losses include deep placement and split application of N supported by balanced and adequate application of other nutrients to boost crop growth (Prasad 2013). Another approach has been the use of nitrification inhibitors (Prasad and Power 1995), urease inhibitors (Kiss and Simihian 2002), and slow-release N fertilizers (Prasad et al. 1971; Trenkel 1997; Shaviv 2001). These materials have met with mixed success. The government of India has decided to coat all urea manufactured or imported in the country with neem (*Azadirachta indica* Juss) (Prasad and Shivay 2015). Neem-coated urea was developed by Prasad et al. (1994, 2007) at the Indian Agricultural Research Institute, New Delhi, and is based on the mild nitrification-inhibiting properties of neem (Reddy and Prasad 1975).

Phosphorus

As a contrast to N, which is available in infinite amounts in the atmosphere, P fertilizers are made from phosphate rocks, which are a nonrenewable resource and are sufficient only for 1000 years or less, depending upon the processes used for their extraction and manufacture and the methods of their use on agricultural fields (Smil 2002; Zhang et al. 2008). The global estimates of phosphate rock are at 67,000 billon metric tons (BMT), and in Asia, only China has sizeable phosphate rock deposits (3700 BMT) (van Kauwenbergh et al. 2013).

Although recovery efficiency of P by rice is about 15–30 %, the rest of P gets fixed in soil (Sample et al. 1986). Submergence of rice fields leads to a flush of available P in soil (Kirk et al. 1990); however, continued submergence can reverse this effect as P is precipitated in the oxidized rhizosphere and sorbed on the solid phases during reduction (Patrick and Mahapatra 1968). A well-planned integrated P management using organic manures, crop residues, and P-solubilizing microorganisms is therefore important (Blaise et al. 2014). In the RWCS, drying during wheat season reduces P availability (Kumar and Yadav 2001). Good response to P application has been reported from India (Prasad 2007; Singh et al. 2014), China (Zhu et al. 2007; Bi et al. 2014; Guan et al. 2014), and Brazil (Fageria et al. 2014). Adequate P fertilization of rice is therefore necessary for sustained good yields of rice.

Potassium

Like P, K minerals are also a nonrenewable resource. The global deposits are estimated at 250 billion metric tons (BMT) (USGS 2008) with Canada having the largest deposits, followed by Russia. In Asia, only China has sizeable K mineral deposits, and in 2014/2015, it produced 5 MMT of potash fertilizers against its consumption of over 9 MMT (Tan 2015). Response of rice to K in China is much higher than in India. Zhang et al. (2010) observed that addition of 100 kg ha^{-1} to each rice crop in rice–rice rotation was not enough to maintain initial K availability in soil. Red and lateritic kaolinitic soils have less total K and non-exchangeable K than calcareous illitic and vertic smectitic soils and are therefore likely to need more K fertilization in rice (Sekhon et al. 1992). This would explain why response of rice to K fertilizers was more (9.7 kg grainkg^{-1} K) in Western Ghats and Karnataka Plateau having red and lateritic soil than in north Indian alluvial plains having calcareous illitic soils (Tandon and Sekhon 1988). Tiwari (2014) estimated that a harvest of 200 MMT of food grains per year will lead to a deficit of 5.8 million metric tons of K from the soil, which has to be replenished. Thus, adequate K fertilization of rice is important.

Zinc

Nene (1966) was the first to report that *Khaira* disease of rice (brown/maroon coloring of leaves) that was due to zinc (Zn) deficiency. Good response of rice to zinc fertilization is reported from all over the world (Alloway 2008). Further, Zn deficiency in soils is also linked with low Zn concentrations in grains of cereals including rice. Therefore, efforts are underway to develop GM rice with grains having higher concentration of Zn (Stein 2010) as well toward agronomic biofortification of rice with Zn (Prasad et al. 2014).

1.8.2.3 Pesticides

It is estimated that about 120–200 MMT of rice grain is lost in tropical Asia due to insects, diseases, and weeds (Gianessi 2014). Conventional rice-growing regions are humid to subhumid, and there are a large number of diseases such as blast, brown leaf spot, sheath blight, bacterial blight, tungro virus, and grassy stunt virus (Hollier et al. 1993). Blast epidemics in Malaysia and the Philippines caused a 50–70 % yield reduction (Gianessi 2014). Similarly, the damage due to sheath blight caused a loss of 17–25 % in Malaysia (Banniza and Holderness 2001), 10 % in India, and 20 % in Thailand (Boukaew and Prasertan 2014). It is difficult to breed rice varieties with high genetic resistance to these diseases; however, the development of multiple resistances for diseases and insect pests is the only solution to the problem (Singh et al. 2012; Suh et al. 2013). Details have been discussed in the chapter “Disease Management in Rice.”

Similarly, there are a large number of insect pests that attack the rice crop. Some important ones are brown plant hopper, white-backed plant hopper, green leaf hopper, rice mealy bug, rice aphid, rice leaf folder, rice swarming caterpillar, rice gall midge, and rice gundhi bug (Pathak and Khan 1994). Stem borers alone can cause yield losses up to 70 % in an epidemic year (Rahim et al. 1992). Insecticide sale in South and Southeast Asia increased from US$ 409 million in 2009 to US$ 674 million in 2012 (Gianessi 2014). Current emphasis is on integrated pest management (IPM) (Oudejans 1999). Details have been discussed in the chapter “Insect Pest Management in Rice.”

Weed management using herbicides has become an integral part of modern crop production including rice. Herbicides offer great flexibility of operations, are effective, and are often cost effective as compared to any other method of weed management (Chauhan et al. 2012). In rice, weeds can cause 28–74 % loss in yield (Chauhan 2012). Nevertheless, injudicious and continuous use of a single herbicide over a long period of time may result in the evolution of resistant biotype*s* and a shift in the weed flora. For example, spread of herbicide-resistant weedy rice (red rice, *Oryza sativa* L.) has been reported from Italy (Busconi et al. 2012). California rice farmers are already facing the challenge of managing herbicide-resistant weeds (Lindquist et al. 2011). A large list of biotypes showing resistance to herbicides in the USA is available (Vencill et al. 2012). Details have been discussed in the chapter “Weed Management in Rice.”

1.8.3 Global Warming (GW) and Rice Production

Global warming (GW) in relation to rice cultivation has to be viewed from two angles: (1) impact of GW on future rice production and (2) contribution of rice cultivation to GW.

1.8.3.1 Impact of Global Warming on Rice Production

In a simulation study, a 2◦C increase in temperature brought about a 3–10 % decrease in grain/seed yield of rainy season crops, such as rice, groundnut (*Arachis hypogaea* L.), and soybean (*Glycine max* L.), and a 29 % decrease in grain yield of winter crops such as wheat (Prabhjyot-Kaur and Hundal 2006). In addition to the direct effects of climate change on rice plants, Chauhan and Johnson (2010a, b, c) and Chauhan et al. (2014) pointed out that increased weed growth and changed weed flora could adversely affect rice growth and production. Many weeds are C_4 plants and have a competitive advantage over rice, a C_3 plant (Yin and Struik 2008).

There are two major abiotic stresses that can affect rice production, namely, drought and salinity. Analysis of models based on soil moisture changes, drought indices, and precipitation minus evaporation suggests increased risk of drought in the next 30–90 years over many land areas either by decreased precipitation or increased evaporation (Dai 2013). However, Trenbath et al. (2014) observed that increased heating due to global warming may cause droughts to set in earlier than predicted. Wassman et al. (2009) observed that current temperatures are already approaching critical levels during the susceptible stages of the rice plant in Pakistan/north India (during October), south India (during April, August), east India/Bangladesh/Myanmar/Thailand/Laos/Cambodia (during March–June), Vietnam (April/August), the Philippines (April/June), Indonesia (August), and China (during July/August) and drought stress is expected to affect rice growth and production. Wassmann and Dobermann (2007) observed that increasing temperatures or hotter night temperatures can cause increased spikelet sterility and reduce grain yield in rice.

Intergovernmental Panel on Climate Change (IPCC 2001) predicted that between 1990 and 2100, sea level may rise by 9–88 cm in different regions of the world. This will affect rice production in mega-deltas in Vietnam, Myanmar, and Bangladesh (Wassmann et al. 2009). The other hot spot with especially high climate change risk is the Indo-Gangetic Plains (the rice–wheat copping system belt), which will be affected by the melting of the Himalayan glaciers (Wassmann et al. 2009). Developing rice production systems and production technology with higher resilience to flooding and salinity is the key for maintaining sustained rice production in these areas.

1.8.3.2 Contribution of Rice Cultivation to Global Warming

Under submerged rice paddy conditions, methane (CH_4) is produced due to anaerobic conditions, while nitrous oxide (N_2O) is produced due to nitrification–denitrification processes from the applied fertilizer N both under aerobic upland and anaerobic lowland conditions. Both these gases contribute to GW. The global warming potential (GWP) of methane is 72 times that of carbon dioxide (CO_2) (which is taken as 1.0) for a life span of 12 years. According to Sass et al. (1999), CH_4 emission is 13–17 Tg y^{-1} from China (Wang et al. 1994), 2.4–6.0 Tg y^{-1} from India (Parashar et al. 1994), 0.04–8.77 Tg y^{-1} from Japan (Yagi et al. 1994), 0.31–7.0 Tg y^{-1} from the Philippines (Neue and Saas 1994), and 0.328 Tg y^{-1} from the USA (Leip and Bocchi 2007). Of the total methane emission from a country, rice contributes about 1.3 % in the USA, 3.7 % in Italy, 24 % in Japan, 30 % in China, and 35 % in India (Leip and Bocchi 2007).

Total CH_4 emission from the world is anticipated at 16–34 Tg y^{-1} and is considered to be 63 % of total anthropogenic CH_4 emission in the world (Saas et al. 1994). However, IPCC (1996) estimated that the contribution of rice cultivation toward total global methane emission is 5–20 %. Addition of rice straw to rice fields increases CH_4 emission (Sass et al. 1990; Rath et al. 1999). Midterm drainage during rice-growing period or alternate wetting and drying can substantially reduce CH_4 emission from rice fields, but it increases N_2O emission (Sanders et al. 2014; Pandey et al. 2014). Methane production is negligible under non-flooded aerobic conditions (Ramakrishna et al. 1995). However, there are uncertainties in estimating methane emission, and recently, Tian et al. (2015) using process-based couple biogeochemical model estimated total methane CH_4 from global terrestrial ecosystems during 1981–2010 at 144.39 ±12.90 Tg C y^{-1}; annual increasing trend was 0.43±0.06 Tg C y^{-1}. The most rapid increase in methane emission during 1981–2010 was found in natural wetlands and rice fields due to increased cultivation area and climate warming (Tian et al. 2015). Sanders et al. (2014) observed that in rice fields CH_4 contributed about 90 % of the total GWP.

The GWP of N_2O is 289 times that of CO_2 and its life span is 114 years. Thus its potential for GW is much higher than CH_4. However, the amounts of its emission are much smaller than CH_4. Tian et al. (2015) predicted global N_2O emission at 12.52 ± 0.74 Tg N y^{-1}, while Davidson and Kanter (2014) estimated it to be between 10 and 12 Tg N y^{-1}. Net anthropogenic N_2O emission is estimated at 5.3 Tg Ny^{-1}, out of which 66 % is predicted from agriculture and business-as-usual emission scenarios project almost doubling of N_2O emissions by 2050 (Davidson and Kanter 2014). The largest increase in N_2O emission during 1981–2010 occurred in upland crops due to increasing air temperature and N fertilizer use (Tian et al. 2015).

1.9 Rice Cultivation and Environmental Pollution

Fertilizers applied to rice contribute considerably toward environmental pollution. Only about one-third of the N fertilizer applied is taken up by the rice crop, while the rest two-thirds, except for a small fraction being immobilized by the soil organisms, is lost through ammonia volatilization, denitrification, and leaching and surface runoff; estimates for these losses are at 4.1 Tg, 3.1 Tg, and 3.1 Tg, respectively (Pathak 2013). While ammonia produced by volatilization and nitrous oxide produced by denitrification are lost to the atmosphere, nitrates are leached down the profile or move with surface runoff (Prasad and Shivay 2014) and are responsible for eutrophication of surface (lakes and estuaries) and groundwater. Similarly the recovery efficiency of P fertilizer applied to rice is only 15–30 %.

1.9.1 Eutrophication of Surface and Groundwater

An important current issue is the need to reduce anthropogenic nutrient inputs to aquatic ecosystems in order to protect drinking water supplies and to reduce eutrophication of lakes and estuaries including the proliferation of "algal blooms" and "dead zones" in coastal marine ecosystems (Conley et al. 2009). Algal blooms lead to the depletion of dissolved oxygen in water (hypoxia), which can lead to fish mortality, and their decomposition impairs such waters for drinking, recreation, and industry (Foy 2005). Since Schindler (1974) established that P was the primary limiting nutrient for algal growth, national water policy in the USA, Canada, and Europe during the 1970s focused on P control in the lakes; however, in the last two decades, it has emerged that N is the main pollutant in the estuaries (Howarth and Marino 2006). Elevated levels of N and P have been reported from the three major lakes (Taihu, Chaohu, Dianchi) in China (Gao and Zhang 2010). Also there has been a threefold increase in nitrate concentration in the estuary of Yangtze River during the last 40 years, from 1.3 mg L^{-1} in the 1980s to 5.0 mg L^{-1} in 1999–2004 (Duan et al. 2000), and a 30 % increase in phosphate concentration during the same period from 0.056 mg L^{-1} in the 1980s to 0.73 mg L^{-1} in 1999–2004 (Zhou et al. 2008). Jin (1995) reported that up to 35 % of N and 68 % of P in surveyed lakes was from agricultural runoff. A good correlation between N concentration in river waters and N fertilizer applied in the catchment areas has been recorded (Chen et al. 2000). Duan et al. (2005) and Liu et al. (2007) observed that the risk of P loss from agricultural land is increasing. In Southern China, the leaching loss from rice fields varied from 6.7 to 27.0 kg N^{-1}, while that from runoff varied from 2.5 to 19.0 kg N ha^{-1} (Sun et al. 2003). Xia et al. (2008) reported that in rice, application of 0, 25, 60, 120, and 240 kg P ha^{-1} resulted in a loss of 0.13, 0.50, 0.94, 3.02, and 5.97 kg P ha^{-1}; thus, losses were proportionally higher as the rate of application increased. Further Zhang et al. (2007b) reported that losses were most within 1–2 months of application.

Due to nitrate leaching from agricultural fields, over half of the groundwater samples in Northern China revealed nitrate concentration higher than 50 mg L^{-1}, the World Health Organization (WHO) recommended safe level; even nitrate concentration higher than 300 mg L^{-1} was recorded in several samples (Dong et al. 2005). The situation in India is not that bad, and in studies in the rice–wheat cropping system belt in Punjab (Bharadwaj et al. 2012) as well as in the rice–rice cropping system region in Nalgonda district in Andhra Pradesh (Karthikeyan et al. 2012), about 72 % of samples of groundwater analyzed had less than 50 mg nitrate L^{-1}, and water was safe for drinking. This is because general rates of N and P application in

China are 150–200 kg N and 22–30 kg P ha^{-1} (Jin et al. 2002), while those in India are only 86–163 kg N and 4.4–25.8 kg P ha^{-1} (Sharma et al. 2010). However, in China efforts are being made to determine ecologically optimum rather than the conventional economic optimum rates of N for rice (Xia and Yan 2012). This would lead to reduced N application in rice.

1.9.2 Depletion of Ozone Layer

Ozone in the stratosphere of the earth's atmosphere works as a bio-protective filter against ultraviolet (UV) radiation, which can cause skin cancer (Narayanan et al. 2010) and cataract in eyes (Roberts 2011) of the humans. Ultraviolet radiation is also reported to adversely affect plant growth (Hollosy 2002; Zuk-Golaszewska et al. 2003). Nitrous oxide (N_2O) is a major cause of ozone layer depletion (Ravishankara et al. 2009), and about two-thirds of N_2O is produced by nitrification–denitrification reactions in agricultural fields from the applied fertilizer N (Zumft 1997; Lassey and Harvey 2007; Thomson et al. 2011). Rice cultivation due to changes in redox potential caused by submergence has therefore a role in the destruction of ozone layer in the stratosphere.

1.10 Summary and Conclusions

Rice is the staple food for nearly half of the world's population which makes it a crop of focus. As rice is grown on a variety of soils under diverse ecological conditions in all the six inhabited continents of the world, hence diverse and site-specific production technologies are required rather than a single production technology. Compared with the past (1962–1979; rice yield growth rate 2.5 %), the growth rate of rice yields per annum has been declined (1980–2011; rice yield growth rate 1.4 %).

Natural resources, land, water, and labor are becoming scarcer worldwide, and rice is going to suffer the most, because with the present production technologies, its water and labor requirements are the highest among field crops. In this backdrop, the rice production technologies with lower labor and water input hold significance. Growing rice under water-saving production systems and adoption of mechanization in developing countries are important in this regard. However, practical and social constraints in the way of such developments are desired to be resolved using current knowledge, research, and available resources. For example, weed infestation is an important issue of aerobic rice cultivation, while high financial requirement is a constraint in the installment of drip irrigation infrastructures in the rice production systems. Such issues are desired to be resolved for sustainable rice production. Other salient research issues in the rice production include the development of site-specific integrated nutrient management plans, addressing the environmental problems resulting from the overuse of N, and the development of integrated pest management plan.

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Chapter 2
Rice Production in China

Lixiao Nie and Shaobing Peng

2.1 Summary

Rice is one of the prominent cereal crops in China, and about 65 % of Chinese people rely on rice. Nearly 95 % of the rice grown in China is produced under traditional puddled transplanted conditions in China with prolonged periods of flooding. However, several factors have threatened the sustainability and productivity of traditional puddled transplanted rice production system, such as climate change, decline in rice planting area, scarcity of labor availability, narrow genetic background of rice varieties, overuse of fertilizers and chemicals, poor extension system, and oversimplified crop management. Chinese government and rice scientists put sincere efforts to cope with these constraints. New breeding techniques such as marker-assisted selection, transformation, and genetic engineering were adopted to increase yield potential. Synergy among fertilizer, water, and pest and weed management should be considered to maximize overall efficiency of the rice production system. Nowadays, labor shortage in rural areas is the major constraint to the flood-transplanted rice production in China, and the mechanization for rice production is the key to solve this problem. Direct seeding rice is a promising planting technique in face of water and labor shortages in rice cultivation with advantages of less input requirement, more economic returns, and less methane and CO_2 emissions.

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2.2 Introduction

China is a leading rice-producing country in the world, contributing 28.7 % of the global rice production (FAOSTAT 2013). Rice is a major staple food in China and the subsistence crop for most of the resource-poor farmers and consumers in rural areas. Rice is grown in almost every province of China except Qinghai. Three-quarters of the total rice area is planted with indica rice varieties and the rest with japonica rice varieties. Indica rice varieties are generally grown in the south and japonicas in the north. During the past decades, China became self-sufficient in basic food for the first time in modern history. Hybrid rice is one of the greatest innovations and miracles in the world, which contributed greatly to the food security in China in the past 30 years. Hybrid rice varieties occupy about 50 % of China's total rice planting areas (Yuan 2003).

China ranks first in the world in total annual rice production (about 203.6 million tons in 2013). Despite the sufficient current rice production, an additional 20 % increase in rice yield is still desired to meet the demands of the growing population by the 2020s (Peng et al. 2009). Land resources suitable for rice cultivation are currently limited in China; hence, improvement in the rice productivity is necessary to meet the future food demands. However, available evidence indicates that increasing trends in the Chinese rice yields have slowed down in recent decades (Cassman et al. 2003; Peng et al. 2009; Ray et al. 2012). Yield gap analyses reveal that Chinese rice yields have been approaching their biophysical potential ceiling in recent years (Cassman et al. 2003; Lobell et al. 2009; Licker et al. 2010; Neumann et al. 2010; van Wart et al. 2013). Recently, a simulation model has indicated that the current average Chinese rice yield is approximately 82 % of the national yield potential (van Wart et al. 2013). Reaching potential yield ceiling has been considered as the yield stagnation (Cassman 1999; van Wart et al. 2013).

China's agricultural production is facing the global climate change, population increase, serious disease and insect damage, labor shortage, water scarcity, yield stagnation, and environmental pollution. All these factors are threatening the sustainability and productivity of rice production systems in China.

2.3 History, Importance, Area, and Production

More than 28 % of the total global rice is produced in China, and the stability of rice production in China plays an important role in the world's food security (FAOSTAT 2013). It is one of the prominent cereal crops in China as about 65 % of Chinese people rely on rice (Zhang et al. 2005). Rice was grown on 18 % of the total arable area of China, representing 34.6 % of the total Chinese grain production (FAOSTAT 2013). In China, nearly 95 % of the rice grown is produced under traditionally puddled conditions subjected to transplanting with prolonged periods of flooding (Peng et al. 2009).

Rice production in China has increased more than three times over the past six decades due to vertical increase in grain yield per plant, per unit area rather than horizontal expansion of area. The increase in grain yield has resulted from the development of new varieties such as semidwarf varieties in the 1950s and hybrid rice varieties in the 1970s and from improved crop management practices such as nitrogen fertilization and irrigation (Peng et al. 2009). Since the 1990s, the adoption of hybrid rice varieties has been widely increased because of the heterosis from hybridization. The proportion of hybrid rice varieties to the total rice planting area was hovering around 60–65 %; however, the proportion has never exceeded 70 % in China (Mao et al. 2006).

Although rice production in China is distributed across temperate, subtropical, and tropical areas, most of the rice is produced in the subtropical areas. Based on the climate and cropping systems, rice production in China has been classified into six agroecological zones and 15 subzones (China National Rice Research Institute 1988).

2.4 Rice-Based Cropping Systems

Southern China is the main rice production area in China, accounting for 94 % of national rice planting area and 88 % of national rice production (Ma et al. 2013). The rice-based cropping systems in China are diverse due to a diversity in agroclimatic zones. There are three major rice cropping patterns in China: single rice cropping per year, annual rice-upland crop rotations, and double rice cropping annually. Single rice cropping system is mainly located in Northern China, and it accounts for 17 % of the total rice production in China (National Bureau of Statistics of China 2011). Annual rice-upland crop rotation system (rice-wheat or rice-rapeseed rotation) is mainly located in Central China (in the provinces of Jiangsu, Anhui, Hubei, and Sichuan along the Yangtze River Valley), and it accounts for 49 % of total Chinese rice production (National Bureau of Statistics of China 2011). Double rice cropping system mainly located in South China accounts for 34 % of the total rice production in China (National Bureau of Statistics of China 2011). However, planting area of double rice cropping in China has been decreasing continuously. The proportion of double rice cropping area to total rice production area has dropped from 71 % in 1970s to about 40 % at present (Bai 2013; Zhu et al. 2013). The main reasons for this decline are labor shortage, low degree of mechanization, and low production efficiency for double rice cropping. However, the planting area of single rice cropping system with japonica rice varieties in Northeast China has increased by 485 % because of the relative high comparative profits of rice production and the improvement of people's living standards (Xu et al. 2010; National Bureau of Statistics of China 2011).

2.5 Varieties and Genetic Improvement

Hybrid rice research was initiated by Prof. Yuan Longping in the1960s. In the 1970s, the first hybrid combination was developed with good heterosis and high grain yield. Technology for large-scale hybrid seed production was fully developed in 1975. The release of hybrid rice for commercial production was started in 1976. Since then, China became the first country to adopt hybrid rice technology over a large production area (Ma and Yuan 2015). At present, hybrid rice cultivars occupied more than half of the total rice-growing area in China, including both three-line system and two-line system hybrid rice varieties (Virmani et al. 2003). In recent years, two-line hybrid varieties are grown in 3 million ha. It has been demonstrated that the two-line system hybrids provide 5–10 % higher yield than the three-line system hybrids (Ma and Yuan 2015).

The methods for rice breeding include both conventional breeding and molecular breeding. Conventional breeding selects genotypes indirectly through phenotypes which are generally effective for qualitative traits but not for quantitative traits, while molecular breeding refers to the development of new rice varieties by integrating the means of modern biotechnology into conventional breeding methods, which mainly involve marker-assisted selection and molecular breeding. The transformation of rice breeding from conventional genetics to molecular design of new varieties is a general trend, which ensures the breeding of new varieties with improved agronomic traits in terms of the yield, grain quality, resource-use efficiency, disease and pest resistance, and stress tolerance. In recent years, great efforts have been made in rice genome sequencing, and there have been significant developments in functional genomics. A number of genes have been successfully transferred in mega rice varieties. Multiple chromosome segment substitution lines are constructed, and a large number of quantitative trait loci (QTLs) have been identified.

In order to meet the food requirement of China in the twenty-first century, a super rice breeding program was launched in 1996 by the Ministry of Agriculture in China. Following the super rice breeding program, Prof. Yuan put forwarded the theory of super hybrid rice, emphasizing on the plant morphological improvement and utilization of the inter-subspecific heterosis. To increase rice production quantitatively and qualitatively in harmony with the environment, Zhang (2007) proposed strategies for developing Green Super Rice (GSR) in 2007. GSR should possess the following characteristics: adequate resistances to major diseases and insects, high efficiency in nutrient uptake and utilization, resistance to drought and other abiotic stresses, good quality, and increased yield potential. The general strategy is to develop green super rice (GSR) by introducing and evaluating the rice germplasm resources originating from all over the world, developing the introgression populations, and mapping the elite genes/QTLs with the molecular markers through the collaborative research of ten institutes in different ecological areas. After 10 years of struggle, a national molecular rice breeding network and a molecular breeding platform have been developed, and a series of new varieties with high yield potential and water-saving, disease, and insect resistance were developed.

In recent years, great progress has been made on molecular breeding in rice, and the productivity per unit area has been significantly improved in China. More attention has been given to the development and utilization of wild rice, because wild rice provides rich genetic resources with good traits such as strong pest resistance and stress tolerance. Furthermore, a great focus has been given for understanding the vital role of wide compatibility resources in rice heterosis.

2.6 Rice Production Methods

Rice planting methods in any specific area rely on the prevailing environment, ecological conditions, and the socioeconomic factors. Traditional rice planting technology based on artificial transplanting will no longer be able to meet the social and economic requirements; therefore, it is inevitable to develop cost-efficient and labor-saving rice planting methods. Major rice planting methods include manual transplanting, direct seeding (manual and mechanical direct seeding), throwing transplanting, mechanical transplanting, and ratooning rice. Area of manual transplanting is continuously declining due to the labor shortage in rural areas, and now manual transplanting is mainly limited to areas of relatively high population density, low per capita arable land area, small-scale farming, and abundant labor force. Area of direct-seeded rice (DSR) has increased from 2 % in 2000 to about 11 % of the total rice area in 2009. Over the same period, mechanical transplanting increased from 2 % to about 13% of rice area (Zhang et al. 2012).

In Europe, America, and Australia, most of the rice was produced by direct seeding, whereas Japan and South Korea farmers mainly adopted mechanical transplanting for rice cultivation and to some extent mechanical direct seeding. DSR technology has been proposed to reduce water and other input requirements, for saving energy and labor demand, lowering the risk of methane emission, and increasing the system productivity. DSR refers to the process of establishing the crop from seeds sown in the field rather than by transplanting seedlings from the nursery. There are three principal methods of DSR systems: dry seeding (sowing dry seeds into dry soil), wet seeding (sowing dry or pre-germinated seeds on puddled soil), and water seeding (seeds sown into standing water). DSR, especially dry DSR, is becoming popular nowadays because of less water consumption, reduced labor intensity, easy mechanization during crop establishment, and less methane emission. In the world, 23 % of rice is grown under DSR system. In China, the planting area for DSR is increasing rapidly since the 1990s, and DSR is mainly located in the middle and lower reaches of Yangtze River in Jiangsu, Anhui, Zhejiang, Guangdong, Yunnan, Hubei, and Xinjiang provinces. The proportion of DSR area to total rice planting area in China has increased to around 10 %. Wet seeding accounts for over 80 % of DSR planting area, and manual broadcasting is common in this method (Su et al. 2014). Taking Zhejiang Province as an example, the DSR developed fast from the 1990s (Wang 2015). During 1995–1999, the proportion of DSR planting area to total rice planting area in Zhejiang Province was around 10 %, which increased

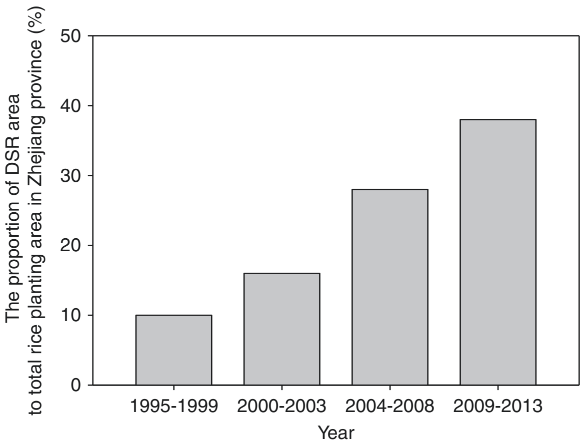


Fig. 2.1 The proportion of DSR planting area to total rice planting area from 1995 to 2013 in Zhejiang Province, China (Modified from Wang 2015)

from 11 % in 1999 to 20 % in 2003; and during 2008–2013, this proportion reached to 37 % (Fig. 2.1) of the total rice production area.

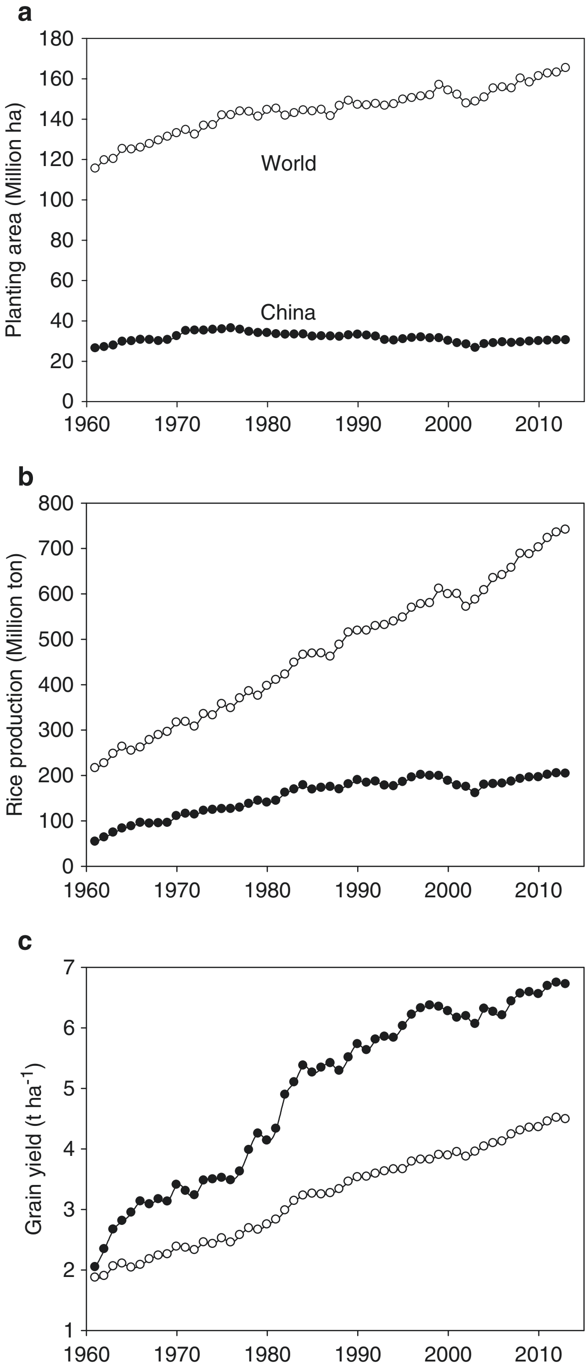
2.7 Major Production Constraints

2.7.1 Instability in Rice Planting Area and Decline in Labor Availability

In China, the annual cultivated area of rice has reached 30 million ha, which is one-third of the total area of grain crops. During the past three decades, the rice cultivation area has reached the highest record of 33.5 million ha in 1990, and since then, it declined gradually. In 2003, the area under rice in China was dropped to 26.8 million ha. China has introduced many encouragement policies, resulting in restorative growth in rice planting since 2004. In 2013, rice planting area climbed to 30.6 million ha (Fig. 2.2). The reduction in rice planting area was largely caused by the construction of new buildings and roads and reforestation on marginal arable land. Rice is often in a disadvantageous position when it competes with cash crops for planting area. Therefore, most of the future increase in rice production must come from greater yields on existing crop land to avoid environmental degradation, destruction of natural ecosystem, and loss of biodiversity (Cassman 1999).

Accompanied by the instability in rice planting area, the expansion of urban areas has led to a labor shortage for agricultural production in rural areas (Cai and Chen 2000). In recent years, massive labor force in the age group of 18–40 years has migrated to the cities, and both the quantity and quality of labor for rice production have markedly declined (Fang et al. 2004). Consequently, the daily wage of labor for rice farming has doubled in less than 10 years (Peng et al. 2009).

Fig. 2.2 Rice planting area (**a**), total rice production (**b**), and grain yield (**c**) in China and the world from 1961 to 2013 (FAOSTAT, 2015)



2.7.2 Narrow Genetic Background

Narrow genetic background of parent materials is the main cause for the low crop yield, quality, and weak stress resistance (both biotic and abiotic), while wild rice provides rich genetic resources with good traits such as strong pest resistance and stress tolerance. More than 95 % of wild rice germplasm collections worldwide have never been used in any breeding program primarily because of the technical limitations of the conventional breeding approach (Li 2005). The direct consequence of this under use of germplasm resources by conventional breeding approaches has been documented to low genetic diversity in commercially grown rice cultivars and their vulnerability to biotic and abiotic stresses. The situation is even worst in China because 50 % of the rice planting area is occupied by hybrid rice (Yuan 2003). Hybrid rice varieties were developed using a few male sterile lines as the female parent (Fang et al. 2004). Most of the restorer lines used as a male parent were related to tropical indica rice varieties.

2.7.3 Overuse of Fertilizers

The excessive use of nitrogenous (N) fertilizer has resulted in decreased nitrogen-use efficiency and critical negative effects on the environment (Cassman 1999). China is currently the world's largest consumer of N fertilizers. In 2006, annual N fertilizer consumption in China was 31 million metric tons being 31.7 % (almost 1/3 of worldwide use) of the global N consumption (Heffer and Prud'homme 2008). The average rate of N application for rice production in China was 180 kg per hectare, about 75 % higher than the world average (Peng et al. 2002). Because of the high rate of N application, only 20–30 % of N is taken up by the rice plant in current season, and a large proportion of N is lost to the environment (Peng et al. 2006). Therefore, rice grain yield has increased by only 5–10 kg for every kilogram of N fertilizer input in China (Peng et al. 2006). Overapplication of N fertilizer may actually decrease grain yield by increasing susceptibility to lodging and damage from pests and diseases. The excessive use of N fertilizer is also partially responsible for the overuse of pesticides (Peng et al. 2002). On an average, Chinese rice farmers used 40 % higher pesticides than the actual requirement (Huang et al. 2003).

2.7.4 Poor Extension System and Oversimplified Crop Management

China has about 150,000 agro-tech extension and service stations with 1.03 million staff members (Fang et al. 2004; Peng et al. 2009). Because of insufficient financial support from the government, many extension staff members have to earn part of their salary from selling agrochemicals and seeds to farmers. Therefore, a new technology may not be available to the farmers quickly because of a weak extension system. This phenomenon is associated with the overuse of fertilizers and pesticides by Chinese rice farmers and consequently caused rice yield loss (Fang et al. 2004).

The labor input for rice production has significantly decreased in China, especially in economically developed regions because of labor migration and increase in labor wages. As a consequence, many rice farmers have greatly simplified crop management practices (Cai and Chen 2000; Peng et al. 2009). For example, some rice farmers apply fertilizers only once before crop establishment during the whole growing season to avoid in-season fertilizer application. Some farmers transplant rice at extremely wide spacing to reduce labor cost. As a result, rice grain yield will decline under these oversimplified crop management practices.

2.8 Challenges and Opportunities

2.8.1 Increasing Yield Potential

Rice varieties with higher yield potential must be developed to enhance average farm yield in order to increase total rice production (Peng et al. 1999). In the past, great improvement in rice yield potential was achieved with ample supply of water and nutrients (Peng and Bouman 2007). China has been at the forefront in developing high-yielding varieties using semidwarf, hybrid, and new plant-type breeding approaches. China's "super" rice breeding project has developed many F1 hybrid varieties using the combination of ideotype approach and inter-subspecific heterosis (Yu and Lei 2001; Min et al. 2002). In on-farm demonstrations, these hybrid varieties produced grain yield of 12 tons per hectare, which was 8–15 % higher than that of the hybrid check varieties. Yield records have been frequently broken by newly developed super hybrid rice varieties. However, it is not easy to achieve high yields with the "super" rice varieties consistently across seasons and locations. Because of water scarcity and environmental stresses, increase in rice yield with less water and chemical input is a great challenge (Peng and Bouman 2007). Zhang (2007) proposed strategies for developing GSR. To increase yield potential, new breeding techniques such as marker-assisted selection, transformation, and genetic engineering should be combined effectively with the conventional breeding methods.

2.8.2 Varieties with Abiotic and Biotic Resistance

Rice production in China faces abiotic stresses such as drought, heat, cold, submergence, etc. Due to global warming, drought and heat episodes are more frequent than ever before, causing yield losses in the major rice-growing areas (Tao et al. 2003).

Scientists have dissected the genetic basis and mapped the genes (QTLs) in crosses between drought-tolerant germplasm and elite cultivars (Yue et al. 2006). A molecular breeding approach has been used to develop new varieties with drought tolerance, and many candidate genes have been identified for engineering drought tolerance in rice (Zhang 2007). Studies demonstrated significant genotypic variation in high temperature-induced spikelet sterility, and tolerant varieties were identified (Prasad et al. 2006).

In China, rice crop also suffers from insect infestation (e.g., brown plant hopper, stem borer, etc.) and diseases (blast, bacterial blight, sheath blight, leaf blight, false smut), which are causing huge yield losses every year (Wang et al. 2005). Infestations of brown plant hopper have become severe in recent years, probably because of the breakdown in ecosystem stability caused by the heavy use of pesticides and the increase in air temperature associated with global warming. It was estimated that China lost 2.77 million tons of rice because of brown plant hopper outbreaks in 2005. Scientists in China have already isolated and cloned many genes with disease and insect resistance from cultivated and wild rice species (Zhang 2007). These genes with multiple resistances have been transferred into the local varieties through transformation or backcrossing. Bt-transgenic rice is a successful example for controlling stem borer although it has not been released officially for commercial production (Huang et al. 2005). For disease resistance, another strategy is to focus on quantitative resistance (mostly polygenic) that provides broad-spectrum resistance against multiple pathogen races or different pathogens (Mew et al. 2004). This can be combined with major resistance genes to achieve a higher crop resistance.

Because weeds germinate concurrently with rice and there is no water layer to suppress weed growth, DSR fields are more species rich with greater diversity in weed flora than flood-transplanted rice (Tomita et al. 2003; Rao et al. 2007; Jabran et al. 2015). High weed infestation can incur 74 % yield losses under dry DSR system, and sometimes it may result in total crop failure (Jabran et al. 2012; Jabran and Chauhan 2015). In China, weeding in dry DSR is usually done by labor; however, farmers have been shifting to herbicides application because of less labor availability and high labor cost. In recent years, a series of herbicides have been successfully used, including single herbicides and the combination of different herbicides to control weeds. Although herbicides have played an important role in controlling rice weeds, nonetheless, intensive use of herbicides brought negative effects on the rice seed emergence, risk of herbicide resistance in weeds, and environmental pollution (Heap 2012). Various nonchemical methods of weed control have been explored, such as development of weed-competitive cultivars, increasing seeding rate, and use of crop residue as mulches. Development of varieties with early seedling vigor and rapid leaf area development during the early vegetative stage has been proven to be the most cost-effective strategy for weed suppression (Mahajan and Chauhan 2013). However, further studies on genotypic variation in weed tolerance traits, including early seedling vigor and allelopathy, are needed.

2.8.3 *Integrated Crop Management*

It is generally believed that the contribution of optimal crop management to yield increase is greater than that of new varieties (Fang et al. 2004). Optimum crop management practices have been developed in China in the past. Scientists in Jiangsu province have highlighted the plant and canopy morphological parameters to guide the crop management at different growth stages for achieving maximum grain yield (Ling et al. 1993; Su et al. 2002). In order to raise rice seedlings for transplanting, dry bed has been adopted nationally since 1990s instead of wet bed by modifying the technology originated from Japan (Chen 2003). Another popular practice since the 1990s was seedling throwing. In 1999, the total rice planting area using seedling throwing reached 6 million hectares in China (Zhu 2000). Rectangular planting with wide spacing between rows and narrow spacing between hills within a row has become a common planting geometry for panicle-weight-type rice varieties such as "super" hybrid rice (Zou 2006). Zhong et al. (2007) technically specified "Three Controls" nutrient management technology for irrigated rice, which includes four parts, i.e., the determination of total fertilizer-N input, fertilizer-N timing and split rates at key growth stages, amount and timing of phosphorus and potassium requirement, and adoption of the other crop management measures. Some of these technologies have significantly contributed in increased rice yield, although their impact on the environment and on resource-use efficiency was largely ignored.

Socioeconomic assessment was not commonly conducted for each new technology, and there was a lack of integration among the different components of crop management practices. In the future, new crop management technologies will have to be developed using system approaches as rice farming faces many challenges in China. The newly developed practices should have a sound scientific basis. Synergy among fertilizer, water, and pest management should be considered to maximize overall efficiency of the production system. Furthermore, a new technology should not be based merely on yield and farmers' profit, but its short- and long-term impacts on the environment, i.e., sustainability, should also be considered. Sustainability of the rice production systems can be maintained only when the natural resource base is protected and ecosystem services of the rice system are maximized. These points have been addressed on site-specific nutrient management (SSNM) in six provinces of China and its dissemination through farmer participatory research (Peng et al. 2006; Hu et al. 2007).

2.9 Nitrogen Fertilizer and Pest Management

The average rate of N application for rice production in China is180 kg ha^{-1} (Peng et al. 2010), and N rates of 150 to 250 kg ha^{-1} are common (Wang et al. 2001; Peng et al. 2006). In Jiangsu Province, the average N rate reached to

300 kg ha^{-1} (Peng et al. 2010). It has been reported that indigenous N supply capacity of irrigated rice fields in China was about 50 % higher than other major rice-growing countries; therefore, yield response of rice crop to N fertilizer application is low. Overapplication of N fertilizer may actually decrease grain yield by increasing susceptibility to lodging (Pham et al. 2004) and damage from pests and diseases (Cu et al. 1996). Peng et al. (2006) reported that the average agronomic N use efficiency was 5–10 kg grains kg^{-1} N in the farmers' production fields of China. The abnormal high rates of N fertilizer input and improper timing of N application in China have led to low N use efficiency.

Site-specific N management (SSNM) was developed to increase N use efficiency of irrigated rice (Dobermann and Cassman 2002). It was reported that SSNM recorded higher grain yield and N use efficiency compared with farmers' N fertilizer practice in China (Peng et al. 2002). After a decade of collaborative research work on SSNM between IRRI and Chinese scientists, researchers and farmers have a deep understanding of N fertilizer management for irrigated rice in China. SSNM is becoming a matured technology for improving both fertilizer-N use efficiency and grain yield. However, the procedure of SSNM is too complicated, and it is difficult to accurately estimate N response and select the right agronomic N use efficiency based on SSNM procedure. To disseminate SSNM technology widely in China, we should further simplify the procedure of SSNM. Therefore, future research is needed to develop SSNM based on remote sensing technology for its large-scale implications.

In China, insect pests, diseases, and weeds are the major challenges to rice production (Oerke and Dehne 2004). Globally, an average of 35 % of potential crop yield is lost due to preharvest pests (Oerke 2006), while actual losses were estimated at 40 % for rice grains (Oerke and Dehne 2004). Pesticides, as an important input in agricultural production, have made a great contribution to the development of agriculture and food supply to mankind (Wang and Li 2007). Existing data have indicated that one-third of pest-induced yield losses worldwide were avoided and recovered because of application of agrochemicals (Liu et al. 2002). At present, China is ranked first in the world regarding production ability and application of pesticides. However, Chinese farmers usually overestimate the crop losses caused by pests resulting in an indiscriminate and overuse of pesticides in rice production (Fang et al. 2004). To avoid yield losses, farmers sometimes spray their rice crop weekly to control pests and diseases. Econometric analysis showed that education and quality of the extension system are the major determinants for the improper perceptions of farmer's regarding yield losses.

Overuse of pesticides has raised several environmental issues and led to several health hazards; therefore, several nonchemical approaches for controlling rice diseases, insect pests, and weeds have been studied and implicated, specifically, e.g., (1) using rice resistance genomic diversity;(2) changing rice seeding time/transplanting date;(3) rearing fish, frogs, or ducks in rice paddy fields; (4) soaking rice seeds in biogas fermentative liquid and cultivating seedlings with biogas fermentative residues; and (6) using Frequoscillation Pest-killing Lamps (Huang et al. 2014).

2.10 Harvesting and Yields

In this modern era, rice harvesting through mechanical means is common in China. Mechanical harvest is divided into “mechanical cutting and mechanical picking” and “harvesting by combine harvester.” At present, combine harvester is used in more than 80 % of the rice planting area of China (Huang and Guo 2014). Harvesting of rice by using combine harvester gives the highest efficiency and the lowest cost; however, seed moisture content should be considered. Especially in some places without drying facilities, rice can be harvested when seed moisture content drops below the safe water content. It was estimated that more than 80 % of the rice area cannot be harvested at proper time due to poor dehydration, which usually causes 5–10 % of yield loss (Huang and Guo 2014).

Rice processing is a combination of several operations to convert paddy rice into well-milled silky-white rice, which has superior cooking quality attributes. The marketing values of rice as an agricultural product depend on its physical characters after the processing. The percentage of whole grain is the most important parameter for the rice processing industry (Marchezan 1991). In China, the brown rice percentage and head rice percentage are relatively lower compared with that in Japan. A multiyear survey (2008–2012) reported that brown rice percentage and head rice percentage in China are 63.4–66.3 % and around 55 %, respectively, and are declining year by year (Tan et al. 2014). The decline in brown rice percentage and head rice percentage was mainly caused by overprocessing, because at present, rice processing industry in China is still in the stage of pursuing the appearance quality (Tan et al. 2014). Overprocessing has resulted in the loss of nutrients and the increase in the amount of by-products. Accuracy in processing may increase the brown rice percentage and head rice percentage (Tan et al. 2014).

Rice aging during storage is a complicated process, which involves changes in the physical and chemical properties of rice grain. Starch, protein, and lipids are the main rice grain components which affect cooking and eating quality. Safe storage plays an important role in reducing food losses and ensuring rice quality. According to Food and Agriculture Organization of the United Nations, 15–16 % of the rice was lost due to improper storage and postharvest processing (FAOSTAT 2006). The edible quality of rice will obviously change with storage time and storage conditions, mainly expressed as decrease in viscosity, taste, and aroma. At present, China has a wide range of uniform regulations on the safe water content (13.5 % for indica rice and 14.5 % for japonica rice). However, with increasing mechanized farming, traditional rice drying after the harvest is gradually simplified due to lack of space and other reasons, and the rice grains with high moisture content are directly transferred to the market. Previously, Huang (2014) reported that mold growth on rice surface was reduced at 20°C storage. It was also observed that rice respiration, enzyme activity, and propagation of insects and mold during storage were inhibited below 10 °C (Huang 2014). The safe moisture content of rice in China for a long-term storage at room temperature is limited to 13.5 %; however, for low temperature storage, the safe moisture content of rice can be kept below 15.5 % for japonica rice and 14.5 % for indica rice (Han et al. 2014).

2.11 Heavy Metal Pollution

In China, nearly 10 billion (100 million) ha of arable land has been contaminated by heavy metals mainly, cadmium, arsenic, lead, copper, nickel, zinc, mercury, and chromium (Jin 2014). In Zhujiang delta region of southern China, 28 % of soil has been reported to be contaminated with heavy metals (Xue et al. 2013). Soil contamination by the heavy metals is governed by several factors including solid-waste disposal and atmospheric deposition. Moreover, fertilizer and pesticide use, application of the wastewater irrigation, and sewage sludge in the field are also considered to be the major cause of heavy metal accumulation (Cui et al. 2005; Wilson and Pyatt 2007; Khan et al. 2008).

Rice has been considered to be a major source of heavy metal intake by humans in Asian countries (Tsukahara et al. 2003; Mondal and Polya 2008; Solidum et al. 2012). It is crucial to develop practical and effective strategies for reducing the amount and mobility of heavy metals in soil or to limit their uptake and accumulation in rice grains. Zhao et al. (2010) and Kawasaki et al. (2012) reported a great impact of water management practices on dynamics of heavy metals in soil and their subsequent uptake by rice. Sun et al. (2014) and Liu et al. (2014) suggested that a significant reduction in heavy metals' accumulation in rice grains could be achieved by aerobic-flooded cultivation of rice. It was reported that aerobic and alternate wet and dry cultivation of rice reduced the As and Mo concentration in milled rice, compared to the traditional flooded rice, and decreased the Zn, Mn, Ni, Cu, Cd, and Co concentration in milled rice, compared with upland/aerobic rice (Fig. 2.3).

Bioavailability of heavy metals is closely related to soil pH and soil redox potential (Eh) (Fu et al. 2008; Talukder et al. 2012). Many studies have shown that the availability of metal elements was closely related to the decreasing pH (Itanna 1998; Sukreeyapongse et al. 2002). Along with pH, Eh is also influenced by soil water conditions, thus affecting the elements of availability in soil (Fu et al. 2008; Talukder et al. 2012). There are still many other factors influenced by soil water conditions that affect the heavy metal concentration in rice grain, such as the organic matter content, EC of soil, root activity, and rhizosphere environment (Liu et al. 2001; Zarcinas et al. 2004).

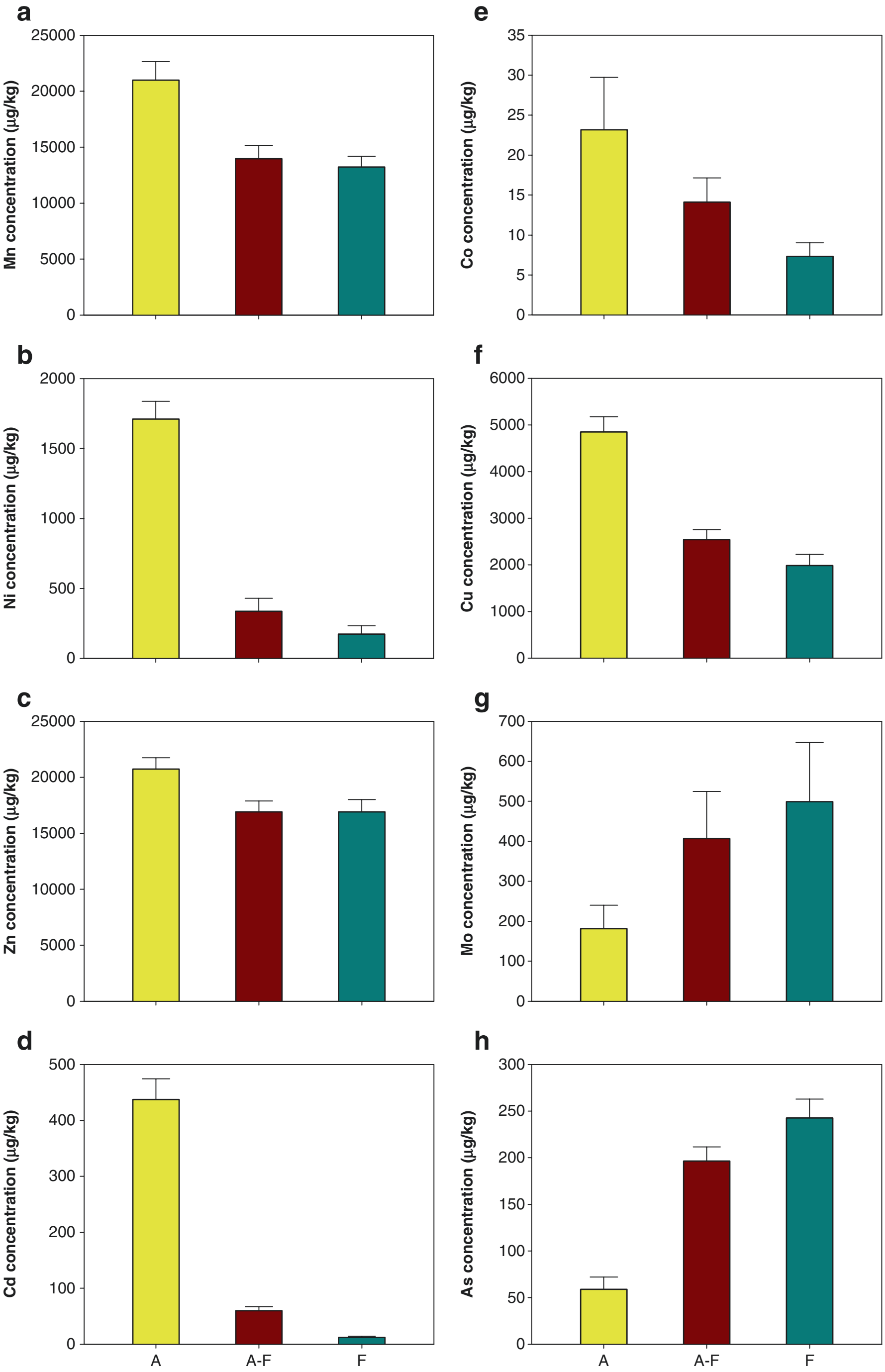


Fig. 2.3 Mn (**a**), Ni (**b**), Zn (**c**), Cd (**d**), Co (**e**), Cu (**f**), Mo (**g**), and As (**h**) concentrations in milled rice in aerobic rice (**A**), aerobic-flooded rice (**A–F**), and flooded rice (**F**) at Wuxue County, Hubei Province, China. Each column represents an average of four rice genotypes over 2 years. Error bars are ±SE

2.12 Conclusions

Due to the increasing population and limited land resources, increases in rice production of China mainly depend on yield improvement rather than expansion of planting area. In such circumstances, scientific and technological innovation will continue to play an important role in increasing rice yields. Developing new technologies of crop management using system approaches is inevitable as rice farming faces many challenges in China. New technology should mainly be judged based on its short- and long-term impacts on the environment along with yield and farmers' profit. Synergy among fertilizer, water, and pest and weed management should be considered to maximize overall efficiency of the rice production system.

Great achievements in super hybrid rice breeding have been made in recent years in China, and the yield of some hybrids is approaching their genetic potential. Therefore, further increase in yield seems to be rather difficult. Exploitation of indica/japonica heterosis can improve the level of yield. With the development of molecular marker technology in rice, the subspecies differentiation of parents can be determined, and the proper contribution of indica and japonica characters in the hybrids can be established for higher yields in combination with harmonious plant types. Furthermore, incorporating the characteristics of high photosynthetic rate in other species (C_4) into rice plants could be worthwhile for future super hybrid rice breeding.

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Chapter 3
Rice Production in India

Gulshan Mahajan, Vivek Kumar, and Bhagirath S. Chauhan

3.1 Introduction

Rice (*Oryza sativa* L.) is a principal food crop of south and southeastern countries. It is the staple food for more than two-thirds of the Indian population, thus holds the key for food security and plays a pivotal role in national economy. The demand for rice is expected to grow continuously as population is continuously growing.

The rice plant belongs to the genus *Oryza* of Poaceae (old Gramineae) family. The genus *Oryza* includes 24 species, of which only two species, viz., *Oryza sativa* and *Oryza glaberrima*, are cultivable and the rest 22 species are wild. Rice varieties which belong to *sativa* are further grouped into three subspecies, viz., *indica*, *japonica*, and *javanica*. India is the producer of rice varieties which belongs to the subspecies *indica* (DRD 2014). Rice is an annual plant which usually grows to a height of 0.5–2 m; however, there are some varieties which can grow up to 6 or 9 m high. Some rice varieties are also in existence which can grow when the flood water level gradually rises.

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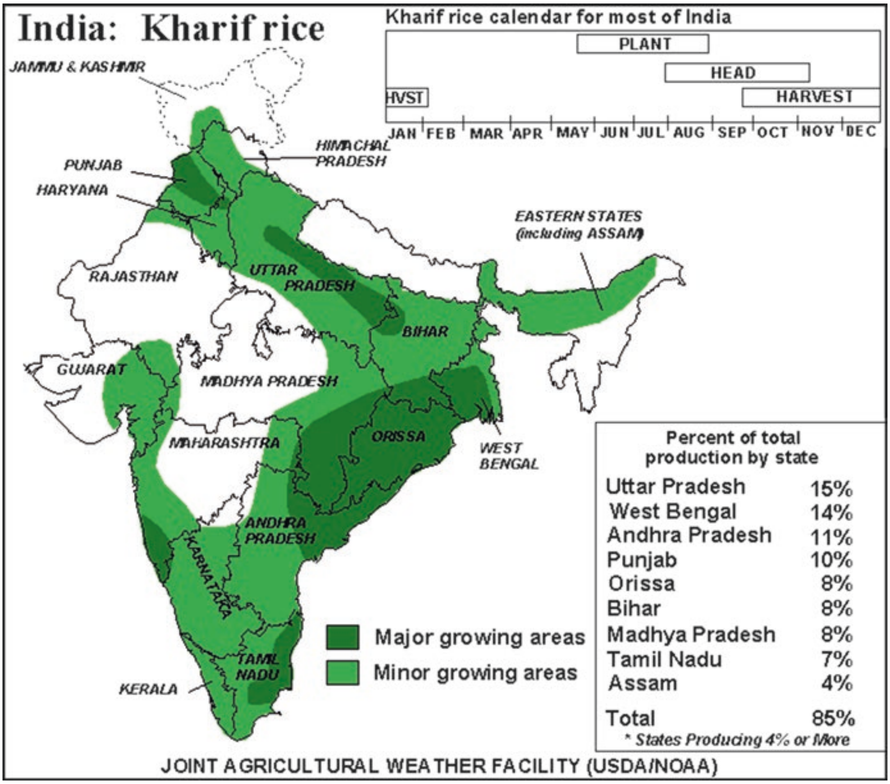
No doubt, India has its own position in rice area and production in the world, but still there are some problems and constraints in rice production in the country. Highlighting issues regarding constraints for increasing and maintaining the productivity of rice-based systems are (1) the inefficient use of resources (water, labor, and fertilizers) and their growing scarcity, (2) effect of climate change, (3) rising fuel prices and emerging energy crisis, (4) reducing farm profitability, and (5) emerging socioeconomic changes such as migration of labor to urban areas, liking for nonagricultural work, and concerns about environmental pollution (Ladha et al. 2009). Besides this, fragmentation of land and abiotic and biotic stress are also main issues which are threatening rice productivity and sustainability. To tackle these problems, new agronomic management and technological innovations are needed.

Currently, water productivity for rice in India is 2500–3500 l/kg. In order to deal with the problem of degrading water resource base, there is a need to improve the water productivity of rice by bringing from the current level of 2500–3500 l/kg to the level of 2000 l/kg (Mohapatra et al. 2013). It can be done by conservation tillage, drip irrigation, soil amendment, and mulching. Nutrient use efficiency needs to be enhanced for increasing and sustaining the rice productivity in India. There is a need to increase nitrogen, phosphorus, and zinc use efficiencies by 20–40, 40–50, and 50–100 %, respectively, for various rice production systems (Mohapatra et al. 2013). This is possible through agronomic manipulations, e.g., time and method of application, vesicular-arbuscular mycorrhizae, biofertilizers, and precision management of nutrients. Besides this, there is a need to work aggressively in collaboration with plant breeders to develop effective screening tools to identify novel germplasm with greater input (water, nutrient) use efficiency, e.g., root studies for high input use efficiency, screening genotypes on the basis of nutrient uptake efficiency indices, stress and biochemical indices, etc.

Reducing labor dependence by one-third from the current level may increase profitability in rice production (Mohapatra et al. 2013). This is possible through mechanization in different practices of rice cultivation, viz., land preparation, sowing methods, nutrition management, harvesting, etc. Combination of various stresses (abiotic, biotic, and nutritional) also limits rice yields (Mohapatra et al. 2013). The major abiotic stress which prevents rice crops from realizing their full yield potential is due to drought, heat, cold, salinity, and submergence. Similarly, biotic stresses, viz., pests and diseases, destroy a large portion of produce during cultivation and storage. For a sustainable yield over the years, these biotic and abiotic stresses need to be removed. Stress tolerance is complex phenomena and require various approaches for providing solution to plants experiencing the multiple environmental stresses (Mohapatra et al. 2013). Field screening of novel germplasm is required to find putative stress-related genes for developing resilient set of new germplasm which can better adapt to withstand with a stressful environment.

The most common method for rice establishment is transplanting of young seedlings into puddled soil (wet tillage) in India. But this production method is becoming less profitable these days because it is a water-, labor-, and energy-intensive method and these resources are becoming increasingly scarce (Kumar and Ladha 2011). Besides this, transplanted rice causes the deterioration of physical properties of soil and also emits methane gas (an important greenhouse gas) in the atmosphere. All these factors act as a driver of the shift from puddled transplanting to direct seeding of rice (DSR). DSR is the technology which is water, labor, and energy efficient along with eco-friendly characteristics and can be used as a potential alternative to conventional puddled transplanted rice (Kumar and Ladha 2011). No doubt, direct seeding method has several benefits as compared to puddled transplanting, which include similar yield level, economized irrigation water, labor, reduced cost of production and thus increased net returns, and methane emission reduction. However, there are also some risks associated with adoption of direct seeding method. These include the introduction of hard-to-control and herbicide-resistant weed flora; evolution of weedy rice; higher emissions of nitrous oxide, a potent greenhouse gas; nutrient disorders, especially N and micronutrients such as Fe and Zn; and increases in soilborne pathogens such as nematodes (Kumar and Ladha 2011).

Rice can be grown under diverse climatic conditions. It is best suited in the regions having high humidity and temperature, prolonged sunshine hours, and assured water supply. Rice can grow well on soils over wide range of pH 5 to 9 and with low permeability soils that provide better environment for its growth. Generally, the loamy soils are best suited for rice cultivation. Because of the adaptability of rice to different soil conditions, it is said that it can be grown on any type of soils including alkaline and acidic soils. This wide physical adaptability of rice plant allows the rice plants to be grown below sea level which includes the Kuttanad area of Kerala up to a height of 2000 m in Jammu and Kashmir, Himachal Pradesh, hills of Uttaranchal, and northeastern hill (NEH) region.



Percent of total production by state

Uttar Pradesh	15%
West Bengal	14%
Andhra Pradesh	11%
Punjab	10%
Orissa	8%
Bihar	8%
Madhya Pradesh	8%
Tamil Nadu	7%
Assam	4%
Total	85%

* States Producing 4% or More

JOINT AGRICULTURAL WEATHER FACILITY (USDA/NOAA)

Host: http://somarmeteorologia.com.br/v3/figuras/culturas/india/india-arrozkharif.gif

In India, the rice-growing areas have been broadly grouped into five regions (Meera et al. 2014a):

3.1.1 Northeastern Region

The northeastern region includes Assam and northeastern states. The main rice-growing area in Assam is the basin of Brahmaputra River. In this area, rice is cultivated under rainfed conditions, because the area receives very heavy rainfall.

3.1.2 Eastern Region

This region includes Eastern Uttar Pradesh, Bihar, Chhattisgarh, Jharkhand, Madhya Pradesh, Odisha, and West Bengal. In India, the basins of Ganges and Mahanadi rivers are the major rice-growing region with the highest intensity of rice cultivation. This region also receives heavy rainfall, so rice is generally grown under rainfed conditions.

3.1.3 Northern Region

Punjab, Haryana, Uttrakhand, Western Uttar Pradesh, Himachal Pradesh, and Jammu and Kashmir are included in northern region. In winter season, low temperature is experienced in this region, and a single crop of rice can be grown from May–July to September–October.

3.1.4 Western Region

This region includes Gujarat, Maharashtra, and Rajasthan. Rice is largely grown under rainfed conditions during June–August to October–December.

3.1.5 Southern Region

Andhra Pradesh, Karnataka, Kerala, and Tamil Nadu cover the southern region. Major rice-growing areas in this region are the deltaic tracts of Krishna, Godavari, and Cauvery rivers and the non-deltaic rainfed areas of Andhra Pradesh and Tamil Nadu. In the deltaic tracts, rice cultivation is done under irrigated conditions.

3.2 Important Growing Ecology of Rice

In terms of photoperiodism, rice is a short-day plant. However, several varieties have been introduced which are nonsensitive to photoperiodic conditions. With the introduction of photoperiod and thermo-insensitive and relatively short-duration varieties of rice, remarkable changes have been observed in the cropping system concepts (Sharma et al. 2004). On the basis of soil variations and agroclimatic conditions in the major rice-growing states of the country, different rice-based cropping systems have been adopted in the different ecologies. India is the only country in the world which has much diversity in rice ecosystems. Because of this diversity in rice ecosystem, four different types of ecosystems have been developed in India (Meera et al. 2014a). These are:

1. Irrigated rice ecosystem
2. Rainfed upland rice ecosystem
3. Rainfed lowland rice ecosystem
4. Flood-prone rice ecosystem

3.2.1 Irrigated Rice Ecosystem

Under the irrigated ecosystem, wet season (June to October) is the main season for rice cultivation; however, in a small area, rice is also grown in dry season (November to May) (Rao et al. 2008). In India, about 22 million hectares area is under irrigated rice ecosystems, which is about 49.5 % of the total rice area in the country. Major states where rice is grown under irrigated conditions are Punjab, Haryana, Uttar Pradesh, Himachal Pradesh, Andhra Pradesh, Jammu and Kashmir, Sikkim, Tamil Nadu, Karnataka, and Gujarat. Bunding of paddy fields is the prerequisite for irrigated rice cultivation.

3.2.2 Rainfed Upland Rice Ecosystem

Globally, upland ecosystem for rice cultivation is present in Asia, Africa, and Latin America. In India, Assam, Bihar, West Bengal, Odisha, eastern parts of Madhya Pradesh and Uttar Pradesh, and northeastern hill region cover 85 % of the upland rice area (Rao et al. 2008). In the country, about six million hectares of area is under upland rainfed rice, which accounts 13.5 % of the total area under rice crop in the country. Monsoon season is the main season for rice cultivation in this ecosystem. The temperature range in this zone is from 25 to 40 °C in July and from 6 to 25 °C in January, and it receives rainfall in the range of 1000–2000 mm or more. In this ecosystem, mostly direct sown rice is grown, and the rice fields are generally dry, unbunded. About 55 % of the total rice area in this zone contain red laterite and lateritic soils such as mixed red and yellow, red sandy, red loam, lateritic, and mixed red and brown hill soils. Besides this, alluvial soil also occupies nearly 27 % of the total rice area.

3.2.3 Rainfed Lowland Rice Ecosystem

In India, rainfed lowland rice is grown in around 14.4 million hectares, mostly in Eastern India, where availability of soil moisture remains for longer period. This area accounts 32.4 % of the total rice area of the country. In these areas, mostly photosensitive varieties having 140 days duration are grown. There is much variations in water depth in this ecosystem, which can be shallow (up to 25 cm), medium deep (up to 50 cm), or deep (up to 2 m). Depending on the water depth in the field, medium- to long-duration cultivars are grown. For better performance, these cultivars should have tolerance to drought at initial stage and submergence at later stage, moderate to high tillering ability, photosensitivity, tolerance to pest and diseases, and elongation ability in semi-deep or deepwater situations.

There is lack of technology in rice production in this ecosystem so there is much variations in production. The major problems in rainfed lowland ecosystem are erratic yields due to drought/flood conditions and poor soil quality.

3.2.4 Flood-Prone Rice Ecosystem

Flood-prone rice is adapted in those areas where farmers have to face temporary submergence of 1–10 days or long period submergence of 1–5 months in depths from 50 to 400 cm or more. This is also adapted where daily tidal fluctuations may also cause complete submergence (Mohanty et al. 2013). Globally, flood-prone ecosystems are found in South and Southeast Asia as extreme floods, and drought often occurred in these areas. In India, 26 % of the total cultivated area and 4.6 % of the total rice-grown area are under flood-prone rice ecosystems. Yield in these ecosystems are very low (1.5 t ha^{-1}) and variable. June to November is the main season for flood occurrence during the wet season. Rice varieties are selected according to their level of tolerance to submergence**.**

3.3 History, Importance, Area, and Production

3.3.1 History

Rice is believed to be originated in Asia. Among the different rice species, the dominant rice species *Oryza sativa* has originated in Southeast Asia. Rice is thought to be developed from wild grass that was grown in the foothills of the Far Eastern Himalayas. It is also believed that the origin of rice plant may be in Southern India, and after its origination, it was adopted in the North India and then in China. Thereafter, it spread to Korea, then about 2000 B.C. in Philippines, and then about 1000 B.C. in Japan and Indonesia (DRD 2014). Some scientists (De Condole 1986; Watt 1892) believe that cultivated rice was originated in Southern India. However, some others (Vavilov 1926) thought that India and Burma (Myanmar) was the place where cultivated rice was originated. After origin, it spread around the world very slowly, but once it reached in any area, it became an important product for the people from agriculture and economic point of view.

It is believed by the historians that the area covering the foothills of the Eastern Himalayas (i.e., northeastern India), stretching through Burma, Thailand, Laos, Vietnam, and Southern China, domesticated *indica* variety of rice. At the same time, the *japonica* variety from wild rice was domesticated by Southern China, which was introduced to India thereafter. It seems that after its adoption in the northern plains, it proceeded to Southern India around 1400 B.C. Then it spread to all those areas which were under the influence of rivers, e.g., fertile alluvial plains watered by rivers. In Assam and Nepal, some perennial wild rice varieties are still being grown (DRD 2014). The word rice is considered to be derived from the Tamil word *arisi*. Rice was first mentioned in the *Yajur Veda* (1500–800 B.C.) and then frequently referred in Sanskrit texts.

Chatterjee (1948) suggested that genus *Oryza* has altogether 24 species, of which 2, viz., *Oryza sativa* and *Oryza glaberrima*, are cultivated and 22 are wild. In most of the rice-growing areas, *O. sativa* is prevalent; however, *O. glaberrima* is grown in West Africa only. So he believed that the cultivated rice might have two centers of origin: West Africa and Southeastern Asia including Myanmar, India, and Thailand.

3.3.2 *Importance*

India is one of the important centers of rice farming and occupied the largest area under rice cultivation (DRD 2014). In the Indian subcontinent in 2011–2012, more than a quarter of the cultivated land was occupied by rice. In the southern and eastern parts of India, it is considered as a very important and essential part of the daily meal. Rice plays a vital role in shaping the diets, culture, and economics of thousands of millions of peoples in the world. It will not be wrong to say that “rice is life” for more than 50 % of the humanity. Rice is an important staple food crop for more than 50 % of the world population. Besides this, rice straw, husk, and bran are also used as cattle feed, in cottage industry for preparation of hats, mats, ropes, sound absorbents, straw board, and as litter material and fuel sources. Keeping its importance in view, the year 2004 was designated as the “International Year of Rice” by the United Nation (DRD 2014).

3.3.3 *Area and Production*

At the global level, rice is the most widely grown crop which occupies an area of about 161.8 million hectares, of which Asia covers about 143.2 million hectares. Similarly, out of the total world rice production of 701.1 million tons of paddy, Asia contributes approximately 633.7 million tons (FAO Statistical Yearbook 2013). Although the largest area under rice crop in the world (43 m ha) is in India, average productivity is much higher in the USA, China, and Japan, i.e., nearly more than twice of that in India. No doubt, much increase in productivity has been reported from 1950–1951 to 2011–2012 in India. In 1950–1951, rice productivity in India was 6.68 q ha^{-1}, which increased to 23.95 q ha^{-1} in 2011–2012. An increasing trend in rice production has been shown from 1950 to1951, and a record level of 105.3 million tons was achieved in 2011–2012 (Mohapatra et al. 2013). Introduction of high-yielding and fertilizer-responsive varieties combined with improved package of practices introduced by agricultural scientists for different regions are the main reasons for increase in productivity of rice which is about 258 % (Mohapatra et al. 2013).

Kharif season is considered as the main season for rice cultivation in the country as the major share of rice is cultivated during this time. However, *rabi*/summer season also contributes a small share of rice in the assured irrigation conditions. Monsoon plays a very important role in Indian rice production as rice production is dependent on monsoon rains to a great extent. Only 59 % of the total rice area is covered under assured irrigation (DRD 2014).

The most important rice-growing and rice-consuming area in India is in the eastern region which accounts for about 63.3 % of India's rice-growing area. It comprises of West Bengal, Bihar, Odisha, Eastern Uttar Pradesh, Assam, and Eastern Madhya Pradesh. In this region, only 35 % of the total people reside; however, their demand is about 49 % of the rice grown in the country (Thiyagarajan and Gujja 2013).

Area, production, and yield of rice during 2010–2011 and 2013–2014 in major producing states is given in Table 3.1.

3.4 Rice-Based Cropping Systems

In any particular area, there are four main factors on which a cropping system depends: water resources, land topography, soil textural properties, and marketing facilities in the area. All these factors vary to a greater extent even within an area or region. In South Asia, particularly in India, the importance of rice-based multiple cropping systems is appreciated because of the changes occurring in socioeconomic system, population, and food production dynamics by the turn of the century. Now, rice-based cropping systems have dominated over all the other cropping systems in the country, as rice is grown all over the country with a number of crops either in intercropping or in sequence with rice, most of these are 1 year cropping systems. In the past, crops other than rice were not grown in the current traditional rice-growing areas, because of prevailing climatic conditions, inadequate arrangements of drainage, and lack of irrigation facilities. But now, either double cropping of rice or inclusion of *rabi* crops in sequence with rice is being adopted. It has become possible due to the improvement in irrigation facilities (Srivastava and Mahapatra

Table 3.1 State-wise area, production, and yield of rice during 2010–2011 and 2013–2014

	2010–2011			2013–2014[a]		
States	Area (m ha)	Production (mt)	Yield (kg ha^{-1})	Area (m ha)	Production (mt)	Yield (kg ha^{-1})
Andhra Pradesh	4.75	14.42	3035	4.51	13.03	2891
Assam	2.57	4.74	843	2.27	4.78	2101
Bihar	2.83	3.10	1095	3.11	5.51	1774
Chhattisgarh	3.70	6.16	1663	3.80	6.72	1766
Gujarat	0.81	1.50	1852	0.79	1.62	2053
Haryana	1.25	3.47	2789	1.23	4.00	3256
Jharkhand	0.72	1.11	1541	1.22	2.74	2238
Karnataka	1.54	4.19	2719	1.33	3.76	2828
Madhya Pradesh	1.60	1.77	1106	1.93	2.78	1438
Maharastra	1.52	2.70	1776	1.56	2.95	1891
Odisha	4.23	6.83	1616	4.18	7.58	1815
Punjab	2.83	10.84	3828	2.85	11.27	3952
Tamil Nadu	1.91	5.79	3040	1.79	5.54	3100
Uttar Pradesh	5.66	11.99	2120	1.79	5.54	3100
West Bengal	4.94	13.05	2639	5.50	15.31	2786
Others	1.79	3.82	–	1.71	3.83	–
All India	42.86	95.98	2239	43.95	106.54	2424

Source: Agricultural Statistics at a Glance 2014 (2015)

[a] Fourth Advance Estimates

2012). Besides this, introduction of high-yielding photo- and thermo-insensitive rice varieties of relatively shorter duration also brought remarkable changes in the cropping system concept (Sharma et al. 2004).

The Project Directorate of Cropping System Research (PDCSR) has identified approximately 500 cropping systems on the basis of rational spread of crops in different agroclimatic regions of the country, of which only 30 cropping systems are important as there is a sizable area under these cropping systems (Yadav et al. 1998). The largest area in the country is covered by various rice-based cropping systems such as rice-wheat, rice-rice, rice-chickpea/lentil, rice-mustard/linseed, and rice-peanut. Among different rice-based cropping systems, the major share of food grain pool of the nation is contributed by rice-wheat and rice-rice cropping systems. Other rice-based cropping systems such as rice-mustard, rice-peanut, rice-chickpea, rice-green gram, etc., have their significant contribution to the national production of oilseed and pulse crops (Tiwari et al. 2013).

In India, more than 44 million hectare area is occupied by rice under three major ecosystems, rainfed uplands (16 % area), irrigated medium lands (45 %), and rainfed lowlands (39 %), with a productivity of 0.87, 2.24 and 1.55 t ha^{-1}, respectively (Tiwari et al. 2013). Thus, rice-based production systems provide livelihood for more than 50 million households. The population has already crossed one billion mark, and by the year 2030, it is expected to reach around 1.5 billion. To meet the demand of Indian population, currently the food grain demand is estimated at 240 million tons. Keeping this in view, the National Food Security Mission had been launched by the Government of India to achieve the production of additional 10, 8, and 2 million tons of rice, wheat, and pulses, respectively (NFSM 2012). The mission met with an overwhelming success and achieved the targeted additional production of rice, wheat, and pulses. The mission is now continued with new targets of additional production of food grains of 25 million tons of food grains comprising of 10 million tons rice, 8 million tons of wheat, 4 million tons of pulses, and 3 million tons of coarse cereals by 2017. In order to make agriculture an attractive, profitable, and sustainable enterprise, it is necessary to shift from traditional food grain production systems to newer cropping systems under rice-based production systems depending upon the agroclimatic conditions (Rao et al. 2008). State-wise area under different rice-based cropping systems is given in Table 3.2.

For the revolutionary increase in rice production, it is necessary to divert the *kharif* area to the rice crop in *kharif* season in the states of Punjab, Haryana, Himachal Pradesh, Jammu and Kashmir, western Uttar Pradesh, and Rajasthan where irrigation facilities are available. Actually, in most parts of the country in the states mentioned above, such a change in the cropping pattern has already been occurred. It is expected that the major irrigated *kharif* areas will be under the rice crop during the course of the next decade (Srivastava and Mahapatra 2012).

3.4.1 Rice-Based Cropping Systems Under Different Ecologies

The multiple crop demonstrations have been conducted under the National Demonstration Scheme to find the efficient cropping system in different parts of the country. These demonstrations have shown that a rice-wheat rotation can give a total annual production of over 10 t ha^{-1} $year^{-1}$ in the states of Uttar Pradesh, Himachal Pradesh, Haryana, and Punjab. In the north and the northwestern parts of the country, rice followed by wheat has proved to be a very productive and profitable crop sequence. However, rice followed by rice is the most efficient system in terms of production in the south and southeastern states of the country. In Eastern India, for the slightly dry hot zone, the rice-wheat rotation was the best under the upland to medium land conditions and for the slightly moist and hot zone; rice-rice rotation was the best under medium to lowland conditions. In Western and Central India, the highest production in *kharif* was obtained from the rice crop. However, wheat which follows rice produces less yields as compared to the wheat crop grown after maize or sorghum. Thus, a yield level of 10–15 t ha^{-1} $year^{-1}$ can be obtained in all the rice-growing ecologies with a proper selection of crops, varieties, and agronomic practices (Srivastava and Mahapatra 2012).

In multilocational experiments conducted under the Cropping System Research Projects, many rice-based cropping systems suited to different soil and climatic conditions have been identified in terms of agronomic productivity, physiological output, and economic feasibility (Annual Report 2001–2002). Promising rice-based

Table 3.2 State-wise area under different rice-based cropping system in India

Cropping system	State	Area ('000 ha)	Cropping system	State	Area ('000 ha)
Rice-wheat	Assam	100.0	Rice-rice	Andhra Pradesh	1393.0
	Bihar	1511.1		Assam	1131.0
	Gujarat	248.7		Gujarat	257.3
	Haryana	867.0		Karnataka	684.7
	Himachal Pradesh	58.3		Kerala	143.3
	Jammu and Kashmir	305.5		Odisha	139.5
	Madhya Pradesh	594.8		Tamil Nadu	2145.2
	Maharashtra	56.1		Total	5894.0
	Punjab	1750.0	Rice-vegetables	Gujarat	90.7
	Uttar Pradesh	4122.7		Maharashtra	89.1
	West Bengal	233.1		Odisha	100.0
	Total	9847.3		Tamil Nadu	20.9
Rice-fallow	Bihar	1554.0		West Bengal	941.9
	Jammu and Kashmir	127.0		Total	1243.5
	Karnataka	242.0	Rice-lathyrus	Bihar	88.0
	Madhya Pradesh	2038.1		Madhya Pradesh	862.0
	Maharashtra	458.8		Total	950.0
	Total	4419.9	Rice-mustard	Bihar	12.0
Rice-peanut	Andhra Pradesh	188.0		Madhya Pradesh	52.0
	Karnataka	55.0		Odisha	22.6
	Maharashtra	5.1		Uttar Pradesh	35.8
	Odisha	14.7		West Bengal	358.3
	Tamil Nadu	760.1		Total	480.7
	Total	1022.9	Rice-black gram	Andhra Pradesh	367.0
Rice-gram	Maharashtra	105.9		Odisha	231.9
	Odisha	24.5		Total	598.9
	Uttar Pradesh	78.5	Rice-green gram	Andhra Pradesh	143.0
	Total	208.9		Karnataka	19.0
Rice-sugarcane	Bihar	52.0		Odisha	435.5
	Gujarat	370.4		Total	597.5
	Tamil Nadu	10.2	Rice-potato	West Bengal	462.4
	Total	432.6	Rice-jute	West Bengal	120.1

Source: Yadav and Rao (2001)

Table 3.3 Existing and proposed rice-based cropping systems under different agroclimatic zones of India

Agroclimatic zone	Cropping system	
	Existing	Proposed
Indo Gangetic Plains	Rice-wheat, rice-pulses, rice-potato, rice-toria-wheat, rice-maize-berseem, rice-rice, rice-potato-sesame	Rice-winter maize-cowpea, rice-berseem, rice-peanut-sesame, rice-wheat-pulse, rice-early potato-peanut, rice-linseed/pea/lentil, rice-potato-soybean, rice-sunflower-green gram
Eastern Himalayan region	Rice-wheat, rice-pulses	Rice-toria-wheat, rice-berseem-soybean, rice-sunflower, rice-vegetables
Western Himalayan region	Rice-mustard, rice-wheat, rice-linseed, rice-oats, rice-berseem	Rice-potato, rice-berseem (relay cropping), rice-toria-wheat, rice + soybean intercropping
Western dry region	Usually sole crop of rice grown in limited areas, rice-mustard	Rice-wheat, rice-mustard, rice-peanut, rice-potato, rice-sunflower
East-west coast plains	Rice-black gram, rice-peanut, rice-finger millet, rice-rice	Rice-sunflower, rice-peanut-cowpea, rice-potato-sesame, rice-maize-cowpea, rice-vegetables, rice-relay cropping with black gram, field pea, lathyrus in rainfed system
Eastern, western, central, and southern plateau regions	Usually monocropping with rice, intercropping with pulses or oilseeds is practiced	Rice-sunflower, rice-peanut, rice-black gram, rice-chilly
Island region	Rice monocropping, rice-rice, rice-green gram/black gram	Rice-peanut, rice-sunflower, rice-winter maize, rice-rice, rice-vegetables

Source: Rao et al. (2008)

cropping systems with high productivity and intensive land use for diverse agroclimatic situations of India are given in Table 3.3 (Rao et al. 2008).

Different ecologies have their specific cropping systems in India. In rainfed upland ecosystems, short-duration varieties of 90–105 days are cultivated. The sowing is completed during the onset of monsoon, so as to vacate the fields early for the second crop (Saha et al. 2003). Major crops in this ecosystem are mustard, castor, linseed, safflower, black gram, lentil, horse gram, etc., which take advantage of residual soil moisture and late monsoon rains. System productivity and farmer income can also be improved by intercropping of rice with short-duration pulses like green gram, black gram, or oilseeds like peanut (Tiwari et al. 2013). Cropping intensity and total productivity of the system is very low in northeastern hill (NEH) region because successful *rabi* cropping is very difficult. It can be increased by intercropping soybean, pigeon pea, and peanut with rice. Rice + pigeon pea (4:1 row ratio) and rice + peanut/soybean (4:2 row ratio) have been found promising in NEH regions. Intercropping with legumes helps in reducing weed problem, improving soil fertility, and enhancing farm income (Das et al. 2012).

Under the irrigated medium land situations, the major cropping systems are rice-rice, rice-wheat, rice-winter maize, rice-peanut, rice-sunflower, rice-potato, rice-mustard, rice-chickpea, and rice-winter vegetables. The cropping intensity of this system is 200 %. However, there is still scope to increase the cropping intensity by introducing a third crop of short-duration pulses like cowpea, green gram, black gram, or oilseed crops like sesame. This can be possible only in those areas where facilities are available to provide 1–2 lifesaving irrigations to the third crop. In West Bengal, rice-potato-sesame, rice-wheat-green gram, and rice-wheat-jute are found most suitable. While in Punjab conditions, rice-potato-sunflower, rice-potato-winter maize, and rice-toria-sunflower have been found to be more productive than the conventional system of 200 % cropping intensity with rice-wheat or rice-winter maize (Tiwari et al. 2013).

In the rainfed lowland ecosystem, medium to long duration rice varieties of 140–155 days are usually grown in shallow lowlands of Eastern India. Some short-duration crops like green gram and black gram are grown with residual soil moisture in harvested rice fields (Saha and Moharana 2005). In intermediate deep and deep-water rice ecologies of east coast and lower Gangetic Plains of India, long-duration (155–180 days) photosensitive rice varieties can be grown. In these areas, rainwater is harvested during the monsoon period of June–September which is used in growing several winter vegetables like pumpkin, bitter guard, okra, and chili, along with other crops like black gram, green gram, sunflower, peanut, and sesame during the dry season. Generally, monocropping of rice is done in the salt-affected rainfed coastal areas. However, certain salt-tolerant crops like sunflower, chili, watermelon, sugar beet, cotton, and barley are grown along with rice, depending on the availability of harvested rainwater, soil, and climatic conditions (Singh et al. 2006).

For the successful cultivation of rice-based cropping system, it is very important to select suitable varieties and adjust the dates of planting. Development of efficient rice-based cropping systems for irrigated and rainfed areas and their evaluation in respect of their production potential with or without resources constraints per unit area per unit time and their long-range effects on improvement of soil health is the remedy for increasing rice production (Srivastava and Mahapatra 2012).

3.5 Varieties and Genetic Improvement

For the diversity in rice varieties, India is considered one of the richest countries in the world (Table 3.4). Several different rice varieties have been reported in India, depending on variations in the soil structure, plant characteristics, weather conditions, and purposes of use. It has been estimated by Dr. R.H. Richharia, one of the most outstanding rice scientists of the world, that during the *Vedic* period, about 400,000 varieties of rice existed in India (Thiyagarajan and Gujja 2013). Even now, as many as 200,000 rice varieties have been estimated to exist in India.

Table 3.4 Some of the popular varieties developed before 1960 in India

State	Popular variety
Andhra Pradhesh	MTU 1, MTU 15, HR 19
Madhya Pradesh	Hybrid 2, Hybrid 18, Dubraj
Mumbai	Kolamba strains
Orissa	T 141, SR 26 B
Punjab	Basmati 370
Tamil Nadu	CO 26, ASD 1, GEB 24 m, CO 2, CO 25,
Uttar Pradesh	T 136, N 22
West Bengal	Chinsura 7

Source: Krishnaiah (1998)

Over the last 50 years in tropical Asia, India has released the greatest number (643) of varieties. India may therefore be chosen as a case study for evaluating the genetic diversity of cultivated varieties. In the last 30 years, 632 varieties were developed and released for commercial cultivation in India for different ecosystems. Of the 632 varieties, 14 (2.2 %) for deepwater, 30 (4.7 %) for rainfed semi-deepwater, 33 (5.2 %) for hill ecologies, 87 (13.7 %) for rainfed uplands, 123 (19.4 %) for rainfed shallow lowlands, and 374 (59 %) were released for the irrigated ecosystem. About 77 % of the total rice area in the country is occupied by high-yielding varieties (FAO 2003). As a result of concerted efforts over the last two decades, more than 50 hybrids have been released so far. Important hybrids from public sector are KRH-2, DRRH-2, and Pusa RH 10 and from private sectors PHB 71, PA 6201, PA 6444, and PA 6129. The yield advantage of hybrids is in the range of 15–20 % over the high-yielding inbreds. However, still area under hybrid rice has reached only about 1.5 m ha. Some of the considered reasons for poor adoption of hybrid rice technology are (i) lack of hybrid seed availability at reasonable cost and weak infrastructure for quality hybrid seed production, (ii) low magnitude of heterosis, (iii) poor grain and cooking quality, (iv) low yield on seed parent resulting into high seed cost, (v) susceptibility of hybrids to biotic stresses (blight, blast, BPH), and (vi) lack of suitable hybrids for fragile ecosystem (drought, salinity, submergence, acidity, low temperature). There is a need for mapping of heterotic QTLs in promising hybrids and their transfer to breed super parental lines. There is also need for utilization of yield enhancing heterotic QTL from land races and wild relatives. Improved version of KMR 3, the male parent of KRH 2 carrying heterotic gene block from same land races, and *O. rufipogon* have been developed which are likely to enhance the level of heterosis. Development of Pusa RH 10, the first super fine grain aromatic rice hybrid has proved that if the parental lines are carefully bred and selected, the hybrid with excellent grain and cooking quality can be developed. Now several genes conferring resistance to bacterial blight, blast, brown plant hopper have been identified and mapped using molecular markers. The potential of marker-assisted selection has been amply demonstrated in breeding for resistance to bacterial blight (BB) through development of inbreds PR-124, Improved Pusa Basmati 1, Punjab Basmati 3, and Improved Samba Mahsuri. The fragile rice ecosystem consisting of drought, submergence, salinity/alkalinity, acidity, and low-temperature stress constitutes more than 50 % area under rice in India. Now with the availability of tightly linked markers for gene like *Sub 1* (Swarna Sub 1) and Saltol conferring seedling stage submergence (Pokkali rice) and salinity tolerance (CSR-30), it should be possible to incorporate these genes into elite material. Similarly genes for phosphorus uptake (*Pup 1*) and drought tolerance (Sahbaghi Dhan, Dhan 201, Dhan 202) are now mapped and are being deplored to harness their potential through improved lines in stress environment.

At present, in 28 state agricultural universities (SAUs), more than 125 rice research stations are working on all aspects of rice. Identification of several varieties was done by intensive selection from local population in different parts of India. It proved to be the stepping stone for the modern breeding program in which high- and stable-yielding varieties with resistance to major diseases and insects were developed.

3.6 Rice Production Methods

Four rice agroecosystems have been identified and categorized by the International Rice Research Institute (IRRI). These are (1) irrigated rice ecosystems, (2) rainfed lowland rice ecosystems, (3) upland rice ecosystems, and (4) deepwater rice ecosystems. For all these conditions, one set of cultural practices cannot be used efficiently. For example, transplanting is the main method of rice establishment in irrigated areas, but in some areas, direct seeding is being done. There are three principal systems which have been adopted in India. These are dry system, semidry system, and wet system. Soil types, topography of the land, rainfall pattern, etc., are the factors which affect the selection of method to be adopted (Srivastava and Mahapatra 2012). Besides this, availability of labor is also an important factor, which affects the choice of establishment method. Thiyagarajan and Gujja (2013) found that the source and availability of water are the most important factors which finally decide the method of crop establishment in the different ecosystems (Table 3.5). There are mainly two types of soils in India in which rice is grown, i.e., uplands and lowlands. Broadly, rice sowing methods can be classified into two methods:

(a) Dry or semidry upland cultivation. This method is further divided into two categories:
    (i) Broadcasting the seed
    (ii) Sowing the seed using a plough or a drill

Table 3.5 Methods of crop establishment in different rice ecosystems having different sources of water in India

Rice ecosystem	Water sources	Crop establishment method
Irrigated	Perennial and seasonal river (rainfed, reservoir fed, snow fed) System tanks filled by river water Seasonal tanks filled with rainwater Groundwater (whole season and supplementary)	Transplanting in puddled soil Seeds broadcasting in puddled soil Drum seeding in puddled soil Seedling throwing in puddle soil Direct seeding in dry condition and convert into wetland after rains
Rainfed wetland	High rainfall	Transplanting in puddled soil Direct seeding in dry condition and convert into wetland after rains
Rainfed dryland	Low rainfall	Seeds broadcasting in dry condition Seed-drill sowing (tractor drawn) in dry condition Seed-drill sowing (animal drawn) in dry condition Line sowing behind plough in dry condition
Deepwater	Rainfall flooding	Seeds broadcasting in dry condition and fields flooded with rain water

Source: Thiyagarajan and Gujja (2013)

(b) Wet or lowland cultivation. This method also is further divided into two categories:

   (i) Transplanting in puddled fields
   (ii) Broadcasting sprouted seeds in puddled field

Broadly speaking, main methods of raising rice crop are direct seeding and transplanting. In case of transplanting, seedlings are raised in the seed bed before they are transplanted in the main field, whereas in case of direct seeding, seeds are sown straight to the main field either by broadcast seeding or by row seeding in wet or dry soil. This is the basic difference between these two methods.

3.6.1 Direct-Seeded Rice

The main method of rice establishment in the country is transplanting. But this production system is water, labor, and energy intensive. Nowadays, these resources are becoming increasingly scarce, so this system is becoming less profitable. This system also adversely affects the soil physical properties, thus the performance of succeeding upland crops, e.g., wheat, and deteriorates the environment quality by contributing to methane emissions. All these factors played an important role to increase in demand for shifting from puddled transplanting to direct seeding of rice (DSR) in irrigated rice ecosystems (Kumar and Ladha 2011; Mahajan et al. 2012; Chauhan et al. 2012).

Table 3.6 Classification of direct-seeded rice systems with seed and seedbed conditions and area

Direct seeding system	Area	Seed condition	Seedbed condition and environment	Seeding method
Dry direct-seeded	Mostly in rainfed areas and some in irrigated areas with precise water control	Dry seeds	Dry soil, mostly aerobic	Broadcasting; drilling or sowing in rows
Wet direct-seeded	Mostly in irrigated areas with good drainage	Pre-germinated seeds	Puddled soil, may be aerobic or anaerobic	Various
Water seeding	In irrigated areas with good land leveling and in areas with red rice problem	Dry or pre-germinated seeds	Standing water, mostly anaerobic	Broadcasting on standing Water

Source: Thakur et al. (2004) and Balasubramanian and Hill (2002)

DSR refers to the process of establishing a rice crop from seeds sown in the field rather than by transplanting seedlings from the nursery. This method is mostly adopted in rainfed uplands, medium lands, and lowlands where rainfall is uncertain, the topography is undulating, and fields are unbunded. Actually, direct seeding is not a new concept; rather it is the oldest method of rice establishment. DSR was the most common method before the 1950s but was gradually replaced by puddled transplanting (Grigg 1974; Pandey and Velasco 2005). In DSR, there are three principal methods: wet seeding (sowing pre-germinated seeds on wet puddled soils), dry seeding (sowing dry seeds into dry soil), and water seeding (seeds sown into standing water). All these methods are different form each other by different land preparations or by different crop establishment methods or by both (Table 3.6).

3.6.1.1 Direct Seeding on Dry Seed Bed or Dry-Direct Seeded Rice

In this method, plowing and leveling are done properly before or at the onset of monsoon. Rice seeds are directly sown in the field at row spacings of 15–20 cm using seed rates of 25–50 kg ha^{-1} depending on variety and time of planting and are covered with soil by shallow tillage or planking (Mahajan et al. 2011; Mahajan and Chauhan 2016). In dry DSR, different methods are used, including:

1. Broadcasting of dry seeds on unpuddled soil after either zero tillage or conventional tillage
2. Dibbled method in a well-prepared field
3. Drilling of seeds in rows after conventional tillage or reduced tillage using a power tiller-operated seeder

A seed-cum-fertilizer drill can be used for DSR in conventional or zero tillage which drills the seeds and places the fertilizer simultaneously. The seedbed condition in this system is unpuddled and dry, so the aerobic environment is provided to seed. Rainfed upland, lowland, and flood-prone areas of Asia are the main regions where this method is traditionally practiced (Rao et al. 2007). However, as the water scarcity is increasing in irrigated areas also, so this method is gaining importance in these areas. In spite of promising benefits from the adoption of dry DSR, farmers may not be able to adopt this technology until the problems of cultivation in dry DSR is solved and the technologies are fine-tuned to suit farmers' conditions.

Adoption of dry DSR on a large scale is possible; however, public-private partnerships and prioritizing resources are the key to success. To achieve success in dry DSR, precise laser- leveled fields, drills having improved seed metering systems, and trained tractor drivers and pesticide operators are the key components. The sowing of DSR at shallow depth is important for good establishment. Short-duration cultivars, hybrids, and basmati rice gave superior performance under dry seeding, but breeding rice cultivars for dry seeding is the important thrust area for further productivity gains in dry DSR (Mahajan et al. 2015). Weeds pose a serious problem in dry DSR for high productivity. Pre- and postemergence herbicide applications are needed for effective weed management; however, the choice of herbicides varies according to dominant weed flora (Mahajan et al. 2009, 2015). For effective and sustainable management of weeds in dry DSR and for delaying herbicide resistance in weeds, integrated weed management strategies are needed in dry DSR. Effective weed management in dry DSR starts from the timing and method of land preparation, choice of herbicides relative to the dominant weed species and soil moisture at the time of application, and the effect of weather on weeds and during herbicide application.

3.6.1.2 Direct Seeding on Puddled Seedbed or Wet Direct-Seeded Rice

In wet direct seeding method, field is puddled by repeated plowing and laddering in standing water. The mud is then leveled, and the excess water is drained to ensure good establishment of seedlings. Then, the pre-germinated seeds are sown with a radicle varying in size from 1 to 3 mm on or into puddle soil. These seeds are either broadcast by hand or sown in line using a drum seeder at the seeding rate of 80–100 kg ha^{-1}. This method is further classified into two categories, i.e., aerobic wet-seeded rice and anaerobic wet-seeded rice. In aerobic wet-seeded rice, pre-germinated seeds are sown on the surface of puddled soil, so the seed environment becomes aerobic. When pre-germinated seeds are sown/drilled into puddled soil, the seed environment is mostly anaerobic, hence known as anaerobic wet direct-seeded rice. In both aerobic and anaerobic methods, seeds are either broadcast or sown in line using an anaerobic seeder with a furrow opener and closer (Balasubramanian and Hill 2002) or a drum seeder (Rashid et al. 2009; Khan et al. 2009).

3.6.1.3 Water Seeding

In this method, seeds are water soaked and incubated for 24 h, and then these pre-germinated seeds are broadcasted in standing water on puddled soils, and this process is known as wet-water seeding. When these pre-germinated seeds are broadcasted in standing water on unpuddled soil, process is known as dry-water seeding (Kumar and Ladha 2011). Seeds sink in the standing water getting a good anchorage. Those rice varieties are most suitable for water seeding which are tolerant to a low level of dissolved oxygen, lowlight, and other stress environments (Balasubramanian and Hill 2002). Besides irrigated areas, water seeding is popular in those areas also, where chances of early flood occurrence are more and drainage of excess water become difficult task in that fields.

3.6.2 Transplanted Rice

It is the most elaborate method of cultivation of rice in the country. It is clear from the name of method that seed is sown in one place and the seedlings are transplanted to another after specific growth. This method is practiced to ensure higher yields and less weed problem. It is practiced in those areas where irrigation facilities are available or where water is not a limiting factor. First, the seedlings are raised in a nursery, and then 4–6-week-old seedlings are transplanted into puddled fields with standing water. Transplanting gives the rice crop a head start over emerging weeds and ensures a uniform plant stand (Chauhan et al. 2012; Thiyagarajan and Gujja 2013). Transplanting may also allow crop intensification as the crop remains for less time in the field. Transplanting shortens the duration of the crop in the main field, thus providing opportunity to the farmers to accommodate rice crop to an uncertain and finite water supply. This provides the ability to farmers to make adjustments in the planting dates in response to water availability.

In transplanting method, internal structure of soils is broken down by puddling; thus, water loss through percolation is reduced and water holding capacity in the surface layer of soil is increased by development of a plow pan or hard layer. This is the way how utility of limited water is extended in transplanting systems (Maclean et al. 2002). Raising of nursery is the prerequisite for this system. The agronomic techniques involved are raising healthy wet nursery and transplanting in the main field with optimum population. Generally, nursery is raised on an area of 8–10 % of the total area for transplanting. Seedlings can be raised in wet or dry nursery beds, depending upon water availability. A new approach for nursery raising, called *dapog* method, and in this method a thick stand of seedlings is raised in plastic sheets without any contact with soil. This technique was developed in the Philippines (Thiyagarajan and Gujja 2013). Transplanting method is further divided into two categories, i.e., manual transplanting and mechanical transplanting.

3.6.2.1 Manual Transplanting

Manual transplanting is the most widely used method in India for transplanting of rice. Costly machines are not required in this method, so it is most suited for labor-surplus areas and for small rice fields. For manual transplanting, any method of nursery raising, viz., wet, dry, or mat type, can be used. Manual transplanting of seedlings is very much practiced in irrigation command rice areas of the country. No doubt, it gives uniform crop stand; it is quite expensive and requires a lot of labor besides involving a lot of drudgery (Manjunatha et al. 2009). Depending on soil type, 1 ha of rice requires 25–30 person days to establish. Manual transplanting is done either at random or in straight rows (Rice Knowledge Bank 2015a).

Random Method

Seedlings are transplanted without any definite row arrangement in this method. By manual transplanting method, equal distances between hills are difficult to determine. But it must be ensured that the estimated distances should not be too close or too wide as compared to the recommended spacing.

Straight-Row Method

In this method, a uniform spacing between plants is maintained. The seedlings are transplanted in straight rows. The optimum plant spacing is 20 × 10 cm or 20 × 15 cm under normal conditions, but it can be slightly narrower, i.e., 15 × 10 cm under subnormal conditions (Meera et al. 2014b). In the straight row transplanting method, application of herbicides, fertilizers, or insecticides and management practices such as hand or rotary weeding are very easy to be practiced.

3.6.2.2 Mechanical Transplanting

Mechanical transplanting of rice is the method of transplanting young rice seedlings, which have been grown in a mat nursery, by using a self-propelled rice transplanter. It is the most promising option for rice transplanting as it ensures timely transplanting, saves labor, and attains optimum plant density that ultimately contributes to high yield (Manjunatha et al. 2009; Manes et al. 2013). In conventional manual transplanting practice, for transplanting one acre, 8–12 laborers are required. However, only three people can transplant up to four acres in a day by using a self-propelled rice transplanter (Rickman et al. 2015). Kamboj et al. (2013) revealed that rice can be easily grown by mechanical transplanting method under non-puddled and no-till conditions with yield advantages over the conventional puddled transplanting system. For mechanical transplanting method, mat-type method is used for nursery raising. In mat-type nursery, rice seedlings are raised on a thin layer of soil and farm yard manure (FYM) or compost mixture placed on a polythene sheet (Rickman et al. 2015).

3.7 Major Production Constraints

Though India has its own position in the world for rice area and production, yet it is still counted in the countries with the lowest rice yields. Rice yield has been reported lower than the national average yield in about 70 % of the 414 rice-growing districts of the country (Srivastava and Mahapatra 2012). It clearly shows that even after the implication of high-yield technology, a sizable area of the country is categorized as low producing. Bihar, Jharkhand, Odisha, Assam, West Bengal, and Uttar Pradesh occupy 60 % area of low rice-producing states. Even in the irrigated rice areas, also, 32 % area produces less than the average yield. As compared to China and Egypt, where yields are 6.1 and 8.3 t ha^{-1}, respectively, India's yields in irrigated fields are too low, i.e., 4.2 tons paddy ha^{-1} (Tiwari 2002). It has been revealed in the yield gap analysis that we achieve 30–40 % less yield than that of the potential yield which is achievable by using the available high-yielding cultivars on high productivity irrigated land. The major reasons for this gap are the degraded and less fertile soils, pockets of endemic pests and diseases, defects in cropping systems, low input use, and less adoption of high-yielding technology (Srivastava and Mahapatra 2012).

Although it is a well-recognized fact that the key to India's sustained food security lies in the rice-producing region, still we have inadequate understanding of the production constraints which tend to reduce yield and factor productivity in rice farming. In the past, several studies have been conducted to examine the production constraints at the farm level (Mahapatra 1995; Siddiq 1996). The Indian Council of Agricultural Research (ICAR) in 1987 had undertaken the "Special Research to Development Programme." Similarly, the Ministry of Agriculture conducted "Special Rice Production Programme" and "Front Line Demonstration" since 1990. But India is still lagging behind to make strategies to remove them.

The problems and constraints faced by the farmers in rice production vary, not only from state to state but also from area to area. The eastern region is the major rice-growing region of the country, and almost every year, this region has to face the problem of high rainfall and severe flood. However, in the upland ecology, either high rainfall or drought situations cause the yield reduction. Besides this, desired yield response to the balanced application of fertilizers cannot be achieved due to some soil-related problems in some specific regions. Nonavailability of quality seeds of suitable high-yielding varieties is also a big constraint in rice production in some areas. A list of major constraints in different states or agroecologies is given by CRRI (2011) (Table 3.7).

Table 3.7 Major constraints of different states or agroecologies of India

Constraints	States/agroecologies
Saline and alkali soils	Punjab, Haryana, Western Uttar Pradesh, Gujarat, West Bengal, Andhra Pradesh, Odisha, Tamil Nadu, Karnataka, Kerala, Maharashtra, etc.
Poor adoption of production technology	Mostly in uplands and lowlands
Delayed and prolong transplanting as a result of delay in monsoon	Mostly rainfed lowlands
Low and imbalanced use of fertilizers	Northeastern and eastern states
Use of traditional varieties	Mostly eastern states
Flash floods, waterlogging due to poor drainage	West Bengal, Assam, north Bihar, and eastern Uttar Pradesh
Erratic rainfall with poor soils	Odisha, Madhya Pradesh, and some parts of Uttar Pradesh
Small and marginal farmers with poor resources to use optimum/recommended inputs	Mostly eastern states of India

Source: CRRI (2011)

The main problems and constraints for rice production in India have been grouped into three categories (Thanh and Singh 2006). These are:

1. Agroecological constraints
2. Technical constraints
3. Socioeconomic constraints

3.7.1 Agroecological Constraints

Analysis on the agroecological constraints revealed that Indian farmers face five main problems or constraints in rice production (Thanh and Singh 2006). Dependence of farmers on the monsoon is the foremost production constrains in India. Sowing of rice crop in West Bengal regions is dependent mostly on monsoon, and almost all farmers grow only one crop per year due to this problem. Land or soil problem is also considered as the major rice production constraint. Uneven topography, waterlogging, degraded land/soil, soil salinity, and lack of fertility are the main factors which cause the land constraints. Environment pollution, lack of water for irrigation, and small land holding are the other important agroecological rice production constraints.

3.7.2 Technical Constraints

The results of technological constraints analysis revealed that Indian farmers perceived 11 technical constraints (Thanh and Singh 2006). Major rice diseases, viz., blast, sheath blight, stem rot, and pests, viz., stem borer, are considered as major constraints in rice production. Lack of proper cultivars, postharvest technologies, and storage facilities cause the reduction in rice production and productivity in many regions of India. For example, in many regions of West Bengal, even now the farmers use traditional low-yielding cultivars and traditional manual methods of postharvest technology. Low price of rice produce, less availability and high price of fertilizers, plant protection and weed problems, lack of skilled labor, and poor processing facilities are the other technical constraints for Indian rice-producing farmers.

3.7.3 Socioeconomic Constraints

The most important socioeconomic constraint is the poor infrastructures like nonavailability of transporting facilities and problems of poor road for transportation (Thanh and Singh 2006). Production cost of rice is increasing day by day due to increase in the price of important inputs such as herbicides, fertilizers, insecticides, fungicides, fuels and electricity charges for irrigation, etc., which led to decrease in net profits. Besides this, inadequate inputs, lack of trainings, credit problems, poor extension services, and lack of support from local governments are also considered as socioeconomic constraints for rice productions.

Barker (1979) classified the constraints to high yields into two categories: those that affect the crop potential under a farmer's environment and those that affect a farmer's ability and willingness to achieve the potential yield on the farm. Rice productivity in different growing zones is affected adversely due to all these problems/constraints. According to Mahapatra (1994), different production constraints can be classified into six broad categories:

(a) Biophysical constraints
(b) Technological constraints
(c) Administrative constraints
(d) Institutional constraints
(e) Procedural constraints
(f) Socioeconomic constraints

Widawsky and O'Toole (1996), by including rice biotechnology programs, classified the constraints into biotic and abiotic constraints. Thus, the factors which restrict the adoption of improved technologies and attainment of potential yield may be biotic and abiotic, or technical and socioeconomic, or combinations of these. There is a need to make a multidisciplinary approach for solving these constraints as these factors are intertwined with each other.

Besides these constraints, a new challenge of climate change and its consequences are expected to be a big problem in future to achieve a high productivity of rice. There is a need to formulate the agricultural research in such a way that the constraints are converted into opportunities, not only for increasing the rice production but also for providing food security to the poor farmers of the country.

3.8 Challenges and Opportunities

3.8.1 Challenges

Total rice area in the country is 44 million hectare, out of which, 18.8 million hectare is under rainfed conditions and 67 % of that lies in the Eastern India only (Mohapatra et al. 2013). The challenges may include land fragmentation/ degradation, water scarcity, shifting of labor to other sectors, declining profit margin, increasing cultivation cost, distress sale, ensuring nutritional and food security to the people lying below poverty line, lack of infrastructure for storage, intellectual property regime, postharvest losses, and emerging environmental issues in areas of intensive agriculture. The detailed information about the major challenges for rice production has been given below (Mohapatra et al. 2013).

3.8.1.1 Land Scenario

Population is increasing at an alarming rate in India, so, per capita total land availability is reducing (Mohapatra et al. 2013). In 2001, total land availability per capita was 0.32 ha in India as compared to the world average of 2.19 ha. But it is estimated to be decreased to 0.23 ha in 2025 and 0.19 ha in 2050. Area is shifting from agricultural to nonagricultural uses over the years, so area under nonagricultural uses is increasing. Because of the fast growth of industrialization, urbanization, and the population, farmers have been encouraged to exploit marginal lands for rice cultivation. This cultivation of rice on marginal lands like acid soils, tidal lands, forest lands, etc., limits the rice yield.

3.8.1.2 Soil-Related Challenges

Deterioration of Soil Quality

At the farm as well as at the ecosystem level, the quality of Indian soils is being deteriorated gradually (Mohapatra et al. 2013). Loss of organic carbon, erosion, nutrient imbalance, compaction, salinization, waterlogging, decline in soil biodiversity, urbanization, and contamination with heavy metals and pesticides are the major challenges to the soil quality in the country. Defective farming practices like increased use of machinery, permanent waterlogging and rice monoculture, continuous soil puddling and submergence, injudicious use of inputs (fertilizer, pesticides), excessive use for irrigation, and contamination of underground water with toxic industrial wastes in rice cultivation cause the deterioration of the soil quality.

Excessive Mining of Soil

With the introduction of improved rice varieties, soil mining has become a big challenge in rice-producing regions (Mohapatra et al. 2013). Improved rice varieties have the ability to exhaust soil fertility more rapidly as compared to traditional varieties. On an average, for the production of one ton of rough rice (paddy), 20 kg N, 11 kg P_2O_5, 30 kg K_2O, 3 kg S, 7 kg Ca, 3 kg Mg, 150 g Fe, 675 g Mn, 40 g Zn, 18 g Cu, 15 g B, 2 g Mo, and 52 kg Si are removed by rice crop from soil. However, only macronutrients in the form of fertilizers are applied to soil, while some essential micro- and secondary nutrients are neglected. Thus, in the long run, deficiency of the microelements has been emerging causing an imbalance in soil nutrient status and adversely affecting the grain yield.

3.8.1.3 Water-Related Challenges

About 55 % of the areas cultivated to rice are under irrigation in India. In the coming years, due to spatial and temporal variations, increasing competition of water among different sectors coupled with the climate change (high evaporation, continuous droughts), water-related challenges are going to be broadened. The success of rice crop primarily depends on the availability of water. The major water-related challenges in the country are the following.

Decreasing Availability of Water

It has been estimated that about 22 % of the geographic area and 17 % of the population will be under absolute water scarcity by 2050 (Mohapatra et al. 2013). The per capita water availability is projected to be 1235 cubic meters in 2050 as compared to 1704 cubic meters in 2010. As the demand for drinking and industrial water as well as for the energy sector is increasing, the availability of water for agriculture, especially for rice cultivation, will decrease substantially.

Water Use Efficiency

Water is considered as the most important input for rice cultivation. It is a well-known fact that for producing 1 kg of rice, 2500–3500 l of water are used in many areas (Mohapatra et al. 2013). However, more amount of water is being used in the states like Punjab and Haryana, to produce the same quantity of rice. So, there is a need to make strategies to increase the water use efficiency. This has prompted the respective state governments to issue advisory to avoid transplanting rice during the period of high evaporative demand (May–June). The genetic improvement in rice plant to improve water use efficiency has become a challenge, and it needs strategic interventions. The recent study of Sharda et al. (2016) on use of solar-operated drip irrigation in direct-seeded rice has shown that drip irrigation in rice can bring threefold transformation in cultivating rice in South Asia with high water-, energy-, and nutrient-use efficiency while ensuring the food and livelihood security. This was the first study on drip irrigation in rice in South Asia and in future policy might be tilted toward promotion of use of such type of system in rice for water saving.

Deterioration of Water Quality

In the last two decades, water quality has become a serious concern (Mohapatra et al. 2013). Saline water intrusion and injudicious use of fertilizers and pesticides are the major factors which caused deterioration of groundwater quality with high arsenic, iron, and fluoride content. It is estimated that in the coming years, water quality would further decline with the increased rate of urbanization, industrialization, and overexploitation of natural resources.

3.8.1.4 Widening Yield Gap and Stagnation of Yield

The yield gap is the gap between the research station yield and actual farm yield. The yield gap derived as the percent difference between achievable (experimental) and average farmer's yield in India reveals that the bridgeable gap is quite wide, even though some reduction has been reported recently. It is in the range of 35–75 % in the country with the exceptions of Tamil Nadu (15 %) and Punjab (22 %) (Srivastava and Mahapatra 2012). In the eastern states, yield gap is higher than other regions.

Moreover, yield stagnation has been reached in the irrigated region of northwest India where favorable climatic conditions such as high solar radiation, long day length, and low night temperature exist. Though yield gap has been reduced by the interventions of modern varieties coupled with improved agronomic practices in recent years, bridging the yield gap would not be easy because of the diversity prevailing in the country in agroecological and socioeconomic conditions (Mohapatra et al. 2013).

3.8.1.5 Biotic Stresses

Due to the introduction of modern semidwarf varieties and increased use of nitrogen fertilizers and insecticides, biotic challenges have been increased in the country. In relation to the economic losses to the crops, the status of pests like stem borers, brown plant hoppers, and leaf folders and diseases such as bacterial blight, blast, and sheath rot has changed from low to high (Mohapatra et al. 2013). It is estimated that due to climate change and increased use of chemicals, the pest scenario will be very different by 2050 from today's scenario (Mohapatra et al. 2013). The occurrence of insects-pests and diseases, which were considered minor in the past, is increasing these days. Therefore, there is a challenge for the scientists to minimize losses due to these stresses by developing tolerant varieties and sustainable management practices.

3.8.1.6 Climate Change/Variability

Potential negative impacts of the climate change such as increased CO_2 and temperature, deficit or excess rainfall, and rise in sea level are expected on rice varieties and farming practices (Mohapatra et al. 2013). It has been confirmed from the researches that there is a positive effect of elevated CO_2 level on rice production (Mohapatra et al. 2013). However, the associated events, such as altered patterns of rainfall, rise in temperatures, and possibly increased events of drought and floods, may increase production risks and affect the rice yield adversely. The rise in temperature may not be a real challenge for rice in India. Rather, the extreme events of climate change such as floods, drought, and cyclones and other related problems such as salinity pose the real challenge to rice in India.

3.8.1.7 Rice Quality

In the wake of climate change, physical, chemical, and nutritional quality characteristics are more likely to be negatively influenced by the environmental factors (salinity, drought, and temperature extremes) (Mohapatra et al. 2013). So improving and maintaining the quality characteristics of rice is an important challenge in the future. However, it is estimated that the consumer will be more informative and health conscious with a higher purchasing capacity by 2050. Therefore, in the future, preference for nutrient-rich and good cooking quality rice will be increased.

3.8.1.8 Lack of Mechanization

The current level of the average farm power availability is 1.7 kW ha^{-1}, which needs to be increased to at least 3.0 kW ha^{-1} for timely and quality operation in heavy fields (Mohapatra et al. 2013). The main problem for mechanization in India is the fragmentation of land holding which is not suitable for adoption of machineries and difficulty in consolidation of land holdings. Due to disaggregation of the joint family system, an increase in land fragmentation is expected. Thus, inadequacy of farm power and machinery is a big challenge for rice production in India.

3.8.1.9 Environmental Problems

Production of methane gas is the foremost serious problem in flooded rice production systems (Mohapatra et al. 2013). Besides this, problems of groundwater depletion, waterlogging, salinity and alkalinity, greenhouse gas emission, and water pollution are also caused by the irrigated rice in India as well as other parts of the world. The excessive use of agrochemicals in rice production may cause these problems and, thus, health hazards through drained water.

3.8.2 Opportunities

India has the first and second position in area and production of rice in the world, respectively. Though modern varieties and advanced agronomic practices have been developed in the country, there are still huge gaps between actual yield obtained by farmers and the potential yield (CRRI 2011). It is estimated that postharvest losses are about 20–30 %. Nitrogen fertilizer or water utilization efficiencies remain varied between 30 and 50 % that can be increased by developing good management practices. Therefore, the priorities are given to narrowing yield and efficiency gaps, valuing addition to cropping or farming systems, and reducing postharvest losses to increase rice production and farmers' net profit while keeping the environment safe.

Knowledge in rice functional genomics for precise trait modification is still very limited in India. It makes the task difficult for manipulation of the traits precisely for gaining maximum economic benefits as the important traits are mostly of genetically complex nature (Mohapatra et al. 2013). Recent scientific advances in marker-assisted breeding and genomics have made the way for exploiting gene bank materials at large scale for identifying and embedding the genes responsible for more complicated target traits. There are many stresses such as biotic and abiotic and their combination and nutritional factors, which limit the crop yields. These multiple environmental stresses cannot be removed by a single approach. So the development of a resilient set of new germplasm which can better adapt to the stress environments is needed. It is feasible to identify and pyramid stress tolerance multiple genes in high-yielding genotype background and would be practicable for tailoring novel rice varieties in future.

It is expected that in the coming decades, hybrid rice can give a quantum jump to overall rice production in India (Mohapatra et al. 2013). Some progress in hybrid rice in irrigated areas of subhumid to semiarid regions has already been made. However, there is a need to enhance the yield through increasing magnitude of heterosis and introgression of known disease and pest tolerance genes in the parents. Hybrids for rainfed lowland ecosystems of high rainfall regions also need to be developed. Under such situations, there is a need to increase the yield potential of hybrids by improving the magnitude of heterosis by developing suitable parental lines. Besides this, grain protein and micronutrient contents in rice can be improved by using conventional and modern biotechnological approaches by utilizing existing genetic variability. It is necessary because in spite of having a remarkable progress for rice production in the country, malnutrition due to micronutrient, protein, and calorie deficiency is still a problem among the poor population in rural areas (Mohapatra et al. 2013).

Identification of superior alleles and bioprospecting novel genes for abiotic and biotic stress tolerance, resource use efficiency, nutritional quality, male sterility/fertility restoration, and yield traits are the main focus of rice research during the current scenario. There is a huge potential for increasing the rice productivity by developing C_4 rice. It is expected that genes present in C_3 species can be recruited into cell-specific functions in the C_4 pathway without alterations to their gene sequence. Transgenic technologies are likely to be used to engineer N_2-fixing rice and new rice plants that have a new photosynthetic pathway.

Conservation agriculture has potential to increase and sustain the crop productivity (Mohapatra et al. 2013). Conservation agriculture will become a common and an easy practice in the coming days because of development of third- and fourth-generation machinery. This type of machinery performs multiple functions including residue incorporation/retention, sowing, and fertilizer application with the help of different sensors and GIS platform.

3.9 Fertilizer and Pest Management

3.9.1 Fertilizer Management

Like any other crop, rice also requires all the 16 essential elements for its growth and completion of life cycle. Farmers usually use chemical fertilizers for macronutrients only to compensate the nutritional losses, while loss of some essential secondary and micronutrients is neglected. Results of the long-term rice-based cropping system experiments conducted on different agroecological regions revealed that the continuous and indiscriminate use of inorganic nitrogen fertilizer leads to long- and short-term deterioration, influencing the sustainability of rice due to deficiencies of macro- and micronutrients like S, Mg, Mn, and Zn (Thiyagarajan and Gujja 2013).

Integrated nutrient management (INM) is an approach that aims to increase agricultural production and safeguard the environment for future generations. INM approach involves the use of both organic and inorganic plant nutrients for achieving high crop productivity, preventing soil degradation, and also helps in meeting future food supply needs. The main aim of INM is to improve soil health and sustain a high level of productivity and production (Prasad et al. 1995).

Panda et al. (2007) found that higher crop productivity and a more favorable balance of nutrients in the soil can be maintained by applying combined NPK fertilizers at optimum levels in balanced proportions on the basis of soil test along with FYM at 5–10 t ha^{-1} $year^{-1}$ to *kharif* rice in multiple cropping systems as compared to N, NP, or even NPK fertilizers. Besides the FYM, other sources of nutrition like incorporation of residues of cereal crops; green manuring with *Sesbania* or dual-purpose grain legumes like green gram, black gram, or cowpea; and biofertilizers such as blue-green algae, *Azolla*, *Azospirillum*, *Azotobacter*, etc., have shown promise in improving soil health and crop productivity. So all these sources can substitute a part of the recommended dose of chemical N fertilizer, without affecting the crop yield. Panda et al. (2004) suggested some INM practices for different rice ecosystems which can increase rice yield significantly and improve soil fertility. In uplands, 75 % of optimum NPK + 5 ton FYM + green gram/black gram intercrop as green manure between the paired rows of rice has been suggested. In medium lands/irrigated rice, 50–75 % NPK + 5 ton FYM ha^{-1} + in situ *Sesbania*/sunhemp green manuring and, in shallow lowland rice, *Sesbania* green manuring supplemented with N topdressing have been suggested for improving rice productivity and soil conditions.

Site-specific nutrient management (SSNM) for sustaining rice production is a novel approach which involves science-based principles for guiding the judicious and efficient application of fertilizers as and when needed by crops. Inherent spatial variability associated with fields during crop production are recognized by this approach and thus provides the guidelines for optimal use of indigenous nutrients originating from soil, plant residues, manures, and irrigation water (Satyanarayana et al. 2011). Instead of reducing or increasing the fertilizer use, the main aim of SSNM is to apply nutrients at the optimal rate and time in order to achieve high rice yield and high nutrient use efficiency (Buresh et al. 2005). For the implementation of SSNM in rice crop, early applications at 14 DAT or 21 DAS of N, P, and K are done, adjusted to plant need. Subsequent topdressing of N is done on the basis of plant's need as determined with the leaf color chart (LCC) and application of K adjusted to plant need at early panicle initiation. The SSNM approach, in which determination of nitrogen fertilizer needs through use of the LCC and determination of fertilizer P and K needs through use of nutrient omission plot technique, can consistently increase grain yield and profit in farmer's fields (Swarup et al. 2008).

The common fertilizer dose cannot be recommended for different regions, because in different agroclimatic zones, soil fertility status varies to a considerable extent. Therefore, keeping in view the variation in soil fertility and local conditions, agricultural departments of various states and state agricultural universities have formulated fertilizer recommendations for rice crop in respective states.

3.9.2 Pest Management

Until now, more than 100 species of insects as the pest of rice have been reported in India. Of these pest species, a dozen are of economic significance. A yield loss of about 1 t ha^{-1} can be averted if these insect pests are not controlled effectively (Pasalu et al. 2008). Pasalu et al. (2004) found that leaf folder, leafhoppers, and plant hoppers which were of minor importance have now gained the status of major rice pests. Other pests, viz., whorl maggot, rice hispa, green leafhopper, gundhi bug, and thrips, are considered as the minor pests of rice crop (Pasalu et al. 2008). Gall midge has become a serious pest in many areas and has also extended its activity to dry season, particularly in the coastal areas. In Punjab and Haryana, stem borer was not known earlier, but now it is considered as a deadly pest in these states. Sporadic pests like ear-cutting caterpillar, rice hispa, and gundhi bug have been causing serious damage to rice (Pasalu et al. 2004).

Dhaliwal and Arora (1993) reported that pests cause 25 % loss in rice crop. However, Pasalu et al. (2004) estimated the yield losses ranging from 21 to 51 % due to moderate to serious incidence of plant hoppers, stem borer, gall midge, and other sporadic pests in the rice-growing regions of the country. Assessment of losses in rice crop was analyzed at 135 multilocation trails under the All India Coordinated Rice Improvement Project which revealed that the losses due to insect pests are 28.8 % (Pasalu et al. 2008).

Different approaches have been developed for controlling the insect pests. These are host plant resistance, cultural control, chemical control, use of botanical pesticides, biological control, use of biopesticides, insect sex pheromones, etc. As rice is grown in different agroecosystems, the conditions of climate, soil, and seasons vary under each zone. Hence, the pattern of insect infestation differs from region to region and from season to season.

To tackle these problems, the best strategy is to adopt an integrated pest management (IPM) approach. The development of suitable IPM strategies is necessary to overcome the insect pest constraints for realizing yield potential of rice. A framework for integrated knowledge, skill, and information on rice pest management is provided by rice IPM. Regular pest monitoring, research on the optimal use of pesticide, complimentary weed control strategies, and alternative cultural and biological controls are included in an IPM approach (Prakash et al. 2014).

3.10 Harvesting and Yield

Harvesting is the process of collecting the mature rice crop from the field. Paddy harvesting activities include cutting, stacking, handling, threshing, cleaning, and hauling.

3.10.1 Harvesting Time

The most suitable time of harvesting is when panicles turn into golden yellow and the grains contain about 20 % moisture (DRD 2014). A heavy loss of crop occurs due to shattering of grains and damage by birds and rodents if moisture content in the paddy grains reaches 16–17 % in the standing crop in the fields. When 80 % of the panicles become straw colored and 20 % grains in lower portions are in the hard dough stage, the crop is ready to harvest (Expert System for Paddy 2015). Optimum time of harvesting has been specified by the extensive studies. The results of the various studies revealed that right time of harvesting can be specified on the basis of three criteria, viz., (i) the moisture content of the grains, (ii) the dry matter of the plant or seed, and (iii) the number of days after planting or flowering (Rice Knowledge Bank 2015b).

3.10.2 Methods of Harvesting

Nearly 15–20 days after 50 % flowering, the grains in the lowest portion of the panicles are in the dough stage, irrigation is stopped to the crop, and grains are allowed to harden. Depending on the amount of mechanization and the size of operation, rice can be harvested manually or mechanically. The manual harvesting is mainly practiced in developing countries, while in the developed countries, mechanical harvesting using reaper windrower, reaper binder, combine harvester, stripper harvester, etc., are practiced. However, during the past decade, mechanical harvesting has become popular in India. The different harvesting systems are discussed below (Rice Knowledge Bank 2015b):

3.10.2.1 Manual Harvesting and Threshing

Manual harvesting is a traditional method in which long stalks are cut by sickle about 10–15 cm above the ground. Depending on the sociocultural acceptance of the harvesting labor, there are many variations in the sickle design. For 2 or 3 days, the stalks are laid in small bundles on the stubble to dry their panicles. In manual harvesting, traditional threshing tools such as simple treadle threshers or threshing racks are utilized. Manual harvesting also make use of animals for trampling or by hand using sharp sickles or knives. Grain recovery in manual harvesting method is about 55–60 % (Expert System for Paddy 2015).

3.10.2.2 Manual Harvesting and Mechanical Threshing

Rice is harvested manually, and then cleaning is done with a machine thresher. In mechanical threshing, usually the portable thresher is used. Because of high labor requirements of manual threshing, it has been replaced by small stationary machine threshers. Stationary threshing is generally done in the field or near to the field.

3.10.2.3 Machine Reaping and Machine Threshing

The crop is cut and then laid in a line by a reaper. Threshing is done by a thresher, and cleaning can be performed either manually or by machine.

3.10.2.4 Combine Harvesting

All operations are combined in combine harvesters like crop cutting and its feeding into threshing mechanism, threshing, cleaning, and discharge of grain into a trolley or directly into the bags. Straw is usually discharged behind the combine in a windrow. It gives about 50 % recovery (Expert System for Paddy 2015).

There are a number of factors which affect the selection of appropriate harvesting system (Rice Knowledge Bank 2015b). These are the availability of labor, capital outlay of the farm, availability of time, field layout and accessibility of machines, lodging characters rice varieties, the demand for quality rice, and the demand for straw.

3.11 Threshing and Processing

3.11.1 Threshing

Paddy threshing is the process in which paddy kernels or grains are detached from the panicles through rubbing action, impact, and stripping. Threshing should be done immediately after harvesting to maintain the high quality of the harvested grains. Grain quality is affected adversely by field drying and stacking for several days due to overdrying. The rubbing action occurs when paddy is threshed by trampling by humans, animals, or tractors. If threshing is done by carelessness, the potential yield of rice crop is reduced to a great extent. This occurred when good grains are allowed to remain on the panicles or due to grain scattering during improper threshing. Threshing can be done either manually or by using machines (Expert System for Paddy 2015).

3.11.1.1 Manual Threshing

Manual threshing is a common method. In this method, separating of grain from the panicle is done by treading, hand beating, or holding the crop against a rotating drum with rasp bars or spikes. Hand beating methods are used for threshing of rice when grains from panicles tend to be easily shattered. Hand threshing methods include the trampling or foot threshing, beating against a threshing rack, the use of a stick or flail for threshing the crop, and using a pedal or treadle thresher.

Another traditional method which is included in manual threshing is the animal threshing, i.e., threshing with the use of animals. This method is usually carried out at a specific location near the field or in the village. Tractors, if available, can also be used instead of animals for treading. Winnowing is done to clean the grain after animal treading. Besides this, threshing by a pedal thresher or treadle thresher, which consists of threshing drum, base, transmission unit, and a foot crank, is also carried out. The threshing drum rotates by pedaling, and panicles are applied against the threshing drum. In this method, chaff, small straws, and foreign matters are dropped along with the threshed grain, so winnowing is necessary after threshing.

3.11.1.2 Machine Threshing

Mechanical threshing has several benefits as compared to other methods as it removes rice grains from the plant, reduces labor requirements, and speeds up threshing, thus reducing losses. Small stationary machine called threshers is being used for paddy threshing. Peg-toothed threshing drums are fitted in many stationary paddy threshers; however, threshers fitted with rasp bars or wire loop are used as well. Feed-in-type threshers are mostly used threshers in which the entire crop is fed into the thresher. Besides this, hold-on threshers, in which only panicle is fed through the machine, are also used. Generally, these have a lower capacity as compared to feed-in threshers. These threshers are primarily used in the situation where rice straw is to be bundled and stored for later use. Large stationary threshers, in which additional cleaning devices, such as centrifugal blower, an oscillating screen, and wind board are fitted, are also in use in some regions. Threshed grain need not to be cleaned for further handling in these threshers.

3.11.2 Processing of Rice

3.11.2.1 Drying

Drying is the process in which excess moisture from the grains is removed. After drying, the rice grain is ready for processing. Storage life of the grains is increased with proper drying. Besides this, proper drying also ensures the reduction of biological respiration, and thus prevention of deterioration in quality as biological respiration causes the loss of grains quality and milling recovery. There are mainly three methods of drying, viz., mechanical drying, chemical drying, and sun drying. Mechanical drying is the process in which natural or heated air is passed through the grain mass to evaporate the moisture from it. The use of mechanical dryers is more reliable as drying can be done anytime of the year. In chemical drying method, common salt solution having specific gravity of 1.1 to 1.2 is sprayed on the ears of the mature paddy crop. Sun drying is the traditional and the most economical method of drying the paddy grains. Grains are spread on drying surfaces such as plastic sheets, mats, concrete pavement, or even on fields to dry naturally (Expert System for Paddy 2015).

3.11.3 Parboiling

Parboiling is a pre-milling process in which a hydrothermal treatment is given to rough rice to improve its milling and cooking quality, storability, and nutritive value (Expert System for Paddy 2015). There are three steps involved in this process:

soaking, steaming, and drying. Since time immemorial, parboiling of paddy has been practiced in Indian households. In the Eastern and part of Southern India, Eastern Madhya Pradesh, and Uttar Pradesh, the parboiling process is followed extensively. In the process of parboiling, the rice grains are hardened sufficiently which lead to a high milling and head rice recovery. Cooking qualities of rice are also improved with parboiling process. Gelatinization of the starch granules and hardening of the endosperm occurs by parboiling which makes rice grains translucent. Chalky grains and those with chalky back, belly, or core become completely translucent on parboiling.

Traditionally, either single or double boiling method was used for parboiling. In the single boiling method, unhulled rice is soaked in water at room temperature. Then open steaming is done for 20–30 min using iron kettles followed by sun drying. In the double streaming method, first steaming is done to raise the temperature of unhusked rice and then soaked in cold water for 24–36 h. Thereafter, second steaming for 20–30 min is done followed by sun drying.

3.11.4 Milling

Milling is an important step in postproduction of rice. Milling is done to remove the husk and the bran layers and produce an edible, white rice kernel that is sufficiently milled and free of impurities. It is the process in which rice grain is transformed into a form suitable for human consumption. So utmost care should be taken during milling process so that the head rice recovery percentage can be improved. In this process, the rice which is obtained after milling is called raw rice. Nature of rice milling losses can be qualitative or quantitative. Qualitative losses are manifested low head rice recovery or high percentage of broken kernel, while low milling recovery reflects the quantitative or physical loss in rice grains. There are basically two methods of milling (DRD 2014).

3.11.4.1 Traditional Method

This is the traditional method in which rice is milled by hand-pounding method. This method was in practice before the advent of mechanical milling. Implements used in this method are hand stone (*Chakki*), mortar and pestle, and dhenki. The rice milled by this method contains more nutritive value than the machine milling rice.

3.11.4.2 Mechanical Method

This is the method in which milling is performed by machines. The traditional hand-pounding method has steadily decreased with the introduction of mechanized mills. The main mills, which are in use, are huller mills, sheller-huller mills, and sheller-cone polisher mills.

3.12 Conclusions

Rice is the staple food for more than 50 % of the world population and 85 % of Indian population. The demand for rice is expected to grow continuously as population increases. No doubt, rice production had increased in the past three decades continuously beginning with the green revolution. But it has stagnated since 1999. It is estimated that by 2020 at least 115–120 million tons of milled rice is to be produced in India to maintain the present level of self-sufficiency. The challenges before India are the decreasing area and water availability for rice, scarcity of labor for growing rice, increasing cost of cultivation and decreasing profitability, distress sale, problem of ensuring food and nutritional security to the people below the poverty line, storage losses, and emerging problems of climate change. This calls for the implementation of such strategies which could change the challenges and constraints to opportunities in the near future. There is a need to enhance the application of modern scientific tools and technologies to further boost the rice production. To solve the emerging problems, modernization, intensification, and strengthening of basic, applied, and strategic rice research in areas of rice breeding, agronomy, protection, and environmental research in the wake of climate change along with relevant social science disciplines are essential. There is a strong need to monitor rice-based production systems in terms of crop varieties, nutrient dynamics, water table, quality of irrigation water, method of irrigation and insect pests, diseases, and weed problems to evolve site-specific and integrated management techniques. Enriching rice varieties with genetic resources by tapping the biodiversity is of immense importance. It can be proved helpful for improving yield potential, nutritional quality of grain, tolerance to major biotic and abiotic stresses, and input use efficiency. All the strategies need to be planned in such a way that enhancement in rice production could be achieved and maintained without deteriorating the quality of environment and without resource base depletion.

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Chapter 4
Rice Production in Europe

Hansjoerg Kraehmer, Cyrille Thomas, and Francesco Vidotto

4.1 Summary

Rice cultivation in Europe is restricted to a few southern European countries. In 2015, the rice-growing acreage of Italy and Spain together comprised around 75 % of a total area of around half a million hectares. The milled rice equivalents in the EU amounted to 0.4 % of the global rice production. Japonica rice varieties are dominating in Europe. Rice is planted in spring and harvested in autumn. All rice fields in Europe are irrigated. Most rice seed is drilled. In some Spanish areas, pregerminated rice is sown by air. Average yields per hectare range between 4 and 8 tons. In some regions 10 tons can easily be achieved. Monocot weeds are prevailing with wild rice, *Echinochloa*, *Cyperus* and *Heteranthera* species being the most frequent representatives. *Hydrellia griseola*, *Chilo suppressalis*, *Eysarcoris inconspicuus* and *Lissorhoptrus oryzophilus* have to be regarded as the most serious insect problems. *Magnaporthe grisea*, *Cochliobolus miyabeanus* and *Gibberella fujikuroi* are the most widespread disease-causing organisms. A wide range of chemical and biological products is registered for rice protection. For some countries, however, costs for the registration of new products are too high compared with the low acreage so that lacking product innovation becomes a major problem. The acreage of Clearfield rice is continuously growing primarily due to wild rice as an increasing problem. Water shortage is a problem in a few areas in Spain primarily. Irrigated rice provides a habitat for a great number of organisms such as migratory birds and deserves special attention as far as biodiversity is concerned. Greenhouse gas emission and heavy

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Table 4.1 Acreages of rice compared with other European crops between 1963 and 2013 (hectares)

	Rice	Wheat	Barley	Maize	Oilseed rape
1963	464,155	92,488,648	33,791,853	18,413,089	577,863
1988	1,107,301	75,008,416	48,056,455	15,553,984	3,529,714
2013	648,320	57,598,857	24,593,497	19,072,882	9,307,459

Source: FAOSTAT, Europe+ (including Russia)

metal concentration in rice fields have been a problem in some areas in the past. New cultivation methods with a reduced water consumption and new rice varieties should, however, contribute to the reduction of these problems.

4.2 Introduction

Rice has been grown in Europe for many centuries. Several detailed compilations on the history of rice cultivation have been published in recent years, for example, by Ferrero and Vidotto (2010). Rice was already known as a crop in Greece more than 2000 years ago. First reports on the farming of rice in other European countries mostly date back to medieval times. A real change towards larger-scale rice production started, however, only at the end of the nineteenth and beginning of the twentieth century. In the 1980s, the European rice acreage exceeded one million hectares. In 2015, less than half a million hectares were devoted to rice culture in the European Union. This figure is quite small compared with other arable crops as we will show in the next paragraph. It makes clear, however, that rice plays an economic factor and that the area of rice has also an impact on ecology and environment. Some opponents of modern agriculture ask why rice is grown in Europe at all and if the implications of rice cultivation such as methane production should result in political actions against rice cultivation. The main objectives of this chapter are therefore to show where and how rice is grown in Europe, which environmental impacts and problems are associated with rice cultivation and which role rice cultivation plays compared with other crops in Europe.

4.3 Why and Where Is Rice Cultivated in Europe?

The acreage of rice in Europe was always rather small when compared with other crops such as wheat, barley, maize or oilseed rape (Table 4.1).

One can notice a considerable fluctuation in rice and other crops' acreages which has to do with political and technological changes in Europe over the last 50 years. At this point, it has to be mentioned that the statistical data for Europe may vary depending on the definition of Europe. Data for the European Union (EU) and its

Table 4.2 Import and export of European rice compared with selected Asian rice-producing countries (1000 tons)

	EU		China		India		Thailand		Vietnam	
Year	Import	Export	Import	Export	Import	Export	Import	Export	Import	Export
2000	1094	303	278	656	–	4687	–	6549	300	4295
2010	1235	278	366	619	–	2228	300	9047	400	6734
2015	1500	220	4500	400	–	9000	300	11,000	400	6700

Source: USDA, Foreign Agricultural Service, Production Supply and Distribution (PS&D) and Grain: World Markets and Trade as of April 2015

member states are different from the geographically defined European continent which includes, for example, large parts of Russia. A considerable amount of rice is grown in the Black Sea area of Russia. FAOSTAT data in 1963 include 147,000 ha of rice in Russia, for example, and 671,000 ha in 1988, whereas 188,981 ha are reported in 2013. The following paragraphs concentrate on rice in the EU primarily.

When we compare the Asian rice acreages and their drastic increase (110,827,165 ha in 1963, 130,260,774 ha in 1988 and 146,945,430 in 2013 – figures based on FAOSTAT), we might regard rice production in Europe as negligible.

Europe has a constant demand for rice as depicted by data from the USDA (Table 4.2). The European Union imported annual amounts of 1.1 to 1.5 million tons of rice between 2000 and 2015 compared with 0.15 to 0.3 million exported tons (milled equivalents and broken rice). More than three quarters of the imported rice in 2013/2014 came from four countries: India, Cambodia, Thailand and Pakistan (Committee for the Common Organization of Agricultural Markets 2015). Most of the imported rice was indica rice (about two-thirds). Between 2010 and 2015, some Asian countries succeeded in raising their rice export figures considerably such as India, Thailand and Vietnam. China' s rice imports were increased, however, from 0.278 million tons in the year 2000 to 4.5 million tons in 2015, whereas Chinese exports were lowered from around 3 million tons in 2000 to 0.4 million tons in 2015. Total global exports and imports increased from 22.8 million tons in 2000 to 42.6 million in 2015.

Another way to exemplify the global situation of rice production is the comparison of production, consumption and stocks. The annual global production of rice between 2012 and 2015 ranged between 490 and 500 million tons, and the consumption was between 477 and 500 million tons during the same period of time. Annual stocks amounted to 100 to 200 million tons (EU Rice Economic Fact Sheet of the European Commission, March 2015b). Less than 10 % of the global rice production is traded (42.6 million tons of around 500 million tons), and food security plays a high role. Several countries have banned the export of rice from time to time for this reason (e.g. in 2008, DEFRA 2010). The total European production in milled equivalents ranges below two million tons which is less than 0.4 % of the global figure.

In conclusion, European rice production can never contribute to a global overproduction. In contrast, it helps to safeguard domestic demands.

Fig. 4.1 Rice-growing areas in the EU

Table 4.3 Acreages of rice (2013) in the EU and some market data

	Acreage (ha)	t	Yield (t/ha)	Price[a]	Price index[b]
Bulgaria	10,000	54,900	5.49	325	142
France	20,300	82,000	4.04	536	251
Greece	29,200	227,000	7.77	287	126
Hungary	2500	9800	3.92	No data	132
Italy	212,500	1,339,000	6.30	474	157
Portugal	31,200	168,300	5.39	380	154
Romania	11,579	54,646	4.71	No data	218
Spain	113,200	851,500	7.52	355	134

Source: FAOSTAT
[a] Product price in 2012 in US$/t
[b] 2004–2006 equal 100

Rice is grown in several countries of the EU as Fig. 4.1 and Table 4.3 demonstrate.

The major areas of rice cultivation in Italy are located in the Po valley, in France in the Rhone delta and in Central Greece near Thessaloniki. In Spain, rice fields can be found near Aragon; in the Ebro Delta, near Valencia; in the Guadalquivir Valley; and in Portugal in the Tejo and Mondego Valleys (Ferrero 2007). The Plovdiv and the Pazardzhik regions in Bulgaria (Boyadjiev 1996); the counties Ialomița, Brăila, Olt and Dolj in Romania; and the Great Hungarian Plain are typical rice cultivation areas of Eastern Europe. A few thousand hectares of rice are grown in Macedonia (Pacanoski and Glatkova 2009).

Italy and Spain are the two leading rice-producing countries in Europe with more than 75 % of the acreage.

Table 4.4 Japonica- and indica-type rice acreages within the EU between 2010 and 2015

	2010		2015	
	Japonica	Indica	Japonica	Indica
Bulgaria	11,059	70	9839	31
France	16,000	2800	13,743	1207
Greece	10,520	23,200	15,433	10,573
Hungary	2500	0	2191	0
Italy	174,159	73,494	164,234	55,298
Portugal	22,903	5027	16,243	12,425
Romania	5300	8000	9528	1733
Spain	63,718	58,747	58,235	43,003
EU	306,000	171,000	290,000	124,000

Source: DG AGRI/Member States

Table 4.5 European rice classification based on grain shape

Rice group	Grain length (L)	Length/width ratio (L/W)
Round grain	$L \leqq 5.2$ mm	$L/W < 2$
Medium grain	$5.2 < L \leqq 6.0$ mm	$L/W \leq 3$
Long grain A	$L > 6.0$ mm	$2 < L/W < 3$
Long grain B	$L > 6.0$ mm	$L/W \geq 3$

Yields vary considerably in different European countries. The highest yield values are achieved in Greece and Spain. This may have to do with the difference in yields for japonica- and indica-type rice. Greece and Spain produce relatively high amounts of indica-type rice. Average yields for japonica-type rice range between 6.2 and 6.5 t/ha, whereas indica-type rice yields between 7.1 and 7.8 t/ha. Japonica-type rice is, however, cultivated on two-thirds of the European acreage, while indica-type rice on one-third only. This may appear as contradictory to the preferred European consumption of indica-type rice. The price for japonica-type rice is, however, higher on the world market than that of indica-type rice (Table 4.4).

It must be noticed here that a strict genetic separation of indica varieties and japonica varieties is not possible. Introgression of traditional indica and japonica types has increased globally, and the distinctiveness of varietal types has decreased (Sleper and Poehlman 2006).

Also, exotic rice germplasm is constantly introduced to national breeding programs (Cai et al. 2013). On the other hand, rice is categorized not only on the basis of indica- and japonica-subspecies properties but also on length, shape and cooking characteristics.

Following the Regulation (EU) No. 1308/2013 (European Parliament 2013), rice is classified in the EU on the basis of the length/width ratio of the grain into the groups “round”, “medium”, “long A” and “long B” (Table 4.5).

Grain length cannot directly be used for the distinction between japonica- and indica-type rice. A few japonica-type rice varieties have to be classified as long-grain rice such as the Japanese varieties Nongken 58 and Dali (Wang et al. 2014) or various American varieties with a *tropical japonica* background (Sleper and Poehlman 2006).

The rice market is regulated by the EU rice regulatory regime as of February 2015 (European Commission 2015a). It is part of the European Parliament and Council Regulation (EU) No. 1308/2013. This regulation defines rules for buying-in and selling of agricultural products under public intervention. Six EU member states (Greece, Hungary, Italy, Portugal, Romania and Spain) out of the eight rice-producing member states have notified the Commission about their decision to apply voluntary couple payments to the production of rice as from 2015. Global market prices for the four Asian countries Cambodia, India, Thailand and Pakistan ranged between 355 and 430 US$ for milled indica rice in March 2015 (Committee for the Common Organisation of Agricultural Markets 2015). The prices for milled rice in the EU were considerably higher, for example, Italian indica-type rice achieved 640€ in March 2015. Variable conversion rates from € to US$ have to be kept in mind. It becomes, however, evident that the difference is quite high. Major differences exist between milled and paddy rice; also, prices differ between countries. The 3-year average price for japonica-type paddy rice between 2011 and 2014 was at 307 €/t in Italy and at 288 €/t in Spain and the indica-type paddy rice at 275 €/t in Italy and at 271 €/t in Spain.

4.4 How Is Rice Grown in Europe?

An excellent overview on rice cropping in Italy, Spain and France was edited by Ferrero and Vidotto (2006). As in most regions with Mediterranean climate, European rice is planted in spring. Other than in most European countries, it is sown in Italy sometimes in the end of March or beginning of April and harvested between September and October. The planting period can, however, be extended over a wide time range – even to the end of May. Figure 4.2 shows how rice is usually managed in Italy. Before planting, the seedbed is usually prepared by ploughing the field. Fields are laser-levelled annually or every second year (Fig. 4.3). On around 70 % of the fields, rice was broadcast-seeded into flooded fields in 2012 with a centrifugal spreader that can also be used for the application of fertilizers (shown in Fig. 4.6). The seed is usually soaked in water for 24 h to make it sink and germinate in the flooded field. On 30 % of the acreage, rice was drilled into dry soil referred to as the year 2012 (Fig. 4.4). This technology is especially used in fields when Clearfield rice varieties are adopted. These varieties were selected from rice tissue cultures in which tolerance to imidazolinones was observed. The Clearfield technology allows the control of weedy rice, a widespread problem in European rice. The application of agrochemicals is often easier in dry-seeded rice than in flooded fields. Most tractors are equipped with special metal wheels to enter wet rice fields (Fig. 4.5). Tractors with such wheels are usually quite powerful but heavy. They cannot drive on streets and have to be transported by a second tractor (Fig. 4.6). A few farmers

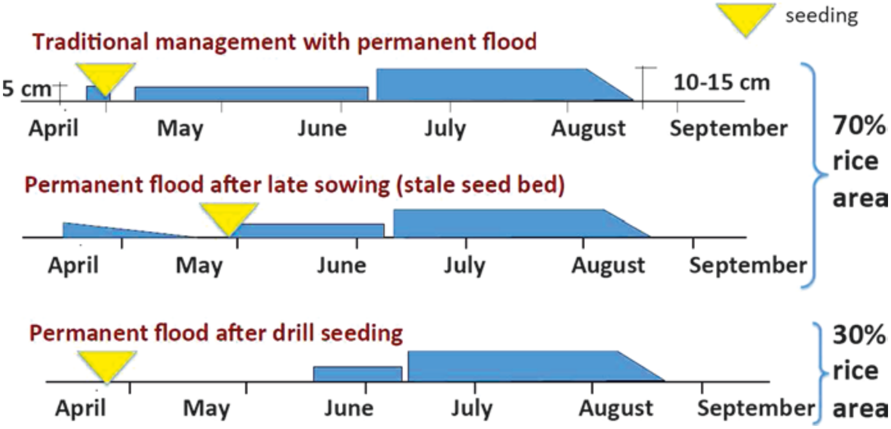

Fig. 4.2 Rice management in Italy (From Vidotto 2013)

Fig. 4.3 Laser levelling done before sowing of rice

therefore use normal tyres as shown in Fig. 4.7. The figure shows, however, that such a tractor leaves relatively wide tracks in a field.

More than one-third of the acreage was planted with Clearfield (CL) rice in 2014 (data based on ENR (Ente Nazionale Risi)). Out of more than 140 planted varieties in 2014, around 10 were grown on 8000 hectares or more each: CL26 (~18,500 ha), Sole CL (~15,400 ha), Centauro (~14,400 ha), Volano (~14,100 ha), Luna CL (12,000 ha), Sirio CL (~11,300 ha), Selenio (~10,700 ha), Gladio (9800 ha), Delfino (~8800 ha) and Baldo (~8000 ha).

Fig. 4.4 Dry-seeded rice in San Martino Siccomario, Italy (May 28, 2015)

Fig. 4.5 Herbicide application with especially equipped tractor wheels near Stroppiana, Italy

Fig. 4.6 Transport of especially equipped tractor, Ente Nazionale Risi, Castello d'Agogna, Italy

Fig. 4.7 Fertilizer application in Mas de la Furane, France

Seeding rates range between 100 and 200 kg seed per ha depending on variety and crop management. In some areas as in the Grange area, rice has been grown as a monoculture for more than 100 years. Outside this area, maize or soybeans are sometimes planted as rotational crops. The dams are, however, kept for later rice crops.

In Spain, rice is sown in May, sometimes even in June. In most cases, pregerminated seeds are sown by airplanes on paddies filled with water. In rare cases, rice is transplanted. The crop is usually harvested in October. New varieties in Spain are regularly characterized by regional institutions such as the IRTA in Catalonia or by the Instituto Valenciano de Investigaciones Agrarias. Popular varieties are Tebre, Sollana, Bomba, Bahia, Balilla x Solana, Montsianell, Gleva, Guadiamar, J. Sendra, Bahia, Senia, Sirio, Piñana or Fonsa. New varieties registered in 2013 are Linda, Basholi, Mata, Montell, Carlet and Riet.

In Andalucía, around 80 % of the rice fields were planted with Puntal in 2015; the second most frequent variety was J. Sendra. In Extremadura, 70 % of the area was grown with Gladio and Thaibonnet and 30 % with Thaiperla and Hispagran. Gleva is the most cultivated variety in Cataluña (Delta del Ebro); the second most frequent varieties are J. Sendra and Montsianell. Valencia grows mainly japonica-type rice: Gleva, J. Sendra, Montsianell, Bahia and Senia. Clearfield varieties (e.g. Sirio) are gaining ground in all areas.

Typical Portuguese varieties are Agulha and Carolino. Agulha is a long-grain indica-type rice variety. Carolino is a native short grain japonica-type variety that is similar to the Italian Arborio. Another quite common variety in Portugal is the Italian japonica-type variety Ariete.

Like in Spain, planting dates in the French Camargue are different from those in Italy. Due to the risk of low temperatures, rice is usually sown between April 20 and mid-May (Delmotte et al. 2011) or even later. A small proportion of rice is drilled; in most farms, however, broadcast seeding with a fertilizer equipment (Fig. 4.7) is the standard.

In France, 34 rice varieties were available in the year 2014 (http://oryza.com/news/rice-news-europe-middle-east/oryza-highlights-34-rice-varieties-grown-france). Half of these were developed directly in France

- Long B: Adret, Albaron, Gine, Paty, Rousty Seyne, Vigueirat
- Long A: Arelate, Caban, Cambon, Riege, Sirbal, Tiber
- Round: Cigalon, Gageron
- Medium: Manobi
- Aromatic: Aychade

The remaining varieties have been developed in Italy.

Irrigation of rice fields in the Camargue prevents the accumulation of salt on the soil surface and allows its cultivation in rotation with rainfed crops; in some areas, continuous rice cultivation is practised (Delmotte et al. 2011).

Fertilizer in most European countries is either applied pre-seeding or after planting. In Italy, the following amounts are typical: 80–120 kg N, 100–150 kg K_2O, 50–70 kg P_2O_5 pre-seeding or 80–120 kg N after planting. In France, 50 kg N before, 50 kg N at tillering and 50 kg at panicle initiation are common practice.

Rice farms in the EU are managed by highly educated farmers. More than 50 % of all Italian rice farmers have either a high school or a university degree. Their farms are usually larger than 100 hectares.

4.5 General Agricultural Problems in European Rice Fields

4.5.1 Weeds

The most frequent weed species in Europe are representatives of the Poaceae, Cyperaceae, Alismataceae, Butomaceae and Pontederiaceae families. *Echinochloa* species, weedy rice (*Oryza sativa*) and *Heteranthera* species cause considerable competition in European rice fields. This is also the case for *Cyperus difformis* L., *Cyperus serotinus* Rottb., *Schoenoplectus mucronatus* (L.) Palla, *Bolboschoenus maritimus* (L.) Palla and *Alisma plantago-aquatica* L. *Leptochloa* species such as *Leptochloa fusca subsp. uninervia* (J. Presl) N. Snow seem to have gained ground within recent years (Osca 2013). *Leptochloa chinensis* (L.) Nees, a serious Asian weed, was spotted in Italy for the first time in the beginning of this century (Benvenuti et al. 2004). It has, however, not become a problem yet and seems to be rare still. The spectrum of rice weeds in dry-seeded rice appears to be different from that of wet-seeded rice. *Heteranthera reniformis* Ruiz & Pav., *Schoenoplectus mucronatus*, *Bolboschoenus maritimus*, *Butomus umbellatus* L. and *Alisma plantago-aquatica* appear to be more frequent in wet-seeded rice, whereas grass species such as *Digitaria sanguinalis* (L.) Scop.and *Sorghum halepense* (L.) Pers. and dicots such as *Polygonum persicaria* L. and *Portulaca oleracea* L. seem to be more frequent in dry-drilled fields. Weedy rice, a considerable problem, seems to be no longer the serious weed that it was in the past. It has, however, to be considered that the tolerance to imidazolinones is starting to outcross into weedy rice (Ziska et al. 2015) as discussed below. The dominant weed genus in rice is *Echinochloa.* The species in this genus are usually difficult to distinguish. The red colour of the stem is normally associated with *E. crus-galli* (L.) P. Beauv.; white biotypes are often identified as *Echinochloa erecta* (Pollacci) Pignatti. Intermediate forms are regarded as hybrids. *Echinochloa phyllopogon* (Stapf) Koss. is usually associated with hairs on the stem and hairs between leaf blade and sheath. Unfortunately, *Echinochloa oryzoides* (Ard.) Fritsch is sometimes regarded as synonymous with *Echinochloa phyllopogon* (Stapf) Koss. (e.g. by Hirosue et al. 2000). Other authors regard *E. phyllopogon* as identical with *E. oryzicola* (e.g. Iwakami et al. 2012). *E. colona* (L.) Link is described as an awnless species in contrast to *E. crus-galli.* It is, however, obvious that awnless biotypes also exist within the species *E. crus-galli. Monochoria vaginalis* (Burm.f.) C. Presl ex Kunth is a problem weed in many parts of the world. It can be a major problem in Southeast Asia, in Australia and in the Americas. It does not

Table 4.6 Importance of representatives of frequent weed genera in rice based on data kindly provided by the Centre Français du Riz

Genus	France	Greece	Italy	Portugal	Spain
Alisma	xx	xx	xxx	xx	xx
Bidens	xx	–	xx	x	–
Bolboschoenus	xxx	–	xxx	–	xxx
Butomus	x	x	x	–	–
Cyperus	xxx	xxx	xx	xxx	xxx
Digitaria	x	x	Xx	x	–
Echinochloa	xxx	xxx	xxx	xxx	xxx
Heteranthera	xxx	xx	xxx	xxx	xxx
Leersia	xxx	xxx	xx	xxx	xx
Leptochloa	xx	xxx	x	xxx	xxx
Lindernia	xx	–	xx	–	xx
Oryza	xxx	xxx	xxx	xxx	xxx
Panicum		x	xx	x	–
Paspalum	xx	xx	x	xx	x
Polygonum	xxx	x	xx	xx	x
Schoenoplectus	xxx	–	xxx	xxx	xxx
Setaria	x	–	x	–	x
Typha	xxx	xx	x	xx	xx

x minor importance, *xx* intermediate importance, *xxx* major importance
In some countries, regional differences have to be kept in mind

play, however, a role in Europe. Minor differences in the weed spectrum of European countries can be observed (Table 4.6). Country- or region-specific weed spectra have been summarized by a number of authors, e.g. by Vidotto (2013) or Sparacino et al. (1996) for Italy, Galhano et al. (2011) for Spain, Audebert et al. (2013) for France, Vasconcelos et al. (1999) for Portugal, Pinke et al. (2014) for Hungary or Pacanoski and Glatkova (2009) for Macedonia.

The spectrum of registered herbicides differs from country to country. Table 4.7 shows that the choice of products with different mode of actions (MoAs) is highest in Italy and Spain (Table 4.8).

For crop selectivity reasons, many products have, however a limitation in application ranges.

In dry-seeded rice, clomazone- and pendimethalin-based products are primarily applied pre-emergence. Due to the rather small acreage in France, not many herbicide options are available.

Resistance of rice weeds to herbicides has been reported in Europe starting from the mid-1990s (Sattin et al. 1999). Most prominent today are publications on weeds resistant to ALS or AHAS inhibitors (ALS, acetolactate synthase; AHAS, acetohydroxy acid synthase) and ACCase inhibitors (ACCase, acetyl coenzyme A carboxylase). Panozzo et al. (2013) characterized the basis of resistance for 14 *Echinochloa crus-galli* populations. Seven populations were highly cross-resistant to ALS inhibitors, two were resistant to a sulfonylurea but not to

Table 4.7 Herbicides registered in Italy, France and Spain for application in rice

MoA, target site[a]	Common name	Chemical family	Timing[b]	Registered in
ACCase	Clethodim	Cyclohexane diones	C	Spain
	Cycloxydim	Cyclohexane diones	A	Italy, Spain, France
	Profoxydim	Cyclohexane diones	A, C	Italy, Spain
	Cyhalofop butyl	Aryloxyphenoxy-propanoates	C	Italy, Spain, France
	Propaquizafop	Aryloxyphenoxy-propanoates	A	Italy, Spain
AHAS or ALS	Azimsulfuron	Sulphonylureas	C	Italy, France, Spain
	Bensulfuron-methyl	Sulphonylureas	C	Italy, France, Spain
	Halosulfuron	Sulphonylureas	C	Italy, Spain
	Imazosulfuron	Sulphonylureas	C	Italy, Spain
	Orthosulfamuron	Sulphonylureas	C	Italy
	Ethoxysulfuron	Sulphonylureas	C	Italy
	Penoxsulam	Sulphonylureas	C	Italy, France, Spain
	Imazamox	Imidazolinones	C	Italy, Spain
	Bispyribac-sodium	Pyrimidinyl benzoates	C	Italy, Spain
Auxins	2,4-DB	Phenoxy-carboxylic acids	C	Italy
	MCPA	Phenoxy-carboxylic acids	C	Italy, Spain
	Triclopyr	Pyridine-carboxylic acids	C	Italy
	Quinclorac	Quinoline-carboxylic acids	C	Italy[c]
DOXP synthase	Clomazone	Isoxazolidinones	A, B, C	Italy, Spain
EPSP synthase	Glyphosate	Glycines	A, B, C	Italy
Fatty acid and lipid biosynthesis	Molinate	Thiocarbamates	C	Spain
Inhibition of cell division	Flufenacet	Oxoacetamides	A, B	France, Italy
Microtubule assembly	Pendimethalin	Dinitroanilines	A, B	Italy
Protoporphyrinogen oxidase	Oxadiazon	Oxadiazoles	A, B, C	Italy, Spain[c]
PS I – inhibitors	Diquat	Bipyridyliums	A, B, C	Italy[d]
PS II – inhibitors	Bentazone	Benzothiadiazinones	C	Spain

(continued)

Table 4.7 (continued)

MoA, target site[a]	Common name	Chemical family	Timing[b]	Registered in
	Bromoxynil	Nitriles	C	Italy
	Propanil	Amides	C	Italy[c], Spain[e]
VLCFAs	Pretilachlor	Chloroacetamides	A, B, C	Italy[c]

[a] According to HRAC (Herbicide Resistance Action Committee) January 2015
[b] *A* pre-sowing, *B* pre-emergence, *C* post
[c] Approved use in rice as a derogation for a limited period in emergency situations
[d] Only for desiccation of rice seed production
[e] Exceptional registration

Table 4.8 Herbicide mixtures for use in rice

Common names	Timing[a]	Registered in
Bensulfuron-methyl + molinate	C	Spain
Bensulfuron-methyl + metsulfuron-methyl	A	Italy
Penoxsulam+cyhalofop	C	Spain
Pendimethalin+clomazone	A, B, C	Italy
2,4-D + MCPA	C	Italy

[a] *A* pre-sowing, *B* pre-emergence, *C* post

an imidazolinone and five were multiple resistant to ALS and the ACCase inhibitor profoxydim. Other studies showed that the structure of *Echinochloa* populations in Italian rice fields and the related variability of herbicide sensitivity are much more complex than previously expected (Vidotto et al. 2007). Busi et al. (2006) compared biotypes of *Cyperus difformis* and of *Schoenoplectus mucronatus* from California, Italy and Spain to describe cross-resistance phenomena to a number of ALS herbicides. Calha et al. (2007) detected Portuguese biotypes of *Alisma plantago-aquatica* which were resistant to bensulfuron-methyl. Busconi et al. (2012) summarize the distribution of AHAS-resistant weedy rice in Italy and discuss the consequences of outcrossing of the Clearfield tolerance genes into weedy rice. According to GIRE, the Italian Herbicide Resistance Working Group, 30 % of all rice fields are infested with herbicide-resistant weeds (http://oryza.com/italian-government-approves-use-chemicals-control-herbicide-resistant-weeds).

Unfortunately, herbicides with new modes of action have become quite rare, and the number of registered products is continuously reduced (Kraehmer et al. 2014a, b). This fact leads to ever-increasing resistance risks and to challenges for farmers.

4.5.2 *Insects*

The smaller rice leaf miner *Hydrellia griseola* Fallen (Diptera) is the globally most widely distributed and one of the most economically significant *Hydrellia* species (Hesler 1995). Also, the Asiatic rice borer or striped rice stemborer, *Chilo suppressalis* Walker (Lepidoptera), and the white-spotted stink bug, *Eysarcoris inconspicuus* H. Sc. (Hemiptera), can cause considerable damage. The latter one especially in Andalusian rice fields. The invasive rice water weevil, *Lissorhoptrus oryzophilus* Kuschel (Coleoptera), is impacting yields in several European parts today. Resistance of insects to insecticides is not regarded as a problem today.

Table 4.9 shows insecticides applied in Italy and Spain.

4.5.3 *Diseases*

Major diseases of European rice are fungal diseases such as rice blast caused by *Magnaporthe grisea* (T.T. Hebert) M.E. Barr*,* brown spot disease caused by *Cochliobolus miyabeanus* (Ito &. Kurib.) Drechsler and bakanae disease by *Gibberella fujikuroi* (Sawada) Wollenw. Resistance to fungicides is – like with insecticides – not regarded as a problem in European rice yet. Rice is treated once or twice with fungicides depending on growth stage and region in Italy. There are also a number of different compounds and tools used as seed dressings as *Pseudomonas chlororaphis* which we will not discuss here.

Table 4.10 contains registered fungicides and mixtures in Spain and Italy. Prochloraz and tebuconazole mixtures are registered in Spain. Fungal diseases are not regarded as a major problem in France due to the dry Mistral wind that is blowing over a long time of the year.

4.6 Environmental Effects Associated with Rice Cultivation

4.6.1 *Water Consumption*

According to the World Bank green data (Voegle and Badiee 2013), 16.9 % of all agricultural land in Italy are irrigated. Agriculture withdraws 44 % of the total freshwater available. In the northern rice-growing areas of the river Po area, there is, however, usually enough water available early in the season so that all crops can be normally irrigated and no groundwater problems are to be expected. Aerobic rice systems as propagated in some Asian countries with a water shortage are not recommended in northern Italy. The situation varies, however, from country to country. The amount of

Table 4.9 Insecticides available for use in rice in Italy and Spain

MoA, target site[a]	Common name	Chemical family/ proteins	Main target insects	Registered in
Ecdysone receptor agonist	Tebufenozide	Diacylhydrazines	*Chilo suppressalis* *Mythimna unipuncta* *Spodoptera* spp.	Spain
Microbial disruptors of insect midgut	*Bacillus thuringiensis* aizawai	B.t. proteins	*Mythimna unipuncta* *Spodoptera* spp.	Spain
	Bacillus thuringiensis kurstaki	B.t. proteins	*Mythimna unipuncta* *Spodoptera* spp.	Spain
Sodium channel modulators	Pyrethroids	Cyhalothrin	*Lissorhoptrus oryzophilus*	Italy
		Cypermethrin	*Lissorhoptrus oryzophilus* Aphids	Italy
		Deltamethrin	Aphids	Italy
		Etofenprox	*Eysarcoris ventralis*	Spain
		Pyrethrum extract	Various	Italy
Modulators of chordotonal organs	Pyridinecarboxamide	Flonicamid	Aphids	Italy[b], Spain[c]

[a] According to IRAC (Insecticide Resistance Action Committee) December 2014

[b] Approved use in rice as a derogation for a limited period in emergency situations

[c] Exceptional registration

irrigation is also dependent on the amount of local rain or water evaporation. In the Vercelli region (Italy), between 15,000 and 40,000 m^3 irrigation water per hectare of rice are quite common per season (Blengini and Busto 2009); in the Camargue 23,000 m^3 irrigation water per ha were published by Desplanques et al. (2006). These are dimensions which are comparable to water amounts used in other parts of the world as in Argentinian irrigated rice where the amounts vary from 13,000 to 19,000 m^3/ha and season (Marano and Filippi 2015). An overview on the EU irrigation situation was published in the Final Report of the Working Group “MED-RICE” prepared for the European Commission in the framework of Council Directive 91/414/EEC (MED-Rice (2003). Hydrologic water balances were discussed for the central Ebro valley by Playán et al. (2008). These authors stressed that the seasonal consumptive water use appears to be similar to other irrigated spring cereals grown in the area.

Table 4.10 Fungicides available for use in rice in Italy and Spain

MoA, target site[a]	Common name	Chemical family	Main target disease	Registered in
C14-demethylase	Flutriafol	Triazoles	Rice blast Brown spot	Italy
	Tebuconazole	Triazoles	Rice blast Brown spot	Spain
	Propiconazole	Triazoles	Brown spot	Italy, Spain
	Prochloraz	Imidazoles	Rice blast Brown spot	Spain
Inhibition of complex III	Azoxystrobin	Methoxyacrylates	Rice blast Brown spot	Italy, Spain
Melanin synthesis	Tricyclazole	Triazolo-benzothiazoles	Rice blast	Italy[b], Spain[c]
Signal Transduction	Iprodione	Dicarboximides		Italy

[a] According to FRAC (Fungicide Resistance Action Committee) January 2015
[b] Approved use in rice as a derogation for a limited period in emergency situations
[c] Exceptional registration expected

4.6.2 Gas Emission

Methane and N_2O emissions from rice fields have become a major concern since their detection in the last century. Both gases so-called greenhouse gases are regarded as major components of global warming. The reasons for the emissions from rice fields are anaerobic degradation processes in the paddy water as caused by microorganisms such as Archaea species (Liu and Whitman 2008). A few measures for the mitigation of methane production in agriculture have been suggested by various scientists as summarized by Smith et al. (2008). In Italy, several studies on methane production of rice fields were carried out within the last decades. Dan et al. (2001) could demonstrate the stimulating influence of fertilizers on methane emission. Lüke et al. (2010) reported on the biogeography of methane-oxidizing bacteria (MOBs) in Italian wetland rice.

4.6.3 Heavy Metals

Unfortunately, rice is assimilating some heavy metals into its grains. For example, arsenic (As) may be found in rice of different parts of the world (Sommella et al. 2013). The concentrations of As in Italian rice may vary from about 0.1 mg/kg grain to 0.3 mg/kg grains depending on sample site, variety and region; Cr-values range from 0.1 mg/kg to 1.0 mg/kg grains; those for Cd are usually lower and are detected at rates between 0.01 and 0.1 mg/kg.

As values from Spanish rice were compared with those for Chinese and US rice samples in another study (Carbonell-Barrachina et al. 2012) and were proved to be lower.

4.6.4 Biodiversity

Irrigated rice provides a special habitat for a great number of organisms and contributes to the existence of species which could hardly survive in a nonirrigated environment of other arable crops. Already, Carretero (1986) reported three decades ago about 29 emergent and 20 floating or submerged plant taxa in rice fields of the Valencia and Tarragona provinces of Spain. Vasconcelos et al. (1999) listed 47 species of vascular plants in 19 families and 7 species of algae in Portuguese rice fields. In the Camargue alone 178 plant species are directly associated with the cultivation of rice (http://plantes-rizieres-camargue.cirad.fr/generalites/la_flore_du_milieu_rizicole/introduction). Some scientists regard the vegetation associated with rice as poor (e.g. Pinke et al. 2014). They make, however, clear that it is composed of plants of phylogenetically diverse origin.

Picazo et al. (2010, 2012) stress the importance of aquatic systems including rice fields for water beetles in Iberia and the Mediterranean basin.

Sánchez-Guzmán et al. (2007) demonstrated how rice cultivation can mitigate the general loss of wetland for migratory water birds. Toral and Figuerola (2010) highlighted the reduction of natural wetlands in the Mediterranean region by 80–90 % in the twentieth century due to pressure from human population growth and the conversion of wetlands into agricultural and urbanized areas. They provided an evidence that rice fields play a major role for water birds today in Andalucia.

Unfortunately, European rice field habitats have become home for a number of invasive species such as the alien crayfish *Procambarus clarkii* Girard (Barbaresi and Gherardi 2000) or various ostracods such as *Candonocypris novaezelandiae*, *Stenocypris macedonica*, *Cypris subglobosa* and *Hemicypris barbadensis* (Valls et al. 2014). Some scientists are concerned about the resurgence risk of Malaria with *Anopheles atroparvus* as its vector (Sainz-Elipe et al. 2010).

4.7 Trends, Chances and Opportunities

4.7.1 Weed Management

It has already been mentioned that the number of herbicide registrations has declined continuously over the last years. It is therefore encouraging to see that still some new technologies for rice are introduced by the agrochemical industry. According to an announcement by Delta Farm Press of April 1, 2015, BASF is about to launch a new weed management system under the trade name Provisia. The new Provisia rice trait will be tolerant to ACCase inhibitors; it is a non-GMO trait that was found through selection and backcrossing into commercial rice varieties (http://deltafarmpress.com/rice/new-tools-continue-provide-us-rice-farmers-edge).

With this technology, farmers will have an additional tool to control some widely distributed weeds such as *Echinochloa* species and weedy rice. This system was also presented at the 2014 annual meeting of the Weed Science Society of America and the Canadian Weed Science Society in Vancouver (Harden et al. 2014). It can be expected that this technology will arrive at European rice fields soon.

4.7.2 Hybrid Rice

Non-GMO hybrid rice cultivation in Italy was started in the year 2012 (Tesio et al. 2014). The first varieties were Clearfield varieties and were planted on around 1800 ha. Recommended seeding rates for conventional direct-seeded varieties usually range between 100 and 200 kg/ha. Seeding rates for hybrid rice are much lower (26.5 kg per ha). The number of tillers in hybrid rice is usually higher than in conventional varieties. In Spain, hybrid rice was commercially sold in 2015. Relatively high costs for the seed and the long growing period of the first varieties did not lead to a high acceptance of the technology so far. This may change, however, with the introduction of more and cheaper varieties.

4.7.3 Gas Emission

Maris et al. (2015) analysed the influence of continuous and intermittent irrigation on the greenhouse gas emission of rice fields and found considerable differences. Dry periods as practiced today with dry-seeded rice can reduce the greenhouse gas emission considerably.

It appears probable therefore that new cultivation methods may contribute to a considerable reduction of greenhouse gas emissions.

4.7.4 Heavy Metals

Several scientists have observed already in the past that differences in the uptake of heavy metals are based on rice genetics (e.g. Ahmed et al. 2011). Snehlata Shrivastav reported on July 15, 2015 in the Times of India that scientists at the CSIR-National Botanical Research Institute (CSIR-NBRI), Lucknow, have developed a variety of rice that minimizes the uptake of arsenic from the soil (http://timesofindia.indiatimes.com/City/Nagpur/Scientists-develop-rice-that-wouldnt-take-arsenic-from-soil/

articleshow/48075568.cms). It has to be expected that further investigations into the rice genome will end up with new varieties in Europe also which help to reduce the risk of heavy metal accumulation in rice grains in the future.

4.7.5 Biodiversity

Some European rice-growing areas are close to natural parks or protected areas such as in the Camargue or in the Ebro Delta (Parc Natural del Delta de l'Ebre). Some initiatives strive therefore for a reduction of the use of agrochemicals in these areas. A very small proportion of farmers have started to produce organic rice a few years ago (Delmotte et al. 2011). In the Camargue, average yields range between 6.3 (for conventional rice) and 4.3/ha (for organic rice). Unfortunately, yields may be highly variable. The worst problem for organic rice production is apparently weed competition.

4.8 Conclusions

The area on which rice is grown in Europe is rather small compared with other rice-growing areas, especially in Asia. It has even decreased considerably during the last 25 years. In some areas, the acreage has become so small that new agrochemicals are no longer registered. The milled rice equivalents in the EU amount to 0.4 % of the global rice production and can therefore not be regarded as a potential source of overproduction. There is, however, a constant demand for rice in the EU which can be safeguarded by a few European nations.

Due to comparable climatic and growing conditions, a number of weed problems in Europe are very similar to those in other rice-growing areas as demonstrated, for example, by Kraehmer et al. (2015). Wild rice, *Echinochloa*, *Cyperus* and *Heteranthera* species, are the most dominant species all over Europe. It can be expected that the pressure caused by *Leptochloa* species will increase similar to other rice-growing areas in the world. The acreage of Clearfield rice is growing due to its advantage of controlling wild rice. Resistance to herbicides creates an increasing risk resulting in an urgent need of herbicides with new mode of actions. Similar to weed spectra, European rice diseases and insect problems are also not unique and have been threats like in other parts of the world. Three major environmental issues result in discussions about rice cultivation in Europe: greenhouse gas emissions, water consumption and heavy metal accumulation. New crop management approaches seem, however, to reduce anticipated problems to a great extent. On the other, it must not be ignored that rice fields are important habitats for a number of plant and animal species, and they are an important resort for migratory water birds. They considerably contribute to biodiversity in an industrialized agricultural landscape.

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Chapter 5
Rice Production in Africa

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5.1 Introduction

Due to high demand, rice production has increased continuously over several decades, from a growth rate of 1.76 % in 1991–2001 to 3.96 % during 2002–2013. This rapid growth rate has made rice the fastest emerging cereal crop in sub-Saharan Africa (SSA) and the second major source of energy on the continent (Seck et al. 2012). However, currently rice production is lower than the demand that is driven by rapid population growth and the preference by urban dwellers for rice as a convenient and easy-to-cook cereal compared to traditional dishes (Seck et al. 2013). Rice is thus one of the most valued food crops on the continent and a very important political crop, shortage or price fluctuation of which can result in civil unrest, as witnessed during the rice crisis in 2007–2008 (Seck et al. 2013).

Although Africa has vast natural resources and the potential to produce enough food for its 900 million people, only 60 % of its demand for rice is produced locally, the rest being imported. Analysts indicate that the current dependence on the

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international market is not sustainable because supply is unreliable and rice prices fluctuate (Wopereis et al. 2013). To overcome this chronic food insecurity, African policy makers have developed ambitious plans for achieving food self-sufficiency and to turn rice into a profitable venture for farmers and other stakeholders. To realize the plans, a wide range of research-for-development activities are being undertaken in partnership with various institutions within and outside of Africa (Tollens et al. 2013).

This chapter provides historical highlights on rice in Africa, its production systems, challenges, and current major activities toward self-sufficiency, as well as the role of the Africa Rice Center (AfricaRice) as a center of excellence for rice research in Africa.

5.2 History and Importance of Rice in Africa

5.2.1 History

Through thousands of years of rice cultivation experience, African farmers have generated diverse rice genetic resources, which are well adapted to diverse agroecologies and multiple biotic and abiotic stresses on the continent (Sanni et al. 2013). African rice, *Oryza glaberrima* Steud, is one of the two cultivated species, and was independently domesticated from its wild ancestor *O. barthii* in the Niger River delta about 3000 years ago (Jones et al. 1997). Since then, it has spread to two secondary centers of domestication, one along the coast in The Gambia, Senegal, and Guinea-Bissau and the second in the Guinea forest between Sierra Leone and the western part of Côte d'Ivoire (Portères 1962, 1976). Molecular investigations through isozyme studies followed by simple sequence repeat (SSR) and single nucleotide polymorphism (SNP) confirmed the uniqueness of African rice and its close genetic relationship to *O. barthii* (Second 1982; Semon et al. 2005). In its evolution as a cultivated crop, *O. glaberrima* has shaped the diet and culture of Africa region, and it even helped Africa to overcome famine in 1203 (GRiSP 2015). Highly sophisticated rice cultivation technologies and cultural practices existed in West Africa, with a variety of production systems used in different environments and landscapes, including the construction of elaborate canals and dikes in coastal swamps (Carney 2001). This indigenous rice production knowledge is believed to have been transferred to North America, through the slave trade that transported people from West Africa to the Americas. This technology transfer seems to have contributed to the economy as well as food culture of Carolina. For instance, a rice recipe called Hoppin' John or red rice that is popular in Georgia and South Carolina came from the West African recipe called Jollo Rice (Carney 2001).

However, after the introduction of Asian rice *O. sativa* into Africa through East Africa by traders from India in the early 1500s (Harlan and Stemler 1976; Ng et al. 1991), *O. sativa* has spread westward (Portères 1962) and the cultivation of *O. glaberrima* has declined. *O. sativa* is now widely cultivated on the continent. Although the two cultivated species have some traits in common, they are significantly different

Table 5.1 Differentiating characteristics of cultivated rice species and their wild progenitors

Origin	Species	Distribution	Biological type	Reproduction
Asian				
Cultivated species	*Oryza sativa* (with two sub spp. indica and japonica)	Asia	Intermediate	Self-pollinated plant (often) and intermediate
Wild species	*Oryza rufipogon*	Asia, Australia, and America	Annual Intermediate	Self-pollinated and cross-pollinated plant, intermediate, and vegetative reproduction
African				
Cultivated species	*Oryza glaberrima*	Africa	Annual	Self-pollinated plant
Wild species	*Oryza barthii*	Africa	Annual	Self-pollinated plant
	Oryza longistaminata	Africa	Perennial	Cross-pollinated plant and vegetative reproduction

Adapted from Agnoun et al. (2012) with permission

from each other (Linares 2002; Agnoun et al. 2012) (Table 5.1). Through thousands of years of production in the region, *O. glaberrima* is well adapted for cultivation in West Africa and possesses important traits such as tolerance of biotic and abiotic stresses; on the other hand, *O. sativa* produces much higher yields and therefore has higher commercial value. Rice breeders have been exploiting the stress tolerance of *O. glaberrima* to improve *O. sativa* for different stress tolerance traits while maintaining high yields (Futakuchi et al. 2012).

The collection, conservation, and utilization of genetic diversity of the indigenous cultivated and wild rice species in Africa is the responsibility of AfricaRice and the genetic resources are kept in trust for humanity under the auspices of the Food and Agriculture Organization of the United Nations (FAO). The AfricaRice gene bank currently has more than 20,000 accessions of *O. sativa* and *O. glaberrima* as well as wild species (*O. longisataminata, O. barthii,* and *O. stapfii*) (Sanni et al. 2013). Using these genetic resources, African scientists have generated “New Rice for Africa” (NERICA) varieties, which combine the high-yielding traits of *O. sativa* with the stress-adaptive traits of African rice, and ushered in the green revolution in Africa (Sie et al. 2012). The genome of *O. glaberrima* has been sequenced through collaborative effort, thus providing new opportunities for quick and efficient exploitation of the genome to develop climate-resilient varieties (Wang et al. 2011).

The ever increasing demand for rice is dynamically shaping the rice production system, intensification, and expansion. Consequently, rice is now grown in 40 African countries on nearly 10 million ha of land (AfricaRice 2011; Diagne et al. 2013) (Fig. 5.1). The five major rice producing countries are Nigeria (1,895,697 ha), Madagascar (1,183,614 ha), Guinea (1,005,822 ha), Côte d’Ivoire (968,271 ha), and Tanzania (942,438) (Diagne et al. 2013). Many of the rice growing countries have favorable policies and national strategic rice development plans, with a keen focus

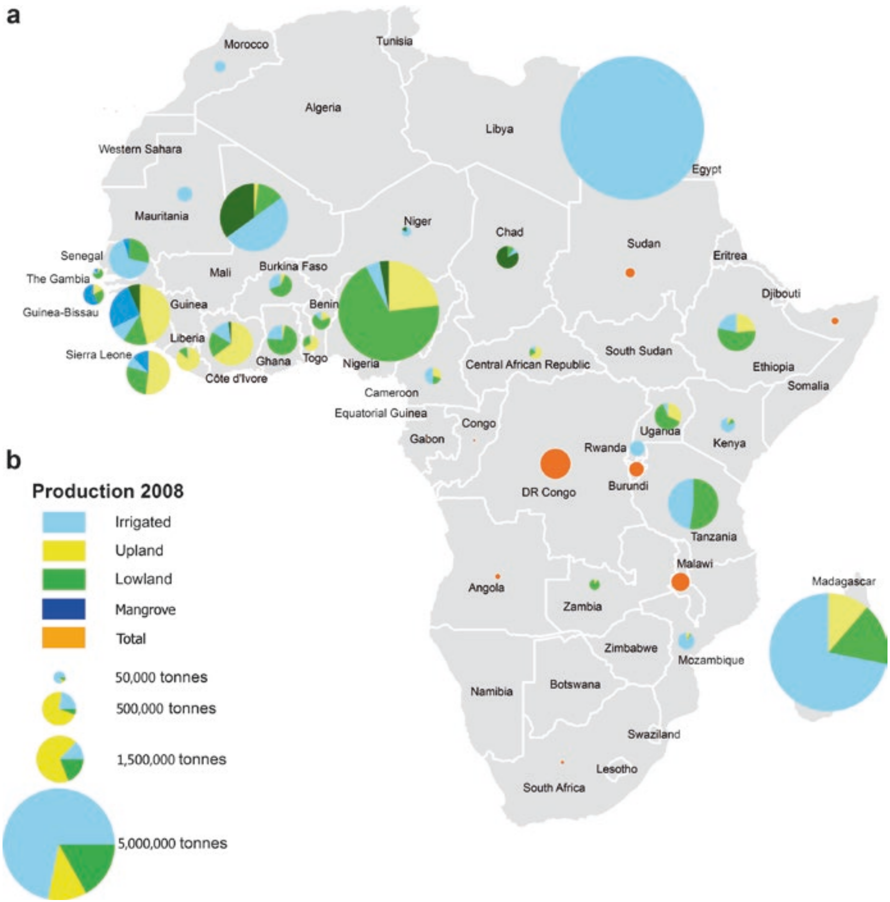

Fig. 5.1 Paddy rice production in Africa (Reprint from (AfricaRice 2011) with permission)

on satisfying demand with local production and benefiting farmers and other stakeholders along the whole value chain (JICA 2009).

5.2.2 Current Trends in Rice Production and Consumption

Rice production and consumption in SSA have progressed at variable rates. From 1961 to 2006, annual rice production growth rate was 3.18 % compared to 2.9 % for annual increase in demand (AfricaRice 2008). Then the increase in production was attained mainly from area expansion. However, from 2007 to 2012, an unprecedented production growth rate of 8.4 % per year occurred. This leap occurred after the rice crisis of 2007–2008 that triggered positive interventions by governments to boost local production—70 % of the increase was due to higher yields per unit area and only 29 % to area expansion. The annual yield increase that is equivalent to 108 kg/ha between 2007 and 2012 is comparable to the one obtained in Asia during the green revolution (Seck et al. 2013). However, despite these developments, the overall rice demand in Africa has outstripped local production and 40 % of the rice consumed is imported. Consumption rate is expected to increase by 130 % in 2035 compared to 2010 (Seck et al. 2013), which urges African rice producers to increase their production capacity drastically to meet the ever increasing demand with local produce.

5.3 Major Rice Production Ecologies in Africa

In Africa, rice is grown in rainfed upland and aquatic environments. Based on topography, water management and genetic adaptability, the aquatic environment is subdivided into four major ecologies: rainfed lowland, deep water, mangrove, and irrigated ecology (Sie et al. 2012). High elevation is considered as a special ecology due to its specific requirement for cold-tolerant varieties (AfricaRice 2011).

5.3.1 Rainfed Upland

Rainfed upland is the second largest rice production ecology in sub-Saharan Africa (SSA) (Diagne et al. 2013) (Table 5.2). In this ecology, rice is grown without soil surface flooding. Most farmers in this ecology are resource poor and cannot afford agricultural inputs. Consequently, they practice the "slash and burn" system as well as permanent rice cultivation without a fallow period. Forest areas are cleared to exploit the natural fertility of the forest soil. However, since no measure is taken to improve the soil fertility and due to weed pressure, rice yields decline drastically after one season and farmers have to constantly clear new forest areas for cultivation, a system called the "shifting cultivation" (Balasubramanian et al. 2007). In sloppy areas, where rice is grown continuously, it is intercropped with other locally adopted crops as a risk management strategy in case the rice crop fails due to drought or poor soil fertility.

Land preparation is carried out manually with a hand-hoe or with the help of Oxen, to be followed by broadcasting or direct seeding 80 kg of seed per hectare. Weeding is done one or two times per season depending on the availability of family labor. The major weed species encountered are *Cyperus* spp., *Imperata cylindrical, Chromolaena odorata*, *Digitaria horizontalis*, *Euphorbia heterophylla, Ageratum conyzoides*, and *Striga* spp. (Rodenburg et al. 2009).

The major biotic stresses are blast, African rice gall midge (AfRGM), stem borers, bacterial leaf blight (BLB), and rice yellow mottle virus (RYMV) (Table 5.2). Despite huge losses caused by insects and diseases, SSA farmers rarely apply appropriate management techniques. They mostly depend on the innate potential of the variety to resist all biotic constraints, while a few control blast with fungicides

Table 5.2 Rice production ecologies in Africa and production potential and yield limiting factors

Rice production ecologies	Shared production area (%)	Yield: actual/ potential (t/ha)	Yield-limiting factors		
			Abiotic factors	Biotic factors	Input use
Rainfed upland	30	1.2/2–5	P and N deficiency, acidity, Al toxicity, drought, erosion, poor soil fertility	Weeds, termites, stem borers, AfRGM Disease (blast, BLB, RYMV), birds, nematodes, and rodents	Very low
Aquatic					
Rainfed lowland	33	1.9/3–6	Water control, N and P deficiency, Fe toxicity	Weeds, termites, stem borers, AfRGM Disease (blast, BLB, RYMV), birds	Low
Mangrove and deep water	4	<1/2–4	Acid sulfate, salinity, Fe toxicity, excess water	Insect pests, diseases, birds	Very low
Irrigated	26	1.9–3.7/5–12	N deficiency, salinity and alkalinity, extreme temperatures	Weeds, stem borers, AfRGM Disease (blast, BLB, RYMV), birds	High
High elevation (*upland and lowland)*	7	1.2/2–6	Cold, Fe toxicity, P and N deficiency, excess water	Weeds, stem borers Disease (blast, BLB, RYMV), birds	Low

Updated from Diagne et al. (2013), Dramé et al. (2013), Haefele and Wopereis (2004)

and by burning stubbles and weeds after harvest to control viruses. In general rice is harvestedand threshed manually, although a few farmers thresh with semiautomatic pedal-operated machines.

Farmers in SSA often experience crop failure as a result of poor cultural practices (such as low inputs, suboptimal crop management practices, and inadequate weed management) and lack of climate resilient varieties. Major constraints per ecology are presented in Table 5.2.

Upland varieties (such as Dourado Precoce and Iguape Cateto), were initially introduced from Brazil but were later replaced by IRAT (Institute for Research in Tropical Agriculture, France) varieties (such as IRAT 10, IRAT 144, and IRAT 13) and recently by NERICA (New Rice for Africa) varieties. Yields under current crop management practices by farmers average 1.2 ton/ha (Dramé et al. 2013) compared to 5 ton/ha with improved NERICA varieties, indicating a huge gap that needs to be closed. Côte d'Ivoire has the largest upland area in Africa (615,325 ha) followed by Nigeria (557,256 ha) and Guinea (532,329 ha) (Diagne et al. 2013). The major genotypes found in this ecology are *O. sativa* tropical japonica type and *O. glaberrima.*

5.3.2 Aquatic Ecology

In SSA about 130 million ha (Diagne et al. 2013) is considered to be under the aquatic ecology, but less than 5% is cultivated with rice (Balasubramanian et al. 2007). Lowland varieties were introduced mainly from Asia—the earliest ones were photoperiod sensitive and susceptible to biotic and abiotic stresses. Some of these accessions with indica background were adopted by farmers due to their consumer preference (e.g., Gambiaka in West Africa, Supa in East Africa, Makalaoka in Southern Africa, particularly Madagascar). They have long grains, good eating and cooking qualities and aroma but give low yields. Although improved versions have been developed through conventional or mutation breeding techniques and released by National Agricultural Research Systems (NARS) institutions, the gap between the potential of the germplasm and actual farmers' yields is still very large.

5.3.2.1 Rainfed Lowland

The rainfed lowland ecology, which comprises gentle slopes and inland valleys, is the largest ecology, covering 33 % of the whole rice production area, and relies on rainfall and ground water (Diagne et al. 2013). Fields could be bunded or unbunded, but there is no water control, with droughts and floods being potential problems Hatibu et al. 2000. Rice is broadcasted or transplanted and one rice crop is cultivated per year followed by vegetables where residual moisture is available. The great potential for rice production in this ecology is highly compromised by biotic and abiotic constraints, including weeds, insect pests (such as stem borers, AfRGM, and rice sucking bugs), and diseases (rice blast, brown spot of rice, and RYMV) (Table 5.2).

Nigeria has the largest rainfed lowland area (1,039,935 ha) followed by Tanzania (677,806 ha) and Madagascar (322,688 ha) (Harlan and Stemler 1976). Since most lowland rice farmers apply minimal inputs and suboptimal crop management practices, the average yield of 1.9 ton/ha is much lower than the potential of up to 6.0 ton/ha (Dramé et al. 2013). Both *O. sativa* indica and *O. glaberrima* are grown in this ecology, of which deep water and mangrove swamps are subdivisions.

Deep Water Ecology

Deep water ecology is found in the low-lying wetlands of Madagascar and the poorly drained inland valleys of Chad, Guinea, Mali, Niger, and Nigeria. Deep water rice, also called floating rice, is sown before the floodwaters rise and flowers just before maximum water depth is reached. Deep water rice varieties that can elongate to a maximum water depth of 1.0 m or more and float are suitable for this ecology. They can elongate at a rate of 2–3 cm/day (Catling 1992) and up to 6 m high and produce adventitious roots to extract nutrients directly from the water. The deep water ecology is currently shrinking due to the expansion of dam construction that restricts the flow of water. Due to the stresses in this ecology, which include drought, stem borers, and weeds, the average yield is about 0.9 ton/ha (Lancon 2002).

Mangrove Ecology

Large tracts of rice production areas in SSA experience excess flooding, tidal submergence, saltwater intrusion, salinity, and acid sulfate soils. Mangrove swamp rice is found mostly in Guinea Bissau, The Gambia, and Guinea Conakry (Defoer et al. 2007). In this ecology, rice can be grown during the rainy season, when freshwater floods create a salt-free period of 4–6 months. Yields are below 1 ton/ha due to salinity, crabs, and other stresses (Lancon 2002). The major constraints for rice cultivation in both mangrove and deep water ecologies are low input management followed by insect pests and diseases (Table 5.2).

5.3.2.2 Irrigated Lowland

Irrigated rice is grown in bunded fields with assured irrigation for one or more crops per year. The irrigated ecology is subdivided into irrigated wet season ecology and irrigated dry season ecology, based on the source of water (IRRI 2002). This ecology is relatively new to Africa and only 26% of the aquatic area is irrigated (Diagne et al. 2013). Rice is produced under irrigation in the Sahel, humid forest, and savanna zones and at high elevations. This ecology requires substantial investment but yields good returns on investment. The major water sources are dams, diversion from rivers, or wells (Saito et al. 2013).

In SSA, Madagascar has the largest irrigated area (782,487 ha) followed by Egypt (518,320 ha) and Mali (335,269 ha) (Diagne et al. 2013). In Madagascar, irrigated rice is produced in both wet and dry seasons in well leveled terraces with water from small earth dams on streams and small rivers. Irrigation schemes are smaller in the humid forest and savanna zones than in the Sahel - rainfall is the principal source of water and water control is difficult. Consequently, irrigation is used as a supplement to protect the crop during dry spells in the cropping season. Yields are generally lower than in the Sahel due to less solar radiation, poor soil fertility, pests and diseases (Balasubramanian et al. 2007).

Land preparation is predominantly by manual labor although animal-drawn tools or hand tractors are also used wherever possible. Large tractors are used only in large public or privately owned fields. Direct seeding is a common practice in the Sahelian zone while transplanting is practiced in the other zones. Seed is sown at

30-40 kg/ha either in nurseries or by direct sowing. Farmers widely use organic manure and compost to improve the soil, while few progressive farmers apply diammonium phosphate (DAP) as basal fertilizer, urea as top dressing, and other compound fertilizers, such as NPK.

Weeds are less diverse in the aquatic than in the upland ecology. The most common weed species are *Sphenoclea zeylanica, Cyperus difformis, Echinochloa spp., Oryza spp* (wild and weedy rices), and *Rhamphicarpa fistulosa* (Rodenburg et al. 2009). Manual weeding is done two to three times per season, depending on labor availability. Mechanical weeders are currently being popularized by AfricaRice and its development partners. Chemical herbicides are used by a few farmers, especially in large farms.

Rice is mostly harvested manually and less than 1% is harvested with machines. Similarly, 80% of the threshing is done manually, sometimes with the help of oxen and tractors, while 15% is with semi-automatic pedal-operated machines; motorized threshers such as Votex and ASI-threshers (developed by AfricaRice in Senegal) are used in less than 5% of cases (AfricaRice 2012; Rickman et al. 2013).

The major genotype cultivated in this ecology is *O. sativa* indica type. In the Sahel as a result of high solar radiation, good water management, low disease pressure, and other favorable conditions, average yields in the Sahel are high – up to 9 t/ha (especially during the dry season) and up to 12 t/ha has been achieved with good agricultural practices (Haefele and Wopereis 2004). Nevertheless, extreme yield fluctuations have been observed due to; sub-optimal crop management practices; poor maintenance of irrigation facilities; extreme temperatures and other factors that are not conducive for rice production. As a result, double cropping occurs in only 10% of the area (Wopereis et al. 2013).

5.3.3 High Elevation

About 7 % of Africa's rice production area occurs in the high elevation zone, above 1200 m above sea level (MASL) (Saito et al. 2013). In the tropical highlands of East and Central Africa and Madagascar, rice is produced up to 1900 MASL (Fig. 5.2). This zone includes fertile rolling uplands, high plateau, and mountainous terrain in the archipelago stretching from Ethiopia southward to Angola and Zimbabwe and has some of the best agricultural lands in Africa (HarvestChoice 2014).

The high elevation consists of both upland and aquatic ecologies. The primary constraints are altitudinal low temperatures and flooding during the cropping season (Zenna et al. 2010) (Table 5.2). National and international agricultural research centers give this zone special attention because of its potential for rice production, intensification and expansion, and its unique requirement for cold-tolerant varieties. Several cold-tolerant varieties with japonica genetic background have been introduced, tested and released through the AfricaRice breeding task force mechanism (Zenna 2015). Varieties with temperate japonica genetic background, which thrive well in cold-prone areas, are more adapted to this ecology than those with indica

Fig. 5.2 Rice production at Betafo, Madagascar; high elevation plateau, 1800 MASL, in Madgascar (Photo: Moussa Sie)

genetic background. Japonicas can be furthermore subdivided into tropical japonica and temperate japonica, and both are being cultivated in Africa.

5.4 Genetic Resource Utilization

The plethora of biotic and abiotic stresses that constrain rice production in Africa and climate change provide a great opportunity for developing varieties that perform well under dynamic stress conditions. The AfricaRice gene bank contains more than 20,000 rice accessions, including 2500 *O. glaberrima* (Sie et al. 2012) and offer a unique opportunity for collaborative breeding programs to generate new varieties in demand.

The earliest breeding programs in Africa focused on the introduction of varieties from Asia and many aquatic rice varieties were successfully released under the name “Sahel”. However, there were no introductions for the upland ecology. To strengthen the rice breeding programs of national agricultural research institutions in SSA, AfricaRice (formerly known as WARDA) established regional breeding initiatives through which WAB 56–50, WAB 56–104, and WAB 56–125 were developed for the upland ecology before the advent of the New Rice for Africa (NERICA) varieties. NERICA varieties inherited desirable qualities of *O. glaberrima* (e.g. drought tolerance, weed competitiveness, and diseases tolerance) and the high yielding potential of *O. sativa* (Jones et al. 1997; Dingkuhn et al. 1999). The most desirable quality attributes of NERICA varieties are early maturity, tolerance of specific biotic and abiotic stresses, and yields that are generally as good as for *O. sativa* varieties (Sie et al. 2012). There are currently 18 upland NERICA (NERICA 1–18) and 60 lowland NERICA (NERICA-L 1–60) varieties. NERICA 4 (rainfed upland) and NERICA-L 19 (rainfed lowland and irrigated ecologies) have been widely adopted by many countries in Africa. They were released through the participatory varietal selection system (PVS) (Sie et al. 2010) initially in Guinea in the 1990s and later in several countries across the continent. Nigeria has adopted NERICA 1 and NERICA 2 on about 200,000 ha. In Uganda, different NERICA varieties were cultivated on 35,000 ha in 2007 alone, and this enabled the country to halve its rice imports between 2002 and 2007. Similar successes have been reported in other countries, such as Burkina Faso, Ethiopia, Guinea, Mali, Sierra Leone, Liberia, and Togo (Tollens et al. 2013). The impact of NERICA adoption on poverty reduction in Benin and Uganda has been documented (Sie et al. 2012). Consequently, NERICA has become a brand name for good rice in Africa and is probably better known than AfricaRice, the organization that developed it (Sie et al. 2012).

PVS was an essential vehicle for sensitizing rice producers to adopt NERICA varieties—many rice lines were presented to farmers in village-based demonstration plots. Farmers were then asked to select their favorite lines at various stages of plant growth and to indicate the reasons for their choices. Over the following two seasons, farmers took increasing control of their chosen “varieties”. Special attention was paid to feedback from women (Fig. 5.3), because most of Africa’s rice farmers are women, and their preferences often turned out to be quite different from those of men. PVS data were also used to facilitate the varietal release process and seed production and the quick adoption of varieties. The PVS technique worked well throughout West and Central Africa as part of the NERICA project, providing the farmers with their preferred varieties and generating valuable feedback for rice breeders (Sie et al. 2012).

Although conventional breeding has been successfully used to develop new varieties, it is essential to complement this with molecular breeding to accelerate the development of varieties with tolerance of abiotic and biotic stresses, especially those that are controlled by several genes. In collaboration with AfricaRice and other international organizations, National Agricultural Research Systems (NARS) scientists are now using genomic tools in their breeding programs to introduce traits of interest into local popular varieties (Ndjiondjop et al. 2013). For example, AfricaRice and its partners have identified several useful genes that are now introduced into a number of popular varieties through marker-assisted breeding technique (AfricaRice 2012; Ndjiondjop et al. 2013) and these are being used in marker-assisted breeding to improve many varieties in West Africa.

In response to the reality of climate change, the new breeding direction at AfricaRice is set to develop rice varieties that are resilient to the changing environment in Africa (AfricaRice 2010; Dramé et al. 2013). Consequently, AfricaRice has set up the Africa-wide Rice Breeding Task Force (BTF), a systematic continent-wide breeding approach involving a variety of partners. The BTF is expected to accelerate the development, exchange, and release of rice varieties (Mohapatra 2011). For example, it was used to launch “ARICA” (“Advanced Rice for Africa”) (Kumashiro 2016) (Fig. 5.4), a new

Fig. 5.3 Participatory varietal selection (PVS) activities in the rainfed upland ecology in Ivory, Madagascar (Photo: Moussa Sie)

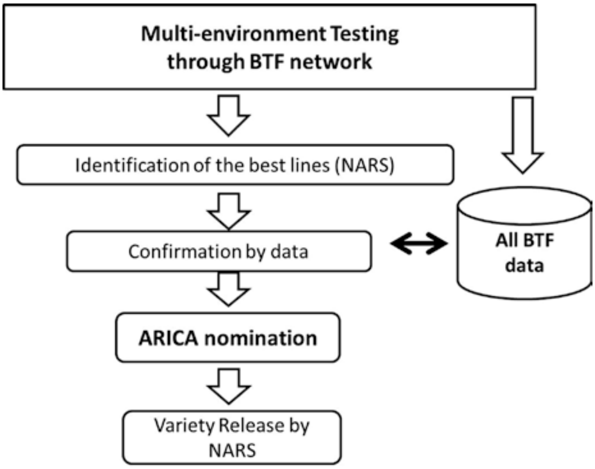

Fig. 5.4 Scheme for the development and release of Advance rice for Africa (ARICA) varieties through the Africa-wide breeding task force mechanism (Modified from (Kumashiro 2016) with permission)

generation of high-perfovrming rice varieties. ARICA varieties are the next generation of rice varieties for Africa, following the success of the NERICA varieties developed in the 1990s and the first decade of this century. Some of the 18 ARICA varieties nominated across ecologies through the BTF mechanism have already been released in Burkina Faso, Guinea Conakry, Mali, and Uganda (Kumashiro et al. 2013).

On the other hand hybrid rice production is gaining momentum in Africa. Starting from 2000, several African countries, such as Côte d'Ivoire, Liberia, Madagascar, Mozambique, Nigeria, Tanzania, and Uganda, have evaluated rice hybrids imported from China. Only Egypt has succeeded in developing a hybrid-rice breeding program and produces Egyptian hybrids on a commercial scale. Yields of 12–14 ton/ha have been reported for these hybrids (El Namaky and Demont 2013). Considering the potential of the hybrid technology, AfricaRice initiated a hybrid-rice program, based at its Sahel Station in Senegal, in 2010, to enhance irrigated rice production (AfricaRice 2010). The hybrid program is now an integral part of the BTF program. Thus 36 multienvironment trials were conducted for the first generation of hybrid lines in Nigeria, Mali, Senegal, The Gambia, and Mauritania through which hybrids with about 20 % yield advantage over the inbred lines were identified. Several of the hybrids emanating from the program are being tested in different countries. Such encouraging results from the breeding program coupled with a sustainable seed production mechanism will boost African rice production capacity (El Namaky and Demont 2013). Hybrid rice technology is expected to contribute to food security in Africa through: (i) exploitation of hybrid vigor to enhance productivity and (ii) involvement of the private sector in seed production research and development (El Namaky and Demont 2013; Kanfany et al. 2014).

5.5 Challenges and Opportunities in African Rice Production

There are large differences (3.2–5.9 ton/ha) between potential and actual yields obtained by farmers ("yield gaps") across all rice growing environments (Table 5.2) (Saito et al. 2013). There is, therefore, considerable scope for increasing yields (Becker et al. 2003). These yield gaps can be closed by introducing improved varieties and good agricultural practices (GAP). GAP is an integrated set of recommended crop, soil, water, and weed management practices (Nhamo et al. 2014). GAP for the lowland ecology may include animal or motorized traction for fine soil tillage, proper bund making, and leveling, use of certified seeds of improved varieties, sowing or transplanting in lines, application of judicious doses of composite fertilizers, and optimally timed weed control using appropriate herbicide dosages followed by weeding with mechanical weeders Becker et al. 2003; Rodenburg and Johnson 2009; Wopereis and Defoer 2007; Mghase et al. 2013; Senthilkumar et al. 2014. Integrated rice management (IRM) options developed by AfricaRice (Lancon 2002) include mechanization, soil-fertility management, and weed management and have increased yields by about 2 ton/ha and benefited farmers in Burkina Faso, Mauritania, and Senegal (Haefele et al. 2000, 2001; Segada et al. 2004, 2005). However, for timely and optimal field management operations, small scale machineries are indispensable.

Lack of appropriate tools for land preparation, harvesting, and postharvest operations is another major bottleneck that makes rice cultivation laborious and time consuming in Africa. For example, lack of appropriate machinery can delay rice harvesting and reduce grain quality (Rickman et al. 2013). The adoption of locally manufactured small-scale machinery is an essential support for rice production in Africa. Consequently, through its Mechanization Task Force, AfricaRice is assisting its NARS partners to identify small-scale machinery and adapting them to local conditions. Private manufacturers who are trained at AfricaRice are now producing and selling mechanical weeders, threshers, and harvesters in different countries (AfricaRice 2012). Availability of such tools can help rice producers to improve the quality of their product and avoid massive losses during the production process.

Crop production generates income for 70 % of farm households in SSA but postharvest losses significantly reduce farmers' real incomes—up to 35 % of the produce is lost during pre- and postharvest processes in the field (CGIAR 2013). Postharvest losses in SSA may be quantitative (15 % and 25 %) or qualitative (estimated by the price difference in imported and locally produced rice) (15–50 %). In Nigeria alone, an estimated 25 % of the total local production is lost due to inefficient postharvest handling and processing (Oguntade et al. 2014).

A reduction in the pre- and postharvest losses is necessary to ensure good quality produce and make rice cultivation a profitable business. Grain quality depends not only on the variety, but also on the whole crop production environment and postproduction management (Futakuchi et al. 2013). In general, locally produced rice in Africa is of lower quality than imported rice, is unable to compete favorably with imported rice, and thus has a limited market share (Manful 2012). Currently, grain quality analysis is carried out on all accessions and breeding lines nominated for multienvironment trials at AfricaRice. The evaluation includes cooking and tasting qualities and aroma. Only entries that satisfy the basic requirements are then distributed for evaluation through the BTF mechanism (Futakuchi et al. 2013). The concern for grain quality could be of major importance to the market; however, quality seed availability could have an immense value for producers to deliver the quality product.

Most African countries have weak seed systems that lack the necessary staff, equipment, and funding. This hinders the availability of sufficient quality seed of

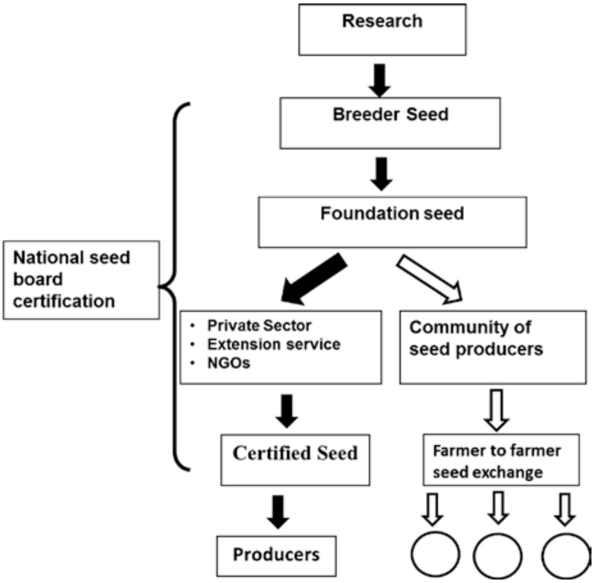

Fig. 5.5 Seed production scheme in Africa—conventional seed production is indicated by solid arrows, while community seed production system (CBSS) is shown with dotted arrows (Adapted from (Sie et al. 2010) with permission)

newly released varieties (AfricaRice 2011). To alleviate this problem, AfricaRice developed the community-based seed systems (CBSS) in the late 1990s, where farmers are trained in best practices for producing "seed of acceptable quality" on their farms for themselves and their neighbors (Fig. 5.5) (Sie et al. 2010). CBSS shortens the time required for seed of improved varieties to reach farmers (Bèye et al. 2013; Sie et al. 2010). There are also regional initiatives, such as by the Economic Community of West African States (ECOWAS) and the Association for Strengthening Agricultural Research in Eastern and Central Africa (ASARECA) for making the seeds of improved varieties available to farmers (Norman and Kebe 2006; Waithaka et al. 2012; Kuhlmann 2015). A sustainable and efficient seed production and delivery system in Africa can be developed in partnership between the private and public sectors. However, such strategic alliance can only prosper by the presence of dynamic national policy for agriculture.

AfricaRice has assisted many countries to prepare their national rice development strategies (NRDS) under the Coalition for African Rice Development (CARD) initiative (JICA 2009). There has been a gradual shift in policy in favor of developing whole rice value chain. The "rice sector development hubs" is an innovative institutional approach to the rice value chain mechanism. Rice hubs are geographical areas where research products, services, and local innovations are integrated across the rice value chain to achieve development outcomes and impact. Hubs are testing grounds for new rice technologies and follow a "reverse-research approach", i.e., starting from the market. In the hubs, research innovations, outputs, and products are tested, adapted, and integrated into "baskets of good agricultural practices". Hubs are built around large groups of farmers and involve other value chain actors and extension agencies that work together to evaluate technological and institutional innovations, facilitate diffusion of knowledge and establish linkages along the rice value chain.

5.6 Conclusions

Rice cultivation in Africa has a long history and has shaped the diet of millions of people. In addition to being a staple food in many rice producing countries, it is also a cash crop for nearly 70 % of the population that earns its income from agriculture. Consequently, rice is considered as the "white gold" of Africa, which is expected to contribute to poverty alleviation and food security on the continent. Based on the positive political will and interventions that produced outstanding achievements since the 2008 rice crisis, it will not be long before Africa produces enough rice to meet its requirements and for export. However, to realize this potential and capitalize on the current demand-driven production momentum, there is a need to inject adequate technological and financial investments into the rice sector. Such investment in innovation platforms would galvanize the whole value chain and the resulting scaling-out of relevant technologies would ensure sustainable rice production (Tollens et al. 2013; Wopereis et al. 2013).

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Chapter 6
Rice Production in the Americas

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6.1 History

Cultivated rice (*Oryza* spp.) is thought to have been brought to the USA from Africa in 1600 AD (Carney 2001; Dugan 2015). By 1650 AD, commercial rice cultivation started in South Carolina and Georgia and then expanded to South America after introduction by Portuguese colonists in the eighteenth century. The growth of the slave population in South Carolina after the mid-eighteenth century also promoted rice production in the region due partly to intergenerational transfer of rice-growing skills. Within 20 years of its introduction in the Americas, rice was cultivated for

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export (Eltis et al. 2007). Currently, US rice is produced predominantly in the South Central region (Arkansas, Mississippi, Missouri, Louisiana, Texas) and the Sacramento Valley of California (Childs and Livezey 2016). The majority of rice produced in the South Central USA is long-grain with minimal medium-grain rice, whereas short- and medium-grain rice are predominantly produced in California (Setia et al. 1994). About half of the US grown rice is exported, mostly to Mexico, Central America, Northeast Asia, and the Middle East (Childs and Livezey 2016; USDA-ERS 2015). Mexico has several rice production niches scattered around its geography and produced close to a million tons of paddy rice a year, prior to the free trade treaty with the USA and Canada. Today, 80 % of its consumption comes from the USA and only 20 % remains locally produced.

In South America, northwest Brazil became a significant center of rice production by the late eighteenth century, while most other South American countries started rice cultivation more recently in the nineteenth or twentieth century. Apart from Brazil, Columbia, Ecuador, Peru, Argentina, Uruguay, Guyana, and Paraguay are notable rice producers in South America. Outside Asia, Brazil is the largest rice-producing country (Schwanck et al. 2015) with important rice-producing regions including Maranhão in the northeast, Mato Grosso in the west, Minas Gerais in the east, and Rio Grande do Sul and Santa Catarina in the south (Eltis et al. 2007; Sharma 2010).

Central American countries are believed to have started rice culture independent of North America in the 1700s (Eltis et al. 2007) due to direct movement of skilled labor from West African regions to the Caribbean islands. However, rice was primarily grown for subsistence in Central America. Currently, Costa Rica, El Salvador, Guatemala, Honduras, Nicaragua, and Panama are notable rice producers in Central America, although the total area under rice production in this region is meager compared to South and North America. Nicaragua, Panama, and Costa Rica are the three major rice-producing countries in Central America. Most countries in the Caribbean islands grow rice, Cuba and Dominican Republic being the most important ones.

The first rice grown in the Americas belonged to *Oryza glaberrima* Steud. spp., which was indigenous to West Africa (Bell 2010; Porteres 1955), whereas *Oryza sativa* spp. (*indica* and *japonica* subspecies) were believed to have been brought from Asia (Eltis et al. 2007; Heyward 1993). Both *indica* and *japonica* types are cultivated in Brazil (Goulart et al. 2014) and elsewhere in South America. In the USA, however, most commercial varieties belong to *tropical japonica*, while *indica* germplasm has been utilized for breeding purposes only and has never been used directly in commercial production (Moldenhauer et al. 2004; Sudianto et al. 2013).

6.2 Area

Rice is cultivated on about 7.2 million ha throughout the Americas across diverse soil and environmental conditions (Haefele et al. 2014). Brazil and the USA comprise more than 60 % of the total rice production in the Americas (Table 6.1). US

Table 6.1 Rice statistics of North, Central, and South America in 2014

Country	Area[a] ('000 ha)	Production[b] ('000 t)	Yield (t/ha)	Import ('000 t)	Export ('000 t)
North America					
USA	1187	10,079	8.49	765	3500
Mexico	44	261	5.93	700	2
Canada	_	_	_	350	_
Central America					
Costa Rica	65	223	3.43	120	_
El Salvador	6	31	5.17	80	10
Guatemala	10	33	3.30	70	_
Honduras	24	110	4.25	165	_
Nicaragua	102	430	4.22	70	5
Panama	88	255	2.90	85	_
South America					
Argentina	231	1560	6.75	7	325
Bolivia	160	355	2.22	60	_
Brazil	2295	12,449	5.42	350	850
Chile	24	164	6.83	140	_
Colombia	445	2047	4.6	350	_
Ecuador	345	1159	3.36	1	_
Guyana	185	977	5.28	_	536
Paraguay	120	781	6.51	2	407
Peru	375	2899	7.73	250	20
Suriname	65	251	3.86	_	35
Uruguay	161	1396	8.67	_	718
Venezuela	140	531	3.79	500	180

Source: IRRI (2016); USDA FAS 2016

[a] Area harvested

[b] Production of paddy rice

rice area increased rapidly since 1995 primarily due to its higher economic returns compared to other crops. In the last 15 years, the highest US rice area of 1.47 million ha was attained in 2010 (IRRI 2016; USDA NASS 2016). The historical trend in US rice area over the past 30 years is provided in Fig. 6.1. US rice is grown in four major regions: Arkansas Non-Delta, Mississippi River Delta, Gulf Coast, and Sacramento Valley of California (Livezey and Foreman 2004). The Arkansas Non-Delta, the largest of the four regions, consists of rice farming in northeastern Arkansas and the Grand Prairie in South Central Arkansas. The Mississippi Delta region is made up of areas in southeastern Arkansas, Mississippi, and northeastern Louisiana lying adjacent to the Mississippi River. The Gulf Coast region includes areas of southwest Louisiana and the upper and lower Gulf Coasts of Texas. The rice area in the Sacramento Valley of California is closer to the west coast.

In 2014, out of the total US rice area (approx. 1 million ha), the South Central USA accounted for about 83 %, with the remaining from California (USDA NASS

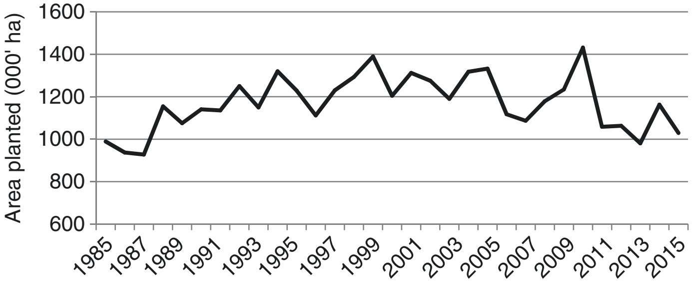

Fig. 6.1 Trends in rice area over the past 30 years in the USA (*Source*: USDA-ERS 2016)

2016). The total US rice production was at 8.5 million metric tons in 2014. Rice production in the USA remained fairly consistent over the past 10 years with an annual variation of <15 %. Arkansas is the top US rice producer (51 % of total rice area), followed by Louisiana (15 %), Mississippi (6 %), Missouri (7 %), and Texas (5 %) (USDA NASS 2016). Rice productivity in the USA has increased from 7.04 metric tons per ha in 2010 to 8.48 metric tons in 2014.

Brazil produces 2.3 million hectares of the total 5.2 million hectares of rice produced in the entire South America (Zorrilla et al. 2013; CONAB. Companhia Nacional de Abastecimento 2015), accounting for 52 % of all irrigated and 38 % of rainfed rice in the continent (Ricepedia – Latin, American, and the Caribbean 2015). The area under rice in Brazil, however, has declined by 27 % between 2000 (3.1 million ha) and 2014 (2.3 million ha) (IRRI 2016; USDA FAS 2016). This decline has been concentrated on rainfed rice in the central and northern parts of the country, whereas irrigated rice area in the southern states has increased slightly. In 2014, Brazil produced 12 million metric tons of rice. About two-thirds of Brazil's total rice production comes from Rio Grande do Sul and Santa Catarina region, all under irrigated conditions, achieving the highest yields in the country. The average rice productivity in Brazil is 5.4 t ha^{-1} (IRRI 2016; USDA FAS 2016), whereas average rice productivity in the Rio Grande do Sul region is at 7.5 t ha^{-1} (CONAB. Companhia Nacional de Abastecimento 2015). Rice area and production in other major South American rice producers (Colombia, Ecuador, Peru, Argentina, Uruguay, Guyana, and Paraguay) are comparatively less (Table 6.1).

The contribution of Central America to world rice production is limited. In 2014, this region produced 1.1 million metric tons of rice on 295, 000 ha (IRRI 2016; USDA FAS 2016). The major rice producers Nicaragua, Panama, and Costa Rica cultivate rice on approximately 102,000, 88,000, and 65,000 ha, respectively (Table 6.1).

6.3 Economics

The majority of rice produced in the USA is exported, whereas it remains an important crop for domestic consumption in many Central and South American countries, particularly in Costa Rica, Mexico, El Salvador, Colombia, Peru, Suriname, and Cayenne (Eltis et al. 2007; Sharma 2010). Notable rice exporters in South America include Uruguay (with 95 % exported), Argentina, Paraguay, and Guyana. The rice economics of USA and Brazil, the two major rice-producing countries of the Americas, is discussed here.

US rice imports have increased significantly over the past decade by 54 % from 480,000 metric tons in 2003–2004 to 740,000 metric tons in 2013–2014 (August to July market year) (USDA NASS 2016), with most of the imports coming from Thailand (430,000 metric tons). For the same period, the USA exported 3.4 million metric tons of rice, which was nearly fivefold of its imports. Rice exports by the USA accounted for US$2.1 billion in 2015 with a slight decrease from 2011 levels. The export and import supplies are highly variable based on the US commodity stocks and the price difference between US rice and major Asian competitors.

Rice farming is one of the most capital-intensive operations in the USA with the highest national average land rental values among all major crops (Baldwin et al. 2011). Economic returns are highly variable due to fluctuating input costs and volatility in commodity and farm prices. The average farm price per metric ton of rough rice in the USA was $310 in 2014 (Table 6.2), which has gradually increased over the past decade (USDA-ERS 2015). The average cost of producing one metric ton of rice is approx. $148 after deducting operating costs (Table 6.2). Irrigation costs also add up to total costs, especially in California where irrigation water is expensive.

Brazil, like the USA, is both an exporter and an importer of rice. In 2014, it exported 850,000 tons and imported 350,000 tons of milled rice (Table 6.1). Rice exports from Brazil was the highest in 2010 (1.3 million tons), which declined by 34 % in 2014 (IRRI 2016) owing to a reduction in area under rice cultivation and cheaper grain prices in neighboring countries. Rice production costs in Brazil (US $2172/ha) are the highest among many neighboring countries in Latin America (South and Central America) (Ricepedia – Brazil 2015). Nevertheless, rice production is viable particularly in the southern region comprising Rio Grande do Sul and Santa Catarina, due to advanced mechanization and irrigated rice production. Conversely, the northeast and other regions of Brazil mainly produce rainfed rice and are less mechanized (Ricepedia – Brazil 2015).

6.4 Rice-Based Cropping Systems

In Arkansas, rice is most commonly grown in rotation with soybean, with 72 % of the 2014 rice area falling under this rotation (Hardke 2015). Based on a 2011 survey of rice crop consultants, 69 % of the scouted rice area in Arkansas and Mississippi was rotated from rice to another crop, mostly soybean (Riar et al. 2013a). The rotation of rice with other crops is viewed by many growers and crop consultants as a critical component in implementing the best management practices for mitigating herbicide-resistant weeds in rice (Riar et al. 2013a). However, rice followed by rice is not uncommon; about 22 % of the 2014 Arkansas rice area was grown following rice the previous year (Hardke 2015). The increase in zero-grade (no slope) rice production in the Mississippi Delta region has favored continuous rice cultivation

Table 6.2 Rice production costs and returns per hectare in Brazil and the USA, excluding government payments (2013–14)[a]

	Brazil	USA
Item	$ (US)/ha	
Gross value of production		
Rice	2078.66	2845.69
Operating costs		
Seed	78.54	244.31
Fertilizers	235.25	334.44
Chemicals	165.65	247.89
Custom operations	190.29	149.90
Fuel, lube, and electricity	230.02	270.66
Repairs	187.55	117.77
Purchased irrigation water	_	29.10
Commercial drying	133.80	90.70
Interest on operating capital	54.19	0.44
Total operating costs	1275.29	1485.21
Allocated overhead		
Hired labor	20.78	66.22
Opportunity cost of unpaid labor	–	163.54
Salaries	145.92	–
Capital recovery of machinery and equipment	419.27	315.15
Opportunity cost of land (rental rate)	169.51	370.87
Taxes and insurance	79.26	40.63
General farm overhead	62.23	61.97
Total allocated overhead	896.97	1018.38
Total costs listed	*2172.25*	*2503.59*
Value of production less total costs listed	–93.59	342.10
Value of production less operating costs	803.37	1360.48
Supporting information		
Yield (metric tons/ha)	7.39	9.20
Price ($US/metric ton)	281.00	309.70
Enterprise size (planted hectares)[a]	–	230.00[a]

Source: Production costs are obtained from USDA-ERS (2015) (USA) and IRGA (2015) (Brazil)

[a]Developed from survey base year 2013

due to the inability of soybean to withstand prolonged periods of saturated soil conditions following intense rainfall events in the zero-grade fields. In Texas, rice-fallow-rice or rice-fallow-fallow-rice is the most predominant system (69 % of area), followed by rice-soybean-rice (14 %) and rice-rice-rice (9 %) (Liu et al. 2016). In California, about 68 % of the rice area is in continuous rice culture due to a lack of viable rotation options in the poorly drained soils.

In the major Central American rice-producing countries (Nicaragua, Panama, and Costa Rica), rice is grown under both irrigated (<40 % of the area) and rainfed systems, with limited rotation in both cases. In irrigated land, 2 to 2.5 harvests are typically expected per year, whereas rainfed rice is usually grown only once in a year, with an occasional second crop in favored areas. A great proportion of rice in Costa Rica and Panama are grown on rental land.

In Brazil, rainfed rice in the north is typically produced in rotation with soybean. In the southern irrigated rice region, most of the rice area remains in fallow during winter, with cattle grazing as the main practice after rice harvest. The integration of rice/cattle intensifies the use of the land and other resources. Recently, area under soybean grown in rotation with rice has been increasing, especially in Rio Grande do Sul, which includes approx. 25 % of the rice area (IRGA 2015). In other regions, however, producers face difficulties in adapting rice-soybean rotation, due to irregular water supply.

6.5 Production Methods

Rice production practices vary across the Americas. The diverse conditions lead to variation in the adoption and utilization of different crop management practices. However, these practices are dynamic and continue to evolve in response to changing political, environmental, and economic conditions.

6.5.1 North America

More than half of the rice in the USA is planted using conventional tillage methods. This usually involves fall tillage when the weather is appropriate, followed by a spring tillage to prepare the seedbed. Rice production methods in the South Central USA are fairly similar. The majority of rice grown in this region is in dry-seeded, delayed-flooded system (flooding at the 5- to 6-leaf stage of rice), with only about 3 % of rice produced under water-seeded system (Hardke 2015). Puddling is a rare practice. Stale seedbed technique is generally utilized as a weed control strategy to terminate already emerged weeds prior to rice planting using tillage or nonselective herbicides. True no-till rice production is not common. California’s rice production is vastly different from that of the southern USA; mechanization is more advanced, involving seeding by aircraft as well as precision fertilizer and pesticide applications. Organic rice production is practiced on about 5 % of the area (McKenzie et al. 2015). In the Sacramento Valley, zero-grade water-seeded system is the most popular rice system (Hill et al. 2006) which relies on permanent earthen levees. No-till rice systems are not successful in California as harvest equipment leaves deep tracks in the heavy black soils, resulting in poor rice establishment and high weed infestations. Fall tillage is necessary to level the field and incorporate rice straw.

6.5.2 Central America

Most of the rice in Central America is grown as a rainfed crop with little transplanting, with the exception of Nicaragua where irrigated rice is more prominent. Mechanized planting and harvesting require renting machinery (about 82 % of the area in Costa Rica). Rainfed rice, which is very common in Costa Rica and Panama, represents >60 % of the total rice area in these countries (Pulver et al. 2012). Almost 100 % of the rice in Guatemala, Honduras, and El Salvador is produced as a rainfed crop. Rainfed rice production represents high-risk agriculture due to unpredictable rainfall and other resource limitations. Rice is usually grown in monoculture in the rainfed cropping systems.

6.5.3 The Caribbean

Dominican Republic is the main rice producer in the Caribbean islands, where most rice production is irrigated and technologically advanced. Rice is usually transplanted, and after main harvest, most farmers go for a ratoon crop (“soca” in Spanish). The other big rice producer is Cuba with excellent conditions for good rice production, but it depends heavily on imports due to internal problems with agricultural development. Haiti, Jamaica, Trinidad and Tobago, and Puerto Rico are minor rice producers in the Caribbean region.

6.5.4 South America

In South America, rice is predominantly cultivated in direct-seeded system (as in the USA) due to high labor costs. This system is practiced in several agroecosystems from the rainfed to the irrigated areas (Maclean et al. 2002). Nevertheless, transplanting is practiced extensively in Peru and coastal Ecuador, whereas water-seeded (pre-germinated) rice system is dominant in Venezuela, Guyana, and Chile. Large farmers use intensive systems, with more mechanization, pesticides, and fertilizers, having a competitive advantage compared to small farmers. The minimum-till cropping system is predominantly used for rice production in lowland areas, because it allows for land preparation throughout the year, reduces production costs, and increases yields by allowing timely seeding. In Rio Grande do Sul state of Brazil, for example, 74 % of the rice is planted under minimum-till system (IRGA 2015). In Santa Catarina, all area under rice is water-seeded, where rice is pre-germinated and then broadcasted in waterlogged fields, whereas in Rio Grande do Sul state, about 93 % of rice is dry-seeded (Raimondi et al. 2014).

6.6 Varieties and Genetic Improvement

6.6.1 North America

During the past 20 years, average rice yields in the USA have increased several folds due to the development and adoption of more productive cultivars along with improved management practices. In Arkansas alone, rice productivity increased by 2.6 t ha^{-1} over the past 20 years (Hardke 2015), and similar increases have been observed in other states as well (Geisseler and Horwath 2016). Rice breeding programs in the USA are not only focused on yield enhancement but also on developing cultivars with disease resistance, drought tolerance, and early maturity particularly for water deficit rice-growing regions of California.

The development of hybrid rice cultivars has greatly contributed to yield enhancement over the years. Currently, almost half of the rice area in the USA is planted with hybrid rice. The introduction of Clearfield™ rice hybrids (non-transgenic, genetically modified rice resistant to imidazolinone herbicides that inhibit the acetolactate synthase "ALS" enzyme) not only improved weed management in rice but also had higher yield potential compared with previous conventional rice cultivars. In 2004, the Clearfield™ rice cultivars accounted for 5–16 % of the total rice acreage in South Central USA, which increased about 400 % by 2014 with the introduction of improved and high-yielding Clearfield™ rice inbred (e.g., CL261) and hybrid (e.g., CLXL729, CLXL745) cultivars (Hardke 2015; Salasi and Deliberto 2010). However, the area under Clearfield™ rice has started to decline due to increasing ALS inhibitor-resistant weeds in this system (Hardke 2015).

California is presently the most productive rice-growing region in the world with an average yield of 9.5 t ha^{-1} (2014) (USDA NASS 2016). Rice producers in California particularly prefer short- to medium-duration cultivars. Calrose cultivars are popular in California since their release in 1948 (Johnston 1958), and now progenies of improved Calrose cultivars occupy nearly 80 % of the current rice area. Apart from these, small area of specialty varieties is also planted, such as sweet rice (also called mochi, glutinous, or waxy), arborio types (Italian short-grain rice with high amylopectin starch content), and aromatic long grains including conventional and a basmati type.

Some of the other notable breeding and varietal development efforts in the USA include the introduction of "Sierra" – an aromatic long-grain rice for southern USA to compete with basmati rice, which is typically imported from India and Pakistan. Sierra is currently being grown under both conventional and organic management systems. "Neches" is the first waxy variety developed for southern USA, providing a market opportunity that has been traditionally filled by imports from Thailand (USDA-ARS 2016).

The Clearfield™ rice cultivars have been widely cultivated throughout the mid-southern USA. However, evolution of ALS inhibitor resistance in prominent rice weeds such as *Echinochloa* spp. (Riar et al. 2012; Osuna et al. 2002) (*E. crus-galli*, *E. colona*, and others) and sedges (*Cyperus esculentus*, *C. iria*, *C. difformis*, and *Schoenoplectus mucronatus*) and pollen-mediated transfer of herbicide resistance from Clearfield™ rice to weedy *O. sativa (*Burgos et al. 2014*;* Shivrain et al. 2007*;* Gealy et al. 2003*)* have led to the loss of this technology in recent years. There is a need for alternative herbicide-resistant rice technologies for effectively managing ALS inhibitor-resistant weeds. In this direction, BASF Corporation is in the process of commercializing Provisia™ rice (Webster et al. 2015) which is also a non-transgenic, herbicide-resistant rice technology that endows resistance to the ACCase group herbicide quizalofop. The Provisia™ technology will facilitate the effective control of ALS inhibitor-resistant weedy *O. sativa* and other weeds. Provisia™ rice is expected to be adopted in rotation with Clearfield™ rice, which will control ACCase inhibitor-resistant weeds. However, due to cases of multiple resistance to ALS and ACCase inhibitor-resistant herbicides (Heap 2016; Fischer et al. 2000), sole reliance on these two herbicide-resistant technologies would not be sustainable. It is important to note that several *Echinochloa* populations in the Mississippi River Delta have evolved resistance to ACCase inhibitor herbicides (Norsworthy et al. 2013; Ruiz-Santaella et al. 2006; Tehranchian et al. 2016). Given this, the longevity of the Provisia™ rice technology is dependent on the adoption of diversified weed management practices.

6.6.2 Central America

Availability of improved varieties increased in recent years in Central America through a regional cooperative program lead by FLAR (Latin American Fund for Irrigated Rice), allowing the release of a number of high-yielding varieties. Almost no hybrid rice is planted in the region. In most Central American countries, few varieties capture most of the planted area, regardless of the cropping system practiced. In Panama, for instance, two varieties derived from FLAR program (IDIAP 145-05 and IDIAP 152-05) released in 2005 (Camargo 2006) occupy about 50 % of the total rice area. Likewise in Costa Rica, the variety “Palmar 18” is also from FLAR, which was released in 2006, and is planted in about 45 % of the rice area (CONARROZ 2016). Clearfield™ rice was introduced in Costa Rica in 2004 and later in Nicaragua and Panama. Readily adopted by farmers initially, Clearfield™ rice provided a valuable tool to selectively control weedy *O. sativa* in cultivated rice. Unfortunately, poor management and noncompliance of the stewardship guidelines and other agronomic factors resulted in the rapid spread and prevalence of imidazolinone-resistant weedy *O. sativa* and the failure of the technology in several areas across the three major Central American rice producers (Valverde 2013).

6.6.3 South America

Rice varieties adapted to different environmental conditions and fulfilling the market needs are the goals of rice breeding programs in South America. Due to the differences in climate and soils among the rice production regions, the largest rice producers have their own breeding programs, allowing for the breeding of varieties adapted to local conditions and market niches. Alternatively, institutions work cooperatively to create varieties and test their adaptation in different countries. Grain yields have drastically increased in the region with the introduction of semidwarf cultivars brought from the International Rice Research Institute (IRRI), beginning with the introduction of the variety IR8 (Zorrilla et al. 2013). These semidwarf varieties have enhanced food security and reduced rice grain costs (Maclean et al. 2002).

Working collaboratively with the International Center for Tropical Agriculture (CIAT), FLAR assisted the development of rice cultivars to partner countries in the region. The rice breeding program established from the partnership of FLAR and CIAT and other public/private entities aims to address the needs of the tropical and subtropical regions, with the goals of developing rice with high yield potential, resistance to blast and other pathogens, lodging resistance, tolerance to harvest delays, and high cooking quality (Zorrilla et al. 2013) In particular, resistance to rice “hoja blanca” virus (RHBV) in the tropics and cold tolerance in the temperate regions are of importance for genetic improvement. Cold tolerance is a valuable trait particularly in Southern Brazil, Uruguay, and Argentina where low temperatures often occur during the planting window.

6.7 Major Production Constraints

6.7.1 Water

Irrigation water limitations are a growing challenge to rice production in several areas. Estimates indicate that about 1600 liters of water is required to produce 1 kg of rice (Pimentel et al. 2004). According to Tran (Tran 1997), about 55 % of the world’s rice area is irrigated, with a water use efficiency of 50–80 %. Irrigation costs are typically high in rice production given the high amounts of water use and elevated costs associated with pumping. Irrigation by intermittent flooding can enhance water use efficiency in rice (de Avila 2014). Other irrigation water conservation practices are discussed under the section on crop management. A major problem related to irrigated rice is the dwindling water supply. In the USA, rice is irrigated principally from groundwater resources, and in many areas, groundwater is depleted faster than it could be recharged (Konikow 2011). The rate of groundwater depletion reached 8 km^3 $yr.^{-1}$ during 2000–2008 in the “US Gulf Coastal Plain” (Konikow 2013). Groundwater depletion adversely impacts the long-term sustainability of water supplies to help meet the crop’s water needs. It is estimated that within a decade, some aquifers will no longer be available. Efficient water saving systems, improved cultivars, and crop management tactics are needed to be developed to enhance water use efficiency in rice. Availability of quality irrigation water is another constraint because water salinity is a problem in all continents (Rengasamy 2006). Salinity issues are usually caused by seawater intrusion, oscillation of soil water table, and irrigation water with high amount of salts. As salinity conditions can severely impact plant stand and yield, adequate soil drainage and water quality monitoring are best practices to mitigate this problem. The development of salt-tolerant cultivars is a great contribution from rice breeding efforts. Research in this area needs to be continued.

6.7.2 Soil

Soil nutrient deficiency or toxicity can be a problem in rice production. Flooding alters various biological and chemical processes in the rice root zone, influencing the availability of various mineral nutrients. The impact of flooding on nutrient availability is likely to be enhanced under low hydraulic conductivity and the presence of a hard pan. Iron toxicity is a common physiological disorder occurring in flooded soils. The stress caused by high concentrations of iron in the soil solution can cause 12–100 % yield loss (Sahrawat 2010). Developing cultivars tolerant to iron toxicity and improved fertilizer management are efficient techniques to minimize this problem. In addition to reduced nutrient availability/nutrient toxicity, certain organic acids are also formed under flooded conditions that can affect rice growth and development. Furthermore, rice paddy is one of the most important anthropogenic sources of greenhouse gases such as methane (CH_4) and nitrous oxide (N_2O). Rice water management and improved cropping systems are important tools to mitigate greenhouse gas emissions from rice paddy.

6.7.3 Pests

Weeds, diseases, and insects are some of the major constraints to rice production in the Americas (see Sect. 8.3). Among the diverse group of weeds infesting rice fields, *Echinochloa* spp., weedy *O. sativa*, and *Cyperus* spp. have been problematic for decades. A very important emerging issue is the rapid evolution and spread of herbicide-resistant weeds in the rice system. Plant diseases and insects, in general, are more of a concern in tropical climates as there are fewer insect and disease problems in temperate regions than in the tropics. Pest occurrence and pressure in rice are affected by climate, crop rotation, and production practices. The most important rice diseases in the Americas include *Magnaporthe* spp., *Sclerotium* spp., *R. solani*, and *R. oryzae*. The most important insects infesting rice fields are *Oryzophagus* spp., *Oebalus* spp., and *Tibraca limbativentris*. The extent of damage caused by diseases and insects is highly variable, depending on rice management and climate. Rice breeding with tolerance to major insect pests and diseases will help address this issue, along with the development and implementation of integrated management practices.

6.7.4 Climate

IRRI recognizes that the global environmental change (GEC) will have a negative impact on rice production worldwide (IRRI 2015). Air temperature is expected to increase due to GEC, and heat stress will be a serious concern particularly in tropical areas. It is estimated that an increase in air temperature by 1 °C can cause 10 % reduction in rice grain yield (Peng et al. 2004). Further, GEC is expected to raise seawater levels (NRC (National Research Council) 2011). Salinity-related problems are expected to increase in rice production areas along coastal regions.

While high temperatures can be a problem for rice production in tropical areas, low temperatures will be a concern in temperate regions. Low temperatures, when occurring during sensitive periods such as seed germination or reproductive stages, can severely affect rice yield. Further, solar radiation is an important climatic variable that will directly influence rice yield potential. The GEC is expected to reduce the quantity and quality of photosynthetically active radiation (PAR) and thereby yield potential.

Another important climatic constraint in the Americas is the rainfall variability caused by “Southern Oscillation” that promotes the “El Niño” and “La Niña” phenomena. In El Niño years, the weather is usually dry in North America and Northern South America (Northern Brazil), whereas in the southern parts of South America (Southern Brazil, Uruguay, and Argentina), rainfall frequency and intensity are greater than the normal. Conversely, in La Niña years, a reversal in weather pattern is expected. High rainfall events can have a severe impact on rice yield, due to the direct effect of flooding during crop establishment or harvest, reduction in solar radiation, and increase in pest pressure. Sparse rainfall and dry conditions can severely impact rice yields due to inadequate supply of irrigation water.

6.7.5 Extension

Lack of adequate extension infrastructure and fragmented program implementation are important constraints to achieve increased rice yields, especially in the Central and South American countries. In the USA, Extension Service is well established, linking producers’ needs with research conducted at the universities. In Central and

South America, extension activities are carried out predominantly by private companies that reach mainly large farms or by the sale force of agrochemical companies. There is a lack of intensive extension to small- and medium-size rice growers. This is a major hurdle in achieving coordinated adoption of best management practices and stewardship of technologies on a regional or national scale. Private-public partnerships among research institutes, millers, and farmers have been successful in the southern zone (Argentina, Southern Brazil, and Uruguay) for an effective technology assessment and adoption system, allowing for high yields and efficient farming.

6.8 Crop Management

6.8.1 Fertilizer Management

The nutrient pool in rice production fields is highly dynamic due to prolonged flooding and its influence on the activity of soil microbial populations responsible for nutrient transformation. Among the essential nutrients, nitrogen, phosphorous, potassium, sulfur, iron, and zinc are generally limiting or unavailable for uptake in rice soils (Synder and Slaton 2001). However, nutrient deficiencies and fertilizer requirements are field-specific and vary considerably across the region. Nitrogen is the most limiting nutrient in rice cultivation because of high crop demand, coupled with high losses from the soil via ammonia (NH_3) volatilization, nitrification-denitrification processes, and nitrate leaching (Buresh et al. 2008). For judicious and profitable nitrogen management in rice, it is important to select a suitable nitrogen fertilizer and formulation and apply the precise amount at the right time with appropriate placement in soil (Norman et al. 2013).

Ammonium or ammonium-releasing fertilizers such as ammonium sulfate and urea are typically the best sources of nitrogen for flooded rice crop (Norman et al. 2009). Most rice varieties in the Americas require 130–200 kg N ha^{-1} to produce satisfactory yields with good milling quality (Synder and Slaton 2001). However, the response to fertilizer application depends on soil type, variety, growth stage at application, cropping system, and straw management (Synder and Slaton 2001). Soil testing is the best way to determine the amount of nitrogen fertilizer needed to fill the gap between crop demand and soil supply (Norman et al. 2013). Nitrogen should be applied early in the season and incorporated into the soil to reduce volatilization losses. In drill-seeded rice, nitrogen applications are recommended 2–3 days prior to flooding to minimize losses from the soil. Alternate flooding and draining influence the nitrification-denitrification process and increase nitrogen losses from the soil. The N losses from applied urea were estimated up to 60 % in tropical soil (Ghosh and Bhat 1998; De Datta 1995). Tropical conditions in Latin American countries lead to high nitrogen losses due to high temperatures and rainfall. The urea fertilizer coated with sulfur, urease inhibitors, and other biodegradable materials can reduce up to 50 % of the ammonia volatilization losses depending on soil type (Junejo et al. 2009). Split application of coated urea improves crop quality and soil fertility compared to single or preplant application. Splitting of nitrogen doses across critical growth stages helps in achieving higher crop yields. For instance, Espinosa (Espinosa 2002) has found that application of nitrogen in three splits consisting of 20 % at planting time, 20 % at tillering, and 60 % at flower initiation provided the best rice yields. However, the standard split method assumes that all soils of a given textural class (i.e., clay or silt loam) require the same N rate, but such an approach may sometimes result in under- or overfertilization with N (Norman et al. 2013). To improve N fertilizer rate recommendations for rice producers, the N-STaR (the Nitrogen Soil Test for Rice) procedure was developed and recommended in North American rice-growing regions. This test can measure the soil's ability to supply N, and the N compounds quantified using N-STaR (amino sugar-N, amino acid-N, and NH_4-N) are not prone to loss due to leaching or denitrification. Thus, the N-STaR method enables N fertilizer prescription on an individual field basis for different rice cultivars (Norman et al. 2013; Roberts et al. 2012).

Phosphorous requirement of rice is less and deficiencies are less common. As phosphorous availability improves with flooding, deficiencies can be observed with alternate wetting and drying, due primarily to temporary fixation of phosphorous in soil (Hardke 2013). Preplant broadcast- or band-applied phosphorous remains available throughout the season. However, adequate phosphorous must be supplied prior to the tillering stage because any deficiency after this period may result in yield loss (Norman et al. 2013). Phosphorous application rates usually vary from 30 to 65 kg ha^{-1}, and the best approach is to make applications on the basis of soil test results (Synder and Slaton 2001).

Potassium is required in substantial quantities to maintain the nutrient balance in soil-plant system. Evidence suggests that potassium plays a critical role in abiotic and biotic stress tolerance (Amtmann et al. 2008; Cakmak 2005; Kant and Kafkafi 2002). Potassium deficiency could trigger susceptibility to diseases or infestation of certain insect pests (Wang et al. 2013). Most of the potassium is accumulated in rice straw; therefore, removal of rice residue from the field warrants application of 60 to 120 kg K_2O ha^{-1} (Williams and Smith 2001). Zinc deficiencies are frequent in rice-growing areas in the Americas, particularly in high pH soils. Adequate drainage is recommended to alleviate zinc deficiency, and, in severe cases, foliar application of zinc fertilizer may be required (Espinosa 2002).

6.8.2 *Irrigation Management*

Most of the area under rice cultivation in North America is irrigated in contrast to Central and South America, wherein only about one-fourth of the total rice area is under irrigation (Zorrilla et al. 2013). Rice is generally cultivated under flooded conditions to meet high water demands of the rice crop and achieve weed suppression with standing water. In drill-seeded rice, the general practice is to establish a permanent flood (5–10 cm depth) from 30 to 45 days after planting until 2 weeks prior to harvest. In wet-seeded rice, the water level is initially kept low to allow for seedling emergence and root establishment. The fields are typically drained when varieties show problems of straight head (a severe Zn deficiency symptom), prior to application of certain herbicides and/or when rice water weevil infestations are substantial.

The increasing concerns about water scarcity has fueled interest in alternative irrigation management strategies in rice, including dry direct seeding, intermittent wetting and drying, and sprinkler irrigation (Crusciol et al. 2013; Nalley et al. 2015; Tracy et al. 2015). These approaches offer benefits such as water and labor savings and reduced costs of cultivation. For example, Nalley et al. (Nalley et al. 2015) reported 21–56 % increase in water use efficiency with alternate wetting and drying. Likewise, Westcott and Vines (Westcott and Vines 1986) and McCauley (McCauley 1990) reported 20–50 % reduction in water use in surface-irrigated rice, compared to flooded rice. A major consideration when using these alternative irrigation systems is proper monitoring and adjustment of weed management practices (Bagavathiannan et al. 2011). Moving away from permanent flooding increases the window for weed emergence. A grower needs to have a season-long weed management plan in place with the adoption of non-flooded systems.

6.8.3 Pest Management

Weeds, diseases, and insects pose a major threat to rice production throughout the Americas, causing significant yield and quality losses annually. Weeds such as *Echinochloa* spp. and weedy *O. sativa*, diseases such as *M. oryzae* and *R. solani*, and insects such as *Oryzophagus* spp. and *O. pugnax* are among the most economically important pests infesting rice fields in the Americas. Effective pest management is critical to securing the productivity and sustainability of rice in the Americas.

6.8.3.1 Weed Management

Weeds are the most widespread and most costly-to-manage pests in rice production. The annual loss estimation in US rice due to mismanagement of weeds is approximately $45 million (Gealy and Moldenhauer 2005). In Brazil the losses are estimated to be about US $200 million annually (Oerke 2006; Florez et al. 1999; Andres et al. 2016).

The spectrum of weeds and dominant weed problems vary greatly with location and rice production systems. In the US rice production, *Echinochloa* spp., weedy *O. sativa*, *Urochloa platyphylla*, *Sesbania herbacea*, and *Cyperus* spp. are among the most important weed species (Norsworthy et al. 2007; Smith 1989; Webster and Levy 2009). Among these, *Echinochloa* spp. and weedy *O. sativa* are the most predominant and troublesome weeds in rice culture in the Americas. Depending upon the cultivar used, weedy *O. sativa* and *Echinochloa* spp. can reduce rice yields by 82 % and 70 %, respectively (Smith 1988). *Echinochloa* spp. with resistance to propanil, quinclorac, clomazone, ALS inhibitor herbicides, and ACCase inhibitor herbicides have been documented in US rice (Heap 2016). Weedy *O. sativa* infestation is also prevalent in rice production in the Americas. In 2006, 60 % of the major rice-growing areas in the USA had weedy *O. sativa* infestation (Burgos et al. 2008), which declined to 25–30 % by the end of the decade due to the widespread adoption of Clearfield™ rice technology. However, this trend has reversed lately due to the development of ALS inhibitor resistance in weedy *O. sativa* in fields where the stewardship programs were not strictly followed. In Brazil, approximately 95 % of the irrigated rice fields are infested with weedy *O. sativa* (Gianessi 2014). Clearfield™ rice technology is the only tool available currently to manage weedy *O. sativa* within rice production fields.

Rice production systems in the USA employ a combination of cultural, mechanical, and chemical control options. Reliance on a single control method does not provide sustainable weed control; thus, integration of diverse weed management tools is utilized. The use of certified seed for planting is recommended to prevent the introduction of weedy *O. sativa* and other troublesome weeds. Planting certified seed is followed by rice growers in North America; there is zero to no tolerance to noxious weed seeds in certified rice seed. Seed certification laws and farmers' use of certified seed may be more lax in other regions of the Americas. A variety of cultural practices employed to manage weeds in rice production include, but are not limited to, crop rotation, preplant tillage, stale seedbed, high seeding rates, and proper water management to suppress weeds.

Herbicides remain an essential component of integrated weed management programs in different rice production systems. Proper selection of herbicides and time of application (weed growth stage) is key to achieving adequate weed control. In US rice production, application timings include burn-down prior to planting and/or preplant applications, preemergence (PRE) applications immediately after planting, delayed preemergence (drill-seeded only) applications at spiking, early-postemergence applications, mid-postemergence applications, preflood applications, and postflood applications. Among the various herbicide options, glyphosate and saflufenacil alone or in tank mix with other PRE herbicides are generally used for burn-down preplant applications. Clomazone, quinclorac, pendimethalin, and thiobencarb are important PRE/delayed PRE herbicides, whereas propanil, cyhalofop-butyl, fenoxaprop-p-ethyl, halosulfuron, bispyribac-sodium, quinclorac, saflufenacil, and carfentrazone are popular postemergence (POST) herbicides (Scott et al. 2013; CPRW (California Rice Production Workshop) 2016).

PRE application of clomazone is widely used in major rice-growing regions of the USA as it provides excellent control of *Echinochloa* spp., *Leptochloa* spp., and *Urochloa platyphylla*. Propanil has long been a popular POST herbicide and is still useful in fields where weed resistance to this herbicide has not yet evolved. Propanil provides excellent control of >50 weed species with proper selectivity at a minimum cost. Additionally, it is compatible with a great number of herbicides with other mode of actions. Quinclorac, pendimethalin, thiobencarb, fenoxaprop-p-ethyl, cyhalofop-butyl, and combinations of these are commonly used for grass control. For broadleaf weeds (including *Amaranthus* spp. and *Commelina* spp.), POST application of saflufenacil and bentazon are most commonly used. For aquatic weeds such as *Heteranthera limosa*, *H. reniformis*, *Ammannia robusta*, and *Sagittaria montevidensis*, chemical control includes application of thiobencarb preflood, bensulfuron-methyl early postflood, and 2,4-D from panicle initiation to panicle differentiation.

In Brazil, a recent shift in rice production from conventional to reduced- and no-till systems along with water-seeded systems have brought many changes to management practices (Andres et al. 2016). In lowlands of Southern Brazil, rice fields are generally left fallowed for one season for cattle grazing. In winter, cattle grazes on cold-adapted grasses and broadleaves (e.g., *Lolium* spp., *Trifolium* spp., and *Vicia sativa*), and in summer, they feed on grasses such as weedy *O. sativa*, *Echinochloa spp*., and some perennial grasses. Integration of crop-livestock in lowland rice fields is an important aspect of weed management in South and Central America (Marchezan et al. 2003). However, in irrigated and well-drained rice fields, rotation with glyphosate-resistant soybean is most common, which offers an effective option for controlling annual grasses such as weedy *O. sativa* and *Echinochloa* spp. Despite the increasing popularity of Clearfield™ rice technology in drained lowlands, the use of conventional rice herbicides is still common in South and Central American countries.

In Brazil, weed control begins with the use of residual herbicides in mixture with glyphosate as preplant application, especially in areas under reduced- or no-till systems with delayed flooding. Clomazone is the most commonly used herbicide for residual control of several grasses including *Echinochloa* spp. (Chaves and Garcia 2005). This PRE herbicide effectively suppresses propanil-resistant *E. colona* and is also used widely in Central America for this purpose (Riches et al. 1997; Valverde et al. 2000). As an early-POST application, propanil mixed with clomazone or pendimethalin is generally utilized to improve weed control (Andres and Machado 2004). In fields infested with *Echinochloa* spp. resistant to auxin-mimic herbicides, alternative products including pendimethalin, thiobencarb, and/or clomazone (PRE) provide adequate control. To manage ALS-resistant grass species, these herbicides are followed by POST applications of quinclorac or propanil. In Latin American countries such as Colombia and Costa Rica, ACCase inhibitor resistance has become an increasing issue. ACCase inhibitor-resistant *Echinochloa* spp. has not yet been reported in Brazil (Andres et al. 2016; Matzenbacher et al. 2014), although there is anecdotal information on its occurrence recently. Thus far, ACCase inhibitor herbicides (fenoxaprop-p-ethyl, cyhalofop-butyl, etc.) are potential alternatives for POST control of *Echinochloa* spp. resistant to ALS inhibitors or auxin-mimic herbicides (Matzenbacher et al. 2015a). These herbicide options allow farmers to adopt 3-year rotation of herbicides, which is helpful in managing resistant weeds (Andres et al. 2016).

6.8.3.2 Disease Management

Numerous fungal, bacterial, viral, and nematode diseases occur in all rice-growing regions, but only some of them significantly damage rice production (Groth and Lee 2002). In the US rice, *M. oryzae* and *R. solani* are the most economically important rice diseases. *Cercospora janseana* can cause yield and quality losses, especially at late plantings and in the ratoon (second) crop (Zhou and YK 2014). *Burkholderia glumae* and *Tilletia barclayana* can also cause severe damage to rice in epidemic years. The USA does not have any of the devastating viral and nematode diseases that occur in other rice production areas of the world. In the Central and South Americas, *M. oryzae* and "hoja blanca" virus are among the most important diseases limiting rice production (Pulver 2002). *Xanthomonas oryzae* pv. *Oryzae* and *C. oryzae* also occur in these regions and can cause economic damages in epidemic years.

There are several options available for managing rice diseases, but employing a single disease management tactic is rarely very effective. Rice producers must manage diseases through an integrated use of sanitation and quarantine, cultivar resistance, chemical control, biological control, and sound cultural practices to maximize efficacy. Effective disease management starts with the use of pathogen-free planting seed. Exclusion of a pathogen from a certain geographic area or from the rice host is the most effective method to prevent various diseases of rice. Plant quarantine and use of certified seed are two effective measures to achieve these goals. Cultivar resistance is an effective means to manage rice diseases. Although no cultivars highly resistant to multiple or all diseases are available, farmers should plant a resistant or partially resistant cultivar as often as possible. Cultivars with high levels of resistance to *M. oryzae* and *C. oryzae* are available, but not to *R. solani* or *X. oryzae*. Fungicides are available for seed and foliar treatments, but farmers often depend on foliar applications to manage diseases.

Proper timing of fungicide applications is key to effective disease control; routine field scouting for diseases especially from panicle differentiation stage is critical to identify suitable application timings. Although biocontrol options are promising, commercial applications are limited. Proper cultural practices can substantially reduce damage caused by diseases. Crop rotation reduces primary inoculum and, thus, the severity of diseases. Farmers should use recommended rates of seed and N fertilizer since excessive N and dense stands tend to increase the severity of many diseases. Planting early can avoid late-season disease pressure and thus reduce rice blast and other diseases. Establishing and maintaining a continuous flood are crucial for rice blast control.

6.8.3.3 Insect Management

Insect pests cause severe damage to rice from planting to harvest. The rice yield losses caused by insect pests in the USA and Brazil are 5 % and 10 %, respectively (Fritz et al. 2013). Each of the rice production areas has its unique complex of insect pests associated with its production ecosystems. Thirteen species are considered as major rice insect pests in the Americas (Pulver 2002). In the USA, *Oryzophagus* spp. and *O. pugnax* are the major invertebrate pests of rice. Other common insect pests that can cause significant damage in certain years and locations include *Diatraea saccharalis*, *Chillo plejedellus*, *Ostrinia nubilalis*, *Eoreuma loftini*, *Pseudaletia unipuncta*, *Spodoptera frugiperda*, *Chironomus* spp., *Hydrellia griseola*, and *H. wirthi* (Hummel et al. 2009; Way 2002; Way and Bowling 1991). In Latin America, especially in Brazil, the Brazilian rice water weevil (*O. oryzae*), which is not the same rice water weevil species found in the USA, is the most important insect pest in rice production (Gianessi 2014). *Tagosodes oryzicolus* is also an important pest of rice in Latin America, and it serves as a vector for "hoja blanca" virus, spreading this disease in most of the rice-growing areas of Central and South America.

The best approach to manage insect pests of rice is to use an integrated pest management (IPM) program consisting of tolerant cultivars, cultural practices, chemical control, and biological control. Field scouting for insect population is key to successful insect pest management. Cultivar selection is important since some cultivars are more tolerant than others to feeding by rice water weevils, rice stinkbugs, and stem borers. A variety of cultural practices can be used for insect pest control in rice. Early planting, draining the field to the point of cracking, and delaying the application of permanent flood are the three primary cultural control strategies for the management of rice water weevil. Early plantings can also reduce attacks by adult rice stinkbugs, armyworms, and stalk borers. Best production practices such as good seedbed preparation, proper seeding rate, and good water management can ensure strong, uniform rice stands and reduce damage caused by insect pests. Weak and thin stands are often susceptible to damage by these pests.

Insecticides are a vital component of the current IPM programs for most rice pests. Applications of insecticides with varying mechanisms of action remain the major method used to control insect pests of rice throughout the Americas. Rice pests can be controlled through seed and/or foliar insecticide treatments at proper timing. However, insecticides should be applied only when a pest population reaches or exceeds the economic threshold for treatment. Biological control has not been widely used for management of rice insect pests, but some naturally occurring parasites such as the wasps can play an important role in maintaining the populations of stem borers and other insect pests below damaging levels. Thus, conscious choice of insecticides that are safe to natural enemies should be promoted.

6.9 Emerging Issues

6.9.1 Herbicide Resistance

Herbicide resistance is an emerging issue in almost all of the rice-growing areas in the Americas. Despite large variability of environment, rice establishment system, crop management, and herbicides used, herbicide-resistant weeds have been occurring in several weed species. Herbicide resistance in the *Echinochloa* complex is the biggest problem throughout the Americas. A diversity of resistance mechanisms, including target-site mutations and enhanced metabolic detoxifications, have been documented in various *Echinochloa* populations across the Americas, sometimes with more than one mechanism within the same resistant population (Riar et al. 2013b; Matzenbacher et al. 2015b). The diversity of resistance mechanisms and occurrence of multiple resistance makes *Echinochloa* complex a serious issue, comparable with *Amaranthus*, *Conyza*, *Lolium*, and *Alopecurus* found in other production systems.

Herbicide resistance in *Echinochloa* spp. occurs to propanil, quinclorac, ALS, ACCase, very-long-chain fatty acid (VLCFA), and 1-deoxy-D-xylulose 5-phosphate (DXP) inhibitors. Crop rotation has not been sufficient to prevent the evolution of herbicide-resistant populations. Multiple resistance is particularly an emerging threat. The replacement of one herbicide with another, used continuously without management diversity, has resulted in the evolution of multiple herbicide resistance. In California rice, *E. phyllopogon* is the most dominant *Echinochloa* species. The herbicide resistance problem in *E. phyllopogon* surfaced with widespread resistance to the ALS inhibitor bensulfuron-methyl and was rapidly succeeded by resistance to ACCase, DXP, and VLCFA inhibitor herbicides (Yasuor et al. 2008) including multiple resistance in some populations. Multiple resistance in some of the Californian *E. phyllopogon* populations was endowed by enhanced metabolic degradation of the herbicides (Yasuor et al. 2008).

In Central America and northwestern parts of South America, herbicide-resistant *E. colona* is frequently found. *E. colona* resistance to propanil was first identified in Costa Rica (Fischer et al. 1993; Valverde et al. 2000) but is broadly distributed nowadays. In Bolivia, Colombia, Venezuela, and Guyana, rice is cultivated twice a year, mainly using pre-germinated systems (Carmona 2013). The double-crop and wet establishment systems used in these areas are a high-risk combination for the occurrence of herbicide resistance due to limited herbicide rotation, short window of herbicide application, and ideal conditions for rapid weed seed multiplication and dispersion. In most of these areas, quinclorac, ACCase, and ALS inhibitors have been widely used, and weed resistance to these compounds is common.

In Central America, propanil-resistant *E. colona* became noticeable after 20 or more years of its use, especially in areas of continuous rice production subjected to multiple (usually two or even three) propanil applications per rice cycle, either alone or in mixture with herbicides not active on *E. colona* (Valverde 2007). Propanil resistance in *E. colona* is endowed by the rapid metabolism (hydrolysis) of the herbicide to 3,4-dichloroaniline by an increased arylacyl amidase activity and its rapid conjugation to nontoxic forms (Leah et al. 1994; Leah et al. 1995). Based on this resistance mechanism, the rice-selective organophosphate herbicides, piperophos and anilofos, were developed as propanil synergists to control propanil-resistant *E. colona* (Valverde 2007; Caseley et al. 1996). This is the only case worldwide thus far by which a weed with nontarget site resistance to a herbicide has been commercially controlled using synergists. The introduction of ACCase inhibitor herbicides provided an alternative mechanism of action to combat propanil-resistant weeds. However, overreliance on the ACCase herbicides such as fenoxaprop and sethoxydim has resulted in *E. colona* populations evolving resistance to these herbicides, in Costa Rica and Nicaragua, respectively (Caseley et al. 1997; Riches et al. 1999). The introduction of bispyribac-sodium (ALS inhibitor) facilitated the control of multiple (propanil and ACCase inhibitors)-resistant *E. colona*, but resistance to bispyribac-sodium also evolved and was further aggravated by the use of imidazolinones in Clearfield™ rice (Valverde 2007).

Clearfield™ rice was introduced initially in Costa Rica in 2004 and later in Nicaragua and Panama. Poor management and compliance to the stewardship programs and other agronomic factors (Valverde 2013) resulted in the prevalence of imidazolinone-resistant *E. colona* and the failure of the technology in several areas across the three major Central American rice producers. Escapes of *E. colona* populations already resistant to bispyribac and cross resistant to imidazolinones were persistently treated with mixtures of quinclorac and propanil at advanced growth stages, thus selecting for low resistance levels to quinclorac (Valverde unpublished findings). *E. colona* has been successfully managed prior to planting using a stale seedbed approach (Valverde and Itoh 2001). For this purpose, glyphosate has been the herbicide of choice (Valverde et al. 2001). Unfortunately, glyphosate-resistant *E. colona* populations are now emerging in Costa Rica (Valverde, unpublished findings). Therefore, multiple-resistant *E. colona* populations that withstand herbicides belonging to five different mechanisms of action (the PS II inhibitor propanil, ACCase inhibitors, ALS inhibitors, auxinic herbicides, and EPSPS inhibitor glyphosate) are now a major threat to rice production in Costa Rica as well as in Panama and Colombia.

In Brazil, Argentina, and Uruguay, *E. crus-galli* is the most frequently found species of the *Echinochloa* complex. In Brazil, despite the intensive use of propanil since the 1980s, resistance to this compound has not occurred, perhaps due to the 2 or 3 years of fallow practiced to reduce weedy *O. sativa* infestations. However, an intensive use of quinclorac and ALS inhibitors has resulted in resistance to these herbicides (Schaedler et al. 2008). Herbicide-resistant weeds are less of a problem in Uruguay compared to other South American countries due to rotation with pastures.

Imidazolinone-resistant weedy *O. sativa* is another important issue in rice cultivation. The development of rice cultivars resistant to imidazolinone herbicides (Croughan 1998) provided an unprecedented tool for weedy *O. sativa* control within rice production fields. Improved weedy *O. sativa* control associated with this technology has substantially increased rice grain yields (approx. 2500 kg ha^{-1}), resulting in benefits at farm and regional levels comparable to that of the dwarf rice varieties introduced in the 1970s (Merotto et al. 2016). This technology has been widely used in the South Central USA and Southern Brazil, and its utilization is increasing in other rice-growing countries in the Americas (Carmona 2013). Gene flow from rice cultivars to weedy *O. sativa* has resulted in the prevalence of imidazolinone-resistant weedy *O. sativa*, challenging the longevity of the technology (Goulart et al. 2014; Sudianto et al. 2013; Valverde et al. 2013). In areas where the Clearfield™ rice technology is still effective, it is important to emphasize the value of adopting stewardship recommendations, which include diversified tactics and crop rotation in reducing the risk of resistance and improving the longevity of the technology.

Resistance in sedges is an emerging issue particularly in Arkansas and other parts of the South Central USA. Some of the important herbicide-resistant sedge species include *C. difformis* (propanil, ALS inhibitors), *C. esculentus* (ALS), *C. iria* (ALS), and *C. odoratus* (ALS). Other notable resistant weeds present at local scales include *Alisma plantago-aquatica* (ALS), *Ammannia auriculata* (ALS), *A. coccinea* (ALS), *Eleusine indica* (ACCase), *Fimbristylis miliacea* (ALS), *Ischaemum rugosum* (ALS), *L. panicoides* (ACCase), *L. scabra* (propanil), *S. montevidensis* (ALS, bentazon), and *Schoenoplectus mucronatus* (ALS, propanil) (Heap 2016).

The widespread occurrence of herbicide resistance in rice weeds warrants the adoption of integrated weed management (IWM) practices. Some of the important IWM measures include, but not limited to, the use of certified planting seeds, crop rotation, stale seedbed, routine field scouting, diverse herbicide mixtures/rotations applied at appropriate timings, and cleaning of farm machinery. The imidazolinone-resistant rice cultivars were considered by many farmers as a silver bullet strategy, but a failure to adopt sound stewardship practices has resulted in the loss of the technology in several areas. This precedence should be considered regarding the utilization of the new ACCase-resistant rice cultivars, which currently are in the process of commercialization (Harden et al. 2014).

6.9.2 Off-Target Movement of Pesticides

Off-target movement of pesticides from rice fields is a growing concern (Marchesan et al. 2007; Resgalla et al. 2007; Silva et al. 2009). Off-target pesticide movement affects nontarget organisms (Silva et al. 2009) and groundwater as well as surface water quality (Silva et al. 2011). After application, only a portion of the applied pesticide reaches the target (Gavrilescu 2005), whereas the rest is present in the broader environment, subject to various fates. Pesticides typically undergo degradation processes (biodegradation, chemical degradation, and photolysis), transport processes (drift, volatility, leaching, and runoff), and retention processes (absorption, adsorption, and desorption). The intensity of each process will determine the persistence, efficacy, off-target movement, and carryover potential of applied pesticides. The amount of pesticide lingering in the environment will depend on the physiochemical characteristics of the pesticide (Martini et al. 2012), the amount applied, and crop production practices (Martini et al. 2013). Contamination of drinking water supplies with pesticides applied to rice fields is of particular concern. Marchesan (Marchesan et al. 2007) and Resgalla (Resgalla et al. 2007) found rice pesticides in rivers in Southern Brazil. To reduce off-target movement of pesticides, it has been recommended in Southern Brazil that rice paddy should not be drained for at least 30 days after application of pesticides. Intermittent flooding and drying can be a tool to reduce pesticide transport to the off-target environment (Martini et al. 2013).

Herbicide injury to rice due to off-target movement (drift and carryover) is another emerging concern in several areas. Herbicide injuries and yield penalties are magnified when they are combined with low temperature stress (Martini et al. 2014), which is common in early-seeded rice in parts of South Central USA and Southern Brazil. Depending on the crop rotation practiced and the burn-down herbicide(s) applied, drift/carryover issues can be variable. Glyphosate drift is often common because of its widespread use in the Americas. In countries such as the USA and Brazil, glyphosate-resistant crops are grown nearby rice fields, and herbicides are often applied using airplanes, leading to high drift potential. Spray drift is the major reason behind the ban of some important rice herbicides in California. Herbicide carryover is an important constraint to rice production in Brazil. In particular, the imidazolinone herbicides used in the Clearfield™ rice system have long half-life in paddy fields and can damage non-tolerant crops grown in rotation (Marchesan et al. 2010; Pinto et al. 2009).

6.10 Harvesting and Postharvest Handling

Rice harvesting and postharvest handling is important to maintain the quality and quantity of the yield and to reduce postharvest losses. Rice harvest window is highly variable across different locations, but proper selection of harvesting date is crucial (Siebenmorgen et al. 2013). High head rice yields are achieved when harvesting occurs at about 28–32 days after heading, when 80 % of the grains have changed color, or when harvesting at 19–21 % seed moisture content for long-grain cultivars and 21–24 % for medium-grain cultivars (Siebenmorgen and Hardke 2013). Combine harvesters are commonly used for harvesting in the USA, Brazil, and Uruguay (Mejía 2002). While postharvest losses are reduced through mechanical handling, cost of mechanical harvesting is a limitation for small producers especially in the developing countries (Lantin 1997). For proper storage and better milling characteristics, paddy is cleaned free of foreign matter and dried to 12–15 % seed moisture content (Gardisser and Saichuk 2014). On-farm drying is not recommended if the moisture content is >20 % because the grain quality deteriorates due to inefficient drying. A temperature of 40–43 °C is suggested for drying rice seeds, and this can be achieved with shade drying. Higher temperatures can lead to physicochemical disorders in the grain (Zheng and Lan 2007). The choice of a drier system normally depends on several factors, including drying capacity needed, simplicity of installation and operation, portability, heat source, and the initial cost of purchase. A diverse range of drying equipment and methods are available for rough rice, and advanced computer-based models have been developed to assist agricultural research workers or farmers in their selection of dryers for a given crop and situation (Dissanayake 1991).

The rice milling operation involves removal of the husk (dehusking) and the bran (polishing) to prepare the edible portion (endosperm) for consumption. On average the hull constitutes 20 % and the bran is 10 % of the original rough rice weight (Siebenmorgen et al. 2016). The milled rice yield (MRY) indicates the mass of the milled rice expressed as the percentage of the original dried rough rice mass, which typically ranges from 68 to 72 % (Siebenmorgen et al. 2016). Head rice yield refers to the yield of kernels retaining three-fourth or more of the original length (after removing broken rice). Head rice yield is also expressed as percent of the original dried rough rice mass and can vary from 0 (all kernels are broken) to 70 % (no kernels are broken). The milling quality is often expressed as the ratio of the head rice to milled rice yield (Siebenmorgen et al. 2016). However, the extent of loss during the milling operation may vary depending on a variety of factors, including variety of paddy, condition of paddy during milling, degree of milling required, type of rice mill used, operator's skills, and level of insect pest infestations (Mejía 2002).

6.11 Summary

Rice will remain an important crop in the Americas due to its vital role in food security and rural economic prosperity. Irrigation water shortage is a growing limitation to rice production in many areas, but development of suitable alternative production methods will be important. Continued technological advancements will facilitate increased resource use efficiency and improved rice yields. Breeding for improved varieties will be critical to address production challenges caused by changing climatic conditions. Pesticide resistance, particularly weed resistance to herbicides, and off-target movement of pesticides need immediate attention for research and development. A strict compliance of stewardship protocols and implementing best management practices are critical to preserve the sustainability of new technologies in rice production and reduce their negative impacts on the broader environment. More investments in research and extension are vital to secure sustainable rice production in the Americas.

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Chapter 7
Rice Production in Australia

Ali Ahsan Bajwa and Bhagirath Singh Chauhan

7.1 Summary

The rice production is a profitable agro-based industry in Australia. Although the area under rice cultivation and total production in Australia is very little in proportion to global rice production, its unique agronomy and crop management are notable. Since the inception of rice cultivation in irrigated areas of New South Wales (NSW) and Victoria states of Australia in the early twentieth century, this industry has progressed by leaps and bounds. Rice sowing methods in Australia include wet seeding in cultivated water bays, direct dry seeding in previous crop stubbles, and direct seeding on permanent raised beds. The medium-grain temperate varieties perform best under Australian conditions, and many of these have been developed locally through breeding, keeping in view the local climatic and edaphic conditions. Australian farmers produce the most water-efficient rice in the world. The escape from major pests and diseases and good management practices allow them to obtain the highest yield per hectare as compared to all other rice-producing countries. Several weeds infest rice fields in Australia, but effective management through herbicides is in practice. The overall crop husbandry is well mechanized right from sowing to harvest. An integrated system connects farmers, industry, and the government stakeholders which ensures the excellent crop production followed by excellent

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processing and marketing within and out of the country. The declining water resources, the terminal cold stress during the reproductive stage of rice crop, and the environmental concerns are major constraints to the Australian rice industry. However, the highest water-use efficiency, rapid adoption of innovative conservation technologies, development of new cultivars suitable for the changing climate, and integrated research with holistic approach are strong features of this enterprise.

7.2 Introduction

The rice production in Australia is quite different from the rest of the world in the perspective of production, processing, and marketing. The rice is produced only in a few regions of the country due to strict regulations about water and land use for rice production. The Riverina region of NSW (latitude 33–36°S) is the main hub of rice production in Australia (Thompson 2002). Almost all the rice is grown in this valley with exception of a small acreage in Queensland and Western Australia. However, the cultivated area and production from those sites are negligible. The Riverina Valley is irrigated by two major rivers, Murrumbidgee and Murray, and the rice crop uses up to 70 % of the available irrigation water. The overall share of rice production from Australia to global production might be only 1 %, but the sustainable production under harsh climates is a success in its own way (Humphreys et al. 2006). With the highest yields per unit area and water-use efficiency, Australian rice has proved its worth internationally (Khan et al. 2010; RGA 2015). The adoptions of technology, immense coordination between growers, policy makers, and marketing authorities, and good management practices have made Australian rice a success. The rice production system in Australia has gone through a series of transformations, and many agricultural scientists quote the Australian rice industry as a fine example of agricultural innovations and technology adoption. One of the leading agricultural development departments in Australia, the Rural Industries Research and Development Corporation (RIRDC), ranked Australian rice industry as the world leader in agricultural innovation, resource conservation, sustainable production, and environmental safety on the eve of launching Rice 2012–2017 Research and Development (R&D) Plan (RIRDC 2015).

The dry climate and shrinking water resources are the main limiting factors to the growth of Australian rice industry (Lewin and Heenan 1985; Humphreys et al. 2006). The rice growers have managed to sustain rice production in spite of immense pressure from the government and community (Lewis 2012). It has emerged as a great enterprise being run by the farmers and government jointly without any added subsidies. Australian rice has not only gained popularity due to high yields and water-use efficiency but is also well known for its high quality (SunRice 2015). Semidwarf temperate varieties developed by Australian scientists have performed very well under local conditions. The rice growers pay special attention to water use, land use, and environmental protection by adopting various efficient production systems suitable under different cropping rotations (McDonald 1994; Thompson 2002; Humphreys et al. 2006). The lower incidence of natural pests and diseases under Australian conditions is an added benefit (Stevens et al. 2006). The future of rice production in Australia is bright, keeping in view the pace of ongoing research and development.

This chapter focuses on the crop husbandry, management practices, and use of innovative technologies for rice production in Australia. The basic principles and practices of rice production in Australia have been discussed. The developments over time and future endeavors have also been highlighted along with the elaboration of constraints and opportunities.

7.3 History

Rice was one of the earliest crops introduced in Australia after British settlement in the continent. Having vast experience of growing rice in America and India, English people also tried rice farming in different regions of Australia. However, due to the climatic differences, varying soil fertility, and other management constraints, it was mostly unsuccessful. Although northern regions of Australia have plenty of water, rice production was never successful there mainly due to iron and manganese toxicity in the soil and pest problems (RGA 2015). Some sources indicate the entry of rice seeds to Australia back in the 1850s when Chinese people came here as a part of famous “Gold rush.” Rice was cultivated first time in 1906 in Murray River basin near Swan Hill by a former Japanese parliamentarian, Isaburo Takasuka, who was given 80 ha for this purpose by the state government of Victoria (RGA 2015). Although it was an unsuccessful experience due to droughts and floods, he continued the effort, and the crop was grown and produced on a commercial scale in 1914. In the 1920s, the opportunity of growing rice as irrigated crop in Murray-Darling basin was availed, and since then, it has become the core area of rice production in Australia (RGA 2015). Almost all the Australian rice production comes from this area. The first commercial rice crop was produced in 1924 by a group of eight farmers in Murrumbidgee Irrigation Area (MIA) (around Leeton and Griffith). The seed was imported from California by the NSW government. In 1928, the NSW government established the Rice Marketing Board to regulate the marketing and export of Australian rice. A company, Ricegrowers Limited (SunRice), was registered to buy and export Australian rice, and it is the sole authorized buyer of rice produced in NSW for domestic and international outlets since then.

During the World War II, rice was declared as an essential and precious food commodity, and the Commonwealth pushed the NSW government to reach the target of 100,000 tons during that period (SunRice 2015). The task was nearly impossible due to shortage of water in the Burrinjuck dam; however, keeping in regard the crucial, the NSW government decided to improve cooperation with farmers and to expand the area under rice cultivation (RGA 2015). In cooperation with the Ricegrowers’ Association of Australia (RGA), the NSW government formed the Rice Production Committee (RPC), and rice cultivation was started in Murray Valley in addition to MIA. After the establishment of RGA, the rice production in Australia flourished a lot. A royal commission not only investigated the causes of rice failure in MIA but also focused on the cooperation and marketing. The "SunRice" worked efficiently on storage, milling, processing, packaging, sale, and export of Australian rice. The first rice mill was opened in 1951 in Leeton. Temperate rice varieties from California performed well in Riverina. In the 1950s, the rice production recovered a boost in Australia. The number of rice farmers in MIA increased from 368 in 1950 to 591 in 1955. In addition, 310 growers also started rice cultivation in Murray Valley by 1955. Such a substantial increment improved the economy of that area, and rice production became a profitable industry (SunRice 2015). Nowadays, over 1500 farm businesses are linked with rice production in MIA of NSW and Murray Valley of NSW and Victoria (RGA 2015).

7.4 Area and Production

Rice in Australia has an area of 52,000 ha, a production of 819,000 tons, and an average yield of >10 t ha^{-1}. More than 85 % of Australian rice is exported to over 70 countries across the globe (RGA 2015). During the last decade, Australia has increased rice yield per hectare by 30 % while reducing the water consumption by 60 %, which is a remarkable achievement by any means in modern-day agriculture. Rice production shares 11 % of the total irrigation water available for agriculture. Some of the key facts about Australian rice are given in Table 7.1. In the recent years, the production has decreased due to drought. The highest yield per unit area, excellent quality, 50 % less usage of water for every kilogram of rice produced as compared to the rest of the world, and environmental friendly cultural practices make Australian rice superior and unique.

Table 7.1 Latest facts and figures about rice in Australia (2013–2014)

Cultivated area	52,000 ha
Annual production	819, 000 tons
Per capita consumption	10 kg per annum
Domestic use	15 % of total production
Export	85 % of total production
Average national yield	10.7 t ha^{-1}
Farm gate value of industry	A$ 350 million
Total value including exports	A$ 800 million
Rank in Australian exported grains	Third
Rank in Australian exported agricultural commodities	Ninth

Sources: Australian Bureau of Statistics (2015), National Farmers' Federation (2015), SunRice (2015)

7.5 Production Methods and Cropping Systems

All the rice sown in Australia is irrigated, mostly through river water or sometimes groundwater. The rice is grown in summer season in Riverina, and sowing starts in the month of October. The rice seeds are either dispersed aerially in flooded fields (wet-seeded) or directly drilled in dry soil (dry-seeded) followed by irrigation (Thompson 2002). Pre-germinated seeds and dry seeds are sown for wet seeding and dry seeding, respectively. For dry seeding, 120 kg seed ha^{-1} is drilled in 15 cm apart rows at the depth of 1–3 cm. First irrigation is applied immediately after seeding, but water is drained out after 24 h (Lewin and Heenan 1985). Rice fields are kept flooded for most part of the growing season. A water depth of 15–25 cm is maintained depending upon the crop growth stage. A layer of water protects rice plants from high day temperatures during early growth stages and also provides insulation against very low night temperatures after the month of January. Under certain instances, flooding is started after the three-leaf stage, but this prolongs the crop (Thompson 2002). The soil type for rice production is very important and given special attention in Australia. The heavy soils with high water holding capacity are usually preferred. Moreover, the whole area allocated to one farmer for rice production cannot be cultivated in one season. In this regard, farmers have to get approval from respective irrigation corporation (the Murrumbidgee Irrigation Limited, Murray Irrigation Limited, or Coleambally Irrigation Cooperative Limited) before having a license from the state government (Thompson 2002; RGA 2015). The land suitability is determined before the approval to grow rice mainly on the basis of soil water holding capacity, infiltration rate, and runoff. No farmer can grow rice beyond a set limit on his farm. The subsoil water percolation should also be less than 200 mm (Beecher et al. 2000; Thompson 2002). Sowing is mostly done on a flat surface, but the raised bed system has also gained popularity due to high water-use efficiency and yield improvement. The land is prepared using laser land levelers, and usually the whole farm layout is designed in such a way that large bays are formed with strong soil embankments (bunds) to hold water (RGA 2015).

In Australia, the rice crop is usually followed by a fallow season of up to 6 months as the intensive cropping systems are not common. Hence, rice is grown as sole crop in most of the rice farming areas (Humphreys et al. 2006). However, some farmers also include winter crops like wheat, barley, and some legumes. As most of the rice fields are kept ponded for most part of the growing season, soil moisture levels are very high for the succeeding crops (Humphreys et al. 2006). The productivity of winter crops grown on rice-based permanent beds was increased by 26 % (Thompson and North 1994). The major benefits in this system were sufficient soil moisture, easy drainage, facilitated interculture and farm operations, and less losses during harvesting (Tisdall and Hodgson 1990; Beecher et al. 2003). Earlier, a single rice crop in 5 years in rotation with legume-based pastures was also common. Still many farmers practice such rotations because they cannot grow rice on more than a specified area (McDonald 1979). The direct drilling of rice in pasture sward is useful to reduce the cost of production (Lewin and Heenan 1985). The seed is drilled at the rate of 140 kg ha^{-1} with a triple disk seeder in a well-grazed dry pasture at 15 cm row-row distance. A knockdown herbicide is applied prior to seeding to avoid pasture regrowth. The permanent water stand is established after three-leaf stage (Lewin and Heenan 1985). This rotation significantly improves rice yield because of improved soil fertility, suppression of diseases and pests, and weed control due to well-established preceding pasture crop (Lewin 1979).

7.6 Varieties

Temperate rice varieties are grown in Australia. More than 80 % of Australian rice is raised from semidwarf medium-grain japonica varieties (Thompson 2002). Similar varieties performed well in the Mediterranean regions and California due to a similar kind of climate (Thompson 2002). Eleven varieties are being successfully grown in Australia. These have high water-use efficiency and yield potential. Australian scientists have developed most of these varieties through breeding by using germplasm from California and other temperate rice-growing regions (RGA 2015). The first semidwarf medium-grain variety, M7, was introduced in 1983 in Australia and proved successful (Humphreys et al. 2006). Several semidwarf varieties were developed and released for commercial use in the following years. Those varieties had multiple quality traits, but major focus was given to the water-use efficiency. Since 2001, almost 97 % rice cultivation in Australia was based on such semidwarf medium-grain varieties (Humphreys et al. 2006). During 4 years field trails in the eastern Murray Valley, the semidwarf medium-grain cultivars, Illabong and Amaroo, produced 9.3 and 10.1 t ha^{-1} rice grains, while a tall variety, Calrose, produced 7.9 t ha^{-1} (Humphreys et al. 2006).

Several semidwarf varieties, including Amaroo, Doongara, Illabong, Jarrah, Kyeema, Langi, Millin, and Opus, were locally developed and released for Australian rice growers during 1987 to 1999. Those varieties covered a large area due to the added benefits of efficient water use and higher yield (Humphreys et al. 2006). The rice industry of NSW not only regulates the development and dissemination of new varieties but also ensures the pure seed availability to all the registered growers. However, growth period reduction to improve the water-use efficiency also caused yield reduction (Reinke et al. 1994; Williams et al. 1999). Developing cold-tolerant (during reproductive stage) varieties in addition to high yield and water-use efficiency is another major task of breeding program (Farrell et al. 2000).

7.7 Irrigation Management

Water shortage is a major concern in Australian rice production. Australia is the driest continent of the planet, and, thus, the freshwater is considered a precious resource (RGA 2015). The rice-producing area of Australia is mainly irrigated by the Murray and Murrumbidgee rivers. The average evapotranspiration during the whole growing season is 1200 mm. Soils having root zone drainage of more than 200 mm ha^{-1} are restricted for rice production (Thompson 2002). Water use for rice production in Australia is almost 50 % less than that for the rest of the world (RGA 2015). Rice growers have improvised the irrigation management in a number of ways to improve the water-use efficiency. The alternate flooding and drying system (intermittent irrigation) is one such conservation method in which water is applied to saturate the root zone every week, but fields are not kept flooded continuously until panicle initiation starts. Rice reproduction being a highly sensitive water limitation, fields are kept flooded onward from panicle initiation (Thompson 2002). In this way, 23–26 % water saving is achieved in comparison with permanent flooding after the three-leaf stage. Heenan and Thompson (1984) concluded that the intermittent irrigation system was water saving, without reducing the yield and quality of rice at Yanco, MIA. The localized irrigation for the rice crop grown on raised beds is another way to enhance irrigation efficiency. Borrell et al. (1997) reported up to 32 % water saving in this system in Queensland. Australian rice water productivity has significantly improved over the years mainly due to higher yields and reduction in water use (Humphreys and Robinson 2002). The improved water-use efficiency of Australian rice is mainly attributed to yield improvement through an innovative approach, rapid technology adoption, varietal improvement, excellent regulations like the Ricecheck approach by the NSW Department of Primary Industries (DPI), improved nitrogen management, and judicious irrigation scheduling (Russell and Dunn 2001; Macadam et al. 2002; Ciavarella et al. 2003; Humphreys et al. 2006). On the other hand, the substantial cuts in water use through setting up a water-use limit, reduction in deep percolation, intermittent irrigation approach, raised bed technique, and good crop husbandry practices have also improved the overall water-use efficiency in rice (Muirhead et al. 1989; Bouman and Tuong 2001; Humphreys et al. 2001, 2003; Beecher et al. 2002; Thompson et al. 2003; Khan et al. 2004; Humphreys et al. 2006).

7.8 Nutrient Management

Nitrogen (N) is the only mineral nutrient applied in the form of fertilizer to rice crop in Australia. A rare use of other macro- or micronutrient-based fertilizers also exists. N is mostly applied in the form of urea as a basal dose, but the amount of fertilizer depends on the rotation being followed (Lewin and Heenan 1985). The use of anhydrous ammonia and ammonium sulfate as N fertilizer has also been reported (McDonald 1979). On the lands where rice is grown in a rotation with legume pastures, usually no N fertilizer is applied. N fixed biologically through legume pastures is sufficient for the rice crop in the following season. Chapman and Myers (1987) found that rice grown in rotation with soybean and sesbania crops had no N fertilizer requirements and the yield was also significantly higher as compared with the rice grown in rotation with fallow fields. Up to 260 kg N ha^{-1} was added by these legumes, which was available for the rice crop. However, the soils having low fertility status needed around 200 kg N ha^{-1} for semidwarf short-grain rice varieties (Lewin and Heenan 1985).

In case of wet-seeded aerially sown rice, the whole N fertilizer is mixed in the soil before flooding, whereas the N is applied at the three-leaf stage in dry-seeded rice when farmers start holding water in those fields (Boerema 1970). There might be N top dressing in some cases depending on rice variety, crop rotation, and total N requirement (Heenan and Lewin 1982; Bacon and Heenan 1997). In a broader view, the average N application rate was reported to be 120 kg ha^{-1} (Batten et al. 2001). The decision about the right dose and timing of N application is very important (Humphreys et al. 2006). The overdose at an earlier vegetative stage may lead to lodging and sterility particularly under cooler conditions during the reproductive phase (Williams and Angus 1994). In some soils, the N supply to plant roots may be hindered due to high ambient temperatures, which is another key factor to determine the adequacy of N fertilizer (Angus et al. 1994). Humphreys et al. (2006) suggested that increasing the N-use efficiency will also improve the water-use efficiency and may help to further enhance the productivity of Australian rice. Farmers still do not have reliable standard protocols to measure the actual N requirements for rice in a particular kind of soil. Research in this area may further boost the vertically oriented Australian rice industry.

7.9 Weed Management

Weeds are a major problem in rice fields, depending upon the sowing method and crop rotation (Lewin and Heenan 1985). A variety of weeds infest rice fields in Australia (Table 7.2). Usually the weed diversity and weed density in wet-seeded rice is much lower than dry-seeded rice. The most problematic weed species in Australian rice are *Echinochloa* spp. Earlier, the postemergence herbicides, thiobencarb, molinate, and propanil, were commonly used to control *Echinochloa* spp. with varying degrees of efficacy (Fisher et al. 1966; Penman and Jones 1984). Some farmers also used to apply postemergence herbicides in water during flooding (Fisher et al. 1966). In such a case, the efficacy was improved, but consideration of water depth and herbicide dose remained critical (Lewin and Heenan 1985). Aerial sowing of rice in flooded bays had problems of *Cyperus difformis* L. which was controlled through application of MCPA (Nott et al. 1974). However, the application of MCPA had a negative effect on rice growth, especially when applied before tillering. The application after tillering was ineffective because weed had already caused substantial losses to crop growth due to resource competition (Cox 1980). The use of thiobencarb to control *C. difformis* has also been reported but a risk of damage to small rice seedlings was associated with it (Lewin and Heenan 1985). The existence of *Typha* spp., especially in a rice crop grown in shorter rotations, was also reported (Lewin, 1979). The best management strategy for *Typha* spp. was found to be the manual eradication and herbicide (MCPA) application during the fallow period (Lewin and Heenan 1985).

Table 7.2 Weed flora of Australian rice

Weed species	Family	Reference
Alisma lanceolatum With.	Alismataceae	McIntyre and Barrett (1985)
Ammannia spp.	Lythraceae	Hill et al. (1990)
Azolla filiculoides Lam.	Azollaceae	McIntyre and Barrett (1985)
Cyperus difformis L.	Cyperaceae	Nott et al. (1974), Cox (1980), McIntyre and Barrett (1985), Lewin and Heenan (1985)
Cyperus eragrostis Lam.	Cyperaceae	McIntyre et al. (1991)
Damasonium minus (R. Br.) Buchenau	Alismataceae	McIntyre and Barrett (1985), Lewin and Heenan (1985)
Diplachne fusca (L.) P. Beauv. ex Roem. & Schult.	Poaceae	McIntyre et al. (1991), Lewin and Heenan (1985)
Echinochloa colona (L.) Link	Poaceae	Penman and Jones (1984), McIntyre and Barrett (1985), Lewin and Heenan (1985)
Echinochloa crus-galli (L.) P. Beauv	Poaceae	Fisher et al. (1966), McIntyre and Barrett (1985), Lewin and Heenan (1985)
Echinochloa microstachya (Wiegand) Rydb.	Poaceae	McIntyre and Barrett (1985)
Echinochloa oryzoides (Ard.) Fritsch	Poaceae	McIntyre and Barrett (1985)
Elatine gratioloides A. Cunn.	Elatinaceae	McIntyre and Barrett (1985)
Eragrostis parviflora (R. Br.) Trin.	Poaceae	McIntyre et al. (1991)
Ludwigia peploides (Kunth) P.H. Raven	Onagraceae	McIntyre and Barrett (1985)
Lythrum hyssopifolia L.	Lythraceae	McIntyre and Barrett (1985)
Marsilea drummondii A. Braun	Marsileaceae	McIntyre and Barrett (1985)
Paspalum paspaloides (Michx.) Lams. Scribn.	Poaceae	McIntyre and Barrett (1985), Lewin and Heenan (1985)
Rumex crispus L.	Polygonaceae	McIntyre et al. (1991)
Rumex dentatus L.	Polygonaceae	Lewin and Heenan (1985)
Rumex tenax Rech. f.	Polygonaceae	McIntyre and Barrett (1985)
Sagittaria montevidensis Cham. & Schltdl.	Alismataceae	McIntyre and Barrett (1985)
Scirpus spp.	Cyperaceae	Hill et al. (1990)
Typha domingensis Pers.	Typhaceae	McIntyre and Barrett (1985)
Typha orientalis C. Presl	Typhaceae	McIntyre et al. (1991)

In a classic study, McIntyre and Barrett (1985) compared the weed flora of flooded rice in NSW and California in order to understand the species composition and diversity under similar cultural and management practices. In NSW, 55 weed species existed, while 60 were present in California. Only 13 species were found to be common at both sites, most of these were well-recognized rice weed species globally. However, large proportions (73 %) of weed species were native in NSW and shifted from aquatic habitats to wetland rice (McIntyre and Barrett 1985). Due to this reason, many native weed species were well adapted to flooded rice and were hard to manage. The effective weed control through herbicides has benefited the rice production in Australia for decades. However, the consistent use of herbicides has caused the evolution of herbicide resistance. The resistance against many commonly used herbicides was reported two decades ago (Hill et al. 1994; McDonald 1994). Taylor (2010) compared the efficacy of four herbicides against weeds in direct-seeded rice in Cobram, Victoria, in order to find a suitable alternative for benzofenap and molinate. Pentoxazone failed to control all the weeds and also had a toxic effect on rice crop when applied at the rate of 100–400 g a.i. ha^{-1}; however, etobenzanid (750 g a.i. ha^{-1}) provided effective control for most of the weeds, including *E. crus-galli* (Taylor 2010). The injury to rice crop was substantial when the rate of etobenzanid was increased to 1000 g a.i. ha^{-1}. Another herbicide, saflufenacil (200–300 g a.i. ha^{-1}), provided complete control of all major weeds with adequate crop tolerance (Taylor 2010). Hence, etobenzanid and saflufenacil might be the alternate herbicides with different modes of action from that of molinate and benzofenap and, thus, could offer a good strategy against herbicide-resistant weeds. Further research is needed in this area with emphasis on integrated weed management options.

7.10 Insect Pests and Diseases

There are only a few insect pests and diseases associated with rice crop in Australia; however, substantial yield losses are caused by them (Lewin and Heenan 1985). The bloodworm (*Chironomus tepperi)* is one of the most important rice insects, as it chews the root tips of rice and also shoots sometimes. To avoid the losses, different chemical insecticides are used, especially in aerially sown rice crop (Jones 1968). Incidence of armyworm (*Pseudaletia convecta*) and leaf miner (*Hydrellia* spp.) as insect pests on Australian rice has also been reported (Lewin and Heenan 1985). However, they can also be effectively controlled through several chemical insecticides. In addition to insects, snails are important pests in rice grown in rotations with winter cereals (Lewin and Heenan 1985). The snails may damage the young rice seedlings and, thus, have the ability to affect the crop stand at early growth stages. Similarly, algal growth in direct-drilled and aerially sown rice also causes a reduction in plant growth (Lewin and Heenan 1985). The use of copper sulfate was found to be effective against both snails and algae (Lewin and Heenan 1985). The nematode, *Paralongidorus australis*, infestation in root zone of rice in Queensland resulted in poor crop growth and yield due to root syndrome (Stirling and McCulloch 1984). Ducks are important bird pests of aerially sown rice and can be controlled through shooting, scare guns, and colored lights (Lewin and Heenan 1985).

Australia is relatively safe from major rice diseases occurring in other rice-growing regions of the world (Cother and Lanoiselet 2003). Only a few diseases have been reported to cause substantial yield losses. The bacterial leaf blight was one of the first reported diseases in Australian rice. The bacteria *Xanthomonas oryzae* was the causal agent of leaf blight and caused severe damage to rice crop in the northern territory (Aldrick et al. 1973). Aggregate sheath blight and sheath spot caused by *Rhizoctonia oryzae-sativae* and *Waitea circinata*, respectively, have also been reported in Australian rice (Lanoiselet et al. 2001, 2002a). According to Lanoiselet et al. (2005), *Rhizoctonia* spp. surviving in the rice fields can cause the disease in the following season. Although rice blast caused by *Magnaporthe grisea* has not been reported in Australia, predictive modeling (CLIMEX and DYMEX) has indicated that many sites in NSW have suitability for a potential outbreak of this devastating disease (Lanoiselet et al. 2002b). Glume blotch and stem necrosis caused by *Pseudomonas syringae* pv. *Syringae* and *Pantoea ananas*, respectively, are also important diseases of rice in Australia (Cother 1974; Cother et al. 2004). Stevens et al. (2006) reported the larvae of chironomid communities (Diptera: Chironomidae) to be causing substantial yield losses in rice crop in NSW. Preventive measures and chemical control have been found to be effective against these pathogens.

7.11 Harvesting, Postharvest Management, and Marketing

Rice fields are drained out after the crop has attained a certain degree of maturity. The timing of draining rice fields in Australia is critical because early drainage can cause lodging and reduction in grain weight (Lewin and Heenan 1985). On the other hand, if drainage of fields is delayed, the crop remains wet at harvest and the grain quality is deteriorated (Lewin and Heenan 1985). Usually, the physical observation serves as a tool for the determination of the right time for drainage (Boerema and McDonald 1965). The late dough stage for lower grains in a panicle is recognized as an ideal stage for field drainage (Hartley et al. 1977). However, in the case of heavy soils, it can be done when lower grains are still in the milky stage. In Australia, the rice crop is harvested at 22 % grain moisture. It improves the grain quality and reduces losses during milling (RGA 2015). Harvesting starts in March and continues up to May, depending upon the crop rotation. All the harvesting is done mechanically through large grain combine harvesters (RGA 2015). These harvesters remove straw and collect paddy (non-milled rice) in large collecting bins from where it is further transferred to containers attached to the operating tractors. In this way, the whole process of harvesting is completed in a single operation.

Paddy after harvesting is transferred to storage facilities through trucks. In the storage facilities, rice is sorted according to varieties and then kept in large bins where moisture contents, humidity, and temperature are regulated through computer-based sensors (RGA 2015). Hot conditions during storage facilitate the drying process. However, further processing is done in milling units. The rice is transported from storage facilities to mills. In mills, the dehusking (removal of husk from paddy) is done to obtain brown rice. Very few people prefer to consume brown rice. Hence, large portion of brown rice is further milled to remove bran, and white rice is obtained after polishing. White rice is further graded and packaged before marketing (RGA 2015). Almost all the rice produced in Australia is sold to Ricegrowers

Limited, which markets it by the brand name of SunRice. SunRice is one of the world biggest rice food companies which markets a large number of rice products across Australia and many other parts of world. A huge proportion of Australian rice (85 %) is exported to over 60 countries in Asia, North America, and the Middle East. Australian rice industry operates without any subsidies in contrast to rice industries of many other countries (RGA 2015). It competes with rice products from many countries in international markets. Every year, rice exports contribute significantly to Australian economy.

7.12 Challenges and Opportunities

Rice production in Australia is on a very limited scale. There are several constraints due to which the area under rice cultivation is limited. The major factor hampering the rice production is limited availability of irrigation water (Lewin and Heenan 1985; Thompson 2002; Humphreys et al. 2006). The climate is mostly arid and water flow in the rivers is less. The rice crop requires a large amount of water and consumes the lion's share out of available water resources. Although the government has imposed many different restrictions to limit the rice-growing area, the changing climate and ever-depleting water resources demand further reductions in rice cultivation (Lewis 2012). In NSW, the rice crop uses the highest amount of irrigation water, and many environmentalists are concerned about the decreased water flow in rivers (Thompson 2002). Not only the limited water availability but certain environmental factors also caused uneven water distribution. According to some ecologists, the reduced water flow in rivers is dangerous for aquatic life and biodiversity sustained through it. However, the Ricegrowers' Association of Australia claims that Australian rice production is purely based on resource conservation especially water saving, and keeping in view the stats, that claim is also realistic (RGA 2015). As climatic conditions are not favorable throughout Australia, a limited area in NSW and Victoria is capable of growing rice (RGA 2015). The major limiting factor is temperature during the growing season (Humphreys et al. 2006). As temperate varieties of rice are successful in Australia, the low temperatures toward their maturity cause substantial yield reductions (Horie et al. 1997). The terminal low temperatures affect the process of grain filling and spike sterility. In contrast to other rice-growing regions, the high temperatures during anthesis are not much harmful (Matsui et al. 2007). The poor stand establishment in dry-seeded rice is another emerging problem. Weed flora has also changed due to changing production systems. For instance, weed infestations have increased in intermittent-irrigated rice systems (Hill et al. 1990). These challenges have posed difficulties to sustainable rice production in Australia.

High-yielding and stress-tolerant varieties, the adoption of short-term rotations, water-saving sowing methods, and irrigation scheduling provide the basis for sustainable rice production in Australia under limited natural resources (Humphreys et al. 2006; Khan et al. 2010; Lewis 2012). Fortunately, very few of the harmful rice insect pests and diseases do exist in Australia, which is really helpful to obtain superior quality production (Thompson 2002). The integrated production regime is another feature of the Australian rice industry which allows sustainable production without subsidies (Lewin and Heenan 1985; Thompson 2002). It also enables the farming community to easily market their product across the country and in the international markets.

7.13 Conclusions and Future Directions

Rice production in Australia may be regarded as a success story in terms of remarkable yield achievement, water and energy savings, innovative adoption of technologies, excellent marketing and export system, and economic benefits. The integrated crop management and optimized postharvest processing enable Australian growers to obtain high-quality produce on a sustainable basis. Although the shrinking water resources and changing climate are haunting Australian rice production which is already restricted to a small area and under observation all the time, the conservation management practices adopted by farmers may help to sustain this production.

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Chapter 8
Rice Production Systems

A.N. Rao, S.P. Wani, M.S. Ramesha, and J.K. Ladha

8.1 Introduction

Rice is one of the major staple cereals with more than 3.5 billion people depending on rice for more than 20 % of their daily calorie intake (IRRI, Africa Rice and CIAT 2010). It is estimated that the rice production must increase by 114 million tons by 2035, but farmers must achieve it under significant threats from climate change (Suzanne et al. 2012) coupled with decreasing amount of available agricultural land, labor, and water for agriculture and increased costs of all inputs. Increasing global food production with minimal adverse impact on resources and the environment is the greatest challenge for food security (Ladha et al. 2015). Hence, for ensuring food and nutritional security of the rice-growing world, it is essential to make consistent efforts to understand and develop innovative rice production systems that are resource use efficient, higher net income generating, and environment friendly.

This chapter attempts to summarize the information on rice production systems, resources used, crop productivity attained, the challenges encountered, and possible research needs for improving productivity in rice production systems, to meet the future food demands.

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8.2 Rice Production Systems Classified

Rice is grown in more than 100 countries spread across six continents and in a wide range of environments. Globally rice is grown on a total area of approximately 158 million ha, producing more than 700 million tons annually (470.6 million tons of milled rice) in 2015 (USDA 2016). About 90 % (nearly 640 million tons) of the rice in the world is grown in Asia (Fig. 8.1), with China and India as the lead producers. Africa and Latin America produce about 25 million tons each. In Asia and sub-Saharan Africa, almost all rice is grown on small farms of 0.5–3 ha per household. Rice is produced in many different environments and in many ways. The rice production systems were classified by different scientists, in different countries, and in different ways at different times, depending on the context. The environmental and socioeconomic conditions of rice production vary greatly from country to country as well as from location to location which affected the performance of rice production in the past and influences the potential of improving future rice production. Rice is cultivated under temperate, subtropical, and tropical climatic conditions with the weather varying from arid and semiarid to subhumid and humid. Based on soil water conditions, rice production ecosystems include irrigated lowland, irrigated upland, rainfed lowland, rainfed upland, and deep water/floating ecosystems (Fig. 8.2). Socioeconomically, farm size cultivated by a household in South Asia, Southeast Asia, East Asia, and Africa is generally small, which varies from less than 1 ha to few hectares. In the developed countries, the farm size is larger.

8.2.1 *Classification of Rice Production Systems Based on the Environment Where the Rice Is Grown*

The classifications of rice environments are based on altitude (upland, lowland, deep water) and water source (irrigated or rainfed).

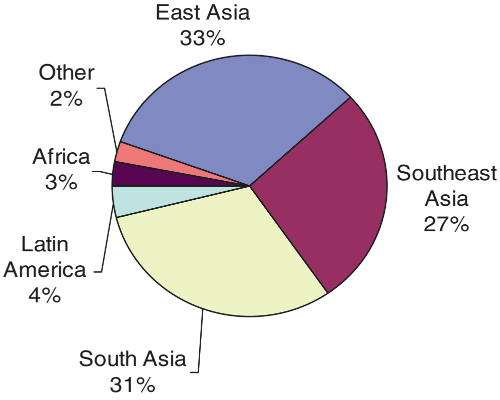

Fig. 8.1 Percent of global rice production by region. 2011 (www.irri.org)

1. *Lowland rice production system* – Continuously grown under flooding (paddy rice). Lowlands are further categorized as:

(i) *Irrigated lowland production system*: Irrigated lowland rice system produces 75 % of the global rice production from about 93 million ha. Asia has around 56 % of the world's all crops in total irrigated area, of which 40–46 % is of rice. Rice occupies 64–83 %, 46–52 %, and 30–35 % of the irrigated area in Southeast Asia, East Asia, and South Asia, respectively (GRiSP, 2013). The countries with the largest areas of irrigated lowland rice are China (31 M ha), India (19 M ha), Indonesia (7 M ha), and Vietnam (3 M ha) (Dobermann and Fairhurst 2000). Irrigated lowland rice production system is the most important rice production system for food security of Asian countries. The most common method of establishment of this production system is transplanting. Rice is also established by direct wet or water seeding in irrigated lowland production systems. In transplanting method of rice establishment, rice seedlings are raised in a rice seedling nursery for 20–40 days prior to their manual or mechanical transplanting into the flooded field. Irrigated rice is grown in bunded fields or paddies, which are surrounded by a small levee that keeps the water surrounded. The farmers, who have small holding (0.5 to 2 acres) of land, normally maintain in the field a water layer of 5–10 centimeters (cm) during the major period of the cropping cycle (Bouman et al. 2006). One or more rice crops can be grown per year as the water supply is assured. Rice–rice and rice-upland cropping systems are followed. Irrigated rice receives about 40 % of the world's irrigation water

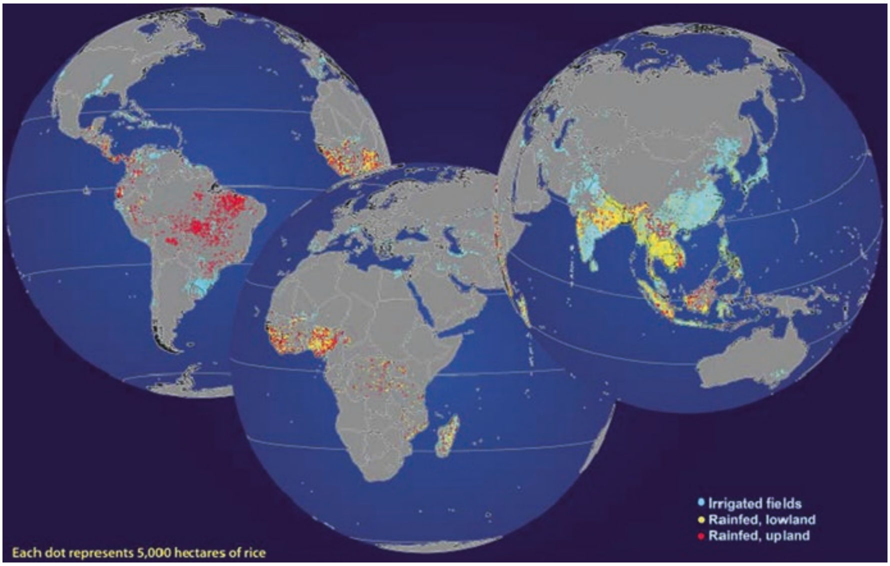

Fig. 8.2 Major global rice-growing areas and ecosystems (GRiSP 2013)

and 30 % of the world's developed freshwater resources. The average productivity of irrigated lowland rice is higher (about 5.4 t/ha) (GRiSP 2013).

Rice is grown under irrigated systems in temperate climatic conditions of Australia, Bhutan, Central Asia (Kazakhstan and Uzbekistan), Chile, China, Japan, Korea, Nepal, Russia, Turkey, the USA, and Uruguay (Jena and Hardy 2012). In Bhutan, Nepal, and part of China, rice is established by transplanting. In the irrigated lowlands of Korea, rice is mostly established by machine transplanting method with hand transplanting practiced on only 1.2 % of marginal rice land. However, with decreased labor availability and rising labor cost, farmers are motivated to shift from transplanting to direct seeding as is practiced in other temperate rice-growing countries. In temperate climatic regions where a single irrigated rice crop is grown per year, productivity of 8–10 t/ha or more is achieved (http://ricepedia.org/rice-as-a-crop/where-is-rice-grown).

(ii) *Rainfed lowland production system (including flood prone)*: Rainfed lowland rice is grown in river deltas and coastal areas of South Asia, parts of Southeast Asia, and essentially all of Africa, where the fields are bunded and flooded with rainwater for at least a part of the cropping season. In this system, the major method of rice establishment is transplanting, but direct wet or dry seeding is also practiced. Globally, around 19 % of the world's rice is produced from 52 million ha of rainfed lowlands (GRiSP 2013). Abiotic stresses, such as drought (in around 27 million ha) and uncontrolled flooding ranging from short-duration flash floods to deep water submergence with 100 cm of water for a few months (20 million ha), prevail due to highly uncertain rainfall and salinity (Dobermann and Fairhurst 2000; Bouman et al. 2005; Wassmann et al. 2009; Clermont-Dauphin et al. 2010; Mackill et al. 2010). Water is 1 to 5 m deep and is supplied by rivers, lakes, or tides in river mouth deltas. Water depth may exceed 5 m in some parts of Bangladesh, as well as in the Mekong, Kariba Dam (Tongas), and Niger deltas. Deep water or floating rice is established by broadcasting rice seed in plowed fields and is normally grown unbunded, in regions where the water level rises quickly after the beginning of the monsoon. Traditional long tiller and few sprout varieties are cultivated. The rice plants elongate and float as the floodwater advances; thus, it is named as "floating rice." Due to the risk involved in growing rice in these most difficult environments, farmers tend to use fertilizers rarely and avoid using improved rice varieties. Thus the rice productivity in rainfed lowland areas is very low (1–2.5 t/ha) (Dobermann and Fairhurst 2000).

2. *Rainfed upland rice production system* – In this system the rice is grown under high rainfall. Rainfed upland rice production system is often used by subsistence farmers in Asia, Africa, and Central America. It can be found in environments ranging from low-lying valley bottoms to steep sloping lands with high runoff. The rice in this system is established by broadcasting or dibbling in dry soil prior to the onset of monsoon or during the rainy season. The aerobic condition prevails in the soil throughout the rice cropping season. Traditionally, one rice crop

is grown annually with minimal input application. Of rice produced in around 15 million ha, rainfed uplands account for about 4 % of the global total rice production (GRiSP 2013). Two-third of rainfed upland rice is in Asia (Bangladesh, Cambodia, China, India, Indonesia, Myanmar, Thailand, and Vietnam). In the rice belt of Africa, upland areas of central and western part represent about 40 % of the African area under rice cultivation and employ about 70 % of the region's rice farmers (Bouman et al. 2007). The ecosystem is extremely diverse, including fields that are level, gently rolling, or steep, at altitudes of up to 2000 m and with rainfall ranging from 1000 to 4500 mm annually. Soils range from highly fertile to highly weathered, infertile, and acidic, but only 15 % of total upland rice grows where soils are fertile and the growing season is long. The productivity of upland rainfed rice is low (about 1 t/ha) because of many biotic, abiotic, and social constraints and the use of the local varieties by farmers that fail to respond to improved management practices. The major constraints of this system are drought, problem soils, and pests (weeds, diseases, insects, nematodes) (Bouman et al. 2007; GRiSP 2013).

3. *Irrigated upland or aerobic rice production system* – In aerobic rice systems, the rice plant is established by direct seeding in non-puddled, non-flooded fields and managed intensively as an upland crop (Tuong and Bouman 2003). Aerobic rice systems can reduce water requirements for rice production by over 44 % relative to conventionally transplanted systems, by reducing percolation, seepage, and evaporation losses, while maintaining yields at an acceptable level (Bouman et al. 2005). There were efforts in the 1980s to develop and popularize the irrigated upland rice or aerobic rice production in Brazil using sprinkler irrigation systems. In northern China, aerobic rice production is being practiced currently at a limited scale in freely drained fields, as a response to water shortage. The areas planted with aerobic rice varieties were estimated to be about 80,000 ha in China and 250,000 ha in Brazil (http://www.fao.org/agriculture /crops /thematic-sitemap/ theme/spi/scpi-home/managing-ecosystems/sustainable-rice-systems/rice-what/en/). In India, the aerobic rice system adoption has been initiated in states like Karnataka (Rao et al. 2015).

8.2.2 Classification of Rice Production Systems Based on the Method of Rice Establishment

The major methods of rice establishment in the world are transplanting and direct seeding. Thus, based on the method of rice establishment, the rice production systems may be categorized as (a) transplanted rice (TPR) production systems and (b) direct-seeded rice production systems. Direct-seeded rice production systems may be further categorized as (i) dry-seeded rice (dry-DSR) production system, (ii) wet-seeded rice (wet-DSR) production system, and (iii) water-seeded rice (water-DSR) production system. These production systems are briefly described below.

8.2.2.1 Transplanted Rice (TPR) Production System

Rice is commonly grown by transplanting seedlings into the puddled soil (wet tillage) in lowlands of Asia (e.g., India, Indonesia, Bangladesh, Myanmar) and Africa (e.g., Madagascar, Mali). Transplanting of rice is done manually (Fig. 8.3) or by machine (Fig. 8.4). The manual transplanting method involves growing of seedlings in a nursery and replanting of 20–30-day-old rice seedlings to puddled soils. The rice seedling nursery may be raised on wet bed or dry bed or dapog or mat or modified mat methods depending on the locality, soil type, rice ecosystem, and the resource availability (for details, refer to http://www.knowledgebank.irri.org/step-by-step-production/growth/planting). In several Asian countries, the labor-intensive transplanted rice production systems are being practiced until now, where even the labor supply is abundant due to the population growth. For machine transplanting the rice seedlings are grown in trays or in mat-type nursery in which a thin layer of sol mixed with farm yard manure or compost is placed on a polythene sheet and rice seedlings are raised. Mats of rice seedlings from the trays or mat-type nursery are used for machine transplanting. In Asia, machine transplanters are now being used to establish rice crops in China, Japan, Korea, and Taiwan. In India, farmers started using it in states like Karnataka and Andhra Pradesh. The traditional TPR production system

Fig. 8.3 The manual transplanting method of rice establishment uses more labor, water, and energy as it involves processes such as rice seedling nursery raising, seedling pulling, and transplanting in flooded soil conditions (Photos by A.N. Rao)

has advantages such as adequate nutrient availability (e.g., phosphorus, zinc, iron) due to creation of anaerobic conditions (Sanchez 1973), assured seedling establishment, initial seedling vigor, and competitiveness against weeds (Rao et al. 2007). However, higher quantities of water are consumed in TPR in order to accomplish the processes such as puddling, surface evaporation, and percolation (Farooq et al. 2011). This production system is labor, water, and energy intensive and is becoming less profitable as these resources are becoming increasingly scarce. It also deteriorates the physical properties of soil, adversely affects the performance of succeeding upland crops, and contributes to methane emissions. However, TPR continues to dominate under certain environmental and socioeconomic conditions of the world.

8.2.2.2 Direct-Seeded Rice (DSR) Production System

Direct seeding of rice is done by (1) dry seeding (dry-DSR), (2) wet seeding (wet-DSR), and (3) water seeding (water-DSR) (Kumar and Ladha 2011). As the rice seeds are sown directly, the dry- , wet- and water-DSR methods are often jointly referred to as DSR. At present 23 % of rice area is direct-seeded globally (Rao et al.

Fig. 8.4 Rice establishment by using transplanting machine reduces the drudgery of women labor, reduces the cost of cultivation, and ensures optimum rice plant population (Photos by A.N. Rao)

2007; Kumar and Ladha 2011). Dry-DSR consists of sowing dry seeds on dry (unsaturated) soils. Seeds can be broadcasted, drilled, or dibbled. Dry-DSR production is practiced traditionally in most of the Asian countries in rainfed upland ecosystems and is also used in irrigated areas with precise water control as aerobic rice. In certain states of India, farmers are cultivating dry-DSR with the onset of monsoon and convert it to irrigated lowland rice after release of the assured canal water in the system (Fig. 8.5) (Rao et al. 2015). Dry-DSR and TPR in the furrow-irrigated raised-bed planting system were also tested (Singh et al. 2006, 2008) for attaining optimal water productivity in the rice–wheat system in the Indo-Gangetic Plains of South Asia. However, rice establishment on furrow-irrigated raised-beds is not currently popular among the rice farming community.

Wet-DSR involves sowing of pre-germinated rice seeds in wet (saturated) puddled soils. Wet- DSR is done by broadcasting the seeds on puddled soil or by using a drum seeder (Fig. 8.6). Wet-DSR is practiced in favorable rainfed lowlands and irrigated area with good facility of drainage as in Malaysia, Thailand, Vietnam, the Philippines, and Sri Lanka (Pandey and Velasco 2005; Weerakoon et al. 2011). DSR is becoming an attractive alternative to TPR. Asian rice farmers are shifting to DSR to reduce labor input, drudgery, and cultivation cost (Rao et al. 2007; Kumar and Ladha, 2011).The increased availability of short-duration rice varieties and cost-efficient selective herbicides has encouraged farmers to try this method of establishing rice (Balasubramanian and Hill 2002). It is quickly replacing traditional

Fig. 8.5 Dry-seeded irrigated rice sown by using seed cum fertilizer drill (Photos by A.N. Rao)

Fig. 8.6 (**a**) The drum seeder and (**b**) the crop of wet-seeded rice (*left*) sown by using the drum seeder (Photos by A.N. Rao)

transplanting in areas with good drainage and water control (Balasubramanian and Hill 2002). Rice is mostly direct-seeded, with only 6 % area under transplanting, in Latin America (GRiSP 2013). In the water-DSR, pre-germinated rice seeds (soaked and incubated for 24 h each) are broadcast in standing water on puddled (wet-water-DSR) or unpuddled soil (dry-water-DSR). The relatively heavyweight rice seeds sink in standing water, resulting in good anchorage. Water-DSR is used for rice establishment in irrigated lowland areas with good land leveling as in California (United States), Australia, and European countries specifically for managing problematic weeds such as weedy rice. In Asia, some countries like Malaysia are adopting it.

In this chapter, the method of rice establishment is considered as the major criteria for classifying rice production systems. The information of these rice production systems on the attained crop productivity, the resources used, and the challenges encountered will be discussed while highlighting the possible research needs for improving productivity in rice production systems to meet the future food demands.

8.3 Productivity of Different Rice Production Systems

Several studies have shown that productivity of TPR and DSR rice will be similar in a given environment provided that they are cultivated using best management practices (Rickman et al. 2001; Mitchell et al. 2004; Kumar and Ladha 2011). Traditionally under rainfed TPR areas, need of ponded water for customary practice of puddling delays rice transplanting by 1–3 weeks (Ladha et al. 2009) resulting in reduced yields. The puddled TPR production systems need a large quantity of water and labor, which are becoming scarce and costly, in addition to the drudgery to transplanting women and children. The profit margins were also reduced due to increasing water and labor cost for TPR (Pandey and Velasco 1999). Hence, a major shift from puddled TPR production system to DSR system is taking place in the irrigated areas of many developing countries in Asia (Pandey and Velasco 2005 , Rao et al. 2007). However, compared to TPR, lower yield was reported with wet- and dry-DSR production systems due to uneven or poor crop establishment; inadequate weed control; higher spikelet sterility than in puddled transplanting; higher crop lodging, especially in wet seeding and broadcasting; and micronutrient deficiencies (Rickman et al. 2001; Rao et al. 2007; Choudhury et al. 2007; Singh et al. 2005). Higher rice productivity was reported when these constraints were alleviated (Bhushan et al. 2007; Yoshinaga 2005).

The performance of different types of DSR production systems varied with countries depending on the cultural practices used, the environment, and their interaction (Kumar and Ladha 2011). Among DSR production systems, line/drill seeding (compared with broadcasting) and wet-DSR (compared with dry-DSR) were reported to yield higher. However, dry-DSR was found to be more resistant to drought with longer survival under drought period and may increase yield stability of rainfed rice than the wet-DSR and transplanted rice systems (Boling et al. 1998). The yield of dry-DSR and TPR systems were similar when irrigation was scheduled daily or at 20 kPa (Yadav et al. 2011a). In China, a meta-analysis revealed that the rice grain yield decreased in rice–rice cropping system and increased in rice-upland cropping system due to the adoption of zero tillage (ZT) (Huang et al. 2015), when compared to conventional tillage (CT). The responses of rice grain yield to ZT did not differ with rice establishment method (TPR or DSR), rice cultivar type (hybrid or inbred), ZT adoption duration (<3 years or 3–6 years or >6 years), and management of crop residues (residues removed or retained) (Huang et al. 2015).

Based on the data of several studies they reviewed, Kumar and Ladha (2011) reported that direct-seeded rice production systems had a lower cost of production by US\$ 22–80 ha^{-1} resulting in higher economic returns of US\$30–50 ha^{-1}compared with conventional puddled TPR production system. They reported the savings in production costs increased in the following order: ZT-dry-DSR > Bed-dry-DSR >CT-dry-DSR > CT-wet-DSR > CT-TPR.

8.4 Resource Use of Different Rice Production Systems

High cost of production and diminishing resources have led to a greater focus on improving the overall eco-efficiencies of agricultural systems (Keating et al. 2010) for achieving optimal agricultural outputs using less land, water, nutrients, energy, labor, and capital inputs in rice production systems.

8.4.1 Water

Irrigated lowland rice is typically grown under flooded conditions, and at the field level, it utilizes up to two to three times more water than other major food crops, due to the unproductive water flows, in the form of seepage and percolation to drains, creeks, or groundwater. This can amount to 60–80 % of all water inputs to rice (Tabbal et al. 2002). The water input for a typical puddled TPR per season was estimated to vary from 660 to 5280 mm depending on the growing season, climatic conditions, soil type, and hydrological conditions, with 1000–2000 mm as a typical value in most cases (Tuong and Bouman 2003). The overexploitation of groundwater to meet the high water requirement of TPR and water scarcity has become a major threat to the sustainability of rice production (Rijsberman 2006). The per capita availability of water is expected to decline by 15–54 % over the next 35 years in several countries of Asia (Gleick 1993), and by 2025, 15–20 million ha of rice lands will suffer some degree of water scarcity (GriSP 2013). Hence, increasing water use efficiency in rice production systems is essential (Ladha et al. 2015). In addition to the consumption of large amount of irrigation water and labor, the process of puddling results in subsurface compaction (Kukal and Aggarwal 2003).

The increasing shortage of water resources has led to the development and adoption of aerobic rice system, which saves water input and increases water productivity by reducing water use during land preparation and limiting seepage, percolation, and evaporation (Nie et al. 2012). In an aerobic rice system, the crop can be dry direct-seeded or transplanted and soils are kept aerobic through the major part of the growing season. Supplemental irrigation is applied when needed. Aerobic rice cultivars are adapted to aerobic soils and have higher yield potential than traditional upland cultivars. Grain yields of 5–6 t ha^{-1} can be reached in aerobic rice system (Nie et al. 2012).The micronutrient deficiencies such as Zn and Fe in aerobic rice are of major concern (Gao et al. 2006). Aerobic rice could considerably improve eco-efficiency in rice-based systems where water, labor, and energy are becoming increasingly scarce, and hence it is gaining importance in South Asia as an alternative to the conventional transplanted flooded rice system (Mahajan et al. 2013).

Dry-DSR production system helps to save irrigation water, especially in fine-textured soils (Yadav et al. 2011a, b). Dry-DSR with intermittent irrigation offers potential water savings at the field level due to reduced evaporation losses, intermittent irrigation, and avoidance of puddling. In dry-DSR and TPR production systems, significant irrigation water input decline was recorded with irrigation at 20 kPa compared to daily irrigation (Yadav et al. 2011a). Novel irrigation water-saving technologies such as alternate wetting and drying (AWD) can also help many rice farmers around the world to cope with water scarcity (Lampayan et al. 2015). In AWD, irrigation is given at intervals of 6–8 days for heavy soils and 4–5 days for lighter soils. Prior to next irrigation, the soil dries naturally after the water disappearance from soil surface and the water quantity applied at each of the irrigation is about 50–60 mm. Thus, the introduction of aerobic periods during the growing season and altering soil chemistry and flooding practices results in reduced water use (Yao et al. 2012; Liu et al. 2013) and reduced global warming potential (GWP) of greenhouse gas (GHG) fluxes (Feng et al. 2013). A 10–77 % saving in water and 20–87 % increase in rice yield with the additional advantages of energy saving, nutrient use efficiencies, and controlling vectors of malaria and Japanese encephalitis were reported with the use of AWD (Van der Hoek et al. 2001). The irrigation at 20 kPa lowered the irrigation water use of dry-DSR, with AWD, by 33–53 % as compared to the respective transplanted rice system (Yadav et al., 2011a).

8.4.2 Nutrients

Of all the nutrients, nitrogen (N), phosphorus (P_2O_5), and potassium (K_2O) remain the major nutrients for increased and sustained rice productivity. The fertilizer use trend in rice indicates the highest consumptions of N fertilizer followed by P_2O_5 and K_2O fertilizers with imbalanced fertilizer use (i.e., very high use of N, less use of P_2O_5, and negligible use of K_2O, S, and micronutrients), increased soil nutrient mining, and decreased soil organic matter and soil fertility (FAO 2006). Proper nutrient management should aim to supply fertilizers adequate for the demand of the rice and applied in ways that minimize loss, maximize the efficiency of use, and improve the productivity and sustainability of rice production systems, because of the high potential for loss and economic and environmental consequences (Chien et al. 2009). The nutrient management strategies for irrigated and rainfed lowland rice production systems vary (Dobermann and White 1999).

Among macronutrients, N is a key nutrient for the optimal rice growth and development to attain optimal rice yield. The rice crop and water management practices for DSR differ considerably from those for TPR. The DSR may have higher nitrogen requirement due to the longer duration of DSR in fields than puddle transplanted rice (Kumar and Ladha 2011).The insufficient N uptake by the DSR crop and resulting lower yield observed in DSR production systems (Kropff et al. 1994) was reported to be due to relatively lower uptake of nitrogen by the shallower roots of DSR (Zhang and Wang 2002) and higher leaching losses of applied nitrogen out of root zone in DSR (Ponnamperuma 1972). Increasing nitrogen quantity in DSR in larger number of splits with optimum irrigation may lead to higher rice yield due to their effect on the nitrogen movement and availability to plants in soils especially in coarse- and medium-textured soils (Shad and De Datta 1988).

N is applied in the larger quantities compared to all other nutrients as most soils of rice production systems are nitrogen deficient. As per global estimates, the fertilizer N recovery by the crop averages only 46 % in rice systems (Ladha et al. 2005). To increase the N use efficiency of irrigated rice, site-specific N management (SSNM) was developed (Dobermann et al. 2002), in which N application is based on the demand of the crop for N as measured by the chlorophyll meter (SPAD) or leaf color chart (Peng et al. 1996). The usefulness of leaf color chart for dry-DSR rainfed lowland rice and wet-DSR was reported by Budhar and Tamilselvan (2003) and Angadi et al. (2002). SSNM was evaluated in farmers' fields in eight major irrigated rice domains in Asia, and the average grain yield increased by 11 % with an increase in average recovery efficiency from 31 % to 40 % and 20 % of all farmers achieving more than 50 % recovery efficiency (Dobermann et al. 2002). Enhanced efficiency nitrogen fertilizers have been developed to decrease N losses and improve N use efficiency in rice production systems (Linquist et al. 2013).

On an average, around 18 kg ha^{-1} of K_2O for the irrigated rice crop is needed (Dobermann and Cassman 1997). K_2O deficiency has become a constraint in soils that were previously not considered as K_2O limiting. The occurrence of K_2O deficiency and response to applied K_2O depend on the yield levels, K_2O buffering capacity of the soil, straw management, and net K_2O inputs from sources other than fertilizer (Dobermann et al. 1996). Clay mineralogy, texture, and K_2O inputs from irrigation or rainwater are needed to be considered along with K_2O inputs from other sources while formulating a rational K_2O management strategy for the rice production systems (Dobermann et al. 1998).

In the irrigated rice production systems, P_2O_5 solubilizes immediately after flooding, leading to an increase in available P_2O_5 to rice (Kirk et al. 1990). However, soil drying reduces its availability to crop (Willet and Higgens 1978; Sah et al. 1989). Hence, phosphorus deficiency is important in drought-prone environments because the mobility of P_2O_5 decreases sharply as soil dries. In systems of low P_2O_5 fertility, the repeated dry-wet transition increases P_2O_5 extraction, further lowering fertility. The upland rice dry-DSR is generally grown on poorly fertile, strongly weathered soil, with high P_2O_5 fixation and severe soil acidity. P_2O_5 deficiency is one of the key constraints of upland dry-DSR production (Gupta and O'Toole 1986). Banding of P_2O_5 fertilizer beneath the dry-DSR crop row is preferred.

The deficiency of secondary and micronutrients is often stimulated by the application of large amounts of N, P_2O_5, and K_2O for achieving higher rice yield targets (Johnston et al. 2009). Iron (Fe) is only slightly soluble in the soil under aerobic conditions, especially in alkaline calcareous soils (Marschner 1995). Fe deficiency is a common nutritional problem in the production of aerobic rice. Current crop management strategies addressing Fe deficiency include Fe foliar application, plant breeding for enriched Fe rice varieties, and adoption of cropping systems (Zuo and Zhang 2011). Across the globe, among micronutrients, zinc (Zn) deficiency is one of the important abiotic factors limiting rice productivity in addition to being a major nutritional disorder affecting human health (Alloway 2009). Zn deficiency is wide spread in traditional lowland (Dobermann and Fairhurst 2000) due to high soil pH and high carbonate content as well as low redox potential (Forno et al. 1975; Alloway 2009). Shifting the method of establishment from TPR to DSR or aerobic rice system and adoption of water-saving technologies like AWD may decrease Zn availability (Gao et al. 2006). Soil or foliar Zn fertilizers application is used to manage Zn deficiency (Rengel et al. 1999) and to increase grain Zn concentration (Jiang et al. 2008). It is essential to utilize breeding programs to increase Zn uptake and utilization in rice production systems as a large genotypic variation (13.5–58.4 mg kg^{-1}) was recorded in Zn grain concentration with differential rice genotypic responses to Zn deficiency (Graham et al. 1999; Quijano-Guerta et al. 2002; Shi et al. 2009; Gao et al. 2009).

It is essential to have a proper blend of organic and inorganic fertilizers for increasing the productivity of rice production systems and for improving soil health. Application of SSNM can help improve nutrient management in rice production systems and attain improved yields and profitability as SSNM is based on scientific principles for optimal site-specific and need-based supply of nutrients to rice in a particular cropping season.

8.5 Pests (Insects, Diseases, and Weeds) and Their Management in Different Rice Production Systems

The estimated average potential yield loss in major crops globally is 18 %, 16 %, and 34 % due to animal pests, (non-virus) pathogens, and weeds, respectively, in the absence of any physical, biological, or chemical crop protection (Oerke 2006). The potentially highest yield loss causing weeds are more problematic in the DSR production system than in puddled TPR production system. The young emerging rice seedlings of DSR do not possess a competitive advantage over weeds as do have the transplanted 30-day-old seedlings in the TPR. Moreover, a layer of water suppresses the initial flushes of weeds in TPR, and lack of flooding in DSR provides a competitive advantage to weeds over rice seedlings in DSR (Rao et al. 2007, Rao and Nagamani 2007). In addition to currently problematic weeds such *Echinochloa* spp., weedy rice is becoming a major threat to dry-DSR production systems which replaced traditional transplanted rice production systems (Rao and Nagamani 2007). Hence, integrated weed management strategies are to be developed for managing the weedy-rice problem in dry-DSR production systems.

A study in tropical Asia covering a wide range of lowland rice-cultivating environments revealed that the injury profiles were dominated by stem rot and sheath blight; bacterial leaf blight, plant hoppers, and leaf folder; and sheath rot, brown spot, leaf blast, and neck blast (Savary et al. 2000). Stem rot and sheath blight were associated with high (mineral) fertilizer inputs, long fallow periods, low pesticide use, and good water management in (mostly) transplanted rice crops of a rice–rice rotation. Bacterial leaf blight, plant hoppers, and leaf folder were more prevalent in direct-seeded rice–rice production system with poor water management and lower fertilizer and pesticide input use or with adequate water management and higher fertilizer and pesticide input usage. Sheath rot, brown spot, leaf blast, and neck blast correspond to low-input, labor-intensive (hand weeding and transplanting) rice crops in a diverse rotation system with uncertain water supply. Weed infestation is an omnipresent constraint. The high weed pressure, severe iron deficiency, and nematode infestation coupled with higher irrigation water inputs were reported to be the reasons for getting rice yields lower than the transplanted rice by the adoption of dry-seeded rice with most frequent irrigations on coarse- and medium-textured soils (Singh et al. 2015).

The rice production systems were reported to differ in the incidence and losses caused due to the pests. A Korean study revealed higher population densities of green rice leafhopper (*Nephotettix cincticeps*) and leaf folders (*Cnaphalocrocis medinalis*) in machine-transplanted than in direct-seeded rice, while abundance of brown plant hopper (*Nilaparvata lugens*) and small brown plant hopper (*Laodelphax striatellus*) was more in dry-DSR (Lee and Ma 1997). However, incidence of the Asiatic rice borer or striped rice stem borer (*Chilo suppressalis*), white-backed plant hopper (WBPH) (*Sogatella furcifera*), and rice stem maggot (*Chlorops oryzae*) did not differ among machine-transplanted and direct-seeded rice production systems (Lee and Ma 1997). In Punjab (India), the leaf folder incidence was higher in the bed-transplanted (BT) (8.87 %) and wet-seeded rice (WSR) (10.62 %) than that in rice grown using the other crop establishment methods (Sarao and Mahal 2013). The incidence of stem borer causing dead heart damage was significantly higher in the WSR system (5.85 %), while that of whitehead damage was higher in the BT (5.89 %) and WSR (6.54 %) plots than in other rice production systems. In Korea, sheath blight (*Rhizoctonia solani*) incidence was not affected by different rice production systems, while the incidence of rice blast (*Magnaporthe grisea*) was affected and favored by unbalanced nutrient contents in the rice plants (especially low SiO_2 and high nitrogen) and high leaf area index (LAI) (Kim et al.1996).

Integrated weed management strategies are available for managing weeds of different rice production systems (Rao 2010; Rao and Ladha 2011, 2013; Rao and Nagamani 2007, 2010; Rao et al. 2007, 2015). The management aspects of the diseases and insect pests of rice are dealt with in other chapters of this book.

8.6 Environmental Footprint by Different Rice Production Systems

Among different sectors that contribute to total greenhouse gas emissions of the world, contribution of agriculture is around 9.3 %, including 1.5 % of rice. Emissions of greenhouse gases (GHGs) from rice fields are common in South, East, and Southeast Asia. Rice ecosystems emit both CH_4 and N_2O and have higher global warming potential (GWP) of GHG emissions and have higher GWP_Y (GWP per unit of yield) than other crops as rice is grown usually under flooded conditions in irrigated ecosystems and uses more water (Linquist et al. 2012).

Due to individual or combined effects of various factors such as soil characteristics, climatic conditions, and management such as soil pH, redox potential, soil texture, soil salinity, temperature, rainfall, and water management, amount of CH_4 emission varies between different rice production systems depending on the rice establishment techniques (Harada et al. 2007; Ladha et al. 2015). The irrigated puddled TPR is considered one of the major sources of methane (CH_4) emissions and accounts for 10–20 % (50–100 Tg year $^{-1}$) of total global annual CH_4 emissions (Reiner and Aulakh 2000). Direct seeding has the potential to decrease CH_4 emissions (Wassmann et al. 2004). CH_4 emissions were reported to be lower in DSR than with conventional TPR (Gupta et al. 2002; Tyagi et al. 2010). In wet-DSR, the reduction in CH_4 emission increased from 16–22 % under continuous flooding to 82–92 % under mid-season drainage or intermittent irrigation as compared with conventional TPR under continuous flooding (Corton et al. 2000). CH_4 gas emission and global warming potential were maximum under conventional TPR, and emission of N_2O was maximum under DSR crop with conservation practice of brown manuring as the addition of organic matter to soil increased the decomposition rate, which resulted in higher emission of GHGs (Bhatia et al. 2011). One of the ways, to minimize CH_4 emissions while attaining equivalent or higher rice yield and lower irrigation water use than those of farmer-managed puddled TPR, is adoption of dry-

DSR with best management practices and conservation agriculture (CA) that uses ZT or minimum till while retaining rotational crop residues (Ladha et al. 2015). Izaurralde et al. (2004) opined that soils under ZT, depending on the management, might also emit less nitrous oxide.

8.7 Challenges and Future Research Needs of Different Rice Production Systems

The challenges vary with the rice production systems. The main factors that limit the yield in irrigated areas include poor management of inputs and resources; losses from weeds, pests, and diseases; inadequate land and water scarcity; and resulting salinity and alkalinity. In rainfed lowlands the challenges include adverse climate, drought, submergence, poor soils, pests, weeds, and absence of appropriate soil, water, crop management technologies, or strategies to suit the farmers' needs and which economically increase rice productivity. In upland dry-DSR environment, the major challenges are the biological constraints such as weeds, nematodes, and diseases (e.g., blast), poor soil fertility, socioeconomic constraints, and lack of productive varieties to suit the microenvironment of uplands and the drought. In TPR production systems, inappropriate management of problem soils, non-judicious use of fertilizers and water, and resulting pest proliferations and increasing cost of cultivation are major challenges. In aerobic rice production systems, lack of fine-tuned need-based technologies suited to different rice ecosystems across globe, non-availability of suitable varieties, micronutrient deficiencies, soil and water management optimization, adaptive weed menace, and pest problems are major challenges.

The future research efforts on rice production systems should ultimately result in (i) evolving practical integrated crop management strategies that improve rice productivity and production efficiently, effectively, and economically in different rice production systems across the globe and (ii) improving the food security and livelihood of the farmers and farming community of rice and rice-based cropping systems globally.

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Chapter 9
Domestication and Development of Rice Cultivars

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9.1 Introduction

Rice can be cultivated under a wide range of climatic conditions including those of plains near to sea levels as well as the Himalayas region which is 2700 m above the sea level (Fuller et al. 2010). The natural progenitors of crop species provide information regarding the evolution of relevant species and are a source of genetic variation (Kovach et al. 2007). Evidences of rice domestication have been collected from the regions between the lower and middle Yangtze River in south of China (Doebley et al. 2006). Recently, Civáň et al. (2015) concluded that there were three different independent centers of rice domestications in different regions of Asia. Wild and domesticated rice types differ for several of the traits such as shattering behavior, pericarp color,

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tiller number, size of seeds, mating type, dormancy, panicle architecture, and number of seeds (Sweeney and McCouch 2007; Vaughan et al. 2008).

All across the world, the cultivated rice includes two species which are African rice (*Oryza glaberrima*) and Asian rice *(Oryza sativa*). African rice is grown mainly in African countries, while Asian rice is generally grown to the rest of the world including some parts of Africa. The two *Oryza* species have been grown for centuries which helped in improving their traits for achieving a better growth and yield. Based on study of 3000 accession, *O. sativa* categories into four main classes: Indica, Japonica, Aus, and Aromatic types. In this chapter, we have discussed the history of rice domestication, the domestication traits, rice types, and rice cultivars in the world.

9.2 History of Rice Domestication from Its Wild Ancestor

Wild rice was probably found throughout the eastern China and Yangtze basin up to the north such as Shandong. Besides, silicon microfossils and phytoliths of structures of rice cell that dated to 11,000–12,000 BC have been discovered at Diotonghuan and Xianrendong sites. During 3000–2000 BC, rice was moved to the Yellow River basin which is located in central China. For the same period (2500–2000 BC), the rice remains were found in Vietnam and Taiwan. In India, archeological work indicated that rice consumption existed in Neolithic site Lahuradewa in the Ganges Valley (i.e., dating to 7000–5000 BC) (Fuller et al. 2010; Itzstein-Davey et al. 2007; Sweeney and McCouch 2007; Wei et al. 2012). Archeological data and molecular clock estimation indicate that the domestication of rice was started ~8200–13,500 years ago, and rice was first cultivated in the Yangtze Valley of China (Molina et al. 2011).

9.2.1 History and Domestication of Asian and African Rice

Cultivated crop species derived from their wild ancestors not only provide valuable sources for genetic diversity for crop improvement but also provide a valuable information to get a glance at the evolutionary history of our domesticated crop species (Kovach et al. 2007). Domesticated rices have 21 wild relatives of the genus *Oryza*. The genus *Oryza* is divided into four species complexes: *O. sativa*, *O. ridleyi*, *O. granulata*, and *O. officinalis* species (Vaughan et al. 2003). Six wild species are included in *O. sativa* complex, i.e., *O. rufipogon*, *O. barthii, O. glumaepatula*, *O. nivara* (considered to be an ecotype of *O. rufipogon*), *O. meridionalis,* and *O. longistaminata*, and two domesticated species in the complex are *O. glaberrima* and *O. sativa*. All these species are diploids. *O. longistaminata* and *O. barthii* are African species; *O. barthii* is widespread in West Africa, and *O. longistaminata* is found throughout Africa. *O. meridionalis* is inhabitant to Australia, and *O. glumaepatula* is widespread in Central and South America. *O. rufipogon* established throughout Oceania and Asia. These distributions are helpful to trace the inherited pools of rice varieties (Vaughan et al. 2003; Sweeney and McCouch 2007).

There are two divergent types of domesticated rice, Asian rice (*Oryza sativa*) and African rice (*Oryza glaberrima*), which have distinctive domestication histories. A hypothesis indicated that *O. sativa* was probably domesticated from *O. rufipogon* approximately 10,000 years ago by East Asian people (Wei et al. 2012). *O. sativa* is subdivided into *indica* and *japonica*, two main subspecies (Fuller et al. 2010). It had been suggested by several researchers that the *indica* group was domesticated originally from *O. rufipogon*, and, afterward, the *japonica* was obtained from *indica* (Chang 1976; Lu et al. 2002). Compared to *japonica*, greater genetic diversity has been seen in *indica* group (Garris et al. 2005). The close genetic association between existing populations of both annual and perennial forms of *O. rufipogon* and *indica* supports this hypothesis. The second hypothesis indicated that the *japonica* and *indica* separation took place as a result of adaptation to various geographical and ecological environments conformity of a single domestication from *O. rufipogon*. A third hypothesis, first proposed by Chou (1948), indicated that there was at least twice independent rice domestication from a pre-distinction ancestor of *O. rufipogon* gene pool (Kovach et al. 2007). Molecular dating of divergence time demonstrated that the genomes of *japonica* and *indica* had separated 0.2–0.4 million years ago, which showed that this divergence time was substantially before the rice domestication time. The results of some studies indicate that Himalaya (India, Myanmar, and Thailand) is the place of domestication for *indica* group and southern China is the place of domestication for *japonica* rice (Doebley et al. 2006; Londo et al. 2006; Sang and Ge 2007). In addition, Molina et al. (2011) pointed out from a single origin and several independent domestication models that *japonica* and *indica* were directly domesticated from *O. rufipogon* (wild rice) and separately from a diverse species range of wild rice. Also, Wei et al. (2012) indicated that *japonica* and *indica* were domesticated from distinct populations of *O. rufipogon*. Recently, Civáň et al. (2015) used the footprints of cultivated rice types (genomes) to demonstrate that there were three different independent domestications in various parts of Asia. They identified wild populations which constitute the *japonica* gene pool source in southern Yangtze Valley of China, and populations in the Brahmaputra Valley and Indo-China which constitute the *indica* gene pool source. They revealed a hitherto unrecognised origin for the aus variety in central India or Bangladesh. They concluded that the result of the hybridization between *aus* and *japonica* was *aromatic* rice and that the temperate and tropical *japonica* versions were afterwards adaptations of one crop.

Previous studies have recognized that *O. glaberrima* was domesticated from *O. barthii* in West Africa near the Niger River nearly 3500 years ago (Callaway 2014; Wei et al. 2012). *O. glaberrima* has unique characteristics, such as its strictly annual habit, short rounded ligule, few secondary panicle branches, and red pericarp color, which differentiate it from Asian rice (Vaughan et al. 2008).

9.2.2 Domestication Traits

Because of the considerable variation and introgression by wild rice, some characters are consistently distinct among domesticated and wild rices. These include changes in size of seeds, shattering, mating type, panicle architecture, pericarp color, tiller number, number of seeds, and dormancy (Sweeney and McCouch 2007; Vaughan et al. 2008).

Many phenotypic distinctions are manifested among wild relatives of *O. sativa* (Li et al. 2006; Sweeney and McCouch 2007; Thomson et al. 2003; Uga et al. 2003). Typically, wild rices exhibit long awns, to guarantee the propagation, display, and seed dispersal by intense shattering, while short awns and decreased shattering for harvesting the maximum number of seeds is observed in domesticated types (Ji et al. 2006; Kovach et al. 2007; Lin et al. 2007; Vaughan et al. 2008; Yao et al. 2015). In addition, Yao et al. (2015), while studying the shattering of seeds in weedy rice, detected three quantitative trait loci (QTLs) and demonstrated that the identified QTLs (wd-qsh5, wd-qsh3, and wd-qsh1) had no overlaps by main shattering loci (e.g., qSH1, SHAT1, SH4, and sh-h). Considering these results, it was suggested that genomic studies of domestication traits could be helpful to produce weedy rice without the contention of wild type of rice at the agroecosystems.

Pericarp of grains from wild rice has a red color because of the pigment in the seed coat. Nevertheless, almost all modern rice varieties appear white or beige in the absence of red pigmentation. Rc is the only locus that has been indicated to affect an alteration of pericarp from red to white. Opposite to its progenitors, the panicle shape of rice has altered from an open panicle along scant secondary branches with few grains, to an aggregated packed panicle, which can contain more numbers of seeds. Therefore, results of domestication studies such as the genes associated and the geographic and distribution of alleles will be useful for breeders to better comprehend ancestors and breed rice for future (Kovach et al. 2007; Sweeney and McCouch 2007).

9.3 Rice Types and Cultivars in the World

Rice is included in the family *Poaceae* and genus *Oryza*. The plants of this species may be annual or perennial and attain a height of 100–200 cm (http://ricepedia.org/rice-as-a-plant).

9.3.1 Cultivated Rice Species

9.3.1.1 *Oryza sativa*

Important subspecies in *Oryza sativa* are (1) *japonica* (short grained and sticky), (2) *indica* (long grained, the nonsticky rice), and (3) *javanica*. *Japonica* varieties are usually cultivated at high elevations (South Asia), in dry fields (temperate East Asia), and in upland areas (Southeast Asia). Tropical Asia contains the *indica* varieties as most grown rice species. These are mostly sown in submerged and lowland conditions. Most probably *japonica* and *indica* were the result of a single domestication occurred in China nearly 8000–13,000 years ago.

Japonica

Japonica rice was originated from China and is grown in Japan. It is usually cultivated in temperate and cooler zones of the subtropics. The plants have a lower height than other types of rice, while its leaves have a dark green color. Low shattering, hard, short, and rounded grains are some of the characters of *japonica* rice. Grains are sticky after cooking.

Javanica or Tropical Japonica

Javanica or tropical *japonica* is another subspecies with an intermediate amylose content and stickiness. "Unoy" and "Tinawon" varieties are the examples for this rice which are grown in an area in the Philippines. *Javanica* plants are tall and have light green, broad leaves and thick and long grains, which do not shatter easily. Its grains are sticky because of the low amylose content.

Indica

This is a major type of rice grown in subtropics and tropics of the world. The leaves of *indica* rice are light green in color, and its plants are long in height. *Indica* and *japonica* types of rice have glutinous or non-glutinous grains.

Glutinous rice: Desserts and snacks are made from this rice. Mostly grown in Southeast Asia; this rice is sticky, white, and opaque after cooking.

Non-glutinous: Non-glutinous rice has lower stickiness than glutinous rice.

Aromatic rice, including basmati from Pakistan and India and jasmine from Thailand: It has 12–13 % share in global trade and earns a premium price in the world markets.

9.3.1.2 *Oryza glaberrima*

The location of domestication for *Oryza glaberrima* (African rice) is upper Niger River. Its domestication dates back to almost 2000–3000 years, while its wild ancestor (*Oryza barthii*) can be found in some parts of Africa even nowadays. Grain quality and yield of this rice is generally poorer than *O. sativa*, while it possesses a better resistance/tolerance against stresses than *O. sativa*.

9.3.2 Grain Characteristics of Cultivated Rice Species

Cultivated rice species have been classified into following major groups based on their grain characteristics.

9.3.2.1 Aromatic Rice Types

Aromatic rice have medium to long grains. Recent research established that aromatic rices have aroma because of the natural chemicals that give them a distinctive fragrance or aroma. In addition to this, they have very low levels of arsenic relative to the nonaromatic rice varieties. Aromatic rices provide fragrance as do the popcorn or roasted nuts. Basmati and jasmine are respectively the most important aromatic rices in the world.

Aroma is an important trait associated with high-quality grains such as those of basmati and jasmine rice. Most of aromatic rice varieties share the same aroma gene, badh2. Farmers have rice containing this gene since thousands of years. However, what makes rice grains aromatic remains a scientific mystery today. Although 2-acetyl-1-pyrroline (2AP), the main aromatic compound responsible for the fragrance of jasmine and basmati rice varieties, has been identified long ago, more than 150 different unknown aromatic compounds are now known to exist. Researchers have not yet fully understand the contribution of these compounds to aroma.

Features of Different Types of Aromatic Rice

Aromatic rice includes basmati, texmati, jasmine, wild pecan rice, and wehani. Grains are light in texture and fluffy after cooking.

Basmati rice Basmati is a customar name for certain rice varieties that are exclusively grown in specific area of Indo gagnetic plains. Basmati is slender, sword shaped, long/extra long, and fluffy with high-volume expansion which almost gets double on cooking and having typical basmati aroma. Basmati rice is photoperiod and thermo sensitive and possesses the following characteristics:

Minimum elongation ratio on cooking	1.7 mm
Minimum average pre-cooked grain length	6.5 mm
Amylose content	Intermediate (19–26%)
Length/breadth ratio	More than 3.5
Gel consistency	Soft
Gelatinization temperature	Intermediate (69–74 %)
Typical basmati aroma	Present
Grain shape	Slender (sword)
Appearance	Translucent

Basmati is historically cultivated since centuries in Indian and Pakistani Punjab provinces and at the foot of the Himalayan mountain ranges. Both Pakistan and India have evolved many basmati rice varieties. Grains of basmati rice are aromatic and long, and basmati means “queen of scents” or “pearl of scents.” The word basmati is derived from the Sanskrit word vas, meaning “aroma,” and mayup, meaning “ingrained” or “present from the begining (Singh et al. 2000). Basmati is a rice that exudes a sweet, delightful smell when cooked. Basmati rice is a part of food culture in many of the European, Arab, and American countries.

Texmati This is an aromatic rice produced in America. This was developed after a cross of basmati rice and long grain (American) rice.

Wehani rice This rice type was developed in the USA from basmati, possesses long grains and an aroma.

US black *japonica* This rice has a black bran and aroma.

US Della, Delrose, and Delmont This rice possesses the characters of both the basmati rice and long grain rice and, thus, expresses aroma after it is cooked.

Red rice This rice is grown in Bhutan and France (as well as some other parts of the world). The grains are reddish brown and possess an aroma.

Arborio rice This is a short grain Italian rice and possesses a high starch content. This is grown in some states of the USA as well.

Carnaroli rice This is arborio rice with larger grains and grown in some regions of Italy.

Jasmine rice This type of rice is present in China and Thailand, possesses long grains, and has fragrance (similar to jasmine). This rice has a good cooking quality which resembles to basmati rice; however, jasmine rice is sticky.

Kalijira rice or Kalo nunia This rice is grown in Bangladesh and has small non-sticky fragrant grains and cooks quickly with a good texture and taste.

9.3.2.2 Nonaromatic and Non-glutinous Rice

Glutinous or nonaromatic rice types are usually neutral in flavor and are short grained. Some rice types have their value because of their color. This color is usually determined by levels of pigment anthocyanin in different layers of the seed coat, pericarp, and outer grain layer.

Black Rice

This rice is considered to have a high nutritious value being rich in vitamin B and containing many other trace elements such as calcium and manganese. Another important characteristic of this type is that it can be stored under refrigeration for using within 3 months, without spoilage. There are several things which distinguish this rice from other rice cultivars, e.g., it is less sticky. It has a sweet flavor, high content of iron, minerals, fiber, and vitamins.

9.3.2.3 Glutinous, Sticky Rice, or Mochi Rice

Glutinous means sticky, this type of rice has short grains and is glue-like after it is cooked. The other names are sweet, botan, waxy, and pearl rice. Glutinous (sticky) rice is consumed mainly in dry areas of northern Thailand, Cambodia, and Laos. It is frequently used for brewing beer and as an important ingredient in snacks and in sweet dishes. Laos with 85 % production is the largest producer and consumer of glutinous rice. This rice has no dietary gluten but has a high amylopectin and a very low amylose.

9.3.3 Rice Varieties in the World

The number of rice cultivars being grown in the world exceeds 40,000. International Rice Gene Bank in the Philippines keeps the germplasm for nearly 127,000 rice cultivars and their wild relatives. This resource is useful for researchers from all rice growing regions in the world.

Based on grain size and average grain length (AGL), the rice grain may be grouped as extra long (>7.5 mm), long (6.6–7.5 mm), medium (5.5–6.6 mm), and short grain rice (<5.5 mm). Based on shape {length (L) to width (W) ratio}, rice grain may be selender (L-W ratio >3), medium (L-W ratio = 2.1–3), Bold (L-W ratio = 1.1–2), and round shape (L-W ratio <1.1). Chalkiness of endosperm, none (0 %), small (<10%), medium (11–20 %), and large (>20 %) (Singh et al. 2000).

Different types of rice varieties have been developed and named in the following countries/regions of the world:

No.	Types of varieties	No.	Types of varieties
1.	Chinese varieties	12.	Laos/Thai varieties
2.	Indian varieties	13.	Cambodian varieties
3.	Bangladeshi varieties	14.	Canadian varieties
4.	Indonesian varieties	15.	United States varieties
5.	Iranian varieties	16.	Spanish varieties
6.	Japanese varieties	17.	Italian varieties
7.	Philippine varieties	18.	French varieties
8.	Sri Lankan varieties	19.	Portuguese varieties
9.	Vietnamese varieties	20.	Australian varieties
10.	African varieties	21.	Dominican varieties
11.	Pakistani varieties	22.	Thai varieties

9.4 Conclusions

Understanding how and when humans domesticated crops from wild progenitors might supply more than a retrospective. Learning the dynamics of domestication of a crop can provide important lessons for the future. Currently, several QTLs detected in rice are being investigated for fine mapping or high-resolution mapping studies for genetic dissection. Ultimately, this knowledge will be useful in breeding programs as well as improving our knowledge about types of rice cultivated in the world with their unique and specific characteristics.

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Chapter 10
Fertilizer Management in Rice

Bijay-Singh and V.K. Singh

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.

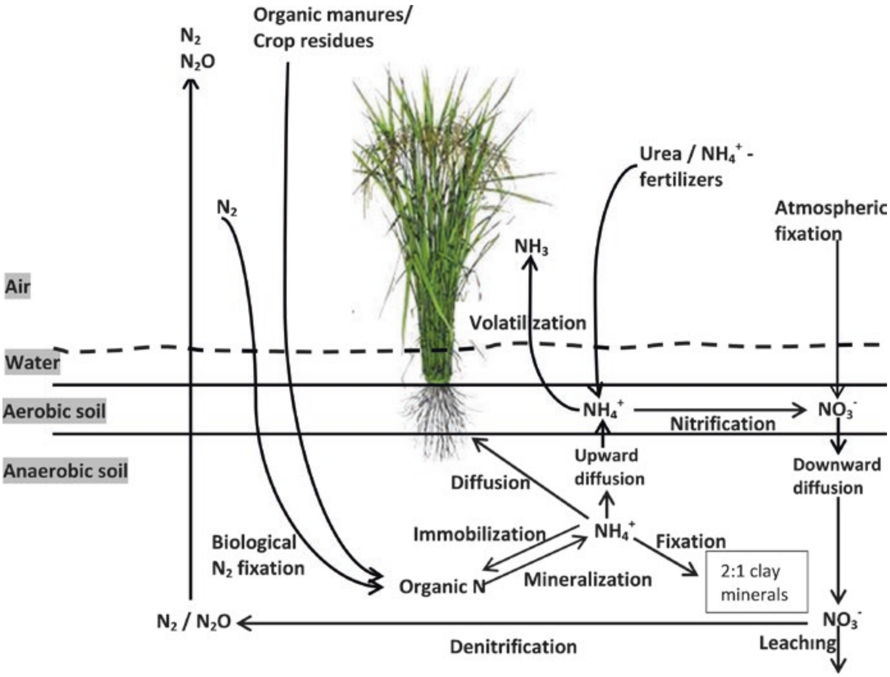

Fig. 10.1 Nitrogen transformations in a submerged soil under lowland rice

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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Chapter 11
Water Management in Rice

Avishek Datta, Hayat Ullah, and Zannatul Ferdous

11.1 Introduction

11.1.1 Background

Rice (*Oryza sativa* L.) is grown in at least 114 countries of the world, and more than 50 of them produce equal to or more than 100,000 t year^{-1}. About 491.4 million tons (mt) of rough rice was produced worldwide from 160.6 million hectares (m ha) of land in 2015 (FAO 2015). Rice, maize (*Zea mays* L.), and wheat (*Triticum aestivum* L.) are the main staple food sources for human, but rice becomes the most important with respect to human nutrition and caloric intake as maize is used for purposes other than human consumption. Most of the countries consume their own rice; therefore, the economic importance of rice is different from other export commodities, and only 5–6 % export occurs worldwide.

Rice is not exclusively a wetland plant (hydrophyte), but its growth in inundated conditions (5–10 cm water layer) is being practiced for a long time. The reasons for growing rice in inundated conditions are mostly agronomic, and it would be possible to grow rice in less water environments like other crops. The main agronomic advantages associated with this practice are suppression of weeds, ease of plowing, storage of water from heavy rainfall (particularly during monsoon season), and provision of habitat for the growth of an aquatic fern *Azolla*. *Azolla* can play an important role in nitrogen (N) fertilization of rice fields by making symbiotic association

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with a cyanobacteria/blue-green alga (*Anabaena azollae*). The demand for rice is increasing with growing population, while water resources are getting scarce. Hence, the rice-growing practices requiring less water input are needed to be adapted. The benefits associated with growing rice under inundated conditions could be achieved even without this practice, for example, by plowing, fertilizing, and weeding through tractors and spraying of herbicides. High labor needs and emission of more greenhouse gases under wet conditions are the other problems associated with rice production under inundated conditions.

Alternate wetting and drying (AWD) and aerobic rice provide a respective 38 and 40 % reduction in water input (Lampayan et al. 2015; Peng et al. 2006) to rice over the conventional flooding; however, the farmers are reluctant to adopt these practices because of possible yield reduction and certain information gaps regarding these systems. The existing practice of rice cultivation where fields are kept continuously flooded is more popular among farmers because of weed suppression and higher yield. However, this practice causes excessive water loss due to higher seepage, percolation, and evapotranspiration (Grassi et al. 2009). Moreover, changing climate with a direct effect on agricultural water availability is a serious threat for the existing systems of rice cultivation (Yoo et al. 2012). Changing climate scenarios (warming in particular) is expected to cause a 13–23 % rise in irrigation water requirement for rice cultivation (De Silva et al. 2007; Thomas 2008; Shahid 2011; Chung et al. 2011). The factors lowering the productivity of rice and diminishing its optimum performance under low water input systems are required to be understood. This will help in judicious use of available water resources for sustainable rice production.

11.1.2 Rice Environments

Unlike other food crops, rice has a wide range of ecological amplitude and can be grown in a variety of habitats with different hydrological conditions, climate, and soil types (Bouman et al. 2007). Rice is unique among cereals due to its ability to grow in wetland environment. Being an extremely versatile crop, rice can grow in dry and wetland conditions and low and high altitudes from the Mekong delta in Vietnam to the highlands of Madagascar (Seck et al. 2012). It has been reported that rice is grown on approximately 158 m ha of land worldwide producing more than 700 m t in 2009 (IRRI, AfricaRice and CIAT 2010). The four main rice production environments based on its hydrology (Bouman et al. 2007; Seck et al. 2012) are summarized below:

(i) Irrigated rice: Almost 75 % of the world rice production comes from irrigated lowland rice with a cultivated area of about 85–90 m ha where the main source of water is irrigation for at least 80 % of crop duration (IRRI, AfricaRice and CIAT 2010). Global food security is largely dependent on this system. Farm size for this type of rice cultivation system is small (0.5–2 ha) where rice is cultivated once, twice, or thrice a year as monocrop or sometimes in rotation with other crops such as wheat. In Asia, 56 % of the total rice-cultivated area is under this system (Swain et al. 2005). Transplanting method of cultivation is commonly used in irrigated rice production with bunded (diked) fields where water is supplied by irrigation. The average yield is around 5.4 t ha^{-1}.

(ii) Rainfed lowland rice: Rainfall is the only source of water for rainfed lowland rice production system. Fields for this system of cultivation are also bunded and are flooded with rainwater for at least part of the cropping season. The share of this system in global rice production is about 20 % with a cultivated area of about 40–45 m ha (IRRI, AfricaRice and CIAT 2010). Nearly 26 % of the total rice-cultivated area in Asia is under this system (Swain et al. 2005). The average yield is low (1–2.5 t ha^{-1}). Some of the major yield-limiting factors for this system include drought, flood, weed infestation, iron toxicity, and disease (Seck et al. 2012).

(iii) Rainfed upland rice: Cultivation of rice like any other cereal is known as upland rice. Fields are characterized by well-drained, unsaturated, and aerobic soil without any ponded water for more than 80 % of the crop growth period. Broadcasting method is commonly used for this system where land is tilled prior to starting of rainy season. No water is held on the surface as there is no bunding. In Asia, only 9.2 % of rice-cultivated area falls under this system. The major constraints for this system include erratic rainfall, poor weed control, low fertilizer use, and high disease incidence. The average yield is about 1 t ha^{-1} (Seck et al. 2012).

(iv) Deep water or floating rice: Rice cultivated in areas where water depth reaches 1 m or more for a period of 10 days–5 months is called deep water or floating rice (Seck et al. 2012). About 11–14 m ha of rice-cultivated area is under this system across the globe. Commonly available varieties of rice are not suitable for this system. Rice cultivated under this system has some special genetic characteristics. These are quick growth and stem/root elongation rate of as high as 10 cm day^{-1} with the rise in floodwater and formation of adventitious roots for direct absorption of nutrients from floodwater in addition to regular root system grounded in the soil (Balasubramanian et al. 2007).

11.2 Rice and Water Input

Total water applied either through irrigation or precipitation to the rice production systems is collectively called water input (Jabran et al. 2015a). Water needed for rice cultivation is more than any other arable crops. Nearly 75 and 80 % of the total existing water resources of the world and Asia, respectively, are devoted to rice production (Bouman et al. 2007). Presently, the traditional ways of growing rice (flooding and puddling the soil followed by seedling transplanting) are increasingly becoming difficult due to acute water and labor shortage in major rice-producing areas of the world (Farooq et al. 2011a; Jabran et al. 2015a, b). Many alternate ways to the traditional system have been developed with a considerable water saving potential such as dry-seeded rice, aerobic rice, and transplanted rice with AWD. Water savings of 35–57 % have been reported for cultivating rice in non-flooded and non-puddled soils compared with traditional transplanted rice (Peng et al. 2006; Bhushan et al. 2007). Similarly, 32–88 % higher water productivity has been recorded for dry-seeded rice compared with transplanted rice (Bouman et al. 2005). Water savings between 20 and 21 % and 32 and 34 % have been reported for transplanted rice with AWD and dry-seeded rice, respectively, compared with transplanted rice with continuous flooding in Punjab, Pakistan (Jabran et al. 2015a). The average value of water input for irrigated rice in Asia is around 1300–1500 mm (Bouman et al. 2007). Total seasonal water input required for rice is up to two to three times higher than other cereals (Tuong et al. 2005). Soil texture plays an important role in deciding water input to rice. Water input could be as low as 400 mm for a heavy clay soil with shallow groundwater table to as high as 2000 mm for a coarse-textured soil (sandy or loamy) with deep groundwater table (Cabangon et al. 2004). Water requirement is the highest for irrigated lowland rice followed by rainfed lowland rice (Bouman et al. 2007). This high demand is due to high outflow by seepage, percolation and evapotranspiration during crop growth. With better crop and water management practices, the amount of water needed for lowland rice cultivation could be minimized. For example, reducing the time lag between soaking and transplanting to a few days, the amount of water required for wet land preparation could be as low as 100–150 mm (Bouman et al. 2007). But in most of the cases with large-scale irrigation systems with poor water control, the time lag between soaking and transplanting can go up to 2 months, and water inputs for land preparation can be as high as 940 mm (Bouman et al. 2007).

Transplanting and wet direct-seeding methods are generally used for lowland rice cultivation in Asia. Land preparation consisting of soaking, plowing, and puddling is an important step before practicing either of the methods. The water input in rice fields is not uniform (different amount of water is needed in different areas and different environments), and depends on various factors such as outflow rate, crop growth, duration and method used for land preparation. For modern high-yielding varieties with a typical 100-day season, the total input of water varies from 700 to 5300 mm based on different factors such as soil characteristics, climate, and hydrological conditions, while for many lowland areas, a typical value is 1000–2000 mm (Tuong and Bouman 2003). For normal growth and maintenance of flooded condition, it is necessary to match outflow of water. Major causes of outflow under flooded conditions are seepage and percolation to the surroundings as well as evaporation and transpiration to the atmosphere. The resistance of soil to water movement and depth of ponded water mainly govern the flow rates of seepage and percolation, both of which are often considered in combination as it is difficult to separate these under field situations. Different stages in the crop growth period have different values of seepage and percolation, for example, seepage and percolation values during land preparation are reported as high as 25 mm day^{-1} due to cracks in the soil (Tuong et al. 1996). During the crop growth period, seepage and percolation values in heavy soil are reported between 1 and 5 mm day^{-1}, and in sandy and sandy loam soil, these are between 25 and 30 mm day^{-1} (Wickham and Singh 1978; Jha et al. 1981). Evaporation and transpiration cannot be separated and a combined term evapotranspiration is used. Evaporation occurs during land preparation from moist soil (ponded water) and from soil and water surface between crops, whereas transpiration occurs from plant surfaces during the crop growth period. In Asia, evapotranspiration value ranges from 4 to 7 mm day^{-1} (De Datta 1981; Tuong 1999). Out of all these outflows from a rice field, transpiration is beneficial as it is directly involved in growth and yield. Seeping water could also be reused downstream in the catchment areas and might not be a true loss. Most of the water input to a rice field should compensate for all types of outflows such as seepage and percolation during land preparation and crop growth period and evaporation during land preparation. All these flows have no role in plant growth and yield.

11.3 Rice Water Productivity

Water productivity can be defined as grain yield per unit of water supplied through irrigation (WP_I), which is known as irrigation water productivity; or grain yield per unit of water input (irrigation plus rainfall) (WP_{IR}), which is known as total water productivity; or grain yield per unit of water loss through evapotranspiration (WP_{ET}), which is known as crop water productivity (Tuong and Bouman 2003; Timsina et al. 2008). Water productivity values for either case are not consistent under field conditions. At field level, a typical value for WP_{IR} is 0.2–1.1 g kg^{-1}, and that of WP_{ET} ranges from 0.4–1.6 g kg^{-1} (Bouman and Tuong 2001). Different environmental conditions provide different values of evapotranspiration and different yields, and for this reason a wide variation exists for WP_{ET} values. Water productivity is also related to N fertilizer rate and other agronomic practices. Due to high unproductive outflows through seepage, percolation and evaporation from rice field, the value for WP_{IR} for rice is less than half of many other C_3 crops. The value of WP_{ET} for rice and other C_3 crops have little difference.

Water productivity can be increased by adopting different water-saving practices such as improved irrigation management (Bouman and Tuong 2001), making efficient use of rainfall and increasing yield per unit evapotranspiration (Tuong and Bouman 2003), growing short-duration cultivars (Bennett 2003) and growing of crop in the period of low evaporative demand by altering the date of transplanting and synchronization of growth cycle (Chahal et al. 2007; Timsina et al. 2008). There is an increased interest to develop water-saving rice production systems all over the world due to water shortage (Farooq et al. 2011a, b; Jabran et al. 2012a, b; Nie et al. 2012). Dressing the soil surface with some amendments, such as mulches, could benefit rice production under water-limited environments by minimizing evaporative losses and enhancing soil water retention (Jabran et al. 2015a). Productive use of water in rice production (basmati rice) can be maximized by adjusting its transplanting time (Mahajan et al. 2015). In Northwest India, delaying transplanting of some photoperiod-insensitive basmati cultivars resulted in higher water productivity (WP_I, WP_{IR}, and WP_{ET}) from reduced irrigation requirement and maintenance of grain yield as these cultivars matured almost 2–3 weeks earlier than other photoperiod-sensitive cultivars (Mahajan et al. 2015). Short-duration cultivars mature earlier; therefore, short-duration cultivars are better than medium- and long-duration cultivars in water-saving rice cultivation systems (Mahajan et al. 2009).

11.4 The Rice Plant and Drought

Rice is the staple food for more than three billion people of the world, especially in developing countries in Asia where water shortage and drought are imminent threats to food and nutrition security. Water is the most important component for sustainable rice production across the globe, especially in those areas where it is grown in traditional ways. Increased competition for water, reduced investments in irrigation infrastructure, water quality deterioration due to pollution and excessive withdrawals of groundwater are some of the major problems that could pose serious threat for sustainable rice production (Lampayan et al. 2015). These issues seem to be even more severe in the future, but rice production must be significantly increased to meet the food demand of the world despite all these challenges. Therefore, the most viable option is the production of more rice with less water that would ensure the food, water, economic and social security of the world.

The main sources of water for rice are the river, the rain and groundwater; therefore, the water scarcity paradigm needs to be carefully defined (Totin et al. 2013). In broad sense, water scarcity can be divided into two main types: meteorological and technical. Meteorological water scarcity is caused by severe reduction in normal rainfall than the mean annual rainfall or shifting of rainfall timing in a season (Totin et al. 2013). It has been reported that the current climate change is causing long-term shift in rainfall timing adding additional uncertainty to the normal variability (Nyakudya and Stroosnijder 2011). Both the gravity irrigated and rainfed crops are affected by low rainfall as there will be less water in the river and wells as well. Technical water scarcity is not due to unavailability of water rather it is caused by certain technical problems such as collapse of canal bank or very high intake of water at a level due to some technical defects in the irrigation infrastructure. In addition, improper or untimely (late) cleaning of irrigation canals also causes severe water shortages in the fields that are at high elevation in the command area. Presence of insufficient water to be pumped to upland part of inland valley is another technical issue that results in water scarcity (Totin et al. 2013). For example, in Indian State of Punjab, 97 % of the area is under irrigation (Hira 2009). A rapid fall of water table in Punjab is evident and is caused by excessive withdrawal of groundwater mainly due to early transplanting of rice and subsidized electricity to tube wells (Hira 2009). Nearly two-third fall in water table could be avoided by delaying rice transplanting from 10 to 30 June and shifting subsidies from input to output (Hira 2009).

The ancestors of cultivated rice were perennial semiaquatic plants (Lafitte and Bennett 2002), and this wetland ancestry of rice is evident in its various morphological and physiological characteristics that are unique among cultivated crop species (Bouman et al. 2007). Lowland rice is extremely sensitive to drought, which is defined here as any situation where there is no standing water and the water content in the rooted soil is below saturation. The effect of drought on rice starts when soil moisture level drops below saturation point. Rice uses various mechanisms to respond to drought conditions summarized by Bouman and Tuong (2001) and Bouman et al. (2007) as follows:

(i) Inhibition of leaf growth and decline in leaf area, leading to less light interception resulting in reduced rate of photosynthesis. Both cell division and cell enlargement are affected by drought stress; however, cell enlargement is more sensitive to drought stress than cell division. When soil moisture tension is greater than 1 kPa (soil dries below saturation), leaf area expansion starts reducing in most of the cultivars, while for aerobic species, the same condition starts when 30 % of the available soil moisture has been extracted (Wopereis et al. 1996).

(ii) Stomatal closure, leading to reduced transpiration rate and photosynthesis. The closure of stomata is not an immediate effect of drought stress and plants keep their stomata open up to a certain time to maintain the process of photosynthesis. Assimilates produced during this time are not used for leaf growth, but stored in leaves, stems or roots and the same may be used for leaf growth and development on return of normal conditions. In some high-yielding varieties (e.g., IR72), closing of stomata starts when soil moisture tension reaches to 75 kPa (Wopereis et al. 1996).

(iii) A rapid senescence of leaves in most cultivars causing a reduction in canopy photosynthesis.

(iv) Rolling of leaf to reduce effective leaf area for light interception.

(v) Changes in assimilate partitioning where roots grow more (number and depth) during vegetative development compared with shoots. Deep root systems help absorb more water from the deeper soil layers. Assimilate partitioning among various shoot components is rarely affected.

(vi) Reduction in plant height, which may or may not cause a reduction in yield.

(vii) Delayed flowering. For photoperiod-insensitive varieties, a delay of 3–4 weeks in flowering can be noted when drought stress is experienced during the vegetative growth stage. The drought induced delay in flowering, however, depends on the crop growth stage where early-season drought has more severe effects than late-season drought.

(viii) Reduced tillering and tiller death. The number of tillers and panicles per hill are reduced when plants are exposed to drought stress. The effect is more prominent when drought occurs before or during tillering stage.

(ix) Reduced number of spikelets when drought stress occurs between panicle initiation and flowering, leading to a reduction in number of grains per panicle.

(x) Spikelet sterility occurs when drought stress is experienced around flowering stage. This causes a reduction in number of filled spikelets resulting in less number of grains per panicle.
(xi) Decreased grain weight when drought affects the crop after flowering.

In the above consequences of drought stress on rice, some processes are irreversible and cannot be restored such as leaf senescence, reduction in number of spikelets, spikelet sterility and a decrease in weight of grain, whereas some other processes could be restored when drought is relieved such as leaf rolling and stomatal closure. Nutrient use efficiency may also be affected by drought stress. Overall, the effect of drought on rice yield depends on its timing, duration, frequency and severity (Bouman and Tuong 2001).

11.5 Water Management Strategies for Rice

11.5.1 Land Preparation

One of the prerequisites for a good crop husbandry is a well-leveled field (Bouman et al. 2007). Higher parts of a field may become dry, whereas water may stagnate in lower parts when fields are not well-leveled, which could result in uneven early crop growth, unequal distribution of fertilizer and greater emergence of weeds. For any crop including rice, one of the basic technology options to help farmers cope with water scarcity at the field level is proper land preparation. A well-prepared field is important to ensure good water management, weed control, nutrient recycling and soil pathogen suppression. The important land preparation practices for good water management include tillage operations, field channels and land leveling (Bouman et al. 2007).

Laser leveling is a modern type of land leveling process during which the land surface is smoothened (± 2 cm) from its average elevation using laser-equipped tractor-pulled scrapers. Large horsepower tractors and soil movers equipped with global positioning systems and/or laser-guided instrument are used for this practice for creating the desired soil slope/level either by cutting or filling. Laser leveling is an efficient technique used for achieving higher level of accuracy and has the potential for water saving and higher crop yields. Some of the benefits associated with this technique include:

(i) Uniform germination resulting in an improvement in crop establishment and consequently high yield due to uniform soil moisture
(ii) Improvement of irrigation efficiency and conservation of water
(iii) Reduction of irrigation time and effort to manage the crop
(iv) Uniform planting that helps achieve higher yield
(v) Reduction of insect pests, weeds, and disease problems
(vi) Cost reduction due to reduced input of seeds, fertilizer, fuels, and chemicals

Some major limitations of laser leveling are (i) high cost of the equipment/laser instrument, (ii) need for skilled operator to set/adjust laser settings and operate the tractor, and (iii) more efficient for regularly sized and shaped field.

11.5.1.1 Tillage Operations

Tillage operations include puddling, bund preparation, and maintenance. It covers various practices ranging from zero or minimum tillage with minimum soil disturbance to a totally puddled soil where soil structure is destroyed. Tillage operations consist of different steps: (i) plowing to dig up (till), mix, and overturn the soil, (ii) breaking of soil clods and incorporation of plant residues through harrowing, and (iii) field leveling. Initial land preparation should start immediately after previous harvest to effectively control weeds and to manage water inputs. Hydraulic conductivity, the capacity of the soil to conduct water downward and sideward of the soil, governs the seepage and percolation flows from a rice field (Bouman et al. 2007). When large and deep cracks are present in a field during soaking (before puddling), a significant amount of water can be lost as these cracks favor downward flow below the root zone. In order to reduce this loss, an additional shallow tillage before land soaking is recommended to close the cracks. A 100 mm reduction in water input was recorded by Cabangon and Tuong (2000) during wet land preparation through additional shallow tillage.

Thorough puddling of soil is helpful in reducing permeability and percolation rates; however, the efficacy of puddling largely depends on soil texture. For example, this practice is more efficient in clay soils compared with coarse soils as clay particles are negligible in a coarse-textured soil to migrate downward and fill the cracks. Puddling itself is a water-consuming process, and there is a trade-off between water consumed during puddling and water saved by reduced percolation rates. In a sandy topsoil with loamy subsoil (at least 5 %), use of heavy machinery for soil compaction is reported to reduce soil permeability (Harnpichitvitaya et al. 1999). It would be difficult for the small farmers to compact their soils due to a high cost involvement, and a larger-scale adoption of this technology could be feasible with government support.

To minimize water loss in form of seepage, bunds should be well compacted, and any cracks and rat holes should be sealed at the beginning of the crop growth period. Height of bund should be between 30 and 50 cm to avoid any over-bund flow during heavy rainfall. Small levees of 5–10 cm height in the bunds can be used to keep water up to 20 cm height (Bouman et al. 2007). Plastic sheets in bunds are also recommended to reduce seepage loss, and a reduction of 450 mm of total water use in the rice field by lining the bunds with plastic has been reported (Bouman et al. 2005).

11.5.1.2 Controlled Irrigation Through Field Channels

Field channels are practically absent in many irrigation systems in Asia. Water flow from one field into the other usually occurs through breaches in the bunds (Bouman et al. 2007). This method has many disadvantages, for example, the amount of water flow from a rice field cannot be controlled and it is not possible to practice field-specific water management. This suggests that farmers may not be able to completely drain their fields before harvest as water keeps flowing inside the field from other fields. In addition, the downstream field may not receive water if farmers of upstream field retain water in their fields or let their fields dry out for harvesting. Continuous flow of water through the fields also causes removal of valuable nutrients from the fields. An improvement in the individual control of water could be possible by making separate field channels to convey water to and from each field with greater efficiency.

11.5.2 Unproductive Water Outflow Reduction

A considerable amount of water is lost both during land preparation and crop growth period through unproductive evaporation, seepage, and percolation flows (Bouman and Tuong 2001). It is essential to reduce these losses for increasing rice water productivity. Unproductive water loss can be minimized through various measures including (i) reducing the duration of land preparation by minimizing the idle periods, (ii) increasing the resistance of soil to water flow, and (iii) reducing the hydrostatic pressure of water (Bouman and Tuong 2001).

11.5.2.1 Reducing the Duration of Land Preparation by Minimizing the Idle Periods

"Idle periods" in rice production is the period that lies in between tillage operations and transplanting. In transplanted rice, seedlings are grown for 2–4 weeks in a seedbed, and during this period, the fields surrounding the seedbed are tilled (land preparation) and flooded using a field-to-field irrigation system. In this case, a huge amount of water is lost through unproductive flows. This land preparation period can be minimized through good irrigation practices such as supplying irrigation water directly to seedlings in nurseries without submerging the main fields and development of irrigation system where farmers can irrigate their fields independent of the surrounding fields. Different countries have different practices for this purpose, for example, specific land areas are devoted to community seedbeds in China and Vietnam that can be irrigated independently (Tuong and Bouman 2003). In Malaysia, about 375 mm water has been annually saved in two rice-cropping seasons under Muda Irrigation System where canal and drainage intensity has been increased from 10 to 30 m ha^{-1}, resulting in a reduction in the duration of land preparation by 25 days (Abdullah 1998). Direct seeding rather than transplanting rice seedling is another way to reduce the "idle periods" of land preparation (Bhuiyan et al. 1995). However, the cropping duration of direct-seeded rice is more than transplanting rice; hence, more water is utilized during this long-growing season.

11.5.2.2 Increasing the Resistance of Soil to Water Flow

Physical properties of soil such as texture, structure, and porosity are important factors that may affect the water flow into the soil. Changing the physical properties of soil can offer more resistance to water flow and hence reduce water loss through evaporation, seepage, and percolation flows. In order to close the cracks in soil, an additional shallow tillage before land preparation is very effective (Cabangon and Tuong 2000). Thorough puddling of soil is helpful in reducing permeability and percolation rates. Soil compaction through heavy machinery has been proven effective in decreasing soil permeability. Different types of physical barriers such as plastic sheets underneath rice soils are also beneficial in reducing water loss through seepage and percolation; however, most of the physical barriers are cost-prohibitive and beyond the financial scope of the poor farmers (Tuong and Bouman 2003).

11.5.2.3 Reducing the Hydrostatic Pressure of Water

A reduction in hydrostatic pressure can be obtained by reducing seepage and percolation flows that result from a changed water management. Instead of keeping the rice field continuously under flooded conditions (5–10 cm of standing water), the floodwater depth can be minimized by keeping the soil around saturation or AWD regimes can be imposed (Tuong and Bouman 2003). Soil saturation is mostly attained by providing irrigation with about 1 cm water depth a day or so after the disappearance of standing water.

11.5.3 Alternate Wetting and Drying (AWD)

It is a technology developed by the International Rice Research Institute (IRRI) and its national agricultural research and extension system to cope with increasing shortage of water for agricultural use, especially for rice. In AWD, irrigation water of about 2–5 cm is applied with an interval of 2–7 days followed by disappearance of ponded water from soil surface (Tuong and Bouman 2003).

Being a high water-demanding plant, a minor decrease in water demand by rice will help save a large volume of this precious natural resource. For this purpose, efforts have been made in the past several decades to increase rice water productivity both from irrigation and rain by decreasing water use in rice production. One of such technologies is AWD where the field is not continuously flooded but the soil is allowed to dry out for one to several days after flooded water disappear and then flooded again (Lampayan et al. 2015). It is an efficient technology capable of reducing water demand by as much as 38 % with no adverse impact on yield when practiced correctly (Lampayan et al. 2015). Proper and correct implementation also indirectly helps in increasing farmers' income by reducing expenses of water pumping and fuel as observed in some Asian countries, for example, 17 % in southern

Vietnam, 32 % in the Philippines, and 38 % in Bangladesh (Lampayan et al. 2015). Adoption and implementation of this technology are very crucial for rice cultivation as only 30 % of agricultural land is occupied by irrigated rice, but water consumption is about 40 % of irrigated water (Dawe 2005). Water scarcity will affect 15–25 m ha of rice lands of the main producing countries of South and Southeast Asia by 2025 (Tuong and Bouman 2003; Bouman et al. 2007). "Intermittent irrigation" developed in India was a first form of AWD. This technique is exceedingly becoming popular in East and Southeast Asian countries, but with different operational methods with respect to timing, frequency of non-flooded period, and duration depending on locality and environment (Lampayan et al. 2015). There were 53–87 mm (13–16 %) savings in irrigation water in the AWD treatments compared with the continuously submerged regime. However, grain yields of rice (7.2–8.7 t ha^{-1}) were not largely impacted by the water regimes. Water productivity was significantly lower in the continuously submerged regime compared with the AWD regime (Belder et al. 2004).

In some regions where scarcity of water is due to competition for water between agriculture and other sectors, for example, in some parts of China, a special type of AWD is practiced (Li and Barker 2004). In this specific practice of AWD, water of about 50–60 mm is applied with an interval of 6–8 days for heavy soils and with 4–5 days interval for lighter soils. This follows a disappearance of water from soil surface and drying of soil in a natural process until the next irrigation is done. However, this method could not gain popularity among farmers possibly due to fear of yield loss and its complicated implementation guidelines. Another type of "safe" AWD was introduced by IRRI in 2002 with easy-to-use tools and simple guidelines to reduce irrigation water input without compromising yield. This practice is recommended for many Asian countries including Vietnam (Rejesus et al. 2014), the Philippines (Rejesus et al. 2011; Lampayan et al. 2015), Bangladesh (Price et al. 2013), and Myanmar (Lampayan et al. 2015). In these countries, this practice has been widely adopted, and the factors responsible for the success in the adoption of AWD could be used to successfully implement this technology in other parts of the world. Bouman et al. (2007) mentioned about three major stages of "safe" AWD:

(i) Shallow flooding during the first 2 weeks after transplanting to help suppress weeds and recover plants from transplant shock.
(ii) Shallow ponding from heading to the end of flowering as this is a very critical growth stage sensitive to water stress. During this stage, growth rate and water requirement are also high.
(iii) AWD during all other stages after flowering and water is provided only when perched water table drops to 15 cm below the soil surface. It has been proved that the threshold of 15 cm does not cause any yield loss as at this stage roots system is strong enough to absorb water from zone below 15 cm. At 15 cm soil depth, water potential is more than −10 kPa that is the critical value for rice and below which it starts showing symptoms of water-deficit stress (Bouman and Tuong 2001).

11.5.4 The System of Rice Intensification (SRI)

The System of Rice Intensification (SRI) is a method of rice cultivation claimed to use less seed (under SRI the seed requirement is reduced by 80–90 %) and less water (water needs reduced by 25–50 %) and is reported to increase rice yields (by 30–100 %) of marginal farmers using traditional varieties without the application of agrochemical products (Stoop et al. 2002; Uphoff 1999, 2004, 2007). This method differs from conventional method of rice cultivation with respect to crop establishment, irrigation management, fertilizer application, and weed management (Berkhout et al. 2015). SRI techniques are based on exploiting the internal genetic potential of rice plant by close observation of the physiological characteristics rather than depending on external inputs. Supporters of SRI consider it more beneficial for poor and marginal farmers as it helps increase the grain yield by improving physiological efficiency in terms of increased root biomass, activity, longevity, and regulating available N status of rice plants without depending on costly seeds and expensive chemical fertilizers (Stoop et al. 2002; Uphoff 2007). The critics of this system do not agree with the claim of record-breaking higher yield, and they note that the SRI approach requires intensive labor inputs, heavy use of organic inputs, and a high degree of water management (Surridge 2004; Latif et al. 2005; Senthilkumar et al. 2008). Despite many negative recommendations, smallholders in many countries including Cambodia, China, India, Indonesia, Myanmar, and Vietnam are reported to have adopted this method (Kassam et al. 2011). SRI is composed of 5–6 major cultivation practices:

(i) Raising seedlings in a carefully managed nursery
(ii) Early transplanting of 8–15-day-old seedlings (careful transplanting just after uprooting in a shallow depth of 1–2 cm)
(iii) Single transplant per hill in a square pattern with wider spacing (typically 25 × 25 cm and possibly wider) of transplants
(iv) Careful water management to promote aerated moist conditions of the soil with a periodic dry spell of 3–6 days
(v) Regular weeding through a rotary hoe to facilitate soil aeration
(vi) The use of organic fertilizers in the form of farmyard manure, compost and green manure (Stoop et al. 2002, 2009)

These practices are considerably different from conventional cultivation methods where 20–40-day-old seedlings are transplanted in closely spaced rows in clumps of two to four plants at a time and the fields are kept flooded for most of the growing season (transplanting to maturity).

Although these benefits are encouraging for resource-poor rice farmers to adopt the system, a detailed literature evaluating diffusion and adoption of this practice is limited. Most of the available literature dealing with SRI is focused on a localized scale. As a result, it is difficult to judge how widely the system is adopted worldwide. In addition, the factors shaping adoption patterns of this technique are also inconsistent but substantially vary with location and season resulting in heterogeneous productivity changes.

11.5.5 *Direct Seeding Method of Cultivation*

Direct seeding of rice (DSR) is a process of rice crop establishment from seeds directly sown in the field rather than by transplanting seedlings raised from the nurseries (Farooq et al. 2011a). There are three primary methods of DSR:

(i) Dry seeding – this is the process in which dry seeds are directly sown into dry soil.
(ii) Wet seeding – sowing pre-germinated seeds on soil that is wet and puddled.
(iii) Water seeding – sowing seeds in standing water.

In Southeast Asia, a major shift has been observed from the traditional transplanting system (TPR) to DSR cultivation during recent years largely due to some major problems associated with TPR cultivation including high water input, high labor demand, and cost reducing the profit margin (Farooq et al. 2011a). The major reasons of the shift from TPR to DSR include (i) increasing water scarcity and decreasing availability of water for agriculture, (ii) labor shortage and increasing labor wages, (iii) crop intensification and recent developments in DSR production techniques, (iv) adverse effects of puddling on soil physical properties and the succeeding non-rice crop, and (v) rising interest in conservation agriculture (Kumar and Ladha 2011). In Asia, about 50 % of total irrigation water is used for rice cultivation, while on global scale, the value ranges from 34 to 43 % (Bouman et al. 2007).

The selection of TPR or DSR is dependent upon various factors, for example, low wages and adequate water favor TPR, while high wages and water shortage favor DSR. In Southeast Asia, DSR is generally practiced in the dry season to ensure better water control, but like global trend, the share of this region in dry-season rice production is less than 25 %. The share of DSR in global production is only 23 % (Rao et al. 2007). Adapting DSR could be helpful in attaining optimal plant density along with high water productivity, specifically for the areas where water scarcity is the main issue. In TPR cultivation, nearly 1-month-old seedlings are transplanted into puddled and continuously flooded soil, which is reported to increase nutrient availability, especially Zn, P, and Fe, and suppress weeds (Singh et al. 2001).

In the present scenarios of water and labor crisis, DSR is a feasible alternative for rice cultivation system in the world in general and Asia in particular. However, there are some constraints of DSR method. The major issue associated with DSR method is weed infestation; however, less weed pressure is reported when both pre- and postemergence herbicides are applied (Mahajan et al. 2013). Farmers use different weed management strategies based on their convenience, but an integration of different weed management strategies is required for effective weed management in DSR system. Precise land leveling is another important issue and is reported to be a prerequisite for DSR. The precise land leveling can be performed using laser levelers (Mahajan et al. 2013). The use of proper seeding depth is a basic requirement of DSR, and it depends on soil type and soil moisture levels (Mahajan et al. 2013). Poor performance of most of the popular cultivars is another limiting factor of DSR method. Short-duration cultivars perform better under DSR production system, and use of long-duration cultivars usually results in lower yield (Mahajan et al. 2013).

11.5.6 Aerobic Rice System

Aerobic rice production is a system of growing specifically developed input-responsive varieties (aerobic varieties) in non-puddled, non-saturated, and well-drained soils without ponded water (Bouman et al. 2007). This is fundamentally a different approach of rice cultivation in a system like other upland crops such as maize and wheat to reduce water inputs in rice. In case of low rainfall, irrigation is applied to bring soil moisture content to field capacity. This is done when soil moisture content drops to certain threshold level, for example, halfway between field capacity and wilting point (Doorenbos and Pruit 1984). Loss of water occurs through evapotranspiration, and irrigation water should compensate that loss. It is practically impossible to apply irrigation water only to the root zone. Some part of the applied irrigation water is lost through deep percolation and is not available for plant absorption. The field application efficiency mainly depends on the irrigation method, for example, the efficiency is about 60–70 % for flash or furrow type of surface irrigation, while it is more than 90 % for drip and sprinkle irrigation (Lampayan and Bouman 2005). The water saving potential of rice cultivation as upland crop varies with soil types. The practice of this method can reduce unproductive water loss from all types of soils, especially on soils with high seepage and percolation rates (Bouman and Tuong 2001). The method not only lowers seepage and percolation loss but also evaporation loss is reduced due to non-standing water layer.

This change from anaerobic to aerobic systems is not only important in relation to water saving but also has major impacts on weed management, diseases, soil organic matter, nutrient dynamics, and greenhouse gas emissions. One of the major issues associated with this shift is poor weed management as water has been traditionally considered as the “cheapest weed control agent,” but this benefit might not be available anymore with the adoption of these water-saving technologies. Another issue is the poor performance of lowland varieties under aerobic conditions. For the development of such rice varieties, a study on the functional genomics of the plant is required to find out the genetic mechanism of plant and its adaptive capability to such stresses.

The practice of upland rice cultivation is common in some parts of the world and generally comprises of two major systems: as a low-input subsistence farming in Asia and as a high-input system commonly found in Brazil and some water-limited areas of China (Lafitte et al. 2002). Majority of farmers grow upland rice as a low-yielding subsistence crop to receive stable yields under the adverse upland conditions. Upland varieties are drought tolerant but are low yielding where water deficit, acid and infertile soils, weed competition, and diseases are the primary yield constraints (Lafitte et al. 2002). On the other hand, some of the lowland varieties are cultivated under upland conditions with supplementary irrigation, but yield loss is significantly high (McCauley 1990). De Datta et al. (1973) conducted an experiment where a high-yielding lowland rice variety, IR20, was grown like an upland crop under furrow irrigation. They observed a total water savings of 56 % and irrigation water savings of 78 % compared with growing rice under flooded conditions, but yield was reduced from 7.9 to 3.4 t ha^{-1}. Westcott and Vines (1986) and McCauley (1990) conducted studies in two states of the USA (Texas and Louisiana) on non-flooded irrigated rice (commercial varieties) using sprinkler irrigation under lowland conditions. A reduction of 20–50 % in irrigation water requirement was recorded compared with flooded conditions depending on types of soil, rainfall, and water management practices, but yield was reduced by 20–30 % compared with flooded conditions.

Ideally high-yielding varieties under upland conditions are required, and for this purpose, new "aerobic rice" varieties are essential that can combine characters of upland and lowland rice varieties, being high yielding like lowland varieties and drought tolerant like upland varieties (Atlin et al. 2006). Brazil and North China are among the pioneers of introducing such varieties. In Brazil, a yield of 5–7 t ha^{-1} is recorded for this system of cultivation under sprinkler irrigation, and about 250,000 ha of land is used for cultivation of these varieties. In North China, flash irrigation system in bunded fields is used for these varieties with a yield of about 6–7.5 t ha^{-1} (Lampayan and Bouman 2005). In China, these varieties are being cultivated on about 120,000 ha of land.

11.5.7 Ground Cover Rice Production System (GCRPS)

Ground cover rice production system (GCRPS) is an innovative production technique developed to use less water and to improve tolerance to low temperature (Shen et al. 1997; Liu et al. 2013). This water-saving technology was first developed by the Agriculture Bureau of Shiyan region in China in 1990 (Shen et al. 1997). In this system, soil surface is covered with a 5–7 μm thick plastic film; traditional lowland rice cultivars are used and grown at soil saturation point without any standing water for the whole crop growth period (Qu et al. 2012). This technique is reported to conserve water, preserve heat, and alleviate low temperature stress during early crop growing stage after transplanting, especially in water-deficit and cool hilly areas (Shen et al. 1997; Qu et al. 2012). It also helps save water through increased WUE by reducing evaporation and seepage. It has been reported that WUE of GCRPS yielded up to 0.8–1.0 kg grain m^{-3} water (Tao et al. 2006) compared with WUE of 0.4 kg grain m^{-3} water with the traditional method of cultivation (Tuong et al. 2005). This technique is also environmental friendly as it helps reduce rate of herbicidal application because plastic film prevents weed germination and development (Wu et al. 1999).

Despite the benefits of GCRPS, some disadvantages are also associated with the application of this technique as reported under different conditions (Tao et al. 2006; Qu et al. 2012). A reduction in grain yield compared with the traditional flooded system was reported for areas without any water scarcity and low temperature stress (Wu et al. 1999) as well as for sandy soils (Tao et al. 2006). However, this system was reported to provide superior yield compared with the traditional flooded system for areas where water is a limiting factor for crop growth and temperature is low during the early crop growth stage (Qu et al. 2012). A significant increase in yield in 22 sites out of the total 36 sites was observed by Liu et al. (2013) in central China where this technique was first developed.

GCRPS is basically an "aerobic rice" system that utilizes plastic mulching or straw mulching in the cultivation system. Plastic mulching with drip irrigation is a relatively new water-saving technology for rice cultivation (He et al. 2013). He et al. (2013) reported a yield reduction of 31.8–52.2 % under plastic mulching with drip irrigation compared with conventional flooding, which was primarily due to a low dry matter accumulation during post-anthesis. However, the WUE was the highest under plastic mulching with drip irrigation (1.5–2.1 times higher compared with conventional flooding cultivation system). Therefore, this method could be used as a better water-saving technology in areas of water scarcity with lower yield potential (He et al. 2013).

11.5.8 Genetic Approach

Water productivity in rice production can be increased by suitable germplasm development (Tuong and Bouman 2003). The primary goal of plant breeding in the past several years has been to increase yield by reducing crop growth duration and to introduce good agronomic traits. Water productivity of the modern "IRRI varieties" with respect to total water inputs is almost three times higher compared with the water productivity of the traditional varieties. Rice varieties developed before the 1980s are more efficient with high WP_{ET} as plant breeding program from the early 1960s to early 1980s emphasizes on yield improvement by reducing growth duration (Tuong 1999). Cultivars released after the mid-1980s have long growth duration with comparatively less WP_{ET}. Tropical japonica rice varieties have 25–30 % higher photosynthesis to transpiration ratio than indica type indicating higher transpiration efficiency of tropical japonica varieties (Peng et al. 1998).

Improvement of genetic resistance to biotic (e.g., rice blast disease) and abiotic stresses (e.g., drought, salinity, submergence) is also important and effective breeding approach to water-saving rice cultivation systems. Plant breeders have been successful in manipulating drought escape in the drought-prone and low-fertility rainfed environments. Reduction in growth duration and minimization of the risk of coincidence of crop sensitive growth stages with water-deficit periods have helped minimize drought exposure (Tuong and Bouman 2003). The development of drought-tolerant rice varieties has been slow mainly because of genetic complexity of the trait and its interaction with the environment (Tuong and Bouman 2003), and the unavailability of a specific method for screening the large number of genotypes required in breeding for drought (Zeigler and Puckridge 1995). However, drought-tolerant varieties are developed and released in upland and rainfed lowland areas (Tuong and Bouman 2003). Development of modern drought-screening facilities and methods is helping in facilitating the process of understanding drought-resistance traits and in selecting drought-tolerant genotypes (O'Toole 2004). In many rice-growing countries, salinity remains the most widespread soil problem, and salinity-tolerant varieties are needed for such environments where the cultivation of conventional lowland varieties is not possible. One of the examples of salinity-tolerant rice varieties is Ir51500–AC11–1 (Tuong and Bouman 2003).

11.6 Conclusions and Future Thrusts

Water has been taken for granted for centuries in irrigated rice production under continuously flooded fields, but the present looming water crisis stresses for a change in rice production system in the future. There is a renewed research interest on some of the traditional water-saving irrigation techniques that gained popularity in the 1970s such as AWD and saturated soil culture. Water-saving potentials of these technologies cannot be denied, but mostly associated with a yield penalty. Asia, the biggest rice producer and severely affected by water scarcity, needs more attention, and farmers in many Asian countries have already started adopting these technologies. For example, AWD is mostly adopted by farmers in China (Li 2001), North Central India, and Central Luzon, Philippines.

A modern concept of water-saving rice cultivation is aerobic rice system. The credit of this system goes to the farmers of northern China and is now commercially popular in Brazil. Water crisis is causing a shift of rice cultivation system from continuously anaerobic to alternate aerobic–anaerobic and then completely aerobic conditions. For this purpose, a more advanced and effective rational engineering strategies are required for the development of rice cultivars with high water productivity. Future research is needed to check the genetic improvement for drought tolerance in rice with respect to crop duration and WUE. An integrated approach is required for gene expression to increase water productivity. Cross-fertilization of hardy wild rice species also needs attention from researchers. Similarly, a combination of traditional breeding methods with genetic transgenic methods might be a better option. Site-specific studies are also required across the continents as a single strategy might not be acceptable worldwide. In future research, focus should also be given on crop nutrition, especially on micronutrients. Ecological monitoring of the new system is also essential and should not be ignored. Overall, different physiological and ecological tools should be explored to achieve maximum rice yield with minimum water use.

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Chapter 12
Insect Herbivores of Rice: Their Natural Regulation and Ecologically Based Management

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12.1 Summary

The management of insect herbivores in rice ecosystems has been strongly influenced by three poorly informed beliefs. These are (1) that insects have predominantly negative effects on crop health, (2) that herbivore damage translates directly to yield loss, and (3) that insecticides are necessary to reduce losses due to insect herbivores'. In the face of global changes, particularly increases in the production and marketing of agrochemicals, these beliefs will lead to unsustainable rice production systems and poor environmental health. This chapter assesses these beliefs, challenges their validity, and (by analyzing the dynamics of herbivore populations and their interspecific interactions in the rice ecosystem) presents a holistic alternative for understanding herbivore impacts on rice production systems. The chapter proposes a focus on "rice ecosystem health" with herbivore management based on ecological principals and incorporating such novel approaches as "ecological engineering" for ecosystem stability and system resilience.

12.2 Introduction

Rice paddies are among the most biologically diverse agricultural systems on the planet. Patterns of productivity in irrigated rice are dominated by flood cycles. These cycles produce periodic shifts from dry to flooded conditions. Such shifts,

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together with high primary productivity, promote a rich diversity of flora and fauna (Catling 1992; Way and Heong 1994; Settle et al. 1996; Horgan et al. 2017a). The biodiversity of rice fields, particularly flooded fields, contributes to the sustainability and resilience of the system through several regulatory ecosystem functions (Settle et al. 1996; Ings et al. 2009; Global Rice Science Partnership 2013). Because of the enormous land area under rice production globally (>160 m ha) (Global Rice Science Partnership 2013), it is imperative to manage rice landscapes recognizing and protecting all their ecosystem functions. Such ecosystem functions include the provisioning of food resources for humans, biodiversity maintenance and conservation, prevention of soil erosion and flooding, and the protection of water resources and soil health (Global Rice Science Partnership 2013).

The arthropods that inhabit rice fields provide a range of essential ecosystem services. A relatively small number of arthropod herbivores damage rice plants (see below); however, the vast majority of arthropods species are beneficial. These recycle organic materials through decomposition, act as natural enemies that reduce herbivore damage, pollinate wildflowers and crops, or reduce weed populations by attacking weed foliage and seeds (Way and Heong 1994; Settle et al. 1996; Schmidt et al. 2015; Westphal et al. 2015). Rice fields, particularly in the tropics, often have a higher diversity of arthropod natural enemies than herbivore species, resulting in rice food webs that are understandably complex (Cohen et al. 1994; Wilby et al. 2006). High complexity in food web interactions is predicted to increase the stability and resilience of rice ecosystems (Ings et al. 2009). Furthermore, by responding to changing herbivore densities at spatial and temporal scales, several arthropods in the rice community are recognized as important regulators of herbivore populations (Sawada et al. 1993; De Kraker et al. 1999a, b; Wagiman et al. 2014). Therefore, any discussion about the arthropod herbivores of rice would be incomplete without a broader focus on their interactions with other components of the rice ecosystem, particularly their natural enemies.

Rice has a complex crop cycle that includes a period with low amounts of living biomass (after plowing and puddling), followed by a sudden and rapid accumulation of rice and weed biomass after transplanting or direct seeding. A diversity of insect natural enemies with distinct habitat requirements, behaviors, and diets are required to maintain herbivores at low population densities (Settle et al. 1996; Wilby et al. 2006; Gurr et al. 2012). For example, early in the rice crop, when much of the biomass is nonliving and invertebrate decomposers are abundant, generalist natural enemies can invade the rice fields and build up numbers – these become the first line of defense against rice pests that arrive to the fields after transplanting or sowing (Settle et al. 1996). As the rice plants grow and develop, herbivores will invade the rice fields, a small number of these can become rice pests if not effectively regulated; however, generalist predators consume many of these early herbivore colonists. At the same time, specialist natural enemies like egg parasitoids (Hymenoptera) and mirid predators (Homoptera: Miridae) begin to colonize the fields and build up numbers (Kenmore et al. 1984; Settle et al. 1996). These specialists are essential to maintain low herbivore numbers throughout the cropping period but are vulnerable to perturbations, particularly during early crop stages. For this reason, it is strongly recommended to promote natural enemy abundance during the early crop by creating suitable habitat (i.e., ecological engineering) and avoiding pesticides (Settle et al. 1996; Gurr et al. 2012). It is important to note that rice attacked by herbivores at early crop stages can often compensate well for damage and suffers no yield reductions (Rubia et al. 1996a; Horgan et al. 2016a) or in some cases over compensates for low levels of damage leading to higher yields (Nik Mohammad Noor et al. 1995; Islam and Karim 1997).

Knowledge of the complexity of the rice ecosystem has increased after several years of detailed studies, particularly during the 1990s – however, the predominant paradigms in rice crop management often overlook this knowledge, or fail to apply it, and can sometimes lead to devastating consequences for rice farmers. Three predominant beliefs or attitudes expressed by rice farmers and agricultural extension workers have been that (1) "insects"(implying "all" or "most" insects in the rice field) consume and damage rice, that (2) the damage they cause is proportional or correlated to yield loss, and that (3) insecticides are an efficient means of reducing that damage, protecting the crop and increasing yield (Litsinger et al. 1987; Heong et al. 1995; Rubia et al. 1996b; Heong and Escalada 1999). However, the reality is much more complex. This chapter examines these common beliefs and presents some new ideas that are generally good news for farmers and that should promote more sustainable and environmentally friendly rice production.

12.3 Addressing Common Beliefs About Insects in Rice Fields

12.3.1 Assessing the Belief that Most Insects Are "Bad"

It is a common concern among researchers working in "pest" management that farmers fail to differentiate "good insects" from "bad insects" and generally have little understanding of the effectiveness of the "good insects" in managing the "bad" (International Rice Research Institute 1993; Lazaro and Heong 1995). Often, farmers that note one or two insects (individuals) attacking a rice plant will exaggerate the potential risk when extrapolating to field scales. A single caterpillar feeding on a plant or a small amount of apparent damage is often enough to precipitate a round of insecticide spraying (Rubia et al. 1996b; Bandong et al. 2002; Escalada and Heong 2004). Lazaro et al. (1993) found that farmers grossly overestimate yield losses from stemborers (Lepidoptera: Pyralidae) and often attributed yield losses from other factors (lack of fertilizer, late planting, etc.) to insect damage. Farmers who have poorly managed their fields, resulting in high densities of some apparent pest (such as planthoppers [Homoptera: Delphacidae]), will often cause their neighbors to unnecessarily spray their own fields in the mistaken belief that pest insects will move from a sprayed field to any adjacent unsprayed field (Litsinger et al. 1987; Rubia et al. 1996b). Unfortunately, pesticide vendors will often capitalize on the farmer's inability to accurately or objectively assess risks from insect herbivores to his/her rice crop by prescribing pesticide applications (Escalada et al. 2009; Thorburn 2015). Farmers' field schools and targeted education campaigns have gone a long way in improving the situation among farmers. For example, Indonesia's National Integrated Pest Management Program and the Farmer Field Schools of the Food and Agriculture Organization of the United Nations (FAO) were apparently successful in reducing insecticide use in the 1990s (Matteson 2000; Thorburn 2015). These schools aimed to train farmers to recognize the beneficial roles of predatory insects; however, such education campaigns have variable impacts in reducing pesticide applications (Lazaro and Heong 1995), suffer from a lack of continuity (due to poor funding), and suffer from aggressive product advertising by agrochemical companies (Escalada et al. 2009; Thorburn 2015), who sometimes become a part of pest management training (Ferroni and Zhou 2012).

12.3.1.1 Contrasting Dynamics of Herbivore Populations

Approximately 800 insect herbivores have been noted to feed on rice, but only about 20 are considered economically damaging (Kiritani 1979; Pathak and Khan 1994). Many are problematic due to their peculiar population dynamics, that is, they rarely cause problems at endemic levels, but can lead to major yield losses when they attain outbreak densities. Some of the characteristics of outbreak species can be summarized as follows:

1. Many outbreak species, such as planthoppers and leaf folders (Lepidoptera: Pyralidae), are migratory. For example, the brown planthopper, *Nilaparvata lugens* (Stål), and rice leaf folder, *Cnaphalocrocis medinalis* (Guenée), make springtime migrations northward from tropical Southeast Asia to northern China, Korea, and Japan with generally smaller migrations southward during the autumn (Riley et al. 1995; Otuka et al. 2010). The rapid and massive concentration of individuals carried on air currents may result in large and sudden increases in abundance that overwhelm natural enemies and lead to severe damage (Otuka et al. 2010). Evidence suggests that this has occurred in rice fields of Northeast Asia for centuries and prior to modern rice cultivation methods (Miyashita 1963; Litsinger et al. 1987).
2. Many outbreak species are tolerant to high levels of intraspecific crowding and have an aggregated distribution in rice fields compared to non-outbreak species; for example, planthoppers aggregate more than leafhoppers (Homoptera: Cicadellidae), whereas stemborers and leaf folders have largely random distributions (Kuno and Hokyo 1970; Ôtake 1976; Iwao 1979). Aggregation often improves conspecific fitness and may promote rapid population increases at early colonizer generations (Horgan et al. 2016b).
3. Outbreak species are often typical r-strategists that have a high reproductive output but consequent low defensive or competitive ability – making them vulnerable to natural enemies (Southwood et al. 1974). Among planthoppers, physiological responses to plant age and conspecific density can also lead to

rapid population increases at early stages of colonization (Padgham 1983). Population density can also determine whether an individual is macropterous (having greater dispersal capacity) or brachypterous (having higher fecundity) and thereby ensures maximum planthopper fitness on the developing rice plant.

4. A number of herbivore species that reach outbreak densities are recognized as invasive. These are species that have spread to new regions where they benefit from reduced interspecific competition or predation. Noted examples include the rice water weevil, *Lissorhoptrus oryzophilus* Kuschel; sorghum stemborer, *Chilo partellus* (Swinhoe) (Pathak and Khan 1994); Mexican sugarcane borer, *Eoreuma loftini* (Dyar) (Lepidoptera: Crambidae) (Hunnel et al. 2010; Wilson et al. 2015); and rice grain bug, *Paromius* nr. *longulus* Dall. (Homoptera: Lygaeidae; recently discovered in the Philippines – Orboc personal communication). Some of these species are not typical r-strategists. For example, invasive black bugs, *Scotinophara* spp. (Homoptera: Pentatomidae), have become more problematic in the Philippines in recent decades but have a relatively low fecundity and are nonmigratory (Joshi et al. 2007). However, they often occur in large aggregations which may be the result of attraction toward village street lights or due to habitat change (personal observations).

Some insect herbivores cause economic losses to rice farmers even at low densities – this is often because they transmit harmful viruses, such as the *Nephotettix* spp. (Homoptera: Cicadellidae) that transmit tungro virus in Southeast Asia or *Tagosodes orizicolus* (Muir) (Homoptera: Delphacidae) that transmits *Rice hoja blanca virus* (RHBV) in Central America and the Caribbean (Fujita et al. 2013). Furthermore, some insect herbivores, such as rice bugs, *Leptocorisa* spp. (Homoptera: Alydidae), are problematic because they damage the rice grains either directly reducing yield at a late stage in the crop or reducing the quality of the seed and thereby its market value (Jahn et al. 2004). These species are often polyphagous and habitat generalists and, in contrast to the outbreak species discussed above, often attain higher population densities in relatively heterogeneous habitats (Pathak and Khan 1994).

12.3.1.2 Regulation of Herbivore Densities

Without natural enemies, population densities of any herbivore species would increase exponentially, and rice cultivation would be impossible. Among the studies that have examined regulation of rice herbivores, there have been two schools with rather different emphases. Early studies, predominantly from Japan, focused on intrinsic rates of natural increase and found density dependent reductions in egg laying and population growth as important regulating factors. This density dependence was often attributed to intraspecific competition with little role attributed to natural enemies (Miyashita 1963; Kuno and Hokyo 1970). Studies in tropical rice, particularly from Indonesia and the Philippines, focused more on the role of natural enemies. These studies often found strong correlations between the abundance of

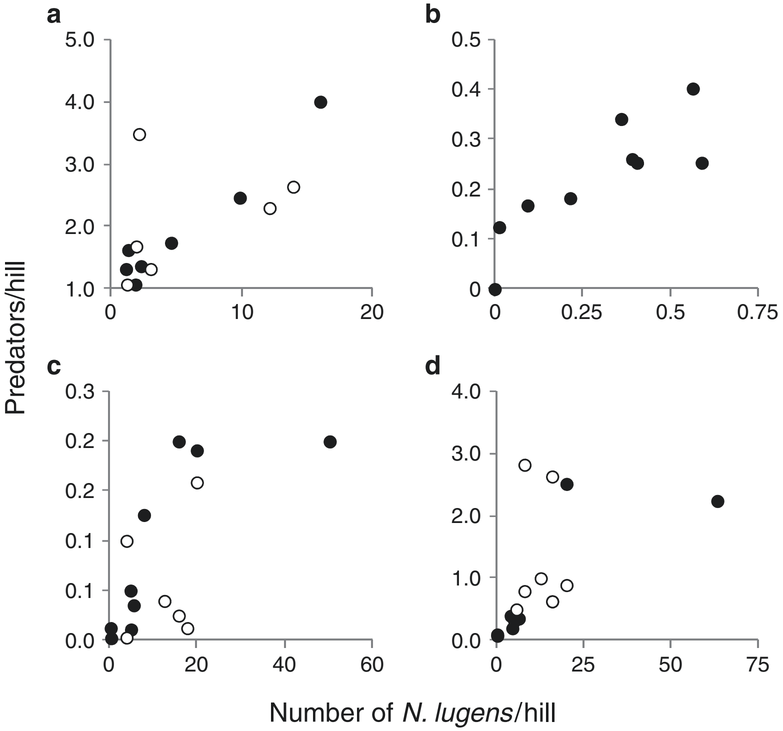

Fig. 12.1 Density-dependent responses by natural enemies to populations of the brown planthopper, *Nilaparvata lugens*, in rice: (**a**) Spiderling numbers in Philippine rice fields during the 1978 wet season. Data are from fields with cv. IR1917 (*solid points*) and cv. IR26 (*open points*), (**b**) *Paederus fuscipes* (Coleoptera: Staphylinidae) in rice fields on Java during 2011, (**c**) *Cyrtorhinus lividipennis*, and (**d**) *Microvelia* spp. (Homoptera: Microveliidae) in Java during 1984/85 (*solid points*) and 1985/86 (*open points*) cropping seasons (Redrawn using data from (**a**) Kenmore et al. (1984), (**b**) Wagiman et al. (2014), and (**c**, **d**) Sawada et al. (1993))

planthopper and spiders, egg parasitoids, or mirid bugs (Fig. 12.1). These observations suggested density-dependent responses. Kenmore et al. (Kenmore et al. 1984) pointed out that spiderling recruitment was highest when prey density was high – suggesting numerical responses to density that were likely to be delayed; but some species, like *Cyrtorhinus lividipennis* Reuter (Hemiptera: Miridae), responded numerically through aggregation to areas of high herbivore densities (Sawada et al. 1993; Way and Heong 1994). Density dependence is a feature of regulation and an indicator of a healthy rice environment.

Regulatory natural enemies are often not the principal mortality factors impacting herbivore populations; mortality due to key factors (the main source of mortality – or main life stage affected by mortality) is often density independent and may be determined by factors such as climate, poor synchronization of some insect life stage with the crop, or generalist predators. For example, the key factor in the dynamics of stemborer populations in deepwater rice is neonate mortality between the time of egg hatch and before the larva enters the rice stem (Islam 1994). During this phase, natural enemies cause high mortality to neonates searching for suitable feeding sites. Herbivore populations in rice are therefore affected by multi-tier systems that may include key factors such as generalist natural enemies that reduce high herbivore densities to lower equilibrium points and regulators that maintain the populations at this lower equilibrium density.

12.3.2 Assessing the Belief that Yield Loss is Proportional to Insect Damage

12.3.2.1 Difficulties in Measuring Yield Losses Due to Herbivores

Rice damage, rice plant responses to damage, and yield losses due to damage are all features of the interactions between herbivores and the rice plant. Therefore, to adequately define damage and yield losses due to herbivores, researchers must account for a range of possible responses by rice plants, some of which are specific to certain rice varieties or to particular cultivation systems. Thousands of rice varieties are currently used in modern agriculture, and most of these are genetically, anatomically, and physiologically different and, hence, respond differently to herbivore damage. For example, some varieties are highly tolerant to damage such that even severe insect damage causes no yield decline (Horgan and Crisol 2013; Horgan et al. 2016a). In some cases, certain insects may actually cause overcompensation, with higher yields after damage (Nik Mohammad Noor et al. 1995; Rubia et al. 1996a; Islam and Karim 1997), whereas other varieties may be highly susceptible to herbivores, e.g., Taichung Native 1 (De Datta 1981). Many studies that have attempted to assess yield losses to herbivores have used only the most susceptible varieties (De Datta 1981). Although fraught with methodological problems, several studies do give some reasonable indication of the potential effects of herbivores on rice yield. However, the following cautions should be taken into account before considering the results of such studies:

1. Whereas scientists have normally focused on a single herbivore species and its effects on a specific rice variety (or at most a small group of varieties), rice plants in the field interact with a complex of herbivores. It is clear that damage from different herbivores is not additive. Different herbivore species, even from the same feeding guilds, have different effects on rice plants (Horgan et al. 2016a). Furthermore, plant-mediated interactions between herbivores or between herbivores and diseases can reduce the negative effects of one or other pest or disease in a way that is ultimately beneficial to the plant (Pangga et al. 1993; Kanno and Fujita 2003).
2. In order to estimate herbivore effects on yield, researchers have often used methods that do not adequately represent field situations. In greenhouse and pot experiments, apart from a lack of natural enemies that would normally limit the

buildup of pests, the herbivores themselves often find optimal conditions (i.e., controlled temperatures) or are adapted to captivity because they have been laboratory reared for multiple generations. Furthermore, plants in pots are not representative of field-grown plants because they often experience root competition in confined spaces (Crisol et al. 2013).

3. Estimates of herbivore damage are often too general: Early reports gave blanket estimates of about 30 % without considering spatial or temporal variability in population densities (Litsinger et al. 1987). For example, it is quite likely that *N. lugens* causes 100 % yield losses in some areas during some outbreaks, but at endemic (chronic) densities, they may cause zero losses or even an increase in yields. Since outbreaks are atypical events and are often the result of poor crop management – such losses should not be taken into account when reporting "typical" herbivore-related yield losses.
4. In considering arthropod effects on yields, studies have been biased toward herbivores. This may seem logical, but only a few studies have quantified in economic terms (as related to yield) the benefits of invertebrate decomposers or the role of pollinators in increasing farm productivity (Settle et al. 1996; Gurr et al. 2016). In recent years, these economic advantages have been given more attention and are differentiated from yield losses as ecosystem services (Schmidt et al. 2015; Westphal et al. 2015). However, researchers have not generally looked at herbivory together with other ecosystem services – which should promote more balanced views and impart further knowledge in support of herbivore management decisions. Some beneficial insects have been implicated in damaging rice, for example, the lady beetle *Micraspis crocea* (Mulsant)(Coleoptera: Coccinellidae) and the cricket *Metioche vittaticollis* (Stål)(Orthoptera: Gryllidae) are efficient predators of rice herbivores, but these also consume rice pollen and leaf tissues (Wilby et al. 2005). This sometimes causes farmers and researchers to mistakenly regard these as pests (Pathak and Khan 1994, personal observation).

12.3.2.2 Estimates of Herbivore-Related Yield Losses

Early estimates of insect damage appear quite variable and often remarkably high, e.g., Grist and Lever (1969) indicated rice yield losses from insect herbivores in the 1960s to be 18–36 % in Asia, but only 2–3.5 % in Latin America. Walker (1987) reviewed estimates of herbivore damage to rice during 1970–1983: National and regional losses ranged from 4 to 45 %; losses to planthoppers in South and Southeast Asia ranged from 1 to 40 %; and losses by stemborers in Asia ranged from 1 to 40 %, whereas in Africa stemborers were estimated to cause 9–23 % yield losses. The rice gall midge, *Orseolia oryzae* (Wood-Mason) (Diptera: Cecidomyiidae), in Asia was estimated to cause yield losses of 6–70 %! It is interesting to note that losses due to leaf folders in India were estimated at 10–18 % in the study, but recently, it has become widely accepted that leaf folders cause negligible or zero yield losses (Matteson 2000). It is likely that most of the higher estimates reported above concerned atypical outbreaks, which often attract researcher attention and result in a bias toward higher estimates. The usual method to assess yield losses in many early reports has been to correlate insect damage and yield, using individual rice plants, field plots, or fields as sampling units (i.e., Katanyukul 1982). Such opportunistic studies are subject to unrepresentative sampling, poor control of plant or plot management, and errors of "cause and effect." Although such studies may guide future research, they are not recommended as a means of gaining concrete data. Furthermore, many older estimates of yield losses from insects can now be deemed unrealistic for modern farms because of changing preferences for rice varieties over the last several decades as well as an emphasis on host plant resistance during national and international rice breeding programs (Pathak and Khan 1994; Fujita et al. 2013). Hybrid rice varieties may be a notable exception: Many hybrid rice varieties are highly vulnerable to insect herbivores but are still grown by millions of farmers worldwide (Cheng 2009; Horgan and Crisol 2013).

Several authors have reported the results of experimental studies that examined the effects of herbivore density on yield losses in rice. Because of the high diversity of insect herbivores and rice varieties used in such experiments, the results cannot be adequately addressed in the present chapter. However, the overall trends from such studies can be largely divided into four categories:

1. No relation between herbivore densities and yield (no effect) or relatively minor declines in yield at high – but unrealistic – densities (e.g., *whorl maggot* (International Rice Research Institute 1988), caseworm, *Nymphula depunctalis* Guenée (Heinrichs and Viajante 1987), rice bug, *Leptocorisa oratorius* (F.) (Van Den Berg and Soehardi 2000))
2. Clear correlations between insect density and yield loss, but with often unrealistically high densities that would exaggerate yield losses if the results were projected to rice fields (e.g., rice hispa, *Dicladispa armigera* Olivier (Coleoptera: Chrysomelidae) (Chatterjee and Bera 1990); African gall midge, *Orseolia oryzivora* Harris (Nacro et al. 1996); *L. oratorius* (Morrill et al. 1989))
3. Clear correlations between insect density and yield loss with realistic densities because the herbivore species in question is prone to outbreaks (e.g., *Scotinophara* sp. (International Rice Research Institute 1988), *N. lugens* (Sarma and ChannaBasavanna 1980), *L. oryzophilus* (Zou et al. 2004))
4. Correlations between insect density and yield loss at relatively low to moderate densities, indicating that the herbivore may cause yield losses at typical field densities (e.g., stemborers (Bandong and Litsinger 2005))

Often the results from different studies that assessed yield losses due to the same herbivore species provide conflicting results (i.e., Morrill et al. 1989; Van Den Berg and Soehardi 2000); this may reflect the different methods or different host plants used in the evaluations. Further studies of yield losses that incorporate multiple plant types (i.e., rice hybrids, pure-line varieties, or traditional varieties) are still required to accurately define economic thresholds for future management programs aimed at particular herbivore species.

Studies that compare protected and control plots (called the "insecticide check method") are useful to estimate yield losses because they give estimates of damage from the complete herbivore community under field situations. The insecticide check method uses heavy insecticide applications, including mixing insecticides with the soil, in an attempt to eliminate herbivores from field plots – these are then compared to adjacent control plots that have received no insecticide applications. Some weaknesses of the system include phytotoxic and phytotonic effects of the insecticides, effects of plot size, and the effects of pesticide drift on control plots and especially on natural enemies (Litsinger et al. 1987). Using this method, Litsinger et al. (1987) presented estimates from the Philippines of insect-related crop losses that ranged from 2 % in traditional dryland crops (yield 2.9 t ha^{-1}) to 23 % in modern dryland crops (yield 4.2 t ha^{-1}) and about 18 % in both traditional (yield 2.2 t ha^{-1}) and modern rainfed crops (yield 3.9 6 t ha^{-1}). Variability between sites was large, with the effects of herbivores ranging from −8 to 69 % yield declines (−8 implying a yield increase). Interestingly, the ranges of grain weight (grain biomass) lost or gained were much more consistent than percentage losses. Gains from insects (potential overcompensation) ranged from 0.04 to 0.3 t ha^{-1}, and losses from insects ranged from 0.1 to 2.4 t ha^{-1} or about 0.5 t ha^{-1} in the rainfed systems. In a similar study conducted over 13 years at four irrigated, double-cropping sites, yield losses were estimated to be about 12 %, i.e., grain weight reduction of 0.6 t ha^{-1}(Litsinger et al. 2005).

Recent estimates of rice crop losses due to insects have not been as rigorous or as frequent as those conducted in the 1980s to1990s. Considering modern varieties with higher yields, better crop management techniques including nutrient management, and a likely maximum loss of about 0.5 t ha^{-1} due to chronic pests, it should be expected that the percentage losses in yield would now be considerably lower than in the 1960s (Grist and Lever 1969), 1970s (Walker 1987) or 1980s (Litsinger et al. 1987, 2005). Until further estimates are available, losses due to herbivores in unmanaged rice fields should be regarded as spatially and temporally variable and likely to be below the economic thresholds for insecticide use at field or larger scales. Certainly, based on the current understanding of herbivore-related yield losses, and considering the capacity of rice plants to compensate for damage, it would be hard to justify any prophylactic insecticide use in modern rice farms.

12.3.3 Assessing the Belief that Insecticides Reduce Yield Losses

A third predominant belief among farmers and extension workers is that insecticides reduce damage and prevent yield losses. This belief has led to a multibillion dollar industry and to a fear among many farmers (known as fear aversion) that rice cannot yield without insecticides (Litsinger et al. 1987; Heong et al. 1994, 2002). The economic value of farmer "fear aversion" is clear (Fig. 12.2). In order to better

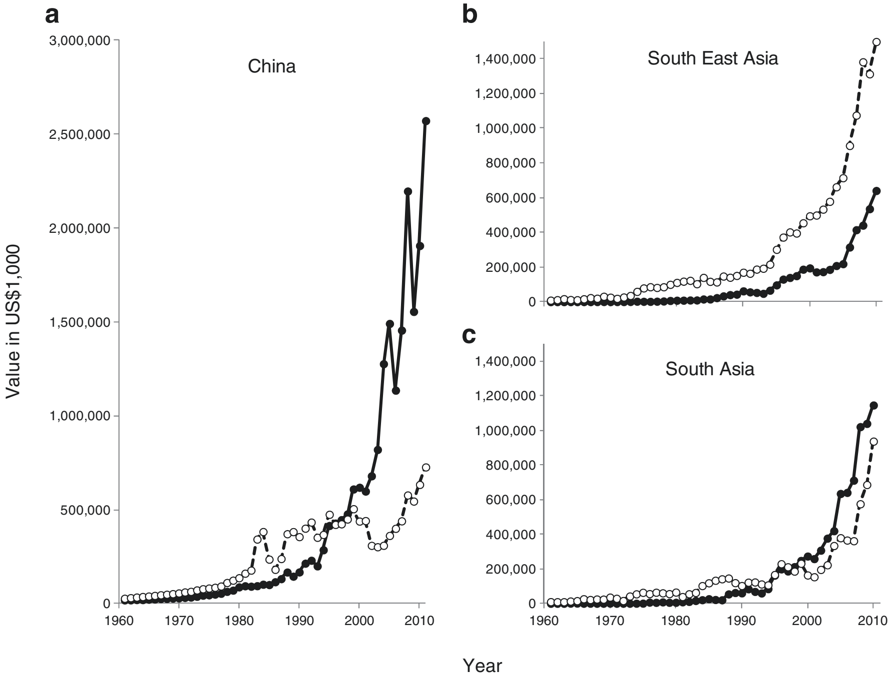

Fig. 12.2 Value of insecticide exports (*solid points*) and imports (*open points*) in (**a**) China, (**b**) Southeast Asia, and (**c**) South Asia between 1960 and 2010. Note that China and South Asia became net exporters between 1995 and 2000 (Source: Food and Agriculture Organization of the United Nations)

understand the issues related to insecticide use and its effects on rice, some points should be considered:

1. Insecticides are toxic and rice plants are living organisms; therefore, the insecticides also affect the plants. For example, studies using a range of insecticides and spraying at different times and at different intensities have indicated that late spraying can directly reduce rice yields (Peñalver 2014).
2. Insecticides will often miss their target pests because of poor timing or because the target is hidden in the stem, located at the base of the plant, or at a life stage that is not affected by the chemical. Insecticides are often not applied properly because of mixing of chemicals or poor access to efficient spray equipment (Heong et al. 2015). Also, because of the rapid development of herbivore resistance to insecticides, many chemical products have a short utility time (Matsumura et al. 2008); however, because products are not removed from markets, they continue to be used without effect.

3. Insecticides can cause physiological resurgence, that is, the target herbivore responds to the insecticide by increasing feeding, reproduction, or population growth. This has now been well documented for planthoppers (Azzam et al. 2009, 2011) and is becoming increasingly clear for stemborers and leaf folders (Wang et al. 2005; Yu et al. 2007; Horgan et al. 2017b).
4. Insecticides are indiscriminate; they usually kill or damage all insects including the beneficial natural enemies of herbivores. Some insecticides are less toxic to natural enemies than to herbivores, but even when natural enemies survive, or where they rapidly recolonize insecticide-treated fields, their efficiency in predation may be reduced (Horgan et al. 2017b). These effects of insecticides on natural enemies can lead to ecological resurgence. Ecological resurgence has been well documented for planthoppers (Kenmore et al. 1984).
5. In some cases, applying insecticides to combat one pest will cause resurgence of a second pest – such is the case with planthopper outbreaks which develop after insecticide applications made to control leaf folders (Ooi and Saleh 1979). Interestingly, herbicides, fungicides, and molluscicides have also been noted to increase herbivore damage to rice (Azzam et al. 2009, 2011; Horgan et al. 2014).
6. Apart from the negative effects on rice ecosystem function and potential negative effects on yield, pesticides also have negative effects on human health and on livestock and wildlife (Pingali and Roger 1995).

Despite these obvious caveats and the need for caution, the pesticide industry has expanded: Asian farmers can now choose from thousands of insecticide products (Litsinger et al. 1987; Heong et al. 1994; Heong and Escalada 1999). Figure 12.2 indicates insecticide imports and exports in Asia over 50 years. It is apparent that since the year 2000, insecticide purchases have increased dramatically in South and Southeast Asian countries. Similar trends have been noted in Latin America and West Africa (Food and Agriculture Organization of the United Nations). Interestingly, the dramatic increases in pesticide imports into South and Southeast Asia began at about the time that China and India turned from being net importers to major exporters of insecticides (Food and Agriculture Organization of the United Nations). Despite the massive increases in insecticide availability in Asia, there has been no proportionate increase in national rice yields (Food and Agriculture Organization of the United Nations). Furthermore, outbreaks of resurgence pests such as planthoppers have become increasingly common during the last 10–15 years (Cheng 2009; Fig. 12.3). Heong et al. (2015) have indicated from their results of over 3800 farmer interviews in Vietnam that rice yields have generally remained constant despite farmers applying insecticides between 0 and >8 times per crop. Judging from recent literature, it is possible that insecticides have become the principal drivers of rice herbivore outbreaks in Asia and are inadvertently the major cause of insect-mediated yield losses when viewed at larger spatial and temporal scales.

Fig. 12.3 Farmers in East Java (Indonesia) manage long, narrow plots of rice and vegetables. Varying degrees of damage to individual fields during a brown planthopper (*Nilaparvata lugens*) outbreak (indicated by differing degrees of browning) highlight the role of poor crop management in inducing outbreaks. All fields in this photo were transplanted at the same time with cv. Ciherang, but farmers applied varying amounts and types of insecticide to their plots

12.4 Building a Sustainable Rice Production System

12.4.1 The Rice Plant at the Center

The rice plant is central to the functioning and dynamics of the rice ecosystem. Rice varieties are generally categorized between susceptibility and resistance based on responses by key herbivores or diseases to the plants (Horgan 2012). Farmers are expected to base their choice of varieties on levels of known resistance. However, this seems to be rarely the case. For example, several reports have indicated that hybrid rice varieties are associated with high levels of damage from planthoppers and stemborers throughout Asia. Despite such apparent susceptibility to damage, hybrid rice varieties have been increasingly adopted by Asian farmers and are the main rice varieties grown in China and northern Vietnam (Horgan and Crisol 2013). Nevertheless, researchers continue to focus on the development of rice varieties with resistance to important insect herbivores and diseases (Chen et al. 2012; Fujita et al. 2013). A recent appraisal of rice pest management literature (Horgan 2012) indicates host plant resistance as the main focus of public research for the last several decades followed closely by research on potential insecticides (Horgan 2012). Furthermore, since the 1990s, research in rice stemborers has been dominated by transgenic approaches to resistance with almost no research into "native" resistance sources (Horgan 2012). Whereas transgenic resistance holds some promise, transgenic resistant rice is not currently available to rice farmers because of logistics around the distribution of transgenic varieties, a lack of confidence among farmers and consumers, and difficulties in managing the development of adapted herbivore populations (Teetes 1994; Horgan 2012). More recently, some reassessment of native host plant resistance against rice stemborers has been reinitiated (Way et al. 2006; Hamm et al. 2012).

The development of resistant rice varieties using conventional breeding techniques has been more successful against herbivores that have intimate associations with their host plant. These are usually monophagous species, such as planthoppers or gall midges, that can regulate plant hormones or sequester plant defenses to allow feeding or gall formation (Bentur et al. 2008; Fujita et al. 2013). Currently over 85 genes have been identified imparting resistance against planthoppers and leafhoppers (Fujita et al. 2013; Horgan et al. 2015). Many of these genes have come from wild rice species, but several are from traditional rice varieties from Bangladesh, India, and Sri Lanka (Fujita et al. 2013). Planthoppers and leafhoppers feed less, gain less weight, develop slowly, and lay fewer eggs on varieties that carry resistance genes. However, the mechanisms underlying these responses have not generally been elucidated (Horgan 2009). Rice gall midge resistance is better understood and appears to be governed by gene-for-gene relationships akin to disease resistance. About 14 gall midge resistance genes have been identified, and these have been incorporated into several resistant rice varieties (Bentur et al. 2008). However, insect herbivores can often quickly adapt to resistant varieties (Peñalver Cruz et al. 2011; Ferrater et al. 2013, 2015; Vu et al. 2014), and recent studies have indicated a gradual loss of resistance against field populations of target herbivores, e.g., *O. oryzae* (Bentur et al. 2008) and *N. lugens* (Horgan et al. 2015; Srinivasan et al. 2015). Clearly, host plant resistance is limited by the emergence of virulent herbivore populations; hence, effective resistance needs to be conserved through careful resistance management. This includes the limited deployment of resistance genes in time and space, careful crop management to avoid compromising resistance (Peñalver 2014), and attention to the preservation of natural enemies, some of which may be more effective in killing herbivores on resistant plants (Kartohardjono and Heinrichs 1984; Horgan 2012).

Several researchers have dedicated themselves to the development of resistant varieties; however, issues of tolerance (the ability of a plant to compensate for damage) have received little attention. Resistance and tolerance are often regarded as antagonistic; however, it seems clear that tolerance traits are also governed by major genes and that breeding for tolerance is possible (Horgan and Crisol 2013). However, it has been difficult to define and screen for tolerance, and the effects of tolerance in the field are difficult to predict (Horgan 2012). For example, tolerance to disease may allow the buildup of disease-causing organisms including insect-vectored viral diseases. Similarly, tolerance to herbivores might cause larger and more widespread outbreaks in poorly managed production systems (Horgan 2012).

The benefit of tolerance for sustainable rice production systems (where natural enemies are promoted) is that it allows herbivore populations to attain relatively high numbers (compared to non-tolerant varieties) before they cause any economic damage to the crop. By maintaining densities of herbivores in rice fields, natural enemies can stabilize the herbivore populations. This suggests that highly tolerant hybrid rice varieties, although often reported as susceptible to herbivores, might be a good option for organic, pesticide-free, or other environmentally friendly production systems (Horgan and Crisol 2013; Horgan et al. 2016a). Tolerance is however also a feature of crop management. High fertilizer use in farmer's fields results in faster growth rates and larger plants which often increases rice tolerance (Horgan and Crisol 2013; Horgan et al. 2016a). Therefore, the development of sustainable rice systems depends on a good knowledge of the rice variety and selection of the crop based on known resistance (including knowledge of resistance genes that are useful for the given region), plant-based tolerance, and proper nutrient management that avoids too high fertilizer levels for the yield potential of the variety.

12.4.2 Creating a Healthy Rice Ecosystem

12.4.2.1 Landscape Approaches to the Management of Herbivores

Some herbivore management practices are effective at field scales. For example, farmers can opt to use resistant varieties, biological control agents, or pheromone traps in their fields to reduce herbivore damage (Lv et al. 2015). Changing farm management practices at landscape scales (because farmers widely adopt some new management practice) can profoundly affect herbivore population dynamics (Song et al. 1982; Kiritani 1988; Thies and Tscharntke 1999; Horgan and Crisol 2013; Srinivasan et al. 2016). Furthermore, the coordination of farmer activities can determine the impact of landscape effects on herbivore populations, e.g., synchronized cropping has been implicated in reducing densities of stemborers and leafhoppers (Horgan and Crisol 2013), whereas it increases densities of planthoppers (Sawada et al. 1992; Wada and Nik Mohammad Noor 1992). Synchrony of cropping is an important criterion for reducing rice viruses that are vectored by insects (Chancellor et al. 1999). Landscape approaches to crop management are expected to contribute to the sustainability of production landscapes and to resilience against perturbations – including stabilizing the effects of poor management by one or other farmer at larger spatial and temporal scales. One landscape approach to pest management that is gaining increasing attention is ecological engineering.

12.4.2.2 Agroecology and Ecological Engineering

Ecological engineering is the deliberate manipulation of habitat for the benefit of society and the natural environment (Gurr 2009; Gurr et al. 2012). The method is strongly knowledge based and requires a thorough understanding of the potential positive and negative effects of any interventions by the practitioner prior to implementation. Ecological engineering for pest management mainly focuses on increasing the abundance, diversity, and function of natural enemies in agricultural habitats by providing refuges and alternate or supplementary food resources (Landis et al. 2000; Lv et al. 2015). Research into ecological engineering in rice production systems largely began in the early 2000s. Reports on the success of the method are now beginning to emerge from recent research conducted at landscape scales in Thailand, Vietnam, China, and the Philippines (Gurr et al. 2016; Horgan et al. 2016c).

During the 1990s, research from the Philippines, although not originally referred to as "ecological engineering," examined the effects of weedy bunds, or bunds planted with dry crops, on the mortality of rice herbivores at different distances from the bunds. These studies indicated that weeds and dry crops provide alternate hosts for some important natural enemies of planthoppers and stemborers; however, weedy bunds often also attracted rice herbivores (Morrill and Almazan 1990; Marcos et al. 2001; Yu 2001; Way and Javier 2001). More recently, ecological engineering for rice pest management has focused on planting flower strips (with nectar producing ornamental flowers or flowering vegetable crops) along rice bunds. For example, several thousand hectares of rice have had flowers planted along bunds in South Vietnam following campaigns by local government (Westphal et al. 2015; Horgan et al. 2016c; Fig. 12.4). Flower strips are predicted to increase the habitat value of rice fields for the natural enemies of insect herbivores. Certain flowering plants have been shown to prolong the life or enhance reproduction of planthopper egg parasitoids and predatory mirid bugs in the laboratory (Zhu et al. 2013a, b). Furthermore, field studies have shown vegetable strips and vegetable plots to reduce planthopper populations in rice; however, the effects were not only due to natural enemies but also due to reduced "apparency" (the ability of the herbivore to find the crop) or to the vegetables acting as a physical barrier to herbivore dispersal (Lin et al. 2011; Yao et al. 2012). Planting strips of mung bean (*Vigna radiata* L. Wilzeck) on rice bunds in the Philippines has been shown to increase spider densities and the ratio of spiders to planthoppers in the rice (Horgan, unpublished data).

Apart from supporting populations of parasitoids and predatory arthropods, strips and plots of vegetables also provide habitat for insectivorous birds and pollinators and will also produce fruits and vegetables as supplementary food for farm households (Horgan et al. 2017a, b; and 12.4). A multisite study conducted between 2009 and 2012 in China, Thailand, and Vietnam found ecologically engineered rice landscapes to produce several economic and environmental benefits (Gurr et al. 2016). Data from across the sites indicated that flower strips on rice bunds could reduce planthopper populations, reduced insecticide applications by 70 %, increased rice grain yields by 5 %, and delivered a 7.5 % economic advantage over conventional rice (Gurr et al. 2016). It is clear from this study that the benefits of ecological engineering were due to the combined effects of flowering bunds creating a habitat for natural enemies together with a lower mortality of natural enemies (and possibly reduced potential for physiological resurgence of rice herbivores) because of reduced pesticide applications (Gurr et al. 2016). In a related study, Lv et al. (2015) found lower herbivore damage, higher farm profits and benefits for the environment that included a higher abundance of frogs at an ecologically engineered site compared to conventionally

Fig. 12.4 High-diversity vegetation patches at a rice farm in Mindanao, Philippines. These patches were interspersed among the rice paddies and produced flowering fruits and vegetables including bitter gourd, mung bean, lady finger, and string beans. Natural enemies of key rice herbivores were attracted to the bitter gourd and mung bean flowers

farmed sites (Fig. 12.5). These results point to ecological engineering as an exciting development for herbivore management in rice that promises to contribute to the sustainability and resilience of rice production systems as research continues.

12.5 Concluding Remarks

Rice farmers, agricultural extension officers, and researchers will need to reappraise some common beliefs about yield losses to rice caused by insect herbivores and about the effectiveness of insecticides in maintaining or increasing grain yields. Three prominent beliefs are not substantiated by current scientific knowledge and should not be held as valid generalizations to guide management decisions. These are (1) that insects have generally negative effects on crop health, (2) that herbivore damage translates directly to yield loss, and (3) that insecticides increase rice yields. Adherence to these unfounded beliefs will reduce the productivity, profitability, and sustainability of rice production landscapes. Such negative consequences will be further enhanced in the face of global changes such as the phenomenal increases in modern industrial output (especially in China and India), in mechanization, in communication technologies and advertising, and in

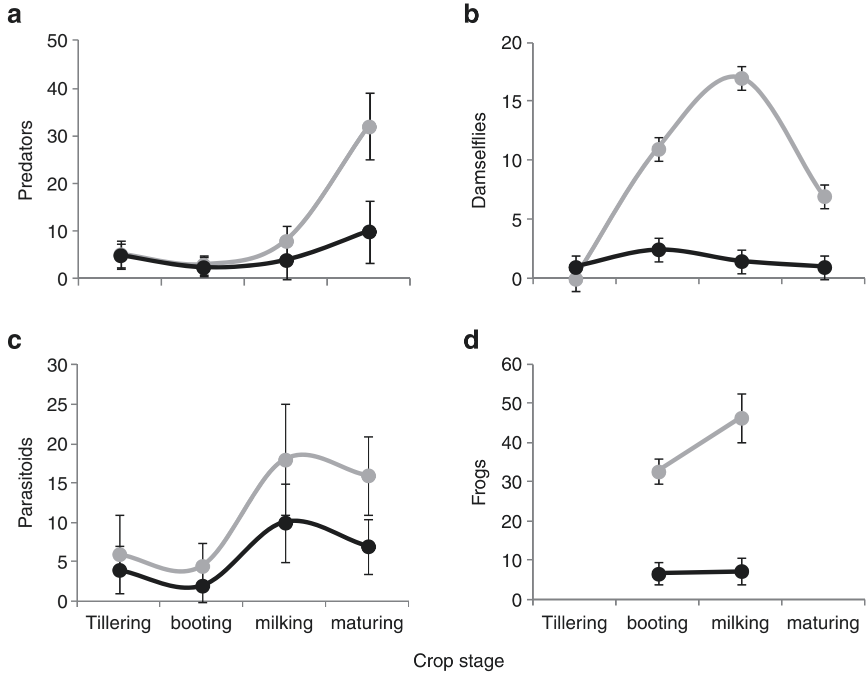

Fig. 12.5 Indices of abundance of (**a**) predatory insects, (**b**) parasitoids, (**c**) damselflies, and (**d**) frogs (*Rana limnocharis* Gravenhorst) at an ecologically engineered site (*grey points*) and adjacent farmers' fields (*solid points*) in China during 2010. The ecologically engineered site had vetiver grass (*Vetiveria zizaniodes* [L.]) and sesame (*Sesamum indicum* [L.]) planted on the rice bunds and reduced insecticide applications by 75 %. The farmers' fields used insecticides only to control herbivores. Average rice yields at the sites were 10.0 t ha^{-1} at the ecologically engineered site and 10.3 t ha^{-1} in the conventional farms. The engineered sites also gained US$ 120/ha from sesame production and saved US$ 150/ha on insecticides. To date, few field studies have assessed the potential of ecological engineering for pest management in rice (Redrawn from Lv et al. (2015))

transportation networks. A common understanding of the potential effects of climate on herbivores is that it may affect species distributions and allow the expansion of pests and diseases to higher latitudes. However, concurrent changes in the distributions of natural enemies are expected to buffer against any negative impacts from expanding herbivore ranges (Kiritani 1999). It is therefore essential to promote a holistic approach to rice production that emphasizes "rice ecosystem health." This will be achieved by recognizing the deleterious effects of insecticides and by enhancing the overwhelming benefits of natural enemies and landscape diversity. Strategies, such as agroecology and ecological engineering that preserve food web complexity, ecosystem stability, and system resilience in rice landscapes, deserve further research attention and constitute an important avenue for attaining global food security.

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Chapter 13

Importance and Management of Rice Diseases: A Global Perspective

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13.1 Introduction

Global agriculture has undergone a significant change with respect to input use, varietal diversity and cropping intensity during the last five decades. In addition, visible changes in the climatic parameters have severely affected the global agriculture. Globally rice is the principal food crop especially in the developing world. Achieving the increased production target for rice has become very challenging due to unabated growth in global population and continuous loss of arable land to industrialization and human settlement. Scarcity of labour and water (particularly in the developing world with semi-mechanized farming) has become a barrier to higher rice production. Intensive rice cultivation accompanied by heavy use of fertilizers and pesticides is adopted in order to achieve high rice production. Non-judicious and over-exploitation of modern agricultural technologies has resulted in sickening of cultivable lands, contamination of groundwater and development of pesticide-resistant strains of pests and pathogens. Widespread cultivation of few high-yielding nitrogen-responsive varieties with narrow genetic base replacing the mosaic of local land races and traditional crop varieties has resulted in unabated spread and epidemic development of different plant diseases (Keneni et al. 2012). Mankind has seen many horrific instances of such epidemics of different plant diseases. The most dreaded

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one was ‘The Great Irish Famine’ which occurred during 1845 due to widespread cultivation of genetically uniform clone of a single potato variety called ‘Lumper’ coupled with favourable weather conditions (Zadoks and Schein 1979). Historically, rice crop has also suffered severe epidemics in the past. The ‘Great Bengal Famine’ during 1942 where an estimated 2 million people died due to widespread occurrence of brown spot disease which devastated the rice crop in Eastern India (Strange and Scott 2005; Barnwal et al. 2013). Severe rice blast epidemics resulted in yield loss ranging from 10–50 % and caused a major food crisis in South Korea in the 1970s (Mew et al. 2004). Rice diseases have always affected the potential yields. Globally, yield losses in rice due to pests (diseases, animal pests and weeds) vary from 20 % to 30 % of the attainable yields (Savary et al. 2012).

The use of disease-resistant cultivars and fungicide application play an important role in minimizing the yield loss caused by different diseases. Fungicide use in South Asia is highest in India and Vietnam where more than 75 % of the farmers apply fungicides (Heong and Escalada 1997) and is expected to increase further. Host resistance has played a major role in sustaining rice productivity, though major emphasis has been given mainly for the major diseases like bacterial blight (BB) and blast (Leung et al. 2003). Evenson (1998) predicted that modern high-yielding varieties (HYVs) with inbuilt resistance to rice diseases would contribute 7–10 % yield gain in rice production. Several resistant rice varieties possessing multiple bacterial blight resistance genes, released in different countries, viz. India, China, Indonesia and the Philippines, exhibited a yield advantage ranging from 11 to 31 % over the standard popular varieties (Leung et al. 2004; Sundaram et al. 2008; Gopalakrishnan et al. 2008). Several rice varieties are also being improved for blast resistance by pyramiding different blast resistance genes (Singh et al. 2011). Efforts are also being made to combine both blast and BB resistance in a single rice variety (Hari et al. 2013; Balachiranjeevi et al. 2015), and such varieties with inbuilt resistance to multiple biotic stresses are expected to further reduce the loss in rice yield due to biotic stresses.

Recently, the intensity and profile of rice diseases has been impacted by changes in several climatic parameters, especially temperature, relative humidity and rainfall pattern, changes in cropping pattern and intensity, increased use of inputs, changes in varietal composition in a particular region and widespread cultivation of few selected high-yielding varieties (narrow genetic base). A number of research reports using controlled experiments have demonstrated that changes in environmental parameters can significantly affect the intensity of plant diseases. Kobayashi et al. (2006) demonstrated that a rise in CO_2 concentration increased leaf blast and sheath blight development indicating that potential risks of rice blast and sheath blight would increase in rice grown under elevated CO_2. Temperature changes may also alter the level of host resistance. Webb et al. (2010) reported that though the effectiveness of most of bacterial blight resistance genes in rice reduces with increase in temperature, BB resistance gene *Xa7* was more effective at higher temperature (35:31 °C, day/night) than at lower temperature (29:21 °C, day/night) in restricting bacterial blight disease severity in rice and population of its pathogen, *Xanthomonas oryzae* pv. *oryzae*. An increase in total rainfall during the month of August resulted in epidemic form of bacterial blight in Punjab, India (Sharma et al. 2007). Climate change would cause increased problem with insect-transmitted diseases, particularly in developing countries (Chauhan et al. 2014).

The changes in cultivation practices and climatic parameters have changed the rice disease scenario in different rice production systems globally, especially in Asia (Mew et al. 2004). Many diseases hitherto considered as minor have become very serious in many rice-growing areas. For example, false smut of rice, which was once considered as the sign of bumper harvest, has now become a serious problem in several countries (Ladhalakshmi et al. 2012b). The problems like neck blast and brown spot have become more widespread especially in Asia (Barnwal et al. 2013; Khan et al. 2014). Bakanae disease, which was considered a minor problem, has become a major threat to rice production in Northwestern India especially on 'Basmati' (scented) rice varieties. In the present chapter, discussion will be confined to major and emerging diseases of rice.

13.2 Bacterial Diseases

Many bacterial diseases are known to infect rice, viz. bacterial blight (*Xanthomonas oryzae* pv. *oryzae*), bacterial leaf streak (*Xanthomonas oryzae* pv. *oryzicola*), bacterial panicle blight (*Burkholderia glumae*), bacterial brown stripe (*Acidovorax avenae* subsp. *avenae*), sheath brown rot (*Pseudomonas fuscovaginae*), bacterial sheath rot (*Pseudomonas syringae* pv. *syringae*) and bacterial foot rot (*Dickeya zeae*, formerly *Erwinia chrysanthemi*). Out of these, bacterial blight and bacterial leaf streak being of economic importance are discussed.

13.2.1 Bacterial Blight

13.2.1.1 History and Geographical Distribution

Bacterial blight (BB) of rice caused by *Xanthomonas oryzae* pv. *oryzae* (Ishiyama) Swings et al. (*Xoo*) is widely distributed throughout the globe (Fig. 13.1). The disease was first reported from Fukuoka Prefecture, Japan in 1884. However, the causal bacterium was described in 1922. Subsequently, the disease was reported from East, South and Southeast Asian countries (Devadath 1992; Win et al. 2013) and Australia (Ou 1985). In Africa, the disease was first reported in West Africa by Buddenhagen et al. (1979) from Mali. Subsequently, it was reported from many other West African and some East African countries (Sere et al. 2013). The disease was reported from most of the rice-growing areas of Caribbean region, namely, Mexico, Costa Rica, Honduras, Salvador and Panama and South America including Colombia, Venezuela, Ecuador and Bolivia (Lozano 1977). From North America, Jones et al. (1989) reported the occurrence of BB from Texas and Louisiana.

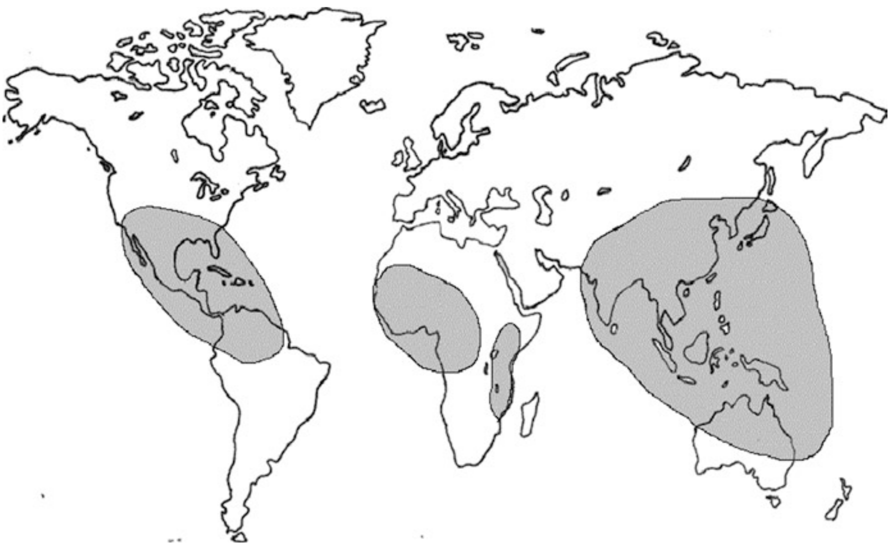

Fig. 13.1 Global distribution of bacterial blight of rice

However, its occurrence has not yet been confirmed from Europe. In India, the disease was first reported from Maharashtra (Srinivasan et al. 1959), and with the widespread cultivation of semidwarf, high-yielding and nitrogen-responsive varieties like Taichung Native 1, it spread like wild fire in almost all the major rice-growing regions.

13.2.1.2 Economic Importance

Though the disease is reported worldwide, it has economic importance mainly in Asia and in some parts of Western Africa (OEPP/EPPO 2007), especially in irrigated and rain-fed lowland ecosystems. BB is essentially a monsoon season disease of high-yielding rice varieties grown under heavy nitrogen fertilization. BB epidemics in Northwestern India during 1979 and 1980 and in South India during 1998, 2010 and 2013 (Laha et al. 2009; Yugander et al. 2014) are some of the examples of its destructive nature in the tropics. BB has become a major problem in several West African countries like Burkina Faso, Niger and Mali causing 50–90 % yield loss (Sere et al. 2005; Basso et al. 2011). Yield losses due to this disease ranging from 2 to 74 % depending on varieties, season, weather conditions, stages of infection and nitrogen application have been reported (Reddy 1989). In India, inoculation of pathogen 30 days after transplanting (DAT) resulted in a highest mean yield loss of 30 %, which decreased significantly with delayed inoculation at 45 DAT and 75 DAT. Among the varieties, the highest yield loss was recorded in Pusa Basmati-1 (45 %) followed by Haryana Shankar Dhan-1 (31 %), while it was minimum in HKR 47, i.e. 23 % (Singh et al. 2013). The BB disease is most destructive in

Southern China which is the major indica rice cultivation region. A major BB epidemic was recorded in Changjiang River valley region during 1974–1975 (Qi 2009). The disease caused yield loss up to 50 % in the Philippines (Mew et al. 1993) and up to 26 % in Nepal (Adhikari and Mew 1991). There has been an alarming increase in BB incidence in Pakistan especially in 'Kaller' belt which is famous for rice cultivation (Khan et al. 2000; Akhtar et al. 2003). In Japan, 0.09–0.15 m ha rice crop was severely affected with BB with an annual loss of 0.022–0.11 m tons during 1954. However, the disease incidence has markedly decreased after 1975. Though reported from few South and Central American countries, BB is not endemic in these regions (Corral et al. 2013).

13.2.1.3 Symptoms

BB is a typical vascular disease and has three distinct phases of symptoms.

Leaf Blight Phase It is the most common phase of this disease, in which water-soaked lesions appear on the tip of the leaves and increase longitudinally downwards (Fig. 13.2b). Initially, the lesions are pale green in colour but later turn into yellow to straw coloured stripes with wavy margins. Lesions may start at one or both the edges of the leaves. Occasionally, the linear stripes may develop anywhere on the leaf lamina or along the midrib with or without marginal stripes. As the disease advances, the lesion covers the entire leaf blade (Fig. 13.2d), turns white and later becomes greyish or blackish due to the growth of various saprophytic fungi. In humid areas, on the surface of the young lesions, yellowish, opaque and turbid drops of bacterial ooze may be observed during early morning (Fig. 13.2b), which dry up to form small, yellowish, spherical beads.

Kresek or Wilt Phase It is the most destructive phase of the disease in the tropics, which results from early systemic infection in the nursery or from seed infection. The leaves roll completely, droop and turn yellow or grey and ultimately the tillers wither away. In severe cases, the affected hills may be completely killed (Fig. 13.2c).

Pale Yellow Leaf Phase This phase of the disease has been reported from the Philippines only. Some of the youngest leaves in a clump may become pale yellow or whitish. The diseased leaves later wither, turn yellowish brown and dry up.

13.2.1.4 Pathogen

Xanthomonas oryzae pv. *oryzae* (Ishiyama) Swings et al. is a Gram-negative, non-spore-forming, rod-shaped, motile bacterium having a single polar flagellum. It produces a characteristic non-diffusible yellow pigment called xanthomonadin (a brominated, aryl polyene pigment) and belongs to family Xanthomonadaceae, order Xanthomonadales, class Gammaproteobacteria and phylum Proteobacteria in the domain Bacteria (Fig. 13.2a).

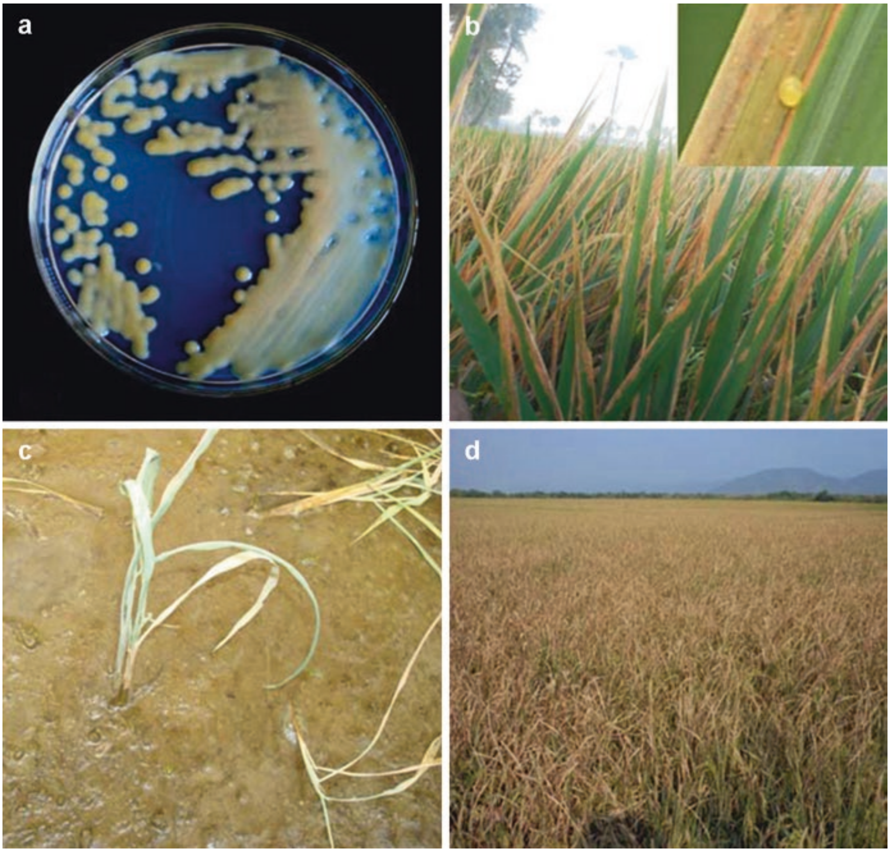

Fig. 13.2 Symptoms and causal bacterium of bacterial blight of rice: (**a**) colonies of *Xanthomonas oryzae* pv. *oryzae*; (**b**) typical leaf blight phase under natural field condition (inset bacterial ooze on infected leaf); (**c**) Kresek phase of the disease; (**d**) rice field severely infected with bacterial blight

13.2.1.5 Disease Cycle and Epidemiology

Studies carried out under All India Coordinated Rice Improvement Project (AICRIP) and at International Rice Research Institute (IRRI), Manila, Philippines revealed that although a high percentage of seed infection can be observed especially in tropical regions, such seeds may not produce diseased plants (Laha et al. 2009). The ratoons and self-grown plants in lowlands constitute the primary source of inoculum in some parts of Asia. In double-cropped areas, infected straw and stubble, infected wild rice and living rice plants growing in ponds, ditches and irrigation channels during off season serve as a source of inoculum. Staggered sowing and transplanting result in overlapping of crops, and in such scenario the spread of the disease is very easy and fast. The pathogen surviving on some grasses like *Leersia hexandra*, *Cyperus rotundus* and *Panicum repens* and irrigation water contaminated with bacteria flowing through the fields also act as a source of primary inoculum. Combination of cloudy and rainy weather or drizzling condition, floods, cyclone or strong winds, excess and late top dressing of nitrogenous fertilizer and moderate temperature of 28–30 °C favour the rapid buildup of the BB disease (Ezuka and Kaku 2000).

13.2.1.6 Disease Management

As chemical control of the disease is not very successful especially in the tropics, host plant resistance is the best solution. Cultural practices, host nutrition and limited chemical control measures help in reducing the initial inocula and secondary spread of the disease.

Host Resistance Breeding and deployment of high-yielding varieties (HYVs) carrying major resistance genes (R genes) are the most effective approach for managing the disease. Following the release of IR 20 and IR 22 as first BB-resistant HYVs from IRRI in 1969, a large number of BB-resistant varieties, mostly possessing BB resistance gene *Xa4*, were released in different Asian countries during the 1970s and 1980s (Khush et al. 1989). However, these varieties have become susceptible in many countries due to the appearance of new and more virulent forms of the pathogen. Subsequently, plant breeders started incorporating other BB resistance genes like *xa5* and *Xa7* (Khush et al. 1989). Paradigm shift in BB resistance breeding took place with the discovery of a major dominant BB resistance gene, *Xa21*, from wild rice *Oryza longistaminata* (Khush et al. 1990).

To date, more than 35 BB resistance genes have been identified from diverse sources (Sundaram et al. 2014; Kim et al. 2015). However, only a few genes, viz. *Xa4*, *xa5*, *Xa7*, *xa13*, *Xa21*, *Xa23*, *Xa27*, *Xa30(t)/Xa38* and *Xa33*, are being used for marker-assisted selection (MAS) breeding. As the resistance conferred by single gene is often short lived, the best way to ensure the durability of resistance is to pyramid multiple resistance genes into a single cultivar using MAS. Using this approach, several BB-resistant varieties have been released by introgressing different BB resistance genes like Improved Samba Mahsuri (*Xa21*, *xa13* and *xa5*) and Improved Pusa Basmati-1 (*Xa21* and *xa13*) in India (Laha et al. 2009; Singh et al. 2012a), Angke (*Xa4* and *xa5*) and Konde (*Xa4* and *Xa7*) in Indonesia, NSIC Rc142 (Tubigan 7) and NSIC Rc154 (Tubigan 11) having a combination of *Xa4* and *Xa21* in the Philippines and Zhonghui 8006 (*Xa21*), Zhonghui 218 (*Xa21*), Guodao 1, Guodao 3, Guodao 6 and II You 8006 in China (Verdier et al. 2012; Rao et al. 2014). Chen et al. (2000) improved BB resistance of Minghui 63, a restorer line widely used in China by introgressing *Xa21* through MAS. Subsequently, Zhang et al. (2006) pyramided two BB resistance genes *Xa7* and *Xa21* in Minghui 63 for providing durable BB resistance. Studies on host plant resistance are not as extensive in Africa as in Asia. Banito et al. (2012) found NERICA 4, NERICA 8 and NERICA 14 as moderately resistant to BB, while Djedatin et al. (2011) found a few accessions of *O. glaberrima* as highly resistant to *Xoo* race A3 from Mali.

Chemical Control Several chemicals, viz. Sankel, phenazine, cellomate, streptomycin, chloramphenicol, have been tested and used for the control of bacterial blight disease. However, none of these chemicals provided satisfactory control under tropical conditions (Srivastava 1972). Some of these chemicals may offer partial control of the disease particularly when disease pressure is low. Two chemicals, ATDA (2-amino-1, 3, 4-thiadiazole) and TF-130, were found to be highly effective against the disease in Japan and other countries but were withdrawn on account of residues in seeds at non-permissible limits (Srivastava 1972).

Seed infection can be eradicated by soaking the seeds for 12 h in 0.025 % solution of Agrimycin 100 (an antibiotic containing 15 % streptomycin and 1.5 % terramycin) plus 0.05 % wettable Ceresan and then transferring the seed to hot water at 52–53 °C for 30 minutes. Overnight soaking of infected seeds in 100 ppm Streptocycline (streptomycin 12 % + chlorotetracycline hydrochloride 1.5 %) solution can also effectively eradicate the seed infection. Two sprays of Agrimycin 100 (250 ppm) can effectively reduce the disease intensity and have been advocated for checking secondary spread of the disease. Five sprays (at 12-day interval) of Agrimycin 100 and Fytolan (copper oxychloride) (50:500) or 665 ppm of Agrimycin 500 (streptomycin sulphate 1.75 % + terramycin 0.17 % + tribasic copper sulphate 42.4 %) can also satisfactorily reduce the disease (Singh et al. 1980). Application of 'Klorocin' (stable bleaching powder) at 12.5 kg/ha at nursery and 10 days after transplanting can reduce the disease (Laha et al. 2009). Singh et al. (2012b) recorded highest BB control in a treatment combination of single spray of 2,4-D ethyl ester (1.0 ml/l) with two sprays of Streptocycline (200 mg/l) + copper oxychloride (2.5 g/l).

Cultural Control The importance of cultural practices is being re-emphasized as an essential component in the integrated disease management practice. Practices like keeping the fields free of weeds like *Cyperus* spp. and *Leersia* spp.; removing infected plant debris, self-grown rice plants and ratoons and infected wild rice; avoiding pruning of leaves either at the time of transplanting or later during the crop season; avoiding field to field irrigation; use of healthy and disease-free seeds; raising seedlings in raised seedbeds/upland nursery; and avoidance of inundation of nursery or main fields till maximum tillering stage can reduce the intensity of the disease. Judicious application of nitrogen in 3–4 splits without sacrificing yield with required level of potassium may be recommended during wet season (Ezuka and Kaku 2000; Laha et al. 2009).

13.2.2 Bacterial Leaf Streak

13.2.2.1 History, Distribution and Economic Importance

Bacterial leaf streak (BLS) caused by *Xanthomonas oryzae* pv. *oryzicola* (Fang et al.) Swings et al. was first reported from the Philippines (Reinking 1918) as bacterial leaf stripe. Since then, BLS has been reported from most of the countries in tropical and subtropical Asia, Australia and several African countries like Burkina Faso, Burundi, Madagascar, Mali, Nigeria, Senegal and Uganda. The disease is currently widespread and of economic importance in tropical Asian countries like India, Indonesia, Malaysia, Cambodia, Bangladesh and Thailand (Shekhawat and Rao 1972; Ou 1985; Nino-Liu et al. 2006; http://www.cabi.org/isc/datasheet/56977). The pathogen has been listed in the Agricultural Bioterrorism Protection Act of the United States as a potential bioterrorism agent, necessitating strict biosecurity and biosafety measures to avoid its release and spread in the environment (Nino-Liu et al. 2006). BLS is economically less important compared to bacterial blight of rice. Though extensive reports are not available, yield loss due to BLS may range from 1.5 to 17 % depending on the cultivars and climatic conditions (Opina and Exconde 1971).

13.2.2.2 Symptoms

Initial symptoms appear as fine, water-soaked to translucent interveinal streaks of various lengths anywhere on the leaves (Fig. 13.3). The lesions enlarge, turn yellowish-orange to brown (depending on cultivar) and eventually coalesce lengthwise resulting in bigger streaks. With time, the leaves may be completely blighted. Numerous tiny yellow beads of bacterial exudate are commonly found on the lesions. In many cases, concurrent occurrence of both BB and BLS in the same field or on the same leaf has also been noted.

13.2.2.3 Pathogen

The morphological characters and taxonomic position of *Xanthomonas oryzae* pv. *oryzicola* are similar to that of *Xoo*.

Fig. 13.3 Characteristic symptoms of bacterial leaf streak under natural condition showing translucent interveinal streaks

13.2.2.4 Disease Cycle and Epidemiology

Infected seed is considered as the primary source of inoculum. The pathogen can survive from one season to another in infected seeds but not in the debris (Shekhawat and Srivastava 1972). In the double- and triple-cropped areas, the bacterium may survive on the living host itself. Infected wild rice can also be a source of inoculum. In addition, this bacterium may be able to survive in irrigation water. The bacterium penetrates the leaf mainly through stomata or wounds, multiplies in the substomatal cavity and then colonizes the intercellular spaces of the parenchyma (Ou 1985). In advanced stages, masses of bacteria ooze out through stomata and get deposited on the leaf surfaces which provide the inoculum for secondary spread by contact, wind and rain. Disease development is favoured by drizzling, stormy weather, high humidity, moderate temperature and excess application of nitrogenous fertilizers.

13.2.2.5 Disease Management

Compared to BB, much less information is available on host plant resistance against this disease. Goto (1965) found that japonica cultivars are relatively more resistant compared to indica varieties. A number of varieties including Zenith, Tetep, H 4, S 67, Co 4, BJ 1 and DZ 60 have been reported to be resistant to this disease (Ou 1985). In contrast to BB, the genetic resistance to BLS in most of the germplasm is quantitative in nature (Tang et al. 2000). In India, varieties like IR 20, Jagannath and Krishna have shown good level of tolerance. In addition to *Oryza* gene pool, a non-host R gene, *Rxo-1* from maize, when introduced in rice, conferred resistance to BLS (Zhao et al. 2005). Since the disease is known to be seed transmitted, the use of disease-free seeds and seed treatment by soaking the seeds in 0.025 % Streptocycline for 12 h or by hot water treatment at 50 °C for 30 minutes can prove effective against this disease. Spraying of Vitavax (0.15–0.3 %) has been found to be very effective against BLS (Shekhawat and Srivastava 1971).

13.3 Fungal Diseases

Of various fungal diseases attacking rice, leaf and panicle blast [*Magnaporthe oryzae* (anamorph: *Pyricularia oryzae*)], sheath blight [*Thanatephorus cucumeris* (anamorph: *Rhizoctonia solani*)], brown spot [*Cochliobolus miyabeanus* (anamorph: *Helminthosporium oryzae*)] and false smut [*Villosiclava virens* (anamorph: *Ustilaginoidea virens*)] are the most serious diseases. The emerging diseases like foot rot and bakanae [*Gibberella fujikuroi* (anamorph: *Fusarium moniliforme*)], sheath rot (*Sarocladium oryzae*) and stem rot [*Magnaporthe salvinii* (anamorph: *Sclerotium oryzae*)] are also causing significant yield losses in some rice-growing regions.

13.3.1 Rice Blast

13.3.1.1 History and Geographic Distribution

Rice blast caused by *Pyricularia oryzae* Cav. [teleomorph: *Magnaporthe oryzae* (Hebert) Barr)] is the most severe and widely distributed disease of rice worldwide having significant economic importance (DRR 1975–2014; Ou 1985). This fungus has been ranked as at the top in the list of world's top ten dangerous fungal pathogens of crops (Dean et al. 2012). Rice blast is one of the earliest known plant diseases and the record of its occurrence can be traced back to as early as the seventeenth century in China (Ou 1985). The disease has now been reported from >85 countries indicating presence of the disease practically in every place where rice is grown commercially (Fig. 13.4; Ou 1985; Kato 2001). In temperate and subtropical Asia, it is highly destructive in lowland rice, while in tropical Asia, Latin America and Africa, it affects upland rice. In India, the disease gained importance when a severe epidemic occurred in Thanjavur (Tanjore) delta of South India in 1919. Presently in India, blast is especially problematic in temperate areas, hilly tracts, tropical uplands and in delta regions.

13.3.1.2 Economic Importance

Blast is the principal biotic production constraint of rice. Several epidemics have been reported from different countries, and it has been estimated that the amount of rice that is lost annually due to blast can feed 60 million people (Zeigler et al. 1994). Average losses in the range of 10–30 % are typical although regional epidemics can be more devastating (Dean et al. 2012) resulting in grain yield loss up to 100 %

Fig. 13.4 Global distribution of rice blast disease

under favourable conditions. Different estimates of yield loss ranging from 5 to 10 % in India, 8 % in Korea, 14 to 50 % in China, 60 % in Thailand and 50–85 % in the Philippines have been reported (Ou 1985; Wang et al. 2014). It is estimated that 157 million tons of paddy was lost due to blast worldwide during 1975–1990 (Baker et al. 1997). Severe yield losses due to blast have been reported in different African countries ranging from 36 to 63 % in Burkina Faso, 35–50 % in Nigeria, 20–30 % in Benin, 64 % in Togo, up to 80 % in Sierra Leone and Cote d'Ivoire and up to 100 % in Ghana and Gambia (Sere et al. 2013). Severe blast epidemics were reported on variety Newbonnet in Arkansas, USA (Lee 1994), and on a newly released variety Colosso in Brazil (Prabhu et al. 2009) causing yield losses ranging from 25 to 50 % and up to 100 %, respectively.

13.3.1.3 Symptoms

The fungus can infect leaves, nodes and various parts of the panicle.

Leaf Blast Greyish or bluish dots of 1–3 mm diameter appear on the leaf blades. On susceptible cultivars, the spots enlarge quickly under humid conditions and become elliptical or 'eye shaped' with grey or whitish centre and brown or dark brown margin (Fig. 13.5b, c). Fully developed spots on the susceptible cultivars may be 1–1.5 cm long and 0.3–0.5 cm broad. In severe infection, seedlings and plants in the nursery may be completely blasted or killed. On the resistant cultivars, minute brown specks of pinhead size may be observed.

Node Blast The pathogen also infects the nodes that turn black and get weakened due to tissue disintegration, resulting in breakage of stem at the nodal region followed by death of all the plant parts above the infected nodes (Fig. 13.5d).

Neck and Panicle Blast At the time of flowering, area near the panicle base is girdled by a greyish brown lesion, and the panicle falls over in the case of severe infection (Fig. 13.5e, f). The neck becomes shrivelled and covered with grey mycelium. If neck infection occurs before the milk stage, the entire panicle may die prematurely, leaving it white and completely unfilled. Later, infections may cause incomplete grain filling and poor milling quality. The pathogen also causes brown lesions on panicle branches and on the spikelet pedicels, resulting in panicle blast. Infection of the neck, panicle branches and spikelet pedicels may occur together or may occur separately.

13.3.1.4 Pathogen

Rice blast pathogen, *Magnaporthe oryzae* (previously *M. grisea*; anamorph: *Pyricularia oryzae*), is a filamentous ascomycetous fungus and is classified in the newly erected family Magnaporthaceae (Fig. 13.5a). *M. oryzae* is a heterothallic fungus and the population is composed of distinct mating types, viz. Mat 1-1 and

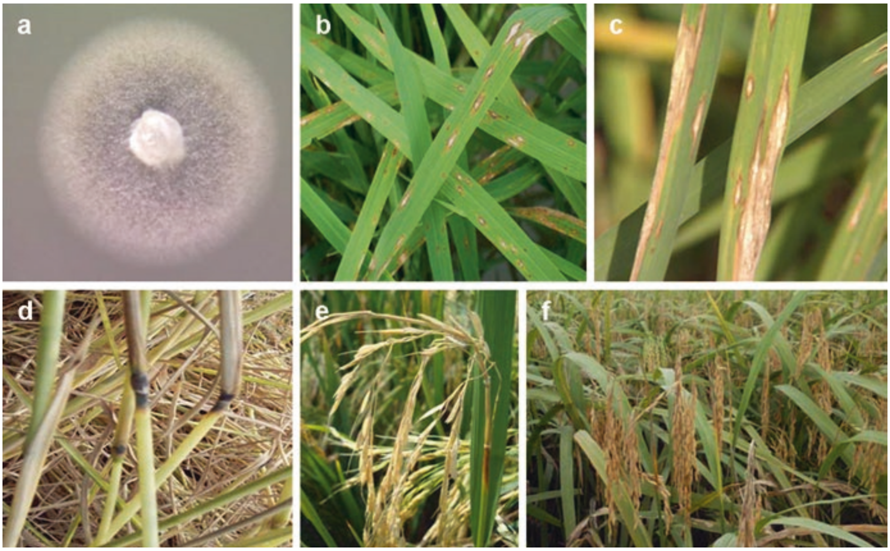

Fig. 13.5 Symptoms and causal organism of rice blast: (**a**) *Magnaporthe oryzae*, causal organism of rice blast disease; (**b**) minute blast lesions on leaves; (**c**) characteristic eye-shaped lesions on leaves; (**d**) node blast; (**e**) typical panicle blast; (**f**) severe panicle blast-infected rice field

Mat 1-2 (Yoder et al. 1986). When the fertile isolates carrying opposite mating types are paired on an appropriate medium, they will form sexual fruiting bodies, i.e. perithecia within 21 days. However, isolates from rice are very rarely sexually fertile because most of the isolates belong to one mating type, i.e. female fertile except for a limited number of hermaphroditic strains (Notteghem and Silue 1992; Kumar et al. 1999; Kang et al. 2000). In contrast, isolates from other hosts like *Eragrostis curvula, Eleusine indica* or *Eleusine coracana* are usually hermaphrodite and capable of mating and producing viable ascospores (Kang et al. 2000). The rice isolates can frequently undergo crosses with hermaphroditic strains from other grass hosts. However, progenies from such crosses are less aggressive on rice and backcrosses are necessary to recover full pathogenic potential on rice (Notteghem and Silue 1992; Priyadarisini et al. 1999). The sexual stage has not been observed in nature and the fungus mainly reproduces asexually through production of conidia.

13.3.1.5 Disease Cycle and Epidemiology

In temperate regions, mycelium and conidia on diseased straw and infected seeds are the principal sources of primary infection. The fungus can attack a number of cereal and grass hosts which could be important source of primary infection. In the tropical climate of South India, where several crops of rice are taken in a year, the pathogen maintains a continuous disease cycle on the rice crop itself. Under favourable conditions, the conidia can produce symptoms within 4–5 days of infection.

Conidia are produced on the lesions 6–7 days after infection and disseminated by wind. A typical leaf blast lesion produces 2000–6000 conidia each day for about 14 days. The rate of sporulation increases with increase in relative humidity, while release and flight of spores increase with enhancement in dew period and wind speed, respectively. The secondary cycles can be repeated many times during the growing season, with the potential for very high amount of disease within the crop. The disease intensity at the termination of vegetative growth phase influences the disease intensity during the reproductive phase. Spores produced near the end of the growing season may infect the collar of the flag leaf producing symptoms called ‘collar rot’. They may also infect the neck when it emerges from the infected collar, causing ‘neck rot’ or ‘neck blast’ symptoms (Ou 1985).

Low night temperature (below 24 °C) alternating with a day temperature of around 28–30 °C coupled with high relative humidity (more than 90 %) favours the disease development. Frequent rains, continuous spell of cloudy weather, dew, fog, high relative humidity and high nitrogen application favour rapid buildup of the disease. High incidence of blast in upland condition can be attributed to longer dew period, drought stress (which induces blast susceptibility) and low silica content (Sah and Bonman 2008; Dodan et al. 2007).

13.3.1.6 Disease Management

Though chemical control measures for managing the disease have been very successful, a major emphasis has been given to host plant resistance due to increased concern of ill effects of chemical pesticides.

Host Plant Resistance Development and use of rice varieties with effective and durable resistance to blast is the most promising choice for disease management. Systematic breeding for blast resistance in different countries like Japan, China, the Philippines, India, Korea, Thailand and other Asian countries and in the United States led to the development and release of several blast-resistant varieties. Varieties like IR 64, Rasi and IR 36 expressed good level of blast resistance in India and elsewhere. A blast-resistant rice variety Katy was released in the United States (Moldenhauer et al. 1990). Several NERICA rice varieties like NERICA # 9, 12, 15, 16 and 18 and other varieties like IRAT 13, ROK-16, LAC 23, Moroberekan and FARO 11 were found resistant to blast in several West African countries (Fomba and Taylor 1994). In India, rice genotypes HKR 04-487, HKR 05-436, HKR 05-476, Haryana Mahak 11, PAU 3237-1-B-B-19, PAU 3237-1-B-B-20 and PAU 3237-1-B-B-22 have been found resistant to both leaf blast and neck blast (Singh et al. 2010a). Breeding for resistance to blast has, however, often been frustrated by the rapid evolution of the pathogen to new and more virulent forms especially when the varietal resistance is based on single gene.

Gene pyramiding seems promising to provide broad spectrum and durable resistance. Since the identification of first blast resistance gene, *Pia* from japonica rice variety Aichi Asahi (Kiyosawa 1967), 100 blast resistance genes and 347 quantitative trait loci (QTLs) have been identified from diverse germplasm (Koide et al. 2009; Sharma et al. 2012; Wang et al. 2014). Most of these genes have been identified from either japonica cultivars (45 %) or indica cultivars (51 %). Only four blast resistance genes have been identified from wild rice, viz. *Pi9* from *O. minuta*, *Pi40* from *O. australiensis*, *Pi54rh* from *O. rhizomatis* and *Pirf2-1*(t) from *O. rufipogon* (Sharma et al. 2012; Wang et al. 2014). Wild rice still remains much untapped resource for blast resistance. Out of the 100 reported blast resistance genes, 22 Pi genes have been cloned and characterized (Sharma et al. 2012; Wang et al. 2014). Some of the blast resistance genes like *Pi1*, *Pi2* (*Piz5*), *Pi54*, *Pi40*, *Pi9*, *Pi5*, *Pita* and *Pizt* have been found to confer high and broad level of resistance to blast pathogen in India and elsewhere (Prasad et al. 2010). Some of these genes have been used for gene pyramiding for durable blast resistance. Hittalmani et al. (2000) pyramided three blast resistance genes *Pi1*, *Piz5* and *Pita* into CO 39, a blast-susceptible cultivar, and the pyramided lines exhibited high level of blast resistance. Similarly, two blast resistance genes, viz. *Pish* and *Pib*, were pyramided in the genetic background of CO 39 by Koide et al. (2010). Blast resistance genes *Pi1*, *Pi2* and *Pi54* have been introgressed in two highly popular rice varieties BPT 5204 and Swarna (Prasad et al. 2010). Singh et al. (2011) reported development of improved Pusa 6A, Pusa 6B and PRR 78, the parental genotypes of rice hybrid Pusa RH 10 by pyramiding two blast resistance genes, *Pi54* and *Piz5*. Miah et al. (2013) advocated combination of major genes with QTLs (slow blasting components) for increased stability of blast resistance. Other strategies like use of cultivar mixtures, near isogenic multilines and use of partial resistance (slow blasting) have been suggested by various researchers (Kapoor 2010) to slow down the pathogen evolution.

Cultural Control Cultural practices like use of healthy seeds collected from disease-free fields; destruction of weeds, collateral hosts and crop residues; raising seedlings in the water-covered seedbeds; balanced application of fertilizers; application of farm yard manure and rice husk ash; and wider spacing have been found to reduce the disease severity in the fields (Dodan et al. 2007). Adjustment of planting time and continuous maintenance of standing water in the field have also been found to be helpful in minimizing the blast incidence (Singh et al. 1999).

Biological Control Reduction of blast disease severity under experimental condition by application of different biocontrol agents like *Pseudomonas fluorescens*, *Bacillus subtilis* and *B. polymyxa* has been reported by several workers (Gnanamanickam and Mew 1992; Chatterjee et al. 1996; Yoshihiriro et al. 2003; Kavitha et al. 2005). However, large-scale field evaluation is still required for commercial use of these organisms.

Chemical Control Chemical control has been practiced and found to be highly satisfactory at many places. Regular monitoring of the fields is an important aspect for successful management of the disease. For example, if leaf blast lesions are present during the booting stage and if environmental conditions are favourable, then one application of a suitable fungicide is required to protect the panicles from neck blast infection. In endemic areas, seed treatment with pyroquilon 50 WP at 1 g/kg or tricyclazole 75 WP at 1 g/kg or carbendazim 50 WP at 2 g/kg has been found to protect the plants from seedling blast. When the leaf blast symptoms appear in fields, the options for chemical control include tricyclazole 75 WP at 0.6 g/l or iprobenphos 48 EC at 2 g/l or isoprothiolane 40 EC at 1.5 ml/l or kasugamycin 3 SL at 2.5 ml/l or carbendazim 50 WP at 1 g/l or azoxystrobin at 1 ml/l or metominostrobin 20 SC at 2 ml/l. Many combination products like tricyclazole + propiconazole, tricyclazole + mancozeb, trifloxystrobin 25 % + tebuconazole 50 %, fenoxalin + isoprothiolane and epoxiconazole + carbendazim were found to be very effective against blast (DRR 1975–2014). However, the farmers are advised to strictly adhere to the use of recommended chemicals, their doses, formulation and time of application for better disease management and to overcome the problem of pesticide residues in rice grains and straw.

13.3.2 Sheath Blight

13.3.2.1 History and Geographical Distribution

Sheath blight (Shbl), also known as 'oriental sheath blight' caused by *Rhizoctonia solani* Kuhn (AG 1 IA) [teleomorph: *Thanatephorus cucumeris* (Frank) Donk], is a potentially devastating fungal disease in all temperate and tropical rice production regions throughout the globe, particularly in irrigated rice production systems. The disease was first reported from Japan in 1910 by Miyake (1910) and subsequently from most of the East and Southeast Asian countries. Thereafter, the disease was reported from many African and North and South American countries (Fig. 13.6; Gangopadhyay and Chakrabarti 1982; Dath 1990; Dasgupta 1992; Ou 1985;

Fig. 13.6 Global distribution of sheath blight disease of rice

Sivalingam et al. 2006). In India, sheath blight was first reported from Gurdaspur (Punjab) by Paracer and Chahal (1963).

13.3.2.2 Economic Importance

It is a major production constraint in tropical Asia and in Southern United States. Yield losses ranging from 20 to 50 % have been reported depending on the intensity of infection and climatic conditions in different countries (Kozaka 1975; Lee and Rush 1983; Ou 1985; Rajan 1987; Kannaiyan and Prasad 1978a). However, under high disease severity, the yield loss may reach up to 70 % (Baby 1992). In earlier studies, Hori and Anraku (1971) reported a yield loss of 25 % if the disease is extended up to the flag leaves and in the range of 30–40 % in the case of severe infection of the sheath and leaf blades (Kozaka 1970). Studies carried out at IRRI, Philippines reported a 24 % yield loss in susceptible cultivars under highest level of disease intensity and nitrogen application (Anonymous 1976). In China alone, about 15–20 million ha of rice area is affected by sheath blight, causing losses of 6 million tons of grains per year (Chen et al. 2014). Under conditions favourable for disease development, rice grain yield losses ranging from 4 to 50 % have been attributed to sheath blight in Southern United States (Marchetti 1983; Lee and Rush 1983; Groth and Bond 2007). In Arkansas, incidence of sheath blight was observed in 50–66 % of rice fields, causing 5–15 % yield losses in 2001 (Annou et al. 2005).

13.3.2.3 Symptoms

Typical sheath blight symptoms appear as greyish, water-soaked lesions on leaf sheaths at or above the waterline. The lesions soon enlarge, with irregular dark brown margins, while the centre is bleached to greyish white. Appearance of many such lesions on the leaf sheath gives the look of snake skin (Fig. 13.7b). The infection spreads rapidly to upper leaf sheaths and leaf blades of the same or adjacent tillers from the water level to flag leaf, ultimately causing death of whole leaf, tiller and the plant (Fig. 13.7c). Infected plants are usually found in a circular pattern, locally referred to as 'bird's nest' bearing few grains only (Hollier et al. 2009; Fig. 13.7e). Under moist conditions, brown silky mycelium and brown to dark brown sclerotia are found loosely attached on the lesions, which get easily dislodged from the plants at maturity (Ou 1985; Dath 1990). The pathogen can also cause infection in the nursery (Fig. 13.7d). The pathogen is also known to cause panicle infection resulting in production of unfilled, chalky and fissured kernels (Candole et al. 2000) and spotted/discoloured seed (Acharya et al. 2004). Seedlings raised from infected seeds bear brownish black to blackish discoloured lesions on coleoptile, first leaf, radicle, second leaf and sheath (Sivalingam et al. 2006). When the relative humidity is more than 90 % and temperature is in the range of 28–35 °C, infection spreads rapidly through runner hyphae to the upper plant parts and also to the neighbouring plants.

Fig. 13.7 Symptoms and causal organism of sheath blight disease of rice: (**a**) *Rhizoctonia solani,* the causal organism of rice sheath blight disease; (**b**) characteristic symptom on sheath; (**c**) characteristic symptom of sheath blight extending up to flag leaf along with fungal sclerotia; (**d**) rice nursery bed showing severe sheath blight infection; (**e**) severely sheath blight-infected rice field resembling bird's nest structure

13.3.2.4 Pathogen

The teleomorph, *Thanatephorus cucumeris*, belongs to class Basidiomycetes. In addition to its anamorph, *R. solani* (Fig. 13.7a), two other species of *Rhizoctonia*, viz. *R. oryzae* causing rice sheath spot and *R. oryzae-sativae* causing aggregate sheath spot, have been found to be associated with this disease. All the three pathogens may occur concurrently and sometimes referred to as rice sheath blight disease complex.

13.3.2.5 Disease Cycle and Epidemiology

Although basidiospores produced by *T. cucumeris* on the host plant can initiate infection, it is generally considered unimportant in the epidemiology of rice sheath blight. Sclerotia produced by the fungus and to a lesser extent the fungal mycelium surviving in the plant debris serve as a major source of primary infection, particularly in humid tropics. Sclerotia can also survive for a long period in the temperate rice production areas. Different agricultural operations such as ploughing, levelling, transplanting and weeding help the surviving sclerotia to come up at the plant water surface and make initial contacts with the host. Rainwater runoff and flood irrigation permit good dispersal of floating sclerotia and consequently provide the primary foci of infection through the vast stretches of rice fields. Several weed plants, viz. *Cynodon dactylon*, *Echinochloa crus-galli*, *E. colona*, *Euphorbia microphylla*, *Leptochloa chinensis*, *Dactyloctenium aegyptium*, *Dichanthium annulatum* and *Paspalum distichum*, growing in and around paddy fields have been found to be naturally and artificially infected by the pathogen and can be an important source of primary infection (Singh et al. 2012c). In the tropics, infected straw piled up on the bunds, stubbles and infected weeds contribute significantly to the primary infection resulting in the appearance of the disease near the bund. The form attacking rice can also attack soybean causing aerial blight, and rice-soybean rotation has been attributed to be one of the major factors for increased sheath blight intensity in Gulf Coast regions of the United States and parts of Brazil (Rodrigues et al. 2003; Groth and Bond 2007). In addition, the pathogen can also be seed-borne, and various workers have reported seed infection ranging from 10 to 39 % (Saksena and Chaubey 1972; Kannaiyan and Prasad 1978b; Dasgupta 1992).

Sheath blight is basically a disease of warm and humid area (28–30 °C temperature and 96–97 % RH). Cultivation of high-yielding, semidwarf, nitrogen-responsive varieties with broad leaves and thick canopy, close planting and heavy application of nitrogenous fertilizers leading to increased plant-to-plant contact and increase in humidity in the microclimate during maximum tillering stage are known to further aggravate the disease.

13.3.2.6 Disease Management

In the absence of a desired level of resistance in commercially popular varieties to sheath blight, the disease management mainly relies on chemical control. Many good fungicides are available for the control of sheath blight. There is an increasing attempt to introduce integrated approach to manage this disease by combining the host plant resistance, cultural methods, biological methods and need-based application of chemicals.

Host Plant Resistance Presently none of the commercially popular varieties have desired level of resistance to sheath blight because of non-availability of high level of resistance in *O. sativa* gene pool. However, traditional rice cultivars like Swarnadhan, Radha, Pankaj, Vikramarya, Tetep, Jasmine 85, Tequing, Bhasamanik, Lalsatkara and selected rice lines, viz. ARC 15762, ARC 18119, ARC 18275, ARC 18545, HKR 99-103, HKRH 1059 and IR 64683-87–2-2-3-3, have moderate level of resistance (Singh et al. 2010b; Srinivasachary et al. 2011). In China, Xie et al. (1992) reported good level of resistance in rice lines LSBR 5 and LSBR 33, while Zuo et al. (2009) reported high level of resistance in a novel rice line YSBR 1, developed from a cross between japonica and indica rice. Moderate to good level of resistance has been reported from different wild rice accessions like *O. nivara*, *O. rufipogon*, *O. meridionalis*, *O. barthii* and *O. latifolia* (Ram et al. 2008; Prasad and Eizenga 2008). The resistance to sheath blight is a complex and quantitative character governed by polygenes, though some reports suggest that sheath blight resistance in some rice cultivars is controlled by few major genes (Pan et al. 1999).

Over the past two decades, several sheath blight resistance quantitative trait loci (QTLs) have been mapped in different rice cultivars like Tetep, Tequing and Jasmine 85 (Srinivasachary et al. 2011). However, many of them are reported to be associated with plant morphological traits and heading dates. Some of these QTLs, confirmed to be associated with sheath blight resistance, could be used for pyramiding into popular rice varieties. Singh et al. (2012a) developed improved Basmati rice lines by combining *xa13*, *Xa21*, *Pi54* and a major QTL qSBR 11-1 for bacterial blight, blast and sheath blight resistance through marker-assisted backcross breeding. Subsequently, Zuo et al. (2014) reported that pyramiding sheath blight resistance QTL qSB-9^{TQ} and morphological trait QTL TAC 1^{TQ} is a potential approach in improving sheath blight resistance as these QTLs exhibited more resistance than the near isogenic lines (NILs) containing only one of them.

Introduction of different chitinase genes (*Chi11* and *RC7* from rice), *McCHIT* (a class I chitinase gene of bitter melon), *Cht42* (a chitinase gene from *Trichoderma* spp.), thaumatin-like protein (tlp) gene, a member of the PR-5 group of PR protein genes, *pinA* and *pinB* (structural protein from *Triticum aestivum*), *Ace-AMP1* (non-lipid transfer protein from *Allium cepa*), β-1,3-glucanase (tobacco β-1,3-glucanase), *Rs-AFP2* (defensin gene from *Raphanus sativus*), *Dm-AMP1* (defence gene from *Dahlia merckii*), *npr1* (non-expressor of PR-1) and rice oxalate oxidase 4 (*Osoxo4*) in different rice cultivars resulted in increased tolerance to rice sheath blight disease. Simultaneous co-expression of some transgenes like rice chitinase (*chi11*) and β-1,3-glucanase, *chi11* and tlp, maize ribosome inactivating protein gene *MOD1* and a rice basic chitinase gene *RCH10* showed enhanced resistance against sheath blight infection (Datta and Datta 2009; Srinivasachary et al. 2011; Molla et al. 2013).

Induced Resistance and Biological Control Few reports suggest that resistance can be induced in rice plants against sheath blight pathogen either by certain chemicals or by plant growth promoting rhizobacteria (Manibhushan Rao et al. 1990). Application of certain tolerance-inducing chemicals such as salicylic acid, gamma-aminobutyric acid and chitosan through seed treatment and/or foliar application was found to reduce sheath blight disease significantly (Laha et al. 1997; Dantre and Rathi 2007; Liu et al. 2012). Nandakumar et al. (2001) reported induced systemic resistance against sheath blight of rice by strains of *Pseudomonas fluorescens*. Several reports have indicated that application of different antagonistic bacteria like *P. fluorescens*, *P. putida* and *Bacillus subtilis* can substantially reduce sheath blight disease severity (Mew and Rosales 1992; Krishnamurthy and Gnanamanickam 1997; Laha and Venkataraman 2001). In China, a microbial pesticide 'Wenquning' (based on *Bacillus subtilis*) has also been found to be effective against sheath blight (Ren 2007). Several commercial botanical pesticides like TriCure and Achook (both containing azadirachtin), Biotos (a product from *Gaultheria*) and Spictaf were found to reduce sheath blight disease severity (Muralidharan et al. 2003a; Biswas and Roychoudhury 2003; Kandhari 2007).

Cultural Control Cultural practices like wider spacing (to reduce high humidity in the plant ecosystem and to reduce plant-to-plant contact), destruction of stubbles and weeds in and around rice fields, adoption of green manuring, avoidance of field to field irrigation, planting of rice seedlings a little distance away from the bunds and keeping the bunds and field free from alternate and collateral weed hosts can significantly reduce sheath blight disease severity. Several studies have indicated that soil amendments with different organic manures like *Sesbania aculeata*, *Crotalaria juncea*, *Gliricidia* leaves and neem cake can drastically reduce sheath blight disease intensity. Application of silica has also been shown to reduce the intensity of sheath blight (Rodrigues et al. 2003).

Chemical Control The disease can be effectively managed by applying various chemicals like validamycin 3 L at 2.5 ml/l or propiconazole 25 EC at 1 ml/l or hexaconazole 5 EC at 2 ml/l or carbendazim 50 WP at1 g/l or thifluzamide 24 SC at 30 g a.i./ha. Several researchers have recorded excellent control of sheath blight with foliar application of strobilurins, especially azoxystrobin. Many a times, the disease appears in patches near the bunds and progresses inside the main fields. In such cases, spraying can be restricted to those patches to reduce the amount of fungicide application and to check further spread of the disease inside the field. Singh et al. (2010c) reported that hexaconazole and diniconazole reduced the disease severity by 72 and 69 %, respectively, along with an enhanced grain yield. Many combination products like Filia 52.5 SE (tricyclazole and propiconazole combination), Nativo 75 WG (trifloxystrobin and tebuconazole combination) and Lusture 37.5 SE (flusilazole and carbendazim combination) have also been found very effective against this disease.

13.3.3 False Smut

13.3.3.1 History and Distribution

False smut caused by *Ustilaginoidea virens* (Cooke) Takahashi [teleomorph: *Villosiclava virens* (Nakata) Tanaka and Tanaka] was first reported in India by Cooke in 1878, and subsequently, the disease was reported from more than 60 countries including China, the Philippines, Indonesia, Vietnam, Thailand, Bangladesh, Burma, Brazil, Fiji, Japan, Pakistan, Egypt, Nepal, Nigeria, the United States and France (Biswas 2001; Ahonsi and Adeoti 2002; Atia 2004; Brooks et al. 2010; www.plantwise.org/KnowledgeBank).

13.3.3.2 Economic Importance

False smut disease had been recognized as a symbol of bumper harvest and in some parts of Southern India it is popularly known as “Laxmi” (goddess of wealth and prosperity) disease. However, with changed cultivation practices involving widespread use of high-yielding varieties, hybrids and heavy use of chemical fertilizers coupled with changes in the climatic parameters, the disease has become a serious problem in different rice ecosystems (Ladhalakshmi et al. 2012a). The yield losses in different states of India have been estimated to vary between 0.2–49 % depending on disease severity and rice varieties (Dodan and Singh 1996). In China, 50–60 % of disease infection with the yield reduction of 5–30 % was reported (Sanghera et al. 2012). Over 25 % yield reduction due to false smut was reported from Tumbes Valley in Peru (Atia 2004). In hybrid rice cultivation, incidence of false smut during the rainy season reduced the yield to 3 t/ha as against 6 t/ha (Elazegui et al. 2009). In Egypt, yield losses ranged from 1 to 11 % (Atia 2004). Globally, yield loss due to false smut has been reported to range between 3 and 81 % depending on the rice variety and disease intensity (Haiyong et al. 2015). In addition to direct loss to the crop, the fungus also produces a toxin known as 'Ustiloxin' (Koiso et al. 1994) which can inhibit seed germination and is also poisonous to domestic animals and humans (Koiso et al. 1998).

13.3.3.3 Symptoms

Pathogen affects young ovary of individual spikelets and transforms them into yellow, olive green to blackish spore balls (smut balls) known as pseudomorph (Fig. 13.8a, e). Initially, the fungal growth is confined between glumes which later get enlarged enclosing the floral parts. Young smut balls are white in colour enclosed in a whitish

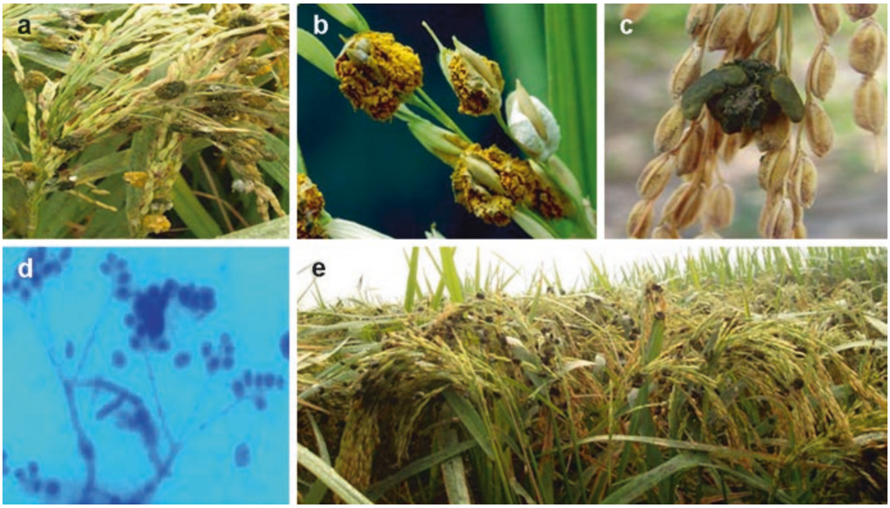

Fig. 13.8 Symptoms of false smut disease of rice: (**a**) yellow to olive green smut balls; (**b**) young smut ball covered with whitish membrane; (**c**) sclerotia of *U. virens*; (**d**) ovoid minute conidia of *U. virens*; (**e**) severe false smut infection under field condition

membrane (Fig. 13.8b). Subsequently, the membrane bursts, releasing orange spore masses which later turn into olive green to black.

13.3.3.4 Pathogen

U. virens produces both sexual (ascospores on sclerotia) and asexual (chlamydospores and conidia) stages in its life cycle (Biswas 2001). Sclerotia are found embedded inside or loosely attached to the pseudomorph or sometimes cover the pseudomorph (Fig. 13.8c). Sclerotia are clavate, reniform, horseshoe shaped to indefinite in shape, concave on the inner side, convex on the outer side and hard in nature. Overwintered sclerotia on germination produce stalked stromata which contain perithecia, and each flask-shaped perithecium contains cylindrical asci with a hemispherical apical appendage. Each ascus contains eight ascospores which are hyaline, one celled and filiform (Tanaka et al. 2008). The yellow-coloured chlamydospores on germination bear hyaline, ovoid and minute conidia (Fig. 13.8d).

13.3.3.5 Disease Cycle and Epidemiology

Sclerotia act as a major source of primary inoculum and chlamydospores play an important role in the secondary infection. Release of ascospores from sclerotia coincides with the anthesis of rice crop and initiates infection on the floral parts producing chlamydospores. These airborne chlamydospores may cause infection again. In addition, hibernated chlamydospores from the soil can also infect the rice panicles. In the hilly areas, the presence of sclerotia can serve as primary inoculum, whereas in the plain region, chlamydospores act as primary inoculum. Other than rice crop, the pathogen also infects maize (Abbas et al. 2002; Gohel et al. 2014) and different weed species, viz. *Echinochloa crus-galli*, *Digitaria marginata*, *Panicum trypheron* and *Imperata cylindrica.* Prevalence of conducive environmental conditions like low temperature (especially low night temperature), high humidity (>90 %) and drizzling conditions during flowering time favours disease development.

13.3.3.6 Disease Management

Use of resistant or tolerant varieties, chemical and cultural practices is important for management of the disease.

Host Plant Resistance In India, several rice cultivars were reported to be resistant or tolerant to false smut under natural conditions, viz. Anupama, Cauvery, China 988, Govind, HKRH 21, MTU 1067, Sakha 102, VL 501, HKR 47, HKR 127, Jhelum and Shalimar Rice-1, HKR 95-222, HKR 98-418, HKR 08-12, HKR 08-17, HKR 08-71, HKR 08-110, IR 50, Paicos-1, PR 113 and PR 114 (Singh et al. 2010b; Sanghera et al. 2012, Dodan et al. 2013; Lore et al. 2013; Singh and Sunder 2015). In China, quantitative resistance was reported against false smut disease by Zhou et al. (2013).

Cultural Methods Several cultural practices like use of sclerotia free seeds, cleaning of bunds, adjustment of sowing dates to avoid coincidence of booting stage with rainy period and application of balanced fertilizer can substantially reduce disease incidence in the fields. Furrow-irrigated rice cultivation system has been reported to have less disease severity compared to flooded fields (Dodan and Singh 1995, 1996; Ladhalakshmi et al. 2012b).

Chemical Control Several fungicides have been found to be effective in reducing false smut disease severity. In India, spraying fields during flowering with chlorothalonil 75 WP at 2 ml/l or copper oxychloride 50 WP at 4 g/l or epoxiconazole 12.5 EC at 2 ml/l or propiconazole 25 EC at 1 ml/l have been found to be effective (Singh et al. 2002a). Foliar spraying of a combination fungicide, trifloxystrobin 25 % + tebuconazole 50 % (Nativo 75WG) at booting or 50 % panicle emergence stage and application of simeconazole at submerged condition 3 weeks before heading have also been found to be highly effective against false smut (Tsuda et al. 2006; Singh and Sunder 2015).

13.3.4 Foot Rot and Bakanae

13.3.4.1 History and Geographical Distribution

The disease was known in Japan since 1828. It has also been called as Fusarium blight, elongation disease, fusariosis and white stalk in China; palay lalake or man rice in British Guiana; foot rot in the Philippines; otoke nae (male seedling) in Japan; bakanae in the United States, Africa and Australia; foot rot and bakanae in French Equatorial, Africa and Ceylon; and foolish plant or foot rot in India. The disease is widely distributed in almost all rice-growing areas of the world including Africa (Ivory Coast, Kenya, Nigeria, Tanzania, Uganda and Cameroon), Asia (India, Japan, Thailand, Vietnam, Ceylon, Indonesia, Malaysia, Taiwan, Pakistan, Iran, the Philippines, Bangladesh, China and Nepal), some North and South American countries (Suriname, British Guiana, Trinidad, the United States, Venezuela, Brazil, Mexico), Australia and some European countries (Italy, Spain and Turkey) (Gangopadhyay 1983; Ou 1985; Khokhar 1990; Singh and Sunder 2012).

13.3.4.2 Economic Importance

The disease is commonly seen in many parts of Southeast Asia, but percentage of infection is usually small. However, under favourable conditions, it has been reported to cause 20–50 % yield loss in Japan, 70 % to almost complete loss in

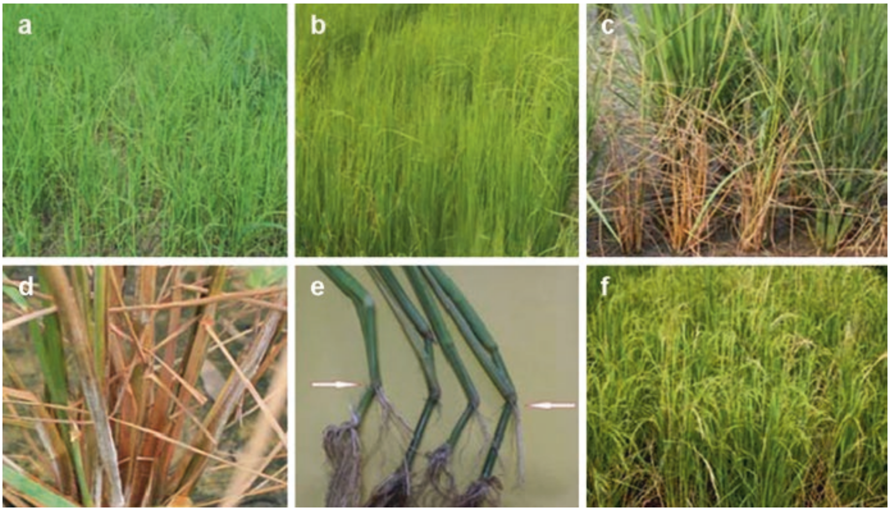

Fig. 13.9 Symptoms of foot rot and bakanae disease of rice: (**a**) elongated seedlings in seedbed; (**b**) field view of bakanae in planted crop; (**c**) wilting or dying of plants; (**d**) mycelium and conidia on dying plants; (**e**) adventitious roots from lower nodes of infected plants; (**f**) white ear heads

Australia, 4–15 % in Thailand, 5–23 % in Spain, 3–95 % in India, 40 % in Nepal and 7–58 % in Pakistan (Singh and Sunder 1997; Yasin et al. 2003).

13.3.4.3 Symptoms

Gibberella fujikuroi causes elongated, slender, pale seedlings that are conspicuous and found to be scattered in the field. Infected seedlings may also be stunted and chlorotic, showing crown or foot rot symptoms. The disease occurs both in main and ratoon crops, in seedbeds as well as in the field (Fig. 13.9a, b).The infected seedlings usually die either before or after transplanting. Often diseased plants have fewer tillers, and their leaves dry one after the other, wilt and die within a few weeks (Fig. 13.9c). The presence of white or pink mycelial growth (Fig. 13.9d), adventitious roots from the lower nodes (Fig. 13.9e) and wider leaf angles with stem are the other diagnostic features of the disease. Plants surviving till maturity bear only empty panicles (Fig. 13.9f). In Japan, infected panicles are often termed as pink panicles.

The fungus is also known to cause grain infection at maturity and pre-emergence seedling death. The type of symptoms produced is mainly determined by the relative amount of growth hormones (gibberellic acid and fusaric acid) produced by the fungus, which are dependent on fungus strain, inoculum level and nutritional conditions of the soil (Webster and Gunnell 1992; Singh and Sunder 2012). At the end of season, lower sheaths become blue and turn into black colour having small scattered pycnidia. Perithecia are also produced on the diseased plants under favourable conditions (Sun and Snyder 1978).

13.3.4.4 Pathogen

Perithecia of *G. fujikuroi* (Sawada) Wollenweber (anamorph: *Fusarium moniliforme* Sheldon) are dark blue and globose to conical, 200–400 × 150–400 μm in dimension. Asci are ellipsoid to clavate and contain 4–8 hyaline, elliptical, 1–3 septate ascospores measuring 15–18 × 6.7 μm. Microconidia are hyaline, oval to clavate, single celled, 5–12 × 3–3.5 μm and formed in chains or false heads from monophialides. Macroconidia are somewhat sickle shaped to almost straight, with a foot-shaped basal cell, usually 3–5 septate, and measure 8.4–66 × 2.4–3.5 μm. The fungus does not produce chlamydospores. Dark blue sclerotia are sometimes present (Hashioka 1971; Ou 1985).

13.3.4.5 Disease Cycle and Epidemiology

The disease is seed-borne and is primarily seed transmitted. The seed infection is caused by secondary airborne conidia and ascospores, discharged from diseased plants from heading to harvest. The fungus is both internally and externally seedborne, and its recovery was higher from lemma and palea than endosperm and embryo (Manandhar 1999). The pathogen can survive in endosperm and embryo to the extent of 15 % and 6 %, respectively, till commencement of next crop season (Kumar and Sunder 2015). Raza et al. (1993) reported a maximum of 22 % seed infection from naturally infested samples from Pakistan. The fungus grows intercellularly in stigma and anthers within 48 h and finally reaches and covers the ovary. Sowing of 100 % infected seeds produced 30–68 % diseased seedlings. The fungus also survives in soil in infected crop residues as thick-walled hyphae or macroconidia, but it is of less significance (Singh and Sunder 2012).

The fungus infects rice seedlings through roots or crowns and grows systemically in the plants, where it produces growth hormones gibberellins and fusaric acid. The mycelium and microconidia of the pathogen concentrate in the vascular bundles, especially in the large pitted vessels and lacunae of the xylem vessels of stem, leaf blades, sheaths and adventitious roots (Singh and Sunder 1997). The disease is favoured by high temperature (30–35 °C), injury to the roots of seedlings during uprooting and application of high dose of nitrogenous fertilizers. Chan et al. (2004) observed that sprouting period was the most sensitive for infection.

13.3.4.6 Disease Management

Host Plant Resistance Cultivation of resistant varieties is the most effective, safe and practical mean of avoiding loss in crop yield. Several genotypes, viz. Co 18, Co 22, ADT 8, PTB 7, GEB 24, GSL-66, GSL-67, GSL-68, IR 20, IR 26, IR 32, IR 38, IR 44, IR 45, KS 133 and Punjab Mahak, have been found to possess tolerance/resistance to bakanae (Ghazanfar et al. 2013; Kumar et al. 2014), and some of these lines can be used as donor in breeding programme. Reaction of rice genotypes to bakanae has been reported to be crop growth stage dependent. In China, Lu (1994) observed that rice genotype Longjiao 86074-6 was resistant at the seedling stage but moderately susceptible at the adult stage; Qingxi 96 was moderately resistant at the seedling stage but resistant at the adult stage, while cultivars Zupei 7, Dongrong 84-21, G-6 and Sui 89-17 were moderately resistant at both stages. Resistance in rice against bakanae is monogenic, recessive in IR 6 and dominant in KS 282. Two quantitative trait loci (QTLs), namely, QB 1 and QB 10 on chromosomes 1 and 10, have been identified for bakanae resistance, which exhibited additive effect (Kumar et al. 2014). Coarse varieties were more tolerant to bakanae disease than the fine ones (Ghazanfar et al. 2013). All dwarf and semidwarf genotypes carrying genes *d 29*, *Sd 6* or *Sdq (t)* showed resistance and may be used as donors for improvement of bakanae resistance in rice breeding programme (Ma et al. 2008).

Cultural Management Uprooting rice nursery in standing water, late planting and rotating rice with pasture crops proved effective in avoiding bakanae infection. Removal and destruction of infected plants from the field can help in minimizing the inoculum and reducing seed-borne infection. Applications of potassium and soil amendment with neem cake, groundnut cake (Kumar et al. 2014) and sugarcane press mud (authors' observation) have also been found to suppress the pathogen. The disease incidence was significantly lower when nursery was raised by sowing seeds under dry conditions compared to sowing of sprouted seeds in puddled beds (Sunder et al. 2014b).

Biological Control and Use of Botanicals Several fungal and bacterial antagonists and botanical extracts are known to suppress mycelial growth, conidia production and germination of *F. moniliforme* and to reduce disease incidence significantly. Kumar et al. (2014) reported effectiveness of several strains of *Pseudomonas fluorescens*, *Bacillus subtilis*, *B. megaterium*, *Trichoderma harzianum*, *T. virens*, *T. asperellum* and *Talaromyces* spp. in suppressing bakanae disease. Treating seeds with antagonists such as *B. subtilis*, *T. harzianum* and *T. virens* reduced the disease severity (Dehkaei et al. 2004). Combining the biocontrol agents as seed treatment was more effective than spraying antagonists. Seed treatment with metabolites produced by different soilborne bacteria also efficiently inhibited bakanae development (Motomura et al. 1997). In China, high efficacy of two antagonistic bacterial strains, viz. B-916 and P-91, has been reported against bakanae (Chen et al. 1998). Kumar et al. (2014) reported that extracts of *Azadirachta indica* and *Decalepis hamiltonii* and oil of *Hedychium spicatum* and *Acorus calamus* were highly anatagonistic to pathogen growth. Aerated vermicompost tea was found highly effective in field trials (Kumar et al. 2014).

Chemical Control Salt water can be used to separate lightweight, infected seeds from seed lots, thereby reducing the seed-borne inoculum. Seed soaking in 0.1 % solution of organomercury compounds (acetate and chloride groups) for 16–24 h or in 0.25 % solution for 2 h was recommended in Japan (Ou 1985). Effective disease control has also been reported by seed dressing or slurry treatment with different fungicides and their combinations like benomyl, benomyl + thiram, mancozeb + benomyl, carbendazim, carbendazim + mancozeb, propiconazole, thiophanate-methyl, thiophanate-methyl + thiram, prochloraz, prochloraz + carbendazim, kasugamycin, triforine, carboxin + thiram, iprodione and ferimzone in different parts of the world. Seed treatment with carbendazim (0.5 g/l) + Streptocycline (0.01 g/l) for 12 h and smearing of the seeds with talc formulation of *T. harzianum* at 15 g/kg of seed immediately before sowing and seedling root dip with *T. harzianum* at 15 g/l water proved most effective against bakanae (Kumar et al. 2014).

Beside seed treatment, seedling dip in 0.1 % carbendazim or benomyl for 6–8 h (Bagga and Sharma 2006) and soil drenching with carbendazim and difenoconazole proved highly effective in curtailing the disease. Foliar application of benzimidazoles (benomyl and carbendazim) at 0.1 % significantly reduced grain infection by the pathogen. In addition, sand mix application of carbendazim in nursery beds at 1 g/m^2, 7 days before uprooting of seedlings, also helps in reducing bakanae incidence in the main field (Kumar et al. 2014; Sunder et al. 2014b). Suzuki et al. (1994) reported the effectiveness of EC formulation of triflumizole (Trifmine) in reducing the bakanae disease.

13.3.5 Brown Spot

13.3.5.1 History and Geographical Distribution

Brown spot of rice is known to occur in Japan since 1900. It has been reported from almost all the countries of Asia, Africa, South and North America including the Caribbean region, Australia and several European countries like France, Spain, Portugal, Switzerland, Serbia, Greece and Turkey (Ou 1985; Khalili et al. 2012; www.plantwise.org).

13.3.5.2 Economic Importance

Brown spot disease appears to be more on rain-fed rice where rice is grown in poor soils coupled with erratic rainfall or water supply and nutritional imbalances, especially nitrogen and available potassium. There are indications of increased occurrence of brown spot in recent years (Savary et al. 2005), perhaps due to changes in climatic conditions especially rainfall pattern. Average grain yield loss ranging from 4 to 52 % has been reported from different countries (Sunder et al. 2014a). However, losses up to 90 % have been observed under certain conditions especially in the rain-fed ecosystem, where water supply is scarce, combined with nutritional imbalance, particularly lack of nitrogen (Sunder et al. 2014a). This disease has historic importance as it caused heavy yield losses in Eastern India which is considered to be a major factor for the 'Bengal Famine' during 1942. Beside quantitative losses, it is also known to reduce the quality and germinability of the seed.

13.3.5.3 Symptoms

The disease appears on coleoptiles, leaf sheath and leaf blade as brown spots with grey or whitish centre, cylindrical or oval in shape resembling sesame seeds usually with yellow halo on leaves (Fig. 13.10a, c). On glumes, black or dark brown spots are produced resulting in discoloured and shrivelled grains. Under favourable conditions, dark brown conidiophores and conidia develop on the spots giving a velvety appearance. Young roots may also show blackish lesions (Ou 1985). The pathogen has also been reported to cause brown to dark brown lesions on panicle stalk at the joint of flag leaf to stalk. These lesions usually extend downwards beneath the sheath resulting in severe wet rotting (Fig. 13.10b) and appearance of greyish mycelial growth (Sunder et al. 2005).

13.3.5.4 Pathogen

The fungus *Drechslera oryzae* Subr. and Jain (syn. *Bipolaris oryzae* Shoemaker, *Helminthosporium oryzae* Breda de Haan) [telemorph: *Cochliobolus miyabeanus* (Ito and Kuribayashi) Drechsler ex Dastur = *Ophiobolus miyabeanus* Ito and Kuribayashi] produces grey to olive or black, inter- and intracellular mycelium. The sporophores are thick, erect, geniculate, dark olivaceous at the base and lighter towards the tip. Conidia are brownish, 5–10 septate, slightly curved, widest at the middle with the oldest conidium towards the base. The sizes of conidiophores and conidia vary from 68 to 688 × 4–20 μm and 15–170 × 7–26 μm, respectively, in different countries (Ou 1985). Perithecia of the fungus are globose to depressed globose, with the outer wall dark yellowish brown and pseudoparenchymatous and 560–950 × 368–377 μm in dimensions. The asci are cylindrical to long, fusiform, 142–235 × 21–36 μm and contain filamentous or long cylindrical, hyaline or pale olive-green, 6–15 septate ascospores measuring 250–469 × 6–9 μm (Ou 1985).

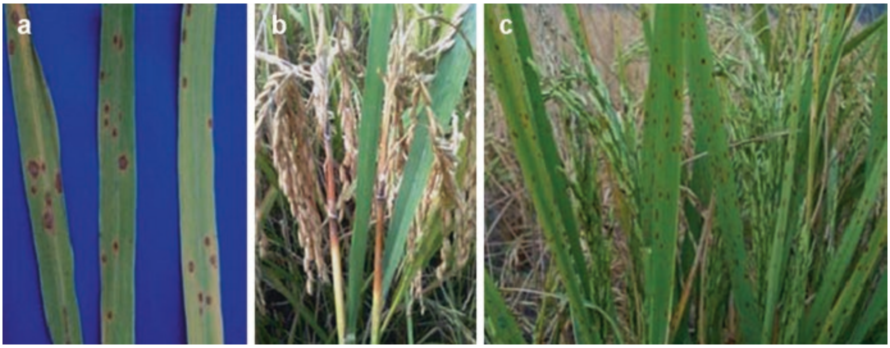

Fig. 13.10 Symptoms of brown spot disease of rice: (**a**) typical brown spots on rice leaves; (**b**) stalk rot phase of brown spot of rice; (**c**) field severely infected with brown spot

13.3.5.5 Disease Cycle and Epidemiology

The fungus surviving in soil and infected plant parts including stubbles, straw and grains acts as primary source of inoculum. Many plant species including *Cynodon dactylon*, *Digitaria sanguinalis*, *Echinochloa colona*, *E. frumentacea*, *Euchlaena mexicana*, *Imperata* spp., *Leersia hexandra*, *Panicum miliare*, *P. miliaceum*, *Pennisetum typhoides*, *Saccharum officinarum*, *Zizania latifolia* and some wild rice including *Oryza coarctata*, *O. granulate*, *O. malampuzhensis*, *O. latifolia*, *O. ridleyi*, *O. perennis*, *O. fatua*, *O. jeyporensis*, *O. montana* and *Zizania aquatica* have been reported to be infected by the pathogen under natural or artificial inoculation conditions (Gangopadhyay 1983; Ou 1985; Sunder et al. 2014a). Some of the workers reported cross pathogenicity as isolates of *H. oryzae* from wheat, oat, *Echinochloa phyllopogon* and *Phragmites australis* attacked rice and a rice isolate attacked maize, sorghum, oats, barley and sugarcane (Sunder et al. 2014a). The primary infection is usually initiated by the infected seed as necrotic lesions on coleoptile and sheath of first leaves. The subsequent lesions on leaves arise from secondary infection by airborne spores produced on primary lesions (Ou 1985).

The disease is aggravated by prolonged leaf wetness, high soil pH, late planting, nutritional imbalances especially low levels of N, K, Mn, Si, free Fe, low CEC and low organic matter. It has been observed that NO_3 induces greater susceptibility than NH_4 (Ou 1985; Datnoff et al. 1992).

13.3.5.6 Disease Management

Host Plant Resistance Partial to complete resistance to brown spot pathogen has been identified in several genotypes including HRC 726, HRC 7288, NIC 105703, NIC 105784 and NIC 1105815 (Shukla et al. 1995) and BPT 1788, MTU 1067 and Swarnadhan (Sunder et al. 2005) under field conditions, and some of these lines may be used as donors for brown spot resistance breeding programme. Resistance to brown spot is known to vary with crop stage (Omar et al. 1979). Sato et al. (2008) identified three QTLs, viz. qBS 2, qBS 9 and qBS 11, on chromosomes 2, 9 and 11 for brown spot resistance in rice cultivar Tadukan, while Katara et al. (2010) identified 10 QTLs associated with brown spot resistance, some of which may be common to those of Sato et al. (2008).

Chemical Control Seed treatment with various chemicals like organomercurials, triforine, bitertanol, pyroquilon, tricyclazole, chlorothalonil, quinolate, edifenphos, carbendazim, benomyl, mancozeb, thiram and captan is quite effective against *H. oryzae* in different parts of the world (Sunder et al. 2014a). Seed soaking in 2-methyl 1,4-naphthaquinone (vitamin K_3), Na-pentachlorophenate, boric acid and β-indole acetic acid and seedling treatment with sulphanilamide and griseofulvin significantly reduced disease severity. Foliar application of many chemicals, viz. mancozeb, Ridomil MZ, edifenphos, iprobenphos, iprodione, chlorothalonil, bitoxazol, propiconazole, hexaconazole, tebuconazole, Sisthane, Shin-mel, triphenyltin hydroxide, thiophanate-methyl, Antracol, azoxystrobin, trifloxystrobin + propiconazole, difenoconazole + propiconazole and antibiotics like blasticidin SM, aureofungin, mycobacillin and versicolin, is highly effective against brown spot. Among these, propiconazole, hexaconazole and mancozeb are commonly used against both leaf spot and stalk rot phases of the disease (Ou 1985; Sunder et al. 2014a).

Biological Control and Use of Botanicals Strains of *Pseudomonas fluorescens*, *Bacillus megaterium*, *B. subtilis*, *Trichoderma viride*, *T. pseudokoningii*, *T. harzianum*, *T. reesei*, *Cladosporium* spp., *Penicillium* spp. and *Aspergillus flavus* are known to inhibit the growth of *H. oryzae* and to reduce the disease incidence in field experiments (Sunder et al. 2014a). Among various botanicals and biopesticides, foliar application of neem cake extract, *N. oleander* leaf extract, *T. viride*, TriCure (5 ml/l), Biotos (2.5 ml/l), Achook (5 ml/l), Neemazal (3 ml/l) and Wanis (5 ml/l) is highly effective in reducing the brown spot severity (Harish et al. 2008; Kumar and Rai 2008; Sunder et al. 2010). Besides, spraying with nonconventional chemicals like ferric chloride, sodium selenate, nickel nitrate, benzoic acid and salicylic acid can also induce resistance and reduce the disease severity significantly (Shabana et al. 2008; de Vleesschauwer et al. 2010; Sunder et al. 2010).

13.3.6 Sheath Rot

13.3.6.1 History and Geographical Distribution

Sheath rot is prevalent in most of the rice-growing countries worldwide, particularly in rain-fed rice ecosystems, and is more prevalent during wet than dry seasons. The disease has been reported from different countries of Asia (Sri Lanka, Pakistan, Nepal, China, Bangladesh, Japan, Korea, India, Malaysia, Indonesia, the Philippines, Taiwan, Thailand, Vietnam and Brunei), Africa (Kenya, Nigeria, Gambia, Cameroon, Cote d'Ivoire, Niger, Burundi, Tanzania and Madagascar), Americas (the United States, Mexico, Cuba, Colombia, Venezuela, Peru, Brazil and Argentina) and Australia (Suparyono 1990; Webster and Gunnell 1992; Gill et al. 1993; www.plantwise.org). The disease has also been described as 'rice abortion disease' in Thailand, the name given by Thai farmers (Singh and Dodan 1995).

13.3.6.2 Economic Importance

Sheath rot is considered to be potential threat to rice cultivation in both temperate and tropical regions due to severe damage and high yield losses. The extent of yield loss ranged from 3 to 20 % in Taiwan, 53 % in the Philippines, 85 % to almost complete loss in Thailand, 11 % in the United States and 3–90 % in India (Srinivasan 1980; Manibhushan Rao 1996). The losses in grain yield varied significantly among the cultivars, but the average losses are estimated to be 15 %. The disease is also known to affect seed germination, seedling vigour, head rice recovery, protein content, total sugar, starch content and market value of the produce due to production of discoloured and shrivelled seeds (Reddy et al. 2000). Infection by rice tungro virus enhanced yield losses due to sheath rot (Singh and Dodan 1995).

13.3.6.3 Symptoms

The pathogen infects the crop just after flowering stage and produces oblong or somewhat irregular lesions, 0.5–1.5 cm long, with brown margins and grey centres on uppermost leaf sheath that covers the panicle. As the disease advances, lesions enlarge and coalesce and may cover most part of leaf sheath, thereby retarding or aborting the panicle emergence. In case of early and severe infection, the panicles do not emerge and are compressed within the leaf sheath, a stage called ‘choking’, or emerge partially bearing discoloured and chaffy grains (Fig. 13.11a, b). The disease is particularly devastating in CMS lines (A lines) in hybrid seed production and in dwarf varieties because of shortened internodes and poor panicle exertion. An abundant whitish powdery growth may be found inside the affected sheaths. A diffuse reddish brown discolouration may also be seen in the sheath (Fig. 13.11c).

13.3.6.4 Pathogen

Sheath rot is caused by several fungal and bacterial pathogens in different parts of the world (Singh et al. 2005). Two fungal pathogens, viz. *Sarocladium oryzae* (Sawada) Gams and Hawksworth and *Fusarium moniliforme* Sheldon, can cause sheath rot symptoms, *Sarocladium oryzae* being the most predominant. *Sarocladium oryzae* produces verticillate conidiophores with one to two appressed whorls of

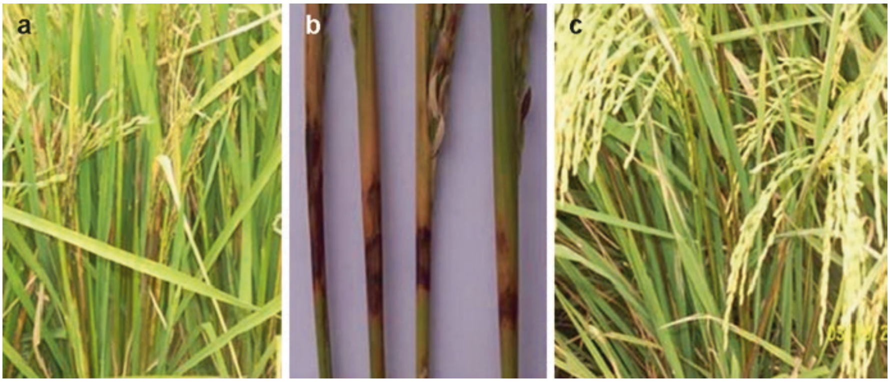

Fig. 13.11 Symptoms of sheath rot disease of rice: (**a**) sheath rot symptoms on panicles and grains; (**b**) typical sheath rot on flag leaf sheath; (**c**) reddish brown discolouration in sheath

branches. Conidia are produced on phialides, cylindrical to slightly fusiform, often somewhat curved, hyaline and single celled measuring 3.5–9 × 1–2.5 μm. The morphological characteristics of *F. moniliforme* isolates causing sheath rot are similar to those described under foot rot and bakanae. However, the strains of *Fusarium moniliforme* causing bakanae do not induce sheath rot.

13.3.6.5 Disease Cycle and Epidemiology

S. oryzae survives as mycelium in the infected residue and on seeds (Singh and Raju 1981; Singh and Mathur 1993). It also infects several weeds and cultivated hosts, viz. *Eleusine indica*, *Monochoria vaginalis*, *Cyperus teneriffae*, *C. iria*, *C. difformis*, *Echinochloa crus-galli*, *E. colona*, *Oryza rufipogon*, *Bambusa balcooa*, *B. vulgaris*, *Hymenachne* spp., *Leersia hexandra* and *Panicum walense* (Singh and Dodan 1995). Isolates of the fungus from weeds and rice have been found to be cross infective. The pathogen infects rice through stomata or wounds and ramifies intercellularly in the vascular bundles and mesophyll tissues of susceptible cultivars. The severity of the disease is more on plants affected by various biotic and abiotic factors like infection by rice tungro virus, rice yellow dwarf virus, stem borer, mites, water and nutrient stress. Generally, the disease intensity is more in late and densely planted fields. The conditions like moderate temperature (20–30 °C), high humidity, cloudy days during booting stage and occasional rainfall favoured the buildup of the disease.

13.3.6.6 Disease Management

The disease can be managed effectively through integrated programme of seed treatment, selection of resistant cultivars and foliar application of fungicides.

Host Plant Resistance Although the spectrum of genetic resistance to this disease is not very broad, many workers have reported sources of resistance to this disease. Generally, the dwarf varieties are more susceptible (Raychoudhuri and Purkayastha 1980). Several workers have reported a number of rice varieties/cultures/wild rice accessions to be resistant or tolerant to sheath rot under natural disease infection, viz. ADT 36, ARC 7717, ASD 5, ASD 17, Intan, IR 26, IR 50, IR 54, IR 60, Sigadis, Tadukan, Tetep, Basmati-370,TOX 3145-TOC 34-2-3, TOX 3344-TOC 3-4, Zenith and japonica type varieties, Moroberekan, VS 99 and *Oryza latifolia* (Acc. 100963) (Singh and Dodan 1995; Srinivasachary et al. 2002; Vivekananthan et al. 2006; Sharma et al. 2013). Nine QTLs on seven different chromosomes, viz. Chr. # 1, 2, 4, 5, 6, 7 and 8, have been identified to impart resistance to sheath rot disease (Srinivasachary et al. 2002).

Cultural and Biological Methods Cultural practices like application of neem cake (1 t/ha), avoiding excess N, application of potassic fertilizers and foliar application of zinc sulphate have been reported to reduce the disease intensity (Alagarsamy and Bhaskaran 1986; Singh and Dodan 1995). Foliar spraying of 5 % neem seed kernel extract (NSKE) twice, viz. during booting and 10 days later (Narasimhan et al. 1993), and gypsum (calcium sulphate) applied at 500 kg/ha, 50 % as basal and 50 % at 35 DAT (Narasimhan et al. 1994), were also very promising in reducing the sheath rot incidence and increasing the grain yield. Treating the seeds with salt solution has been recommended to obtain clean seed and to minimize sheath rot incidence (Rajan 1981). Practices like use of healthy and treated seeds, wider spacing (20 cm × 15 cm), adjustment of planting time and destruction of weeds, collateral hosts and crop residues can greatly reduce the terminal disease intensity (Singh and Dodan 1995; Dodan et al. 1998). Several workers have reported effectiveness of different antagonists like *Pseudomonas fluorescens*, *Azospirillum lipoferum*, *Trichoderma viride* and *T. harzianum* either singly or as consortium (Sakthivel and Gnanamanicham 1987; Eswaramurthy et al. 1988; Sundaramoorthy et al. 2013).

Chemical Control Chemical control has been practiced in many places and has been found quite satisfactory. Several chemicals like carbendazim, tridemorph + carbendazim, benomyl, propiconazole, edifenphos, hexaconazole, iprobenphos, mancozeb, tebuconazole and chlorothalonil have been found to be promising against sheath rot (Singh and Dodan 1995; Lore et al. 2007; Sharma et al. 2013). Seed treatment with carbendazim at 2 g/kg of seeds or mancozeb 75 WP at 2.5 g/kg can control the seed-borne inoculum. Spraying the fields around flowering with carbendazim at 1 g/l or mancozeb 75 WP at 2.5 g/l or propiconazole 25 EC at 1 ml/l or hexaconazole 5 EC at 2 ml/l or thiophanate-methyl 70 WP at 1 g/l can substantially reduce the disease intensity (Singh and Dodan 1995; Dodan et al. 1996b). Foliar application of growth hormone, gibberellic acid, has also been reported to reduce the disease intensity (Raychoudhuri and Purkayastha 1980).

13.3.7 Stem Rot

13.3.7.1 History and Geographical Distribution

The disease was first reported from Italy by Cattaneo in 1876 (Ou 1985). Since then it is known to occur in several countries in Asia (Japan, India, Sri Lanka, Myanmar, Bangladesh, Burma, China, Indonesia, Vietnam, Iran, Iraq, Pakistan, Taiwan, Thailand and the Philippines), Europe (Bulgaria, France, Portugal, Turkey and Spain), Africa (Madagascar, Mozambique, Egypt, Somalia and Kenya), Americas (the United States, Venezuela, Brazil, Costa Rica, Colombia, Guyana, Panama, Suriname, Trinidad and Tobago and Argentina) and Australia (Ahuja and Srivastava 1990; Garrido and Malaguti 1995; Cedeno et al. 1997; Watson and Priest 1998; Javan-Nikkhah et al. 1998; Aye et al. 2009).

13.3.7.2 Economic Importance

The disease is known to cause substantial quantitative and qualitative losses due to increased lodging, smaller panicles, production of light chalky grains and poor milling quality particularly in waterlogged areas. Grain yield losses up to 50 %, 75 % and 80 % have been reported from Vietnam, the United States and the Philippines, respectively (Ou 1985). However, overall annual loss due to this disease has been estimated at 5–10 % (Krause and Webster 1973). Other estimates of grain yield loss include 27–30 % in Iraq (Al-Heeti and El-Bahadli 1982), 6–53 % in China (Li et al. 1984) and 10–30 % in Australia (Cother and Nicol 1999). In India, annual losses of 5–15 % have been estimated with a maximum of 80 % (Paracer and Luthra 1944). Krause and Webster (1973) observed 12–22 % yield reduction by inoculating the plants at different stages of crop growth.

13.3.7.3 Symptoms

The disease appears in the form of small irregular black lesions on the outer leaf sheath near the water level at mid-tillering stage (Fig.13.12a). As the season advances, the lesions enlarge and the fungus moves inward, producing lesions on the inner leaf sheaths. Subsequently, the fungus infects the culms, resulting in partial or complete rotting (Fig. 13.12b) and premature lodging of the crop. Severely infected plants bear partially filled or unfilled grains. The infected plants can be easily pulled out from the soil due to rotting of crown. Dark greyish mycelium may

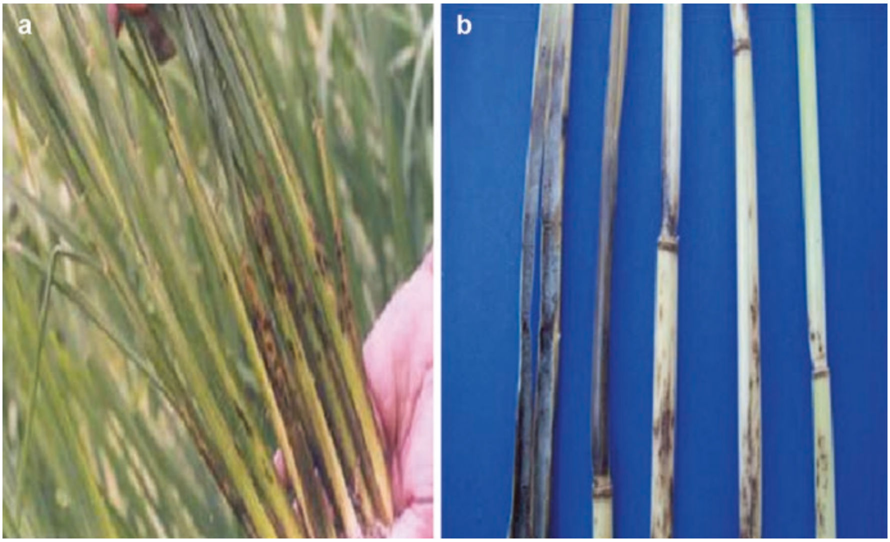

Fig. 13.12 Symptoms of stem rot disease of rice: (**a**) lesions on outer leaf sheath; (**b**) lesions on culm along with fungal mycelium and sclerotia

be found within the sheath and culm, which is converted into numerous small, round and black sclerotia near maturity.

13.3.7.4 Pathogen

Stem rot is caused by *Magnaporthe salvinii* (Catt.) Krause and Webster (conidial state *Nakataea sigmoidea* (Cav.) Hara). The fungus most commonly occurs in its sclerotial state, *Sclerotium oryzae* Catt. The perithecia of *M. salvinii* are dark, globose, 250–650 μm in diameter and found embedded in leaf sheaths. Asci are cylindrical, unitunicate, short stalked, 104–165 × 8.7–17.7 μm and contain eight fusiform, somewhat curved, three septate ascospores, which measure 35–65 × 8.7 μm. Sclerotia are black, globose, smooth and 180–200 μm in diameter. Conidiophores are dark, upright, septate, 100–175 × 4–5 μm and bear fusiform, three septate, curved conidia (29–40 × 10–14 μm) on pointed sterigmata. In addition to *S. oryzae*, *S. hydrophilum* and *S. oryzae* var. *irregulare* have also been found to be associated with this disease (Singh and Chand 1986).

13.3.7.5 Disease Cycle and Epidemiology

The sclerotia produced by the fungus play an important role in the initiation and spread of the disease. The overwintering sclerotia float on the surface of water during various tillage operations, come in contact with plants, germinate to form appressoria/infection cushion and cause infection through leaf sheath, root and stem base. The role of conidia and ascospores in the spread of stem rot is not thoroughly understood. The fungus has also been found to infect certain grass weeds like *Echinochloa colona*, *Eleusine indica*, *Leptochloa chinensis*, *Setaria pallide-fusca*, *Zizaniopsis miliacea* and wild rice (Ou 1985). Disease incidence and severity have been observed to be directly correlated with the number of sclerotia present in the upper layer of the soil before planting (Krause and Webster 1973). The plants have been found to be more susceptible at the internode elongation stage, and the disease is favoured by high humidity and high temperature, nitrogenous fertilizer, dense planting and attack of stem borer, node blast, brown planthopper and jassids.

13.3.7.6 Disease Management

Stem rot can be managed effectively through an integrated approach of residue management, proper fertilization and cultivar selection.

Host Plant Resistance Several workers have reported that resistance to stem rot is either not available or rarely found. However, under natural conditions of disease infection, some cultivars/cultures and wild rice accessions have shown tolerance to stem rot, viz. Cherno Fingo, IRBB 60, ARC 12751, ARC 12753, Jalmagna, Latisail, Pankaj, Rasi, Basmati-370, Taraori Basmati, Pakistani Basmati, *O. rufipogon* and *O. nivara*, in different parts of the world (Singh et al. 2010b; Sunder and Singh 2015). Resistance to stem rot in rice has been reported to be controlled by two loci on chromosome 2 and chromosome 3 (Ni et al. 2001).

Cultural and Biological Control One of the most effective means of managing stem rot is by burning infested crop residue and stubble to minimize overwintering inoculum though environmental pollution issues restrict the use of burning. Harvesting at ground level and removing the straw from the field, management of irrigation water by draining, allowing the soil to crack before irrigation and use of sieving floatation technique were found effective (Singh et al. 2010b). Winter flooding and incorporation of the residue in deeper layers are also helpful in reducing the carry-over of sclerotia to the following season and proved to be the best alternative to burning for stem rot management (Cintas and Webster 2001). Practices like delayed planting, application of burnt rice husk and mustard cakes and crop rotation like rice-lucerne-rice and rice-wheat-*Vigna radiata*-rice rotations have been found to be beneficial in managing the disease (Chand and Singh 1985; Singh et al. 2002b). Strains of the fungal antagonist like *Gliocladium virens* have been found to effectively control stem rot by inhibiting sclerotia formation and reducing sclerotial viability (Singh et al. 2002b; Nishant and Puri 2012).

Chemical Control Though several chemicals have been found to be effective against stem rot, chemical control is not widely practiced for managing this disease. Application of chemicals like carbendazim, validamycin A, edifenphos, benomyl, thiophanate-methyl, difenoconazole and tricyclazole followed by foliar spray with antagonists like *Penicillium glabrum* and *T. harzianum* has been found to be effective (Singh et al. 2002b; Sumitra et al. 2011; Kumar and Sunder 2015).

13.4 Virus Diseases

More than 30 viruses are known to infect rice globally (Abo and Fadhila 2003). However, yield loss could be substantial if virus infection takes place in early crop growth stage. Some of the important viruses in Asia are rice stripe virus, rice dwarf virus, rice gall dwarf virus, rice ragged stunt virus, rice grassy stunt virus, rice transitory yellowing virus, rice black streaked dwarf virus, southern rice black streaked dwarf virus and rice tungro virus disease complex (RTV). Rice hoja blanca virus (RHBV), a member of the genus *Tenuivirus*, is economically important in several South American countries, while rice stripe necrosis virus, rice crinkle disease, maize streak virus, African cereal streak virus and rice yellow mottle virus (RYMV) are reported on rice in Africa. In this section, we will discuss about rice tungro virus disease complex, rice yellow mottle and rice hoja blanca, which are important in South and Southeast Asia, Africa and South America, respectively (Fig. 13.13).

13.4.1 *Rice Tungro Disease (RTD)*

13.4.1.1 Distribution and Economic Importance

'Tungro', which means degenerated growth in Filipino language, was first recognized to be caused by a leafhopper-transmitted virus in 1963 (Rivera and Ou 1965). However, the disease is believed to be present much earlier and was known by different names like 'accep na pula' (red disease) and rice 'cadang-cadang' (yellowing) in the Philippines, 'penyakit merah' (red disease) in Malaysia, 'mentek' disease in Indonesia and 'yellow orange' disease in Thailand (Ou 1985). The disease is widely distributed in South and Southeast Asia and has been reported from India, Pakistan, Sri Lanka, Nepal, Bangladesh, Thailand, Laos, Vietnam, China, Japan, the Philippines, Brunei, Malaysia, Indonesia and Papua New Guinea. Widespread cultivation of different HYVs following introduction of Taichung Native 1 during the 1960s was highly conducive for the buildup of leafhopper population and spread of rice tungro virus. A series of tungro outbreaks was recorded during 1980 to 2000 in India, Indonesia, the Philippines, Malaysia, Thailand and Bangladesh (Azzam and Chancellor 2002; Bunawan et al. 2014). Muralidharan et al. (2003b) reported three epidemics of RTD from 1984 to 1994 in India. The disease assumed a serious proportion during 1981 in many parts of West Bengal (India) where an estimated 0.5 million tons of rice production loss was reported (Krishnaveni et al. 2009). The disease appeared in epidemic form in Gurdaspur and Amritsar districts of Punjab (India) during 1998 affecting about 0.45 million ha of rice crop (Varma et al. 1999). Dai and Beachy (2009) reported that RTD caused 5–10 % reduction in rice yields in South and Southeast Asia.

Fig. 13.13 Global distribution of RTV, RYMV and RHBV

13.4.1.2 Symptoms

The disease results in the discolouration of leaves, stunting of plants and reduced tillering. The extent of stunting and discolouration depends on variety, nitrogen status of the crop and age of plants. Initial symptoms appear as interveinal chlorosis, and leaf discolouration may vary from greenish yellow to reddish brown or yellowish brown (Fig. 13.14a). Often the young infected leaves are pale green to light yellow, while the older leaves are reddish orange in colour. Generally, the infected leaves in *japonica* cultivars show yellow shade, while *indica* cultivars show orange shade. The leaf discolouration usually starts from the tip of the leaves and may extend to the lower part of the leaf blade. Early infection results in non-emergence of panicles or partial emergence bearing chaffy and shrivelled grains. Tungro infection generally delays flowering and there is no uniformity in crop maturity (Fig. 13.14c).

13.4.1.3 Pathogen, Its Transmission and Virus-Vector Relationship

Rice tungro disease is a composite disease caused by two unrelated viruses, viz. rice tungro bacilliform virus (RTBV– a member of the Caulimoviridae, dsDNA) and rice tungro spherical virus (RTSV– a member of Secoviridae, positive-sense

Fig. 13.14 Symptoms of rice tungro disease: (**a**) interveinal chlorosis and leaf discolouration; (**b**) *Nephotettix virescens*, vector of rice tungro virus; (**c**) field infected with rice tungro disease

ssRNA). The plants infected by RTSV alone do not show any definite symptoms. The plants infected by RTBV alone show moderate stunting and discolouration. However, rice plants infected with both RTBV and RTSV generally express severe stunting and yellowing. Rice tungro virus is exclusively transmitted (in a semipersistent manner) by green leafhoppers (Azzam and Chancellor 2002), *Nephotettix virescens* being the principal vector (Fig. 13.14b). The vector can acquire and transmit both particles together. When the vector feeds on plants infected with RTSV alone, it can pick up and transmit RTSV. But, when the leafhoppers are fed on rice plants infected with RTBV alone, it cannot pick up RTBV and no transmission occurs. However, when the leafhoppers first feed on RTSV-infected plants and pick up RTSV particles and then feed on RTBV-infected plants, they can pick up RTBV and transmit both the particles.

13.4.1.4 Disease Cycle and Epidemiology

The virus cannot survive in its vector or in seeds for a longer time. In areas with continuous cropping, the virus might survive from one crop to another. Infected ratoons and volunteer plants (seedlings and the plants that grow from seeds left in the field after harvest) have been shown to be the reservoirs of tungro inoculum and play an important role in its inter-seasonal carry-over. Several weeds, viz. *Eleusine indica*, *Echinochloa colona*, *E. crus-galli*, *Leersia hexandra*, *Sporobolus tremulus*, *Pennisetum typhoides*, *Eragrostis tenella*, *Setaria glauca*, *Paspalum distichum*, *Cynodon dactylon*, *Digitaria adscendens* and *Cyperus rotundus*, and wild rice types are reported to be infected by the virus which could be a potential source of primary inoculum. The insect vectors, in addition to rice, feed on these weed hosts during off season. The spread of RTD depends on the availability of viruliferous leafhoppers and the susceptible hosts at the right stage. The transmission of virus under field conditions depends on the cultivar, plant age, microclimatic conditions, wind speed, meteorological conditions and lunar phases, and a single viruliferous vector can infect up to 40 plants per day (Krishnaveni et al. 2009).

13.4.1.5 Disease Management

The management of rice tungro disease involves deployment of resistant or tolerant varieties, elimination of primary sources of inoculum, vector management, seedbed management and cultural practices.

Host Plant Resistance The best way of managing the disease is through deployment of resistant/tolerant varieties. A variety may be resistant to virus and/or vector. In India a number of high-yielding cultivars with resistance or tolerance to tungro and/or green leafhoppers have been released for commercial cultivation in specific rice-growing areas (Rani et al. 2008). Out of these, two varieties, viz. Vikramarya (IET 7302) and Nidhi (IET 9994), showed very high level of resistance to the disease. Several traditional varieties/land races like Latisail, Kataribhog, Ambemohar 102, Pankhari 203, Utri Merah, Utri Rajapan and Tjina were found to be resistant to both virus and the vector, though only a few of them were genetically characterized. Resistance to RTSV in Utri Merah is governed by two recessive genes, viz. *tsv1* and *tsv2*. Gene *tsv1* is also responsible for RTSV resistance in cultivars Utri Rajapan and Pankhari 203 (Shahjahan et al. 1991; Ebron et al. 1994). Two lines derived from Utri Merah, viz. IR 69705-1-1-3-2-1 and IR 69726-116-1-3, showed resistance to rice tungro disease. Line IR 69726-116-1-3 was released for commercial cultivation under the name ‘Tukad petanu’ and performed well in Bali, East Java and Lombok (Azzam and Chancellor 2002). One mutant line of rice variety IR 64, called MD 83, showed very high level of resistance to RTSV and its insect vector (Zenna et al. 2008). Though transgenic plants expressing RTBV coat protein, polymerase, protease and antisense RNA did not give protection against the disease, plants expressing coat protein genes and replicase genes of RTSV showed moderate to good level of resistance (Azzam and Chancellor 2002; Krishnaveni et al. 2009). RNA interference (RNAi) technology through the expression of DNA encoding ORF IV of RTBV showed promise against rice tungro disease (Tyagi et al. 2008).

Cultural Control Practices like adjustment of sowing time to avoid peak population of vectors; inclusion of a non-host crop like legume, oilseed, fibre or tuber crop in crop rotation to interrupt the disease perpetuation and vector buildup; periodic roguing; and removal of affected plants to reduce the inoculum source and removal of ratoons and self-sown plants can reduce the primary source of inoculum and disease spread (Krishnaveni et al. 2009).

Chemical Control The spread of rice tungro disease can be checked indirectly by controlling the vector by incorporating carbofuran 3 G at 30–35 kg/ha or phorate 10 G at 12–15 kg/ha in rice nursery bed in top 2–5 cm layer of the soil before sowing sprouted seeds or broadcasting the recommended insecticides 4–5 days after sowing in a thin film of water. Foliar application of imidacloprid 200 SL at 125 ml/ha or etofenprox 10 EC at 750 ml/ha or thiamethoxam 25 WG at 100 g/ha or acephate 50 WP at 1200 g/ha or monocrotophos 36 EC at 1500 ml/ha has been recommended for the protection of transplanted crop from RTD.

13.4.2 Rice Yellow Mottle

13.4.2.1 Distribution and Economic Importance

This disease was first recorded in Kenya in 1966 (Bakker 1970). Subsequently, it was reported from most of the West, Central and East African countries, viz. Burkina Faso, Burundi, Cameroon, Central African Republic, Chad, Congo Democratic Republic, Cote d’Ivoire, Ethiopia, Gambia, Ghana, Guinea, Guinea-Bissau, Kenya, Liberia, Madagascar, Malawi, Mali, Mauritania, Niger, Nigeria, Rwanda, Senegal, Sierra Leone, Tanzania, Togo, Uganda and Zimbabwe. Over the last 20–25 years, the disease has become a major production constraint in the irrigated and lowland rice ecosystems of Africa, especially in Burkina Faso, Cote d'Ivoire, Mali, Niger, Senegal and Sierra Leone (Anonymous 2000; Sere et al. 2013). In some areas of Madagascar and Cote d'Ivoire, several rice fields were abandoned due to severe occurrence of this disease (Yoboue 1989; Reckhaus and Randrianangaly 1990). The disease has also been reported from some upland rice fields of Cote d'Ivoire and Guinea-Bissau (Kouassi et al. 2005). Grain yield loss due to RYMV has been reported to range from 10 to 100 % in different countries depending on plant age at the time of infection, level of susceptibility of the varieties and prevailing climatic conditions (Fomba 1986; Reckhaus and Adamou 1986; Anonymous 2000; Kouassi et al. 2005). Several African countries have faced highly devastating epidemics of RYMV in the past (Konate and Fargette 2003). Severe outbreaks of RYMV were reported from Kenya, Niger, Sierra Leone and Liberia (http://www.cabi.org/isc/datasheet/47658). The disease has been reported to cause up to 60 % yield loss in Kenya (Okhoba 1989) and between 84 and 97 % yield losses in Sierra Leone (Taylor 1989).

13.4.2.2 Symptoms

The disease results in yellow to orange discolouration of the leaves, stunting of the plants, reduced tillering, nonsynchronous flowering, poor panicle exertion, spikelet sterility, discolouration of grains and, in severe cases, even death of the plants. In the field, diseased plants may be observed 3–4 weeks after transplanting and are easily noticeable because of their yellowish appearance. The symptoms appear as small, yellow-green, oblong to linear spots at the base of young systemically infected leaves which enlarge along the veins as broken or continuous streaks. The leaves developing later are mottled, often twisted and show difficulty in emerging. Young leaves are more susceptible to infection, and if the plants are infected within 20 days after planting, then the symptoms are very severe and plants may stop growing and eventually die.

13.4.2.3 Virus and Its Transmission

RYMV belongs to *Sobemovirus* group which has isometric particles (ca 30 nm in diameter) with single-stranded linear, positive-sense RNA. Many insect vectors, viz. *Sesselia pusilla*, *Chaetocnema pulla*, *Trichispa sericea*, *Dicladispa viridicyanea* and grasshopper *Conocephalus merumontanus*, are known to transmit the virus (Kouassi et al. 2005). The virus is also transmitted mechanically by farm implements, human and animal activities and plant-to-plant contact. Wind-mediated leaf-to-leaf contact, guttation fluids and irrigation water can also spread the virus. However, RYMV has not been demonstrated to be seed transmitted. The disease is more serious in transplanted rice than direct seeded rice. Any injury to the rice plants can increase the incidence of RYMV in the fields. Sarra (1998) reported that infected rice straw left in the fields after harvest can be a potential source of RYMV.

13.4.2.4 Epidemiology

RYMV can infect different wild species of *Oryza* and several weed species, viz. *Eleusine indica*, *Eragrostis tenuifolia*, *E. ciliaris*, *Echinochloa crus-galli*, *Panicum repens*, *Cyperus rotundus* and *Imperata cylindrica*. Initial infection takes place by the insect vectors which feed on infected wild rice, weed hosts or self-grown or inter-season rice plants (in lowlands), and the secondary spread takes place by wind-mediated leaf-to-leaf contact, mechanically or through insect vectors.

13.4.2.5 Disease Management

The genetic resistance to RYMV has been found to be governed by a recessive gene *rymv1*. Four alleles of this resistance locus have been identified, viz. *rymv1-2* (in an indica variety Gigante originating from Mozambique) and *rymv1-3, rymv1-4* and *rymv1-5*, from different *Oryza glaberrima* accessions, viz. TOG 5681, TOG 5672 and TOG 5674, respectively (Sere et al. 2013). The alleles from *O. glaberrima* have been incorporated in several lowland NERICA (New Rice for Africa) varieties. Subsequently, another recessive resistance gene, *rymv2*, has been identified from *O. glaberrima* (Sere et al. 2013). Recurrent backcrossing has been done to introgress these genes in the elite backgrounds. However, because of the appearance of resistance-breaking strains, efforts are being made to combine two resistance genes in varieties for release and cultivation in hotspot areas. In addition, QTLs conferring partial resistance have been identified in chromosome 7 and 12 (Sere et al. 2013).

Controlling the insect vectors is an important aspect of managing this disease as vectors play an important role in transmitting RYMV from surrounding infected rice or weed plants. The destruction of virus reservoirs by burning during the dry season, removal of rice regrowths and the use of chemical treatment against insect vectors can dramatically reduce primary and secondary infections.

13.4.3 Rice Hoja Blanca

13.4.3.1 Distribution and Economic Importance

Rice hoja blanca virus (white leaf, RHBV) is the most important viral disease of rice in Latin America. Though the disease gained importance only since 1957 when it broke out in threatening form in Florida in Southeastern United States (Atkins and Adair 1957), it was first recorded in Colombia as early as 1935 (Garces-Orejuela et al. 1958). Gradually the disease was spread to different countries in Central America, the Caribbean region and South America. Presently, the disease is widely distributed throughout tropical and subtropical America, viz. Brazil, Peru, Ecuador, Colombia, Venezuela, French Guiana, Guyana and Suriname in South America; Nicaragua, Panama, Costa Rica, El Salvador, Guatemala, Honduras and Belize in Central America; and the United States, Mexico, Puerto Rico, Cuba and Dominican Republic in North America (Morales and Jennings 2010). The disease can cause a significant yield loss ranging from 25 to 75 % in susceptible cultivars due to seedling death, reduced photosynthesis, growth retardation and panicle sterility (Jennings 1963; Morales and Jennings 2010).

13.4.3.2 Symptoms

The disease appears as chlorotic streaks on the leaves which coalesce turning the leaves yellow or whitish. The succeeding leaves are either almost entirely white or mottled. If the infection takes place in early growth stages, then the plants become stunted, and in severe cases, the leaves turn necrotic and plants die. The disease affects the growth and emergence of the panicles and results in poor or partial filling and discolouration of the grains. Infection by this virus also predisposes the plants to brown spot.

13.4.3.3 Virus and Its Transmission

RHBV is a member of the genus *Tenuivirus* and is closely related to other tenuiviruses found in America like *Echinochloa hoja blanca virus* and *Urochloa hoja blanca virus*. The ssRNA genome of *Tenuivirus* consists of four or more segments. The RHBV genome has four visible ssRNA species. The RNA-1 is generally of negative polarity, whereas others (RNAs 2–4) have ambisense translation strategy. RHBV is transmitted by leafhopper *Tagosodes orizicolus* which is the main vector and also by *T. cubanus* which is a minor vector. The vector acquires the virus while feeding on the infected plants, and there is a period of 17–22 days of viral propagation before the planthoppers become viruliferous (Galvez 1968; Webber et al. 1971). There is a high rate of transovarian transmission to the progeny, and the nymphs can transmit the virus soon after they emerge. The virus however cannot be transmitted mechanically. Many cultivated crops like wheat, barley, oats and rye and weeds such as *Echinochloa colona* are susceptible to RHBV both naturally and under artificial inoculation (Morales and Jennings 2010).

13.4.3.4 Epidemiology

The disease epidemics show cyclic and erratic pattern. The disease caused significant loss (25–50 %) during 1957–1964, 1981–1984 and 1996–1999 in Colombia (Morales and Jennings 2010). Genetic resistance of the vectors to the virus, low proportion of the viruliferous insect population (15–25 %) and low fecundity of the RHBV-infected planthoppers are the probable factors for cyclic and erratic nature of the RHBV epidemics (Zeigler and Morales 1990).

13.4.3.5 Disease Management

Initial works using japonicas from Taiwan and other sources resulted in the development of several RHBV-resistant lines like Napal, CICA7 and Colombia 1. Subsequently, two varieties, viz. Oryzica-1 and Metica-1, possessing tolerance to RHBV were developed using Colombia 1 (Munoz and Garcia 1983). The cultivars like Lacrose, Gulfrose l, Tainan-iku No. 487, Pandhori No. 4 and others have been used in resistance breeding programme (Morales and Jennings 2010). Work at CIAT, Colombia and IRD, Montpellier, France, revealed a high-level resistance in two indica varieties Fedearroz 2000 (Fd 2000) and Fedearroz 50 (Fd 50) to RHBV and its vector *T. orizicolus*. Further genetic analysis revealed a major QTL on chromosome 4 in both the varieties explaining about 50 % resistance against RHBV. In addition, one QTL in Fd 2000 on chromosome 5 and another QTL in Fd 50 on chromosome 7 were identified conferring resistance to vector *T. orizicolus* (Romero et al. 2014). The resistance QTL has been mapped and is being introgressed in elite rice varieties.

Removal of volunteer or ratoon rice plants in fields prior to sowing or transplanting of the rice crop can reduce the intensity of the disease in the fields. Crop rotation involving a nonhost crop can reduce the initial inocula and the disease severity. The disease can also be significantly managed by controlling the vectors. However, chemical sprayings for insect vector control led to the resurgence of the vector and high incidence of the disease in Ecuador and Colombia (Buddenhagen 1983).

13.5 Conclusion

There is no silver bullet for management of all the rice diseases in the field. An integrated management approach has a fair chance of success in the field as effectiveness of most of the components of such a method has been identified individually. It would specifically revolve around the use of an appropriate resistant or tolerant variety and a few simple practices for which there are experimental evidences that they can reduce the disease severity individually. These include use of healthy seeds, seed treatment, removal of primary inoculum, avoiding flooding of the fields, avoiding excess nitrogen and applying nitrogen fertilizer in splits and need-based application of chemicals. Regular surveillance of the fields and adoption of the available control measures will certainly help in keeping the diseases below their economic threshold level and in enhancing the rice production.

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Chapter 14
Rice Weeds and Their Management

Vivek Kumar, Gulshan Mahajan, and Bhagirath S. Chauhan

14.1 Introduction

Rice (*Oryza sativa* L.) is a major staple food not only for the people of Asia but for the whole world. In the economic and social stability of the world, rice plays an important role as more than 50 % population of the world consider it as a major staple food. Weeds are the most important biological constraints in the way to attain the potential rice yield because of their ability to compete for resources and their impact on rice quality. Heavy rice yield losses can be expected from weeds, and in the extreme conditions there can be complete crop loss (Ni et al. 2000; Rao et al. 2007; Jabran et al. 2012a, b; Jabran and Chauhan 2015). Losses caused by weeds further depend upon the method of rice establishment. In the absence of effective weed control options, yield losses are greater in direct-seeded rice (DSR) than in transplanted rice (Mahajan et al. 2009). In transplanted rice, the initial flush of weeds is controlled by flooding. Besides this, in the DSR method, the emerging rice seedlings are less competitive with concurrently emerging weeds (Kumar et al. 2008; Rao et al. 2007). It is imperative that investment in weed management practices be made to reduce yield losses caused by weeds. Total losses caused by

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weeds are tied up with cultural practices pertaining to weed control, land preparation, weed control expenses, and reduction in yield quantity and quality.

14.2 Important Rice Weeds

There are different ecosystems in which rice is cultivated, i.e., irrigated, shallow lowlands, mid-deep lands, deep water, and uplands. In these different ecosystems, different types of weed species are found (Singh and Singh 2008). With the change in the surface hydrology and rice establishment method, changes in weed flora have been reported. Ho (1991) observed the changes in the weed flora with the use of the direct-seeding method of rice. By the adoption of dry and wet direct sowing methods of rice, the floristic diversity increased and a change in the relative dominance of the major weed species occurred in comparison with the transplanting method. The dominating weed species of transplanted rice are *Monochoria vaginalis* (Burm. f.) C. Presl., *Ludwigia hyssopifolia* (G. Don) Exell, *Fimbristylis miliacea* (L.) Vahl, *Cyperus difformis* L., and *Limnocharis flava* (L.) Buch. However, in dry-seeded rice, *Echinochloa colona* (L.) Link., *Echinochloa crus-galli* (L.) P. Beauv., *Leptochloa chinensis* (L.) Nees, *Scirpus grossus* L.f., and *F. miliacea* are dominating weeds, while in wet-seeded rice, *E. crus-galli, L. chinensis, F. miliacea, Marsilea crenata* C. Presl, and *Monochoria vaginalis* are the dominating weeds. Information regarding the weed flora in rice has been presented in Table 14.1.

14.3 Yield Losses by Weeds in Rice

Yield losses by weeds are largely dependent on the season, weed species, weed density, rice cultivar, growth rate, management practice, and rice ecosystem. The extent of losses caused by weeds can be ascertained with the following examples. Globally, actual yield losses due to pests have been estimated to be ~40 %, and the highest share of this loss (32 %) is caused by weeds only (Rao et al. 2007). Rao and Moody (1994) found that in uncontrolled conditions, weeds caused rice grain yield losses ranging from 36 to 56 % in the Philippines. Similarly, yield losses by weeds in uncontrolled conditions were recorded from 40 to 100 % in South Korea (Kim and Ha 2005). In India, rice yield losses caused by weeds were observed at about 33 % by Mukherjee (2004) and 32–83 % by Savary et al. (1997), while in Sri Lanka, weeds accounted for 30–40 % of yield losses (Abeysekera 2001). Zhang (2005) found that rice yield reduction caused by weeds is 10–20 % in China, while Azmi (1992) estimated the average rice yield losses due to weeds between 10 and 35 % in Malaysia. More than 70 % reduction in rice grain yield was noted to be caused by uncontrolled weeds in Pakistan (Jabran et al. 2012a). In Bangladesh, rice yield losses due to weeds were

Table 14.1 A comprehensive list of weeds reported in rice fields throughout the world

Weeds	Family	Type	Mode of propagation	Yield losses in rice (%)	Habitat	Height (cm)
Grasses						
Cynodon dactylon (L.) Pers.	Poaceae	Creeping perennial	Mainly by stolons and rhizomes, and also by seeds	55	Upland weed; adapted to dry or moist well drained soils	40
Digitaria sanguinalis (L.) Scop.	Poaceae	Annual	Seeds	70	Upland weed; grows in moist to wet soils	70
Echinochloa colona (L.) Link	Poaceae	Annual	Seeds	85	Upland weed; adapted to dryland conditions	90
Echinochloa crus-galli (L.) P. Beauv.	Poaceae	Annual	Seeds	100	Lowland weed; adapted to wet soils	150
Echinochloa glabrescens Munro ex Hook.f.	Poaceae	Annual	Seeds	7–87	Lowland weed; adapted to wet soils	50–100
Eleusine indica (L.) Gaertn.	Poaceae	Annual	Seeds	80	Upland weed; grows in moist to wet soils	60
Imperata cylindrica (L.) Raeuschel	Poaceae	Perennial	Seeds and creeping rhizomes	–	Upland weed; adapted to dry and moist soil	120
Ischaemum rugosum Salisb.	Poaceae	Annual	Seeds	15–82	Lowland weed; prefer wet soils and swampy areas	120
Leersia hexandra Sw.	Poaceae	Aquatic perennial	Seeds, rhizomes and stolons	60	Lowland weed; grows in constantly flooded or marshy habitat	100
Leptochloa chinensis (L.) Nees	Poaceae	Annual or perennial	Seeds and cuttings of culm or rootstocks	40	Lowland weed; grow well in marshy fields but cannot survive in continuous flooding	120
Oryza sativa f. spontanea	Poaceae	Annual	Seeds		Lowland weed; prefer moist to flooded conditions	100

(continued)

Table 14.1 (continued)

Weeds	Family	Type	Mode of propagation	Yield losses in rice (%)	Habitat	Height (cm)
Paspalum distichum L.	Poaceae	Perennial	Mainly by creeping stolons and, to some extent, by seeds	85	Lowland weed; grows in moist to wet soils	30–60
Rottboellia cochinchinensis (Lour.) W.D. Clayton	Poaceae	Annual	Seeds	100	Upland weed; prefer well drained soils	300
Broad leaf weeds						
Ageratum conyzoides L.	Asteraceae	Annual	Seeds	40	Upland weed; grows in dry to moist soils	120
Amaranthus spinosus L.	Amaranthaceae	Annual	Seeds	80	Upland weed; grows in soil with no stagnant water	120
Commelina benghalensis L.	Commelinaceae	Creeping annual or perennial	Seeds and stolons	50	Upland weed; grows in wet soils	40
Eclipta prostrata L.	Asteraceae	Annual or perennial	Seeds	25	Lowland weed; thrives in continuously wet soils but can grow at dry sites	90
Eichhornia crassipes (Mart.) Solms	Pontederiaceae	Perennial, aquatic	Vegetative offshoots and seeds	100	Deep-water weed; found in rivers, canals and reservoirs	30
Euphorbia hirta L.	Euphorbiaceae	Annual	Seeds	30	Upland weed; grows in dry or moist soils	30
Ipomoea aquatica Forssk.	Convolvulaceae	Perennial vine	Seeds and stem cuttings	30	Deep-water weed; requires aquatic or wet conditions	–
Ludwigia octovalvis (Jacq.) Raven	Onagraceae	Annual aquatic	Seeds	50–80	Lowland weed; adapted to wet and aquatic conditions	100

Marsilea minuta L.	Marsileaceae	Aquatic fern	Rhizomes and spores	70	Lowland weed; grows in lowland fields and along irrigation canals	
Monochoria vaginalis (Burm.f.) C. Presl.	Pontederiaceae	Perennial aquatic	Seeds	85	Lowland weed; grows in subaquatic to aquatic conditions	50
Portulaca oleracea L.	Portulacaceae	Annual	Seeds and stem cuttings	30	Upland weed; grow in dry to moist soils	50
Sphenoclea zeylanica Gaertn.	Sphenocleaceae	Annual	Seeds	45	Lowland weed; grows in wet soils with stagnant water	150
Trianthema portulacastrum L.	Aizoaceae	Annual	Seeds	30	Upland weed; grows in dry to moist soils	40
Sedges						
Cyperus difformis L.	Cyperaceae	Annual sedge	Seeds	12–50	Lowland weed; adapted to moist soils or flooded areas	75
Cyperus iria L.	Cyperaceae	Annual sedge	Seeds	40	Lowland weed; grows in moist to wet soils	60
Cyperus rotundus L.	Cyperaceae	Perennial sedge	Mainly by tubers, but produce few seeds	50	Upland weed; grows in moist soils	75
Fimbristylis miliacea (L.) Vahl	Cyperaceae	Annual sedge	Seeds	50	Lowland weed; adapted to moist soils and areas of occasional flooding	60
Scirpus maritimus L.	Cyperaceae	Perennial sedge	Tubers	60–80	Lowland weed; grows in wet and flooded soils	–

Source: Ampong-Nyarko and De Datta (1991) estimated at 70–80 % in *Aus* rice (early summer), 30–40 % in transplanted *Aman* rice (late summer), and 22–36 % in *Boro* rice (winter rice) (BRRI 2006). Oerke and Dehne (2004) reported 10 % total yield losses due to weeds in world rice production. Similarly, Oerke (2006) reported that 10 and 37 % actual and potential yield losses, respectively, are caused by weeds in rice all across the world. In Sub-Saharan Africa, weeds inflicted yield losses in rice, despite control, in the range of 15–23 % and are conservatively estimated to add up to 2.2 million tons per year, equating to approximately half the current total imports of rice to this region (Rodenburg and Johnson 2009).

Yield losses caused by grasses (mainly *E. crus-galli*), broadleaved weeds, and sedges were 41, 28, and 10 %, respectively (Azmi and Baki 1995). Azmi and Rezaul (2008) found that weedy rice (*Oryza sativa* f. spontanea) is difficult to harvest and it reduces yield as it matures earlier than cultivated rice, and it shatters and lodges easily. Azmi and Abdullah (1998) estimated that weedy rice at 35 % infestation can cause yield losses of about 60 %, and under serious infestation, yield losses can be as high as 74 % in DSR.

Yield losses in rice due to weeds are presented in Table 14.2. Yield reduction due to weeds is more critical in DSR than in transplanted rice (Karim et al. 2004). If weeds were not controlled, the yield reduction in transplanted rice was found to be 13–63 %, while in DSR, it was recorded as 50–91 % (Singh et al. 2005a; Rao et al. 2007; Azmi 1992).

Table 14.2 Yield losses caused by weeds in aerobic rice systems

Weeds	Yield losses (%) (weedy check vs. weed free)	References
C. iria, C. rotundus, E. colona, E. prostrata, E. indica, M. nudiflora, T. Portulacastrum	40[a]	Chauhan and Opeña (2013a)
E. cruss-galli, D. aegyptium, E. colona, C. rotundus, E. alba, E. granulata, T. Portulacastrum	47	Mohtisham et al. (2013)
T. portulacastrum, D. aegyptium, C. rotundus, E. crus-galli, E. prostrata	75	Jabran et al. (2012a)
E. crus-galli, E. colona, D. aegyptium, L. chinensis, E. indica, C. rotundus, C. iria, T. portulacastrum, Ipomoea aquatica, P. oleracea	82–86	Khaliq et al. (2012)
E. crus-galli, E. colona, C. iria, C. difformis, I. rugosum,Commelina spp., *F. miliacea, C. axillaris*	85–98	Singh et al. (2011)
D. sanguinalis, E. colona, E. crus-galli, C. iria, C. rotundus, Sphenoclea spp., *E. hirta, E. prostrata, T. portulacastrum, Ammannia spp. Ludwigia spp., E. alba*	77–82	Mahajan et al. (2009)
C. rotundus, C. difformis, C. iria, S. zeylanica, E. colona, E. crus-galli	80	Hussain et al. (2008)
D. aegyptium, E. crus-galli, E. colona, L. chinensis, C. benghalensis, Caesulia axillaris Roxb., *E. prostrata, E. hirta, P. oleracea, T. portulacastrum, Lindernia spp.*	73	Singh et al. (2007)

Adapted from: Jabran and Chauhan (2015)

[a]Weed-free vs. one hand weeding

14.4 Herbicide Resistance in Weeds

In the modern agriculture, herbicides have a vital role in weed management. The role of herbicides is even more determined in case of aerobic rice system as other methods become less effective and weed infestation is increased in this method. However, with the recurrent use of herbicides, selection and infestation of herbicide-resistant weeds has become a very serious problem. With the continuous selection pressure, many herbicide-resistant weed species have been evolved in rice systems (Fischer et al. 2000). The mechanisms of herbicide resistance are grouped into two types: target site-based resistance and nontarget site-based resistance. Target site-based resistance is caused by the alteration of herbicide target sites. While nontarget site-based resistance includes other resistance mechanisms such as enhanced herbicide metabolism, enhanced herbicide sequestration, and reduced herbicide uptake (Powles and Yu 2010).

A recent report indicated that 48 weed species occurring in the rice crop have evolved resistance against various herbicides (Heap 2016). Acetolactate synthase (ALS) inhibitor resistance has been the most prevalent form of resistance in rice weeds. Major rice weeds that have developed ALS inhibitor resistance against different herbicides are *S. montevidensis*, *Alisma plantago-aquatica* L., *E. crus-galli*, and *C. difformis* (Heap 2016). After a few years of overuse and misuse of phenoxy (2,4-D) and sulfonylurea herbicides in aerobic rice systems, several weed species such as *S. zeylanica*, *M. minuta*, and *F. miliacea* have evolved resistance against these herbicides in Thailand, Malaysia, and Vietnam (Azmi et al. 2005). Similarly, *Echinochloa oryzoides* (Ard.) Fritsch and *Echinochloa phyllopogon* (Stapf) Vasc. have evolved resistance against bispyribac-sodium, molinate, fenoxaprop-ethyl, and thiobencarb in California (Fischer et al. 2000) and *E. crus-galli* against propanil, quinclorac, and clomazone in the state of Arkansas in Southern United States (Bagavathiannan et al. 2011; Talbert and Burgos 2007).

These herbicide-resistant weeds pose a major challenge to the rice growers by reducing yields and increasing production costs (Fischer et al. 2000; Fischer and Hill 2004). So, in the situation of increasing herbicide resistance cases, there is a need to adopt integrated weed management strategies for managing these herbicide-resistant weeds. It may help to avoid or delay the evolution of resistance in weeds against herbicides.

14.5 Control Methods

Weed control methods can be grouped into preventive, cultural, physical, chemical, and biological techniques.

14.5.1 Preventive Measures

Prevention of weed introduction and spread is the most important strategy in managing weeds (Buhler 2002) regardless of crop, establishment method, and ecosystem. There are many sources like crop seed, irrigation channels, machinery, etc., which cause the introduction and spread of weeds from one area to another. Preventive measures should be adopted including the use of weed-free seeds, maintaining clean fields, borders, and irrigation canals, and cleaning farm equipment before moving them from one field to another (De Datta and Baltazar 1996). Thus, prevention involves all those measures that restrict the entry and establishment of weeds in an area. There are many examples of introduction of obnoxious weeds in the lack of preventive measures. Weedy rice is such an example, which has spread in many Asian countries through contaminated rice seeds (Chauhan 2013b) and now it has become a major issue because there is no such selective herbicide that can control weedy rice in conventional rice cultivars.

In recent years, preventive measures have been de-emphasized due to herbicide availability. However, in situations like presence of herbicide-resistant weed biotypes and difficult-to-control weeds, preventive measures become important and play an effective role in weed control (Buhler 2002). Prevention implemented at the community level by enforcement of laws and regulation provides reasonable weed control.

14.5.2 Cultural Measures

14.5.2.1 Stale Seedbed Technique

Stale or false seedbed technique is an effective weed management technique where a crop faces heavy weed infestation in initial stages of growth. In this technique, soil preparation is done a few weeks before the actual sowing of crop to promote the germination of weeds. This causes the depletion of seed bank in the surface layer of soil and thus reduction of subsequent emergence of weeds (Rao et al. 2007). After the emergence of weeds, these are killed either by chemical methods (nonselective herbicide) or by mechanical methods (like shallow tillage) before the sowing of rice.

Under this technique, emerging weed seedlings are killed mostly with herbicides (Oliver et al. 1993). However, stale seedbed can also be implemented by submerging the weed seedlings under water for 10 days, after the stale seedbed period of 7 and 14 days of weed emergence (Sindhu et al. 2010). Singh et al. (2009) reported that after stale seedbed practices in DSR, a 53 % lower weed population was observed. Delouche et al. (2007) and Rao et al. (2007) also recommended the stale seedbed technique to control weedy rice in zero-till DSR where there are limited options available to manage this weed.

14.5.2.2 Land Preparation/Tillage Systems

Land preparation or tillage systems play an important role in rice cultivation, especially in DSR and can be used as an effective way of controlling weeds, thereby decreasing cost and increasing profit. Tillage practices mainly have two objectives: one is to uproot the weeds growing in the field and second is to prepare the land to create favorable conditions for the crop seed to germinate. Vertical weed seed distribution in the soil is influenced differently by different tillage systems and the relative abundance of different weed species in the field is the result of this distribution of weed seed in the soil (Chauhan and Johnson 2009). For instance, most of the weed seeds are left near the soil surface after planting in zero-tillage systems. This provides favorable conditions for germination of weed seeds present on the soil surface. On the other hand, in conventional tillage systems, weed seeds present on the soil surface are buried too deep that may not be able to emerge. However, it is also a fact that weed seeds are more prone to rapid desiccation and predation in case of zero tillage as compared to conventional systems.

It has reported in several studies that weed biomass and weed density were higher in zero tillage system as compared to conventional tillage system, which caused higher grain yield in conventional tillage plots as compared to zero tillage (Fig. 14.1) (Chauhan 2013a, b; Singh et al. 2015). Tillage practices affect the weed abundance not only in the present crop but also in the succeeding crop. Singh et al. (2005a, b) have shown that different tillage practices in wheat selectively alter the relative abundance of grass and sedge weeds in succeeding rice crops.

There is no doubt that tillage practices can be used as an important tool of weed management and any reduction in tillage practices can cause the increase in weed problems (Shrestha et al. 2005). However, tillage cannot be used as an ultimate tool for weed management. It can serve only as a temporary means of weed control because on one hand it buries the weed seed in the deep layers which cannot emerge but on the other hand it bring the buried seeds to the surface layer also, thus provide a favorable environment for their germination (Chauhan and Johnson 2010a, b).

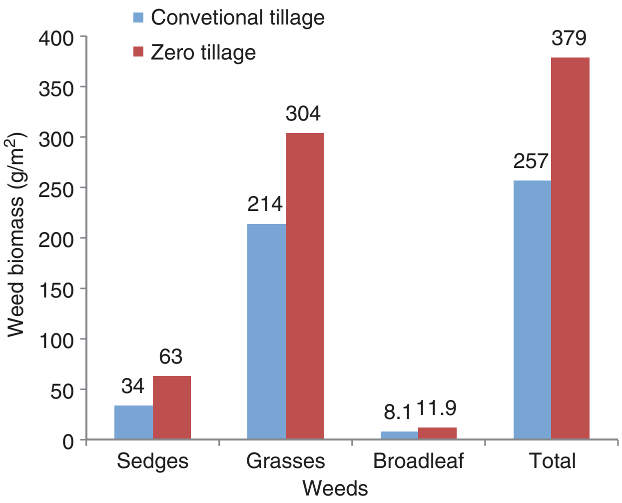

Fig. 14.1 Biomass of different weeds at harvest as influenced by different tillage practices (Source: Singh et al. (2015))

14.5.2.3 Crop Establishment Method

Different crop establishment methods have been introduced for rice cultivation like transplanting, dry direct seeding, wet direct seeding, and water seeding. These methods cause the differences in weed flora of the fields. As compared to the conventional transplanting method, weed control is particularly challenging in DSR systems because of the diversity and severity of weed infestation, and the absence of standing water layer to suppress weeds at the time of rice emergence. Besides this, in DSR, plants cannot take seedling size advantage over the weed seedlings as in the transplanting system, because both rice and weeds emerge simultaneously in DSR systems. Weed seed distribution in the soil profile is influenced by land preparation practices in DSR systems, thus there is abundance of weed species compared to the transplanted method (Chauhan and Opeña 2012).

In conventional-till DSR systems, a large number of perennial species (*P. distichum*, *C. dactylon*, and *C. rotundus*) and annual grasses (*I. rugosum*) and annual sedges (*C. difformis* and *F. miliacea*) dominate (Timsina et al. 2010). However, in the zero-till DSR system, less growth of perennial weeds (*C. dactylon, P. distichum*, and *C. rotundus*) and annual weeds (*I. rugosum* and *F. miliacea*) was observed compared with the conventional-till DSR system. Therefore, crop establishment methods can be used as an effective tool in weed management in rice. Chauhan et al. (2015) reported that grass weeds were higher in dry-seeded rice compared to puddled transplanted rice (PTR) and nonpuddled transplanted rice. The highest total weed density (225–256 plants m^{-2}) and total weed biomass (315–501 g m^{-2}) were recorded in dry-seeded rice, while the lowest (102–129 plants m^{-2} and 75–387 g m^{-2}) in PTR. Chhokar et al. (2014) also found the highest yield and least weed abundance in the PTR. Compared to the transplanting rice, severe weed infestation was found in the dry and wet DSR and thus lesser yield was found in DSR compared to transplanting rice both in the presence and absence of weeds. The yield losses due to weeds in the DSR treatments ranged from 91.4 to 99.0 %, compared to 16.0 and 42.0 % in the transplanting treatments. Weeds, including *C. rotundus*, *D. aegyptium*, *Digera arvensis* Forsk., *Phyllanthus niruri* L., and *T. portulacastrum*, which were present in the unpuddled DSR treatments, were not found in the puddled plots, particularly the puddled transplanting treatments.

In a rice–chickpea system, the density of *E. colona* was reported higher, while that of *C. iria* was lower under puddled broadcast compared to transplanted rice, DSR, and zero till-DSR. Due to higher plant population of rice and better weeds suppression, the lowest weed dry weight was observed in puddled broadcast rice (Mishra et al. 2012). Thus, the choice of appropriate crop establishment technique is an important step toward integrated weed management in rice culture.

14.5.2.4 Seeding Rate and Planting Geometry

Cultural weed management approaches mainly focus on the reduction of the effects of weeds on the crop either by making weeds less competitive or by making the crop more competitive (Gibson et al. 2002). Increased seeding rates and altered planting geometry can be used to improve crop competitiveness and thus can be proved an effective component of weed management strategies. In cereals, altered planting density and geometry have been proposed and tested as a component of weed management strategies (Kristensen et al. 2008). Crop competitiveness against weeds is increased by increasing the crop density through narrowing row spacing (Chauhan and Johnson 2010a). Solar radiation interception, canopy coverage, and biomass accumulation are determined by the planting density of a crop, which have cumulative effect on its weed suppressive ability (Anwar et al. 2011).

Weed suppressing ability of a crop is increased by increasing planting density of the crop that develops canopy rapidly and consequently suppresses weeds more effectively (Guillermo et al. 2009). However, widely spaced plants encourage weed growth. Ni et al. (2004) and Phuong et al. (2005) reported that in the presence of weeds, the highest yields in DSR could be expected where crop plant densities and spatial uniformity were greater. Narrow plant-to-plant spacing (10 cm) significantly reduced weed biomass compared with the wider plant-to-plant spacing (20 cm) (Chauhan and Opeña 2013a, b). Compared with the 20 cm spacing, the plots with 10 cm spacing had 27–37 % lower weed biomass. Zhao et al. (2007) reported that weed biomass was decreased and yield of aerobic rice increased with increasing the seed rate from 100 to 300 viable seeds m^{-2}. Reduction in weed biomass by 40 and 58 % in two consecutive years has been reported with increased seeding rate from 25 to 100 kg ha^{-1} (Chauhan et al. 2011). Gaanie et al. (2014) also found that the increase in seed rate resulted in a significant decrease in the total weed density and total weed biomass at all the stages of crop growth. With increase in seed rate, the number of crop plants per unit area was higher, giving them competitive advantage over existing weeds. Increase in rice seed rate from 10 to 32.5 kg ha^{-1} resulted in decrease in weed density and weed biomass but the rice yield increase beyond 17.5 kg ha^{-1} seed rate was nonsignificant.

Chauhan and Abugho (2013) also found in a pot experiment that growth and reproduction of *E. crus-galli* was reduced with increasing the seeding rate. Thus it was suggested that increasing seeding rates can be used as a weed management tool in both low- and high-input farming systems. However, complete weed control cannot be achieved by crop interference alone. So, it should not be considered as a stand-alone strategy to manage weeds in rice. However, it can be used as an integral part of different weed management strategies to achieve complete control of weeds in rice.

14.5.2.5 Weed Competitive Cultivars

Generally, rice is considered a weak competitor against weeds compared to taller crops such as maize (Saito et al. 2010a). However, variation among cultivars in their ability to suppress weeds has been documented for rice (Gibson and Fischer 2004; Zhao 2006). Besides, superior weed competitive rice varieties can be developed. Development of such cultivars with enhanced competitiveness against weeds could be more acceptable by rice farmers and could help to reduce dependency on herbicides.

There are two main components of crop–weed competitiveness. These are weed tolerance and weed-suppressive ability (Jannink et al. 2000). Weed tolerance is the ability of a crop to maintain high yield despite weed competition, whereas weed-suppressive ability is the ability of the plant to suppress weed growth and reduce weed seed production, thus improving weed management in both the current and the subsequent growing seasons. Because yield stability and the prevention of weed seed production and subsequent seed bank build-up are desirable in crops growing in association with weeds, so both the components are important while considering crop–weed competitiveness (Jordan 1993).

Ideal weed competitive rice varieties should have strong weed-suppressive ability and high yielding under both weed-free and weedy conditions. Weed biomass is assessed under weedy conditions to determine the weed suppressing ability of a crop (Saito et al. 2010b). This approach of weed management that utilizes the suppressing ability of cultivars to control weeds is referred to as the genetic approach of weed management. The role of competitive cultivars can be exploited further with the manipulations in the agronomic practices such as altered planting geometry and sowing time that can be proved helpful in providing supplemental weed control in case of no or less use of herbicides (Mahajan and Chauhan 2011).

Several traits confer weed competitiveness in rice (Mahajan and Chauhan 2013a). These are plant height (Mennan et al. 2012), tiller number (Harding and Jalloh 2011; Mennan et al. 2012), biomass at tillering (Ni et al. 2000), leaf area index (Moukoumbi et al. 2011; Harding and Jalloh 2011), canopy cover (Lotz et al. 1995), specific leaf area (Moukoumbi et al. 2011), root growth (Gibson et al. 1999; Fofana and Rauber 2000), early seedling vigor (Zhao et al. 2006), and seedling leaf area and biomass (Namuco et al. 2009). Fischer et al. (1997) observed that the competitive ability of rice against *E. colona* was correlated more with rice tillering and leaf area than with plant height.

Previous studies have shown significant differences in competitiveness among rice genotypes. Mennan et al. (2012) reported that among different rice cultivars (viz. Osmancık, Kızılırmak, Karadeniz, Koral, and Neĝis), Koral produced significantly more tillers than the other cultivars irrespective of *E. crus-galli* densities and reduced *E. crus-galli* tiller production by about 30 and 16 % at two locations. This cultivar showed the highest competitiveness because of its high biomass accumulation in early growth stages and smaller reductions in plant height in the presence of *E. crus-galli*, compared to the other cultivars. Among different rice varieties, NERICA L19, NERICA L20, and WAS 57-B-B-17-3-3-6-TGR 20 showed encouraging responses and appeared competitive enough against weeds with better growth, yield, and yield components (Harding and Jalloh 2013). The range of weed biomass production was 12.3 g m^{-2} in NERICA L19 to 44.7 g m^{-2} in ROK 10. Yield advantages have been shown by cultivars of the African rice species *Oryza glaberrima* over the Asian *O. sativa* varieties under weedy conditions (Johnson et al. 1998). In other regions also, varieties with superior levels of weed competitiveness have been confirmed, such as Apo and UPLRi-7 in Asia (Zhao et al. 2006, 2007), Oryzica Sabana 6 in Latin America (Fischer et al. 2001), and M-202 in North America (Gibson et al. 2001). Some *O. sativa*, *O. glaberrima*, and interspecific rice varieties that have shown to be weed competitiveness type in Africa, have been listed in Table 14.3.

Table 14.3 Rice varieties with proved superior level of weed competitiveness in Africa

Ecosystem	Variety	Species	Major superior traits	References
Lowland	Jaya	*O. sativa*	Ability to give good yield under weedy and weed free conditions; Weed suppression ability	Haefele et al. (2004), Rodenburg et al. (2009)
	TOG5681	*O. glaberrima*	Weed suppression ability	Rodenburg et al. (2009)
	NERICA-L -6, −32, −35, −37, −42, −53, −55, −58, and −60	interspecific	Ability to give good yield under weedy and weed free conditions	Rodenburg et al. (2009)
Upland	WAB96–1-1	*O. sativa*	Height; Weed suppression ability	Jones et al. (1996)
	SP4	*O. sativa*	Height; Weed suppression ability	Jones et al. (1996)
	IG10	*O. glaberrima*	Biomass; Tiller number; LAI; SLA; Early vigor; Ability to give good yield under weedy conditions; Root length density	Johnson et al. (1998), Fofana and Rauber (2000)
	CG14	*O. glaberrima*	SLA; Tillering; Early vigor; Weed suppression ability	Asch et al. (1999)
	CG20	*O. glaberrima*	SLA; Tillering; Early vigor; Weed suppression ability	Jones et al. (1996)
	ACC102257	*O. glaberrima*	Root length density	Fofana and Rauber (2000)

Adapted from: Rodenburg and Johnson (2009)

Weed-suppressive allelopathic cultivars can also be used to reduce weed infestation without incurring any extra cost. This method of weed control neither harms the environment nor increase weed management costs. Allelopathic weed control may be applied as a single strategy in certain cropping systems (Farooq et al. 2011). Further, it can also be integrated with other methods to achieve effective control. Under allelopathic weed control strategies, the allelopathic potential of crops is manipulated in such a way that the allelochemicals from these crops reduce weed competition (Jabran et al. 2015). Many authors have studied the status of allelopathic cultivars of rice and the weeds suppressed by them in various parts of the world (Table 14.4).

14.5.2.6 Crop Rotation and Cropping System

Every crop allows specific weeds to grow in their association. These specific weeds are recognized in different rotations, and thus are controlled by rotating crops having different life cycle and cultural habits. For instance, different planting and

Table 14.4 The allelopathic rice cultivars and their weed suppression

Allelopathic cultivars	Weed/test species suppressed	Weed suppression (%)	Country	References
Agudo	*E. crus-galli*	54	Korea	Ahn et al. (2005)
Baekjicheongbyeo	*E. crus-galli*	43	Korea	Ahn et al. (2005)
BR17	*E. crus-galli*	45	Bangladesh	Salam et al. (2009)
Buldo	*E. crus-galli*	56	Korea	Ahn et al. (2005)
Dabaegjo	*E. crus-galli*	47	Korea	Ahn et al. (2005)
Dinorado	*E. crus-galli*	60	Iran	Berendji et al. (2008)
Geumjeom do	*E. crus-galli*	47	Korea	Ahn et al. (2005)
Hinohikari	*Lactuca sativa* L.	75	Japan	Kato-Noguchi et al. (2010)
Jaeraejongna	*E. crus-galli*	47	Korea	Ahn et al. (2005)
Janganbyeo	*E. crus-galli*	79–94	Korea	Chung et al. (2002)
Noindari, Baekna, Baekgwangok	*E. crus-galli, Monochoria vaginalis, Scirpus juncoides*, *Eleocharis Kuroguwai*	>50	Korea	Chung et al. (2006)
OM 5930	*Lepidium sativum* L., *Leptochloa chinensis*, *E. crus-galli*	–	USA–Vietnam	Le Thi et al. (2014)
Super Basmati	*Triticum aestivum* L., *Trifolium alexanderum* L., *Hordeum vulgare* L., *Avena sativa* L.	–	Pakistan	Farooq et al. (2008)

Adapted from: Jabran et al. (2015)

harvest dates of rotating crops prevent weed establishment and seed production, and thus provide more opportunities for farmers to control weeds (Rao 2011).

There are three main mechanisms under which rotations cause the alteration of selection pressures. These are (i) altering management practices (timing of field activities, herbicides, etc.), (ii) varying patterns of resource competition, and (iii) allelopathy. However, all the three mechanisms are not utilized by all the rotations. So, it should be considered while looking at the effects of a particular rotation on weed dynamics that which mechanism is being utilized by a particular crop rotation (Nichols et al. 2015). Development of cropping systems such as appropriate spatial arrangement and efficient tillage can be helpful for crops themselves to compete with weeds (Avola et al. 2008). However, good understanding of weed dynamics and influences of crop- and soil-related factors on weed life cycles is required if we want to use the cropping system manipulation as a component of integrated weed management (Davis and Liebman 2003).

Intensification of rice-based cropping sequence caused reduction in weed density as well as weed dry matter production. The rice–wheat–green gram sequence recorded lowest population of all the three groups of weeds. So, crop rotation along with other control methods can be considered as an effective tool of Integrated Weed Management (IWM) that affects the soil seed bank and weed flora.

14.5.3 Physical Control Methods

Physical control of weeds can be done by manual or mechanical methods. Hand weeding is the most widely applied intervention against weeds across rice systems. Although it is effective in reducing direct competition from weeds and in preventing weeds from producing and shedding seeds, it is extremely labor demanding, requiring 250–780 work h ha^{-1} (Rodenburg and Johnson 2009). Roder (2001) found that 150–200 labor-day ha^{-1} are required for manual weeding to keep rice crop free of weeds. Besides this, hand weeding becomes difficult at early stages of growth because of the morphological similarity between grassy weeds and rice seedlings. Damage to the rice seedlings by weeding (Moody and Cordova 1985) and delay in weed control due to unavailability or high wages of labor (Johnson 1996) or due to poor weather conditions are other problems with manual weeding. Singh et al. (2007) also found that manual weeding required 100–120 person-days ha^{-1} to keep fields of DSR weed-free for the whole season. In these situations, mechanical weeding using different tools such as hand hoe/blade hoe/wheel hoe is helpful. In line-sown crops, rotary weeders or cono weeders are also effective in controlling weeds. Different types of weeders or hoes are used either in combination with other methods or independently.

Akbar et al. (2011) found that both hand pulling and mechanical hoeing were better than herbicides in suppression of weeds and increasing yield. Mechanical hoeing caused a 72 % reduction in total weed density and a 25 % increase in grain yield of rice compared to the control. Hasanuzzaman et al. (2007) found that weed density and weed dry matter were effectively reduced by the mechanical and manual weed control methods, and also with the combination of chemical and physical methods. Weed control efficiency was found highest with combinations of chemical and physical control methods.

No doubt, mechanical weed control has been proved very useful. But because of their limited scope to row-seeded crops only, this is not a very common method. Besides this, an optimum soil–water condition is required for mechanical weeders to work efficiently and effectively. However, combinations of mechanical weeding with preemergence herbicide applications can be used as an effective tool in integrated weed management in DSR (Matloob et al. 2015). Moreover, in some situations, where chemical or other methods fail to control weeds (i.e., continuous rains or dry spells), mechanical weeding could be more effective. Mechanical weeders can also help to reduce overall herbicide use.

14.5.4 Chemical Control

The traditional methods of weed control practices include preparatory land tillage, hand weeding by hoe, and hand pulling. Depending on the nature of the weeds, their intensity of infestation and the crop grown, usually two or three hand weedings are normally done for effective control. But, weed control in transplanted rice by mechanical and cultural means is expensive, especially at periods of labor crisis. Besides the high labor costs as well as labor scarcity, unfavorable weather conditions and morphological similarity of some weeds (*E. colona* and *E. crus-galli*) to rice have made chemical methods more popular than traditional methods.

In the recent years, rice growers in many Asian countries are shifting from transplanting to dry seeding systems. Weeds have become the major constraint for farmers practicing direct seeding (Rao et al. 2007). In the traditional transplanting method, weeds are suppressed by standing water, but in DSR systems, the inherent weed control from standing water at rice establishment is lost and weeds emerge concurrently with rice thereby competing with rice for resources. In DSR systems also, various cultural, mechanical, manual, and chemical weed management strategies can be practiced to control weeds. However, among the different weed control strategies, chemical weed control is considered the most efficient and economical (Suria et al. 2011; Khaliq et al. 2012). The use of herbicides reduces the weed control time by 100 h ha^{-1} compared with hand weeding in DSR. Therefore, most rice farmers who practice DSR adopt herbicides (Mazid et al. 2003).

Among herbicides, sulfonylurea and phenoxy compounds are the widely used chemicals for controlling sedges and broadleaved weeds in DSR (Mahajan and Chauhan 2013b). Rao et al. (2007) reported an extensive use of propanil, pendimethalin, fenoxaprop, molinate, thiobencarb, quinclorac, butachlor, and acetochlor for controlling grass weeds. For controlling annual grasses, annual sedges, and broad leaved weeds, oxadiazon herbicide has been found to be effective (Dickmann et al. 1997). Similarly, the application of bispyribac-sodium as postemergence has been found to be very effective against grasses and broadleaved weeds (Jabran et al. 2012a; Khaliq et al. 2012). Pre-emergence herbicides (oxadiazon, pendimethalin, etc.) are applied within three DAS of rice, preferably immediately after planting and before the emergence of weeds and crops (Jabran et al. 2012a,b). Early postemergence herbicides (butachlor, propanil, thiobencarb, etc.) are applied at the two to four leaf stages. Late postemergence herbicides (e.g., bispyribac-sodium, azimsulfuron, fenoxaprop, ethoxysulfuron, 2,4-D) are usually applied on leaves and the application time ranges from 14 to 28 DAS (Awan et al. 2015). Singh et al. (2007) reported that pre-emergence application of pretilachlor + safener at 500 g ha^{-1} or pendimethalin at 1.0 kg ha^{-1} followed by one hand weeding effectively controlled weeds and proved effective in increasing yields of DSR, resulting in higher net income.

When the crop is infested with complex and diverse weed species, a single herbicide cannot control all weed species. In such situations, effective weed control can be achieved by a combination of herbicides (sequential applications or tank mixtures) or a broad-spectrum herbicide along with other cultural practices. This practice can ensure effective control of all groups of weeds such as sedges, broadleaves, and grasses (Awan et al. 2015). Singh et al. (2006) found that both grass and broadleaf weeds were effectively controlled when tank mixture of fenoxaprop-ethyl plus ethoxysulfuronat 50 + 18 g ha^{-1} was applied as postemergence at 18–21 DAS. When different herbicides are used in combination, care should be taken that different herbicides should be compatible with one another and they should not have antagonistic effect. Zhang et al. (2005) also found that there is an antagonistic effect of fenoxaprop activity on *Echinochloa* spp. when applied in combination with bensulfuron, carfentrazone, halosulfuron, and triclopyr. Similarly, a tank-mix application of fenoxaprop-ethyl or cyhalofop-butyl with chlorimuron plus metsulfuron or 2,4-D also showed an antagonistic effect. Awan et al. (2015) found that oxadiazon as the best broad-spectrum herbicide when applied alone or in combinations with other postemergence herbicides in effectively controlling all dominant weed species present at the site (Table 14.5).

Herbicides have been proved very important weed management tool in rice cultivation. However, for effective and safe herbicide use, the appropriate product, application equipment, and application rates are important (Zimdahl 2007). Moreover, herbicide application requires good timing with respect to crop and the growth stage of weeds (King and Oliver 1992), weather conditions (Hammerton 1967), and flooding. For example, foliar active herbicides such as bentazon, 2,4-D, and triclopyr should be applied after draining of water for better contact of the herbicide with leaves (Singh et al. 2009). However, some herbicides such as molinate need to be applied in water as an application on drained fields would result in its loss by volatility. Sulfonylureas should be applied in water, as flood water acts as a carrier for their even distribution. Different herbicides that have been reported to be effective against different types of weeds in DSR are listed in Table 14.6 (Singh et al. 2009).

14.5.5 Biological Control

Biological weed control is the technique in which natural enemies (biological control agents) of weeds are employed to control weeds in crop without significantly affecting the desirable plants. These biological agents include insects, animals, fishes (e.g., Chinese carp), snails, birds (e.g., duck), microbes (fungi, bacteria, viruses, nematodes, etc.), their toxic products, and plants (parasite plants and competing plants) or their products. This approach can be proved even more helpful when there is a need to develop new weed management strategies because of the development of some herbicide-resistant weeds.

Biological control can be classified into two approaches, viz. the classical and the bioherbicide approaches (Hallett 2005). The classical approach that involves the use of exotic predators or pathogens has not been implemented in rice. However, there has been great research interest in the development of bioherbi-

Table 14.5 Effect of herbicide treatments on weed density and weed biomass at 20 days after sowing

Weed control treatments	Weed density (no. m^{-2})				Weed biomass (g m^{-2})			
	G	S	BL	Total	G	S	BL	Total
Oxadiazon	3.12	1.04	3.12	7.28	0.02	0.00	0.02	0.04
Pendimethalin	22.92	45.83	0.00	68.75	0.52	0.91	0.00	1.43
Bispyribac-sodium	905.21	8.33	1.04	914.58	13.94	0.10	0.00	14.04
Bispyribac-sodium fb bispyribac-sodium	942.71	13.54	0.00	956.25	7.11	0.23	0.00	7.33
Fenoxaprop plus ethoxysulfuron	972.92	192.71	0.00	1165.63	12.18	3.37	0.00	15.55
Oxadiazon fb bispyribac-sodium	10.42	3.12	0.00	13.54	0.35	0.58	0.00	0.94
Oxadiazon fb fenoxaprop plus ethoxysulfuron	2.08	0.00	1.04	3.12	0.01	0.00	0.01	0.02
Pendimethalin fb bispyribac-sodium	25.00	59.38	0.00	84.38	0.25	0.82	0.00	1.08
Pendimethalin fb fenoxaprop plus ethoxysulfuron	332.29	107.29	1.04	440.62	4.29	1.81	0.001	6.09
Butachlor plus propanil fb fenoxaprop plus ethoxysulfuron	67.71	5.21	2.08	75.00	0.28	0.04	0.11	0.43
Thiobencarb plus 2,4-D fb fenoxaprop plus ethoxysulfuron	139.58	21.88	1.04	162.50	1.87	0.39	0.04	2.31
Nontreated (weedy)	1300.25	198.16	1.04	1499.45	11.38	6.36	0.01	17.75
Weed-free	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
S.E.D.	389.21	57.44	0.96	415.89	3.90	1.320	NS	4.86
P values	<0.001	0.006	0.011	<0.001	0.003	0.002	0.55	0.003

Source: Awan et al. (2015)
fb followed by, *G* grasses, *S* sedges, *BL* broadleaf weeds, *no* number

cides. The bioherbicide approach is based on the natural enemies that have an ability to reduce the adverse effects of weeds on crop yield by causing damage to them. A number of authors have reviewed the status of bioherbicides (Charudattan 2001; Hallett 2005; Li et al. 2003), and some effective biocontrol agents are listed in Table 14.7.

Table 14.6 Effective herbicides against different types of weeds in direct-seeded rice

Herbicide	Dose (g ha^{-1})	Time of application	Class of weed controlled		
			Grasses	Sedges	Broadleaf
2,4-D	500	Post	Noneffective	Effective	Effective
Azimsulfuron	25–30	Post	Noneffective	Effective	Effective
Bensulfuron methyl	60	Post	Noneffective	Effective	Effective
Bispyribac sodium	25–30	Post	Effective	Effective	Effective
Carfentrazone	20–25	Post	Noneffective	Noneffective	Effective
Clomazone	300–600	Post	Effective	Noneffective	Effective
Cyhalofop-butyl	120	Post	Effective	Noneffective	Noneffective
Ethoxysulfuron	18	Post	Noneffective	Effective	Effective
Fenoxaprop-ethyl + safener	50–60	Post	Effective	Noneffective	Noneffective
Glyphosate	0.5–1 %	PS	Effective	Effective	Effective
Halosulfuron	30–40	Post	Noneffective	Effective	Effective
Metsulfuron + chlorimuron	4	Post	Noneffective	Effective	Effective
Molinate	3000–4000	PE	Effective	Noneffective	Effective
Paraquat	0.5 %	PS	Effective	Effective	Effective
Pendimethalin in dry-DSR	1000	PE	Effective	Noneffective	Effective
Penoxsulam	30–35	Post	Effective	Effective	Effective
Pretilachlor + safener in wet-DSR	500	PE	Effective	Noneffective	Effective
Propanil	2250–3000	Post	Effective	Effective	Noneffective
Quinclorac	250–350	Post	Effective	Noneffective	Effective
Triclopyr	500	Post	Noneffective	Effective	Effective

Adapted from: Singh et al. (2009)
PE, pre-emergence; *Post*, postemergence; *PS*, preseeding

Fungal pathogens can be exploited as biological agents for the management of weeds (Motlagh 2011). The fungus *Trichoderma viride* Pers. and *Gliocladium virens* have been found to control *Echinochloa* spp. in rice under laboratory conditions without any adverse effect on the crop (ICAR 2007). Similarly, fungus *Fusarium equiseti* has been found to infect *Echinochloa crus-galli* in a higher rate compared to rice cultivar (Motlagh 2011). Hence, *Fusarium equiseti* can be considered as a probable bioherbicide for controlling of *E. crus-galli* at the two to three leaf stage of growth of weed. Charudattan (1991) and Smith (1991) reported that an endemic fungal pathogen, *Colletotrichum gloeosporioides* (Penz.) Sacc f. sp.

Table 14.7 Effective biocontrol agents associated with rice used in weed management

Weed species	Biocontrol agent	Country	References
Alternanthera philoxeroides (Mart.) Griseb.	*Fusarium* sp.	China	Tan et al. (2002)
Echinochloa spp.	*Alternaria alternate*	Iran	Motlagh (2012)
E. crus-galli	*Fusarium equiseti*	Iran	Motlagh (2011)
E. crus-galli	*Cochliobolus lunatus* Nelson and Haasis	Netherlands	Smith (1991)
E. crus-galli	*Exserohilum monoceras*	China	Huang et al. (2001)
E. crus-galli	*Exserohilum monoceras*	Vietnam	Chin (2001)
E. crus-galli	*Exserohilum monoceras*	Philippines	Zhang and Watson (1997)
Brachiaria platyphylla (Griseb.) Nash	*Bipolaris setariae* (Saw.) Shoem.	North Carolina	Smith (1991)
Sagittaria trifolia L.	*Plectosporium tabacinum*	Korea	Chung et al. (1998)
S. zeylanica	*Colletotrichum Gleosporiodes*	Philippines	Bayot et al. (1994)
F. miliacea	*Curvularia tuberculate*	Philippines	Luna et al. (2002a, b)
F. miliacea	*Curvularia oryzae*	Philippines	Luna et al. (2002a, b)
Eichhornia crassipes (Mart.) Solms	*Fusarium pallidoroseum*	India	Praveena and Naseema (2003)
E. crassipes	*Myrothecium advena*	India	Praveena and Naseema (2003)
C. rotundus	*Dactylaria higginsii*	USA	Kadir and Charudattan (2000)
Aeschynomene virginica (L.) B.S.P.	*Colletotrichum gloeosporioides* (Penz.) Sacc f. sp. *aeschynomene* (*C.g.a.*)	USA	Smith (1991)
L. chinensis	*Setosphaeria rostrate*	Vietnam	Chin et al. (2003)
C. difformis	*Curvularia tuberculate*	Philippines	Luna et al. (2002a, b)
C. difformis	*Curvularia oryzae*	Philippines	Luna et al. (2002a, b)
Hydrilla verticillata (L.f.) Royle	*Plectosporium tabacinum*	USA	Smither-Kopperl et al. (1998)
Ludwigia decurrens Walt.	*Colletotrichum gloeosporioides* f. sp. *jussiaeae* (*C.g.j.*)	USA	Boyette et al. (1979)
C. esculentus	*Puccinia canaliculata* (Schw.) Lagerh.	USA	Phatak et al. (1987)
C. esculentus	*Dactylaria higginsii*	USA	Kadir and Charudattan (2000)
C. iria	*Dactylaria higginsii*	USA	Kadir and Charudattan (2000)

aeschynomene (*C.g.a.*), has been registered in the United States for control of *Aeschynomene virginica* (L.) B.S.P. in rice (COLLEGO3,4). *Puccinia canaliculata* (Biosedget) was reported to control *C. esculentus* and inhibited new tuber formation by 66 % (Boyetchko 1997). Similarly, *Rhynchosporium alismatis* (Oudem.) J. J. Davis has been reported to control *Damasonium minus* (R. Br.) Buch, an important native plant species considered to be the most important weed in rice growing areas of Australia (Jahromi et al. 2004). Biological strategies of weed control in rice also include wild ducks (Smith and Sullivan 1980) and insects (Oraze and Grigarick 1992). Farmers in Arkansas, USA, attract the ducks by flooding the rice fields during the winter, which control the weedy rice (*Oryza sativa* f. spontanea) by feeding on their seeds. From the 9 consecutive years' field experiments in China, it was reported that under rice–duck farming, the number of weed species in the weed seed bank declined from 38 to 21 and the density of both the weed seed bank and the above-ground weed decreased by more than 90 % (Li et al. 2012). Rice–duck farming resulted in a more uniform vertical distribution of the weed seed bank both quantitatively and qualitatively. Thus, subsequent rice crops are benefited with this strategy. Similarly, aphids are used as controlling agents of some aquatic weeds of rice in California.

The biological control methods can be proved a very helpful tool in weed management of rice. However, integration of biological methods with other control methods is essential in weed management programs in rice production systems (Smith 1991). It is because of the narrow range of the biological control methods. Biological strategies control a comparatively narrow spectrum of weed species compared to chemical or other methods. For example, to control the complex of weed species in the rice field, sole biological method cannot be relied upon.

14.5.6 Integrated Weed Management

As discussed earlier, weeds are a major constraint in rice cultivation, especially in DSR and the success of rice cultivation can be ensured by the proper control of weeds. Until 1940s, physical, cultural, and biological means were the main weed management tools (Juraimi et al. 2013). Since the introduction of herbicides in late 1940s, it has been believed that herbicides can solve the weed problem for long run. But, after over 50 years of extensive use of herbicides, now it is evident that sole reliance on herbicides is not a long lasting strategy (Juraimi et al. 2013). Intensive use of herbicides can cause environmental contamination, the evolution of herbicide resistance in weeds (Heap 2016), and the impoverishment of the natural flora and fauna. Over reliance on herbicides also can cause the shift in weed species dominance (Azmi and Baki 2002). Besides this, presence of intensive and complex weed flora implies that relying on a single practice would not only result in failed weed control, but can also lead to resistance evolution in weeds and development of problematic weed flora (Jabran and Chauhan 2015). Because of all these problems, there is a need to find ways on how to reduce the unwarranted environmental hazards posed by the use of herbicides and how to eliminate labor-intensive manual weeding in rice. So, there is a need to reevaluate the physical, cultural, and biological weed management strategies as integrated with chemical weed control methods judiciously. This system of combining different weed management methods is known as integrated weed management. It involves the selection, integration, and implementation of effective weed control means with due consideration of economics, environmental, and sociological consequences. The integrated weed management better utilizes resources and offers a wider range of management options (Buhler et al. 2000).

Integration of improved agronomic practices, timeliness of operations, optimum fertilization and water management, and incorporation of crop residues in the soil can be helpful to increase the efficiency of applied herbicides and to improve the crop competitiveness against weeds (Chauhan et al. 2012). Subramanian and Martin (2006) reported that effective weed control was achieved by pretilachlor with safener at 400 g ha^{-1} combined with *sesbania* intercropping and azolla dual cropping. Pretilachlor with safener + daincha intercropping + azolla dual cropping maintained its superiority by registering higher grain yield (57.4 q ha^{-1}), which was 60 and 10 % higher than the weedy check and recommended practice of two hand weedings, respectively. As compared to the sole application of butachlor, preemergence application of butachlor + intercrop with *sesbania* incorporation and mechanical weeding at 35 days after transplanting recorded lower weed density at all the stages of crop growth, lower weed seed count, and higher crop yield (Govindan and Chinnusamy 2014). Among different weed control treatments, integrated weed management including criss-cross sowing plus one hand weeding plus herbicide provided better results than those obtained from only one weed control method, that is, two hand weedings and no weeding (Sharma and Singh 2008). Many researchers have advocated adoption of integrated weed management approach for sustainable rice production (Bhurer et al. 2013; Azmi and Baki 2002; Sunil et al. 2010; Jayadeva et al. 2011). Some possible integrated weed management practices in aerobic rice have been elaborated in Table 14.8. Therefore, integrated weed management is the most feasible and practical option to achieve sustainable weed control in rice systems. It provides not only economical weed control but also helps to tackle problems like herbicide resistance, environment degradation, etc.

Some of the outstanding examples of integrated weed management in DSR that proved effective in South Asia, for example, increasing N application rate up to 150 kg ha^{-1} caused significant improvement in grain yield when the weeds were well controlled either by pendimethalin followed by (fb) bispyribac-sodium or by pendimethalin fb bispyribac– sodium fb 1 hand weeding (HW), respectively; however, under poor weed control condition (pendimethalin fb 1 HW), it resulted in a drastic reduction in yield (Mahajan and Timsina 2011). Higher seed rates in DSR caused significant reductions in weed dry matter, whereas higher than optimum seed rate (15–30 kg ha^{-1}) caused reduction in yield (Mahajan et al. 2010). Genotype for instance Punjab Mehak 1 produced similar grain yields in paired and uniform planting patterns (Mahajan and Chauhan 2011); whereas PR 115 had higher grain

Table 14.8 Integrated weed management practices in aerobic rice system

Weed management practices	Dose (g a.i. ha^{-1})	Weed species suppressed	Weed suppression (%)	Increase in rice grain yield over weedy-check (%)	Reference
Penoxulam (pre) + one HW (30 DAS)	15	*T. portulacastrum, D. aegyptium, E. indica, Cyperus* spp.	93	70	Mubeen et al. (2014)
Pendimethalin (pre) + bispyribac-sodium (Post) + one HW (45 DAS)	1000 and 30	*Echinochloa* spp., *D. sanguinalis, E. indica, C. iria, E. alba*	85–91	60	Mahajan and Timsina (2011)
Pendimethalin (pre) + HW (4 WAS)	750	Grasses, broadleaved and sedges	60–87	136	Mahajan et al. (2009)
Pretilachlor with safener + HW (6–7 WAS)	500	Grasses and broadleaved	48–96	196	Singh et al. (2007)
Pendimethalin (pre) + HW (6–7 WAS)	1000	Grasses and broadleaved	40–82	193	Singh et al. (2007)

Adapted from: Jabran and Chauhan (2015)
Pre, preemergence; *Post*, postemergence, *HW*, hand weeding; *WAS*, weeks after sowing; *DAS*, days after sowing

yield in paired rows (5.6 t ha^{-1}) than in uniform rows (4.9 t ha^{-1}). Genotype IET-21214 with the sole application of bispyribac sodium produced grain yield similar to the sequential application of pendimethalin and bispyribac sodium (Mahajan et al. 2014). Plasticity in some genotypes in response to water stress improved their ability to have rapid early growth and smother the weed flora in DSR (Mahajan et al. 2015).

14.5.7 Herbicide-Tolerant Rice

Several selective herbicides have been introduced that affect the weeds adversely, yet do not harm rice. But, herbicide-resistant weeds and weedy or wild rice are becoming more challenging problems for the rice farmers in the world. In both the cases (i.e. herbicide-resistant weeds and weedy or wild rice), the adoption of herbicide-tolerant rice can prove a very useful tool for weed control. When a rice plant is tolerant to a particular herbicide or herbicides that can otherwise damage the plant, this rice is referred to as herbicide-tolerant rice (IRRI 2015). In rice, three herbicide-tolerant rice systems have been developed. These are imidazolinone-, glufosinate-, and glyphosate-tolerant cultivars (Gealy et al. 2003). For glufosinate- and glyphosate-tolerant rice cultivars, transgenic technologies were used. While, imidazolinone-tolerant rice was developed by chemically induced seed mutagenesis and conventional breeding. Herbicide-tolerant rice cultivars provide a classical, safe, and yet novel and effective way of weed management through the application of new generation's highly effective, nontoxic, and rapidly biodegradable herbicides (Mahajan and Chauhan 2013a). Kumar et al. (2008) and Chauhan et al. (2014) also suggested that adoption of herbicide-tolerant rice can solve the problem of weeds, especially herbicide-resistant weeds and weedy rice in DSR.

First, herbicide-tolerant rice (Clearfield® rice) was developed in the USA to deal with weedy rice commonly known as red rice in the USA. Up to 2012, it was the only herbicide-tolerant rice available for farmers in some countries to grow. The herbicide-tolerant Clearfield rice technology provides an option to control weedy rice in rice using imidazolinone herbicides, particularly the imazethapyr (Croughan 2003). Besides the Clearfield rice, some other herbicide-tolerant rice including Liberty Link® and Roundup Ready® rice also have been developed (IRRI 2015).

No doubt, herbicide-tolerant rice can help to improve weed control, including weedy and wild rices, and to reduce weed control costs and the labor associated with manual removal of weeds. However, if this weed management tool, i.e., herbicide-tolerant rice is not managed properly, weed problems are very likely to become more serious, especially in rice monoculture systems. By mismanagement of herbicide-tolerant rice, herbicide resistance can spread to weedy and wild rice via cross-pollination and their control can become more difficult. Besides this, resistance to similar herbicides in a range of weeds can be developed by the increased use of one herbicide type. Thus, the effectiveness of current herbicides could be reduced. Herbicide-tolerant rice can become a problem when the seeds of herbicide-tolerant rice in the soil turn into weeds in subsequent years when different rice varieties are grown. There is a long list of rice weeds globally, which have developed resistance to herbicides (Heap 2016).

14.6 Conclusions

Weeds are the key biological constraints that obstruct the growth and productivity of rice systems. Weed flora is being changed quickly in response to changing agronomic management. Therefore, appropriate weed management strategies and technologies are needed to maintain yield stability and reduce the cost of production. There are several weed management strategies for rice systems in combination with agronomic tools like seed rate, row spacing, planting pattern, planting density, exploiting weed competitive cultivars. The use of any single strategy cannot provide effective, season-long, and sustainable weed control as different weeds have different growth habits. The complex and diverse weed flora along with the risk of herbicide-resistance evolution emphasize the need for integrated weed management strategies, especially in aerobic rice systems. The integrated implementation of weed control practices not only effectively control weeds in rice systems but also improve the quality of the produce.

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Chapter 15
Ecology and Management of Apple Snails in Rice

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15.1 Summary

Apple snails (Ampulariidae) occur throughout tropical and subtropical rice-growing regions. Native apple snails rarely damage rice; however, in hot and humid tropical regions, some native species will damage wet-direct-seeded rice (i.e., *Pomacea* spp. in Suriname and Brazil). Similarly, exotic apple snails in wet, temperate regions can damage direct-seeded rice (i.e., *Pomacea canaliculata* in Japan). However, if left unmanaged, exotic apple snails in warm tropical regions (i.e., *P. canaliculata* and *P. maculata* in South East Asia) can cause significant economic losses even to transplanted rice (which is more robust that direct-seeded rice). The negative impact of apple snails on rice yield can be reduced by reducing seedling vulnerability or controlling snail population densities. Reducing vulnerability is a more sustainable solution to apple snails but requires new methods such as seedling broadcasting and machine transplanting to decrease labor costs. To avoid further spread of apple snails, the implementation of effective quarantine directives is recommended for tropical countries that are vulnerable to exotic apple snails.

15.2 Introduction

Apple snails (Ampullariidae) are regarded among the most destructive invasive species globally. Several species of apple snail—originally from eastern South America—have been introduced and established in the Pacific regions of South America (west of the Andes), in North America, in South East Asia, and in southern

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Europe (Horgan et al. 2014a) (Fig. 15.1). Many of these regions are major rice (*Oryza sativa* L.) producing areas and some (particularly in Asia) are important rice “bowls” for developing nations. Apple snails were introduced into South East Asia between the 1980s and 2000s with devastating consequences for the rice sector. However, it is worrisome, that despite the damage caused by these introductions, apple snails continue to be deliberately introduced to rice-growing regions, e.g., *Pomacea canaliculata* (Lamarck) was introduced to Ecuador about 2005 (Horgan et al. 2014b); *Pomacea maculata* Perry (synonym of *Pomacea insularus*) was introduced to the Ebro region of Spain about 2009 (European Food Safety Authority 2012); *P. canaliculata* was introduced to Haleji Lake, near a major rice-growing region of Pakistan about 2012 (Baloch et al. 2012); and *Pomacea* spp. were introduced to the Ayeyarwady region of Myanmar about 2012 (communications with the Plant Protection Division of the Myanmar Government) (Fig. 15.2).

Apple snails will damage most aquatic crops including taro (*Colocasia esculenta* [L.] Schott), water chestnut (*Trapa bicornis* Osbeck), and water cress (*Rorippa scopoli* spp.) as well as functionally important plants such as Azolla (*Azolla* spp.) and lotus (*Nelumbo nucifera* Gaertner) (Cowie 2002). However, the damage to rice by apple snails has attracted considerable research attention because of the extent of rice-growing activities globally and the importance of rice in human nutrition (Cowie 2002; Global Rice Science Partnership 2013). Apple snails damage rice by rasping the tender rice stems of newly sown and young transplanted rice plants, and by consuming leaves during crop establishment; this often kills the developing seedlings and results in patches of “missing hills” or bare-ground where the plants have failed to develop (Litsinger and Estano 1993). Few studies have estimated the economic impact of rice damage from apple snails or the costs (monitory or ecological)

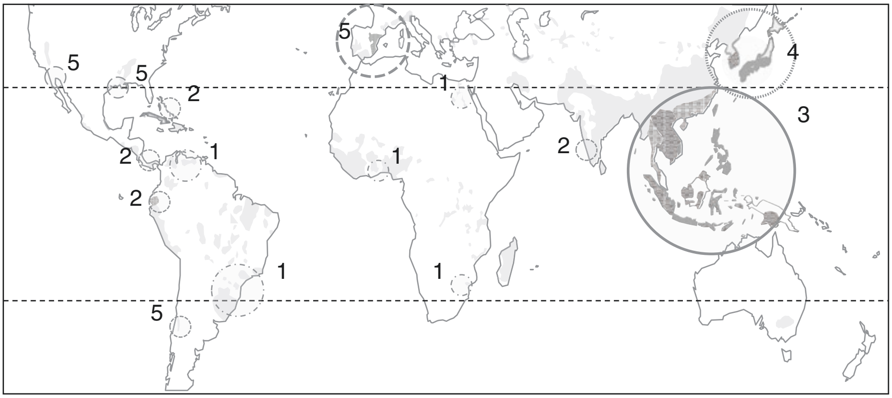

Fig. 15.1 Rice producing regions of the world (*light gray shading*) indicating regions with reports of damage to rice from apple snails. Snail–rice crop interactions are divided into five categories: (1) Rice, mainly direct seeded, damaged by native snail species; (2) newly invaded regions with some key native predators; (3) invaded tropical regions in Asia; (4) cool temperate regions where snails mainly damage direct seeded rice; (5) newly invaded regions with mild Mediterranean climates. Shading indicates the spread of *Pomacea canaliculata* and *P. maculata* between 1980–2012

of the massive increases in molluscicide use that follow invasion (Wada 2004; Adalla and Magsino 2006; Horgan et al. 2014b). However, there is ample evidence to suggest that invasive apple snails severely impact wetland ecosystems in general (Horgan et al. 2014a) and are currently a nuisance to producers over much of the world's rice-growing regions (Joshi and Sebastian 2006). This chapter examines the nature and management of the apple snail species that damage rice crops, focusing on how snail biology and ecology determine their pest status and ultimately dictate optimal, regionally specific strategies for their management.

15.3 Species and Records of Damage to Rice

Apple snails are freshwater snails that naturally occur throughout the humid tropics and subtropics. The genus *Pomacea* and *Marisa* are mainly of South and Central American origin. The genus *Pila* occurs naturally throughout South and South East Asia, and in some parts of Africa (Cowie 2002; Hayes et al. 2008) (Fig. 15.1). There are over 100 species of apple snail; however, research attention has focused on about 14 species (mainly *Pomacea* spp.) that have invaded new regions since the 1960s mainly through the pet trade (Horgan et al. 2014a). The most rapid and extensive

Fig. 15.2 Farmers collect apple snails from rice fields in the Ayeyarwady region of Myanmar during 2014, 2 years after exotic apple snails were first noted in the region (Photo: U Khun Maung Maung, Plant Protection leader, Kayin State, Myanmar)

expansion in apple snail distribution occurred during the 1980s and 1990s when several species (*P. canaliculata*, *Pomacea diffusa* Blume, *P. maculata*, and *Pomacea scalaris* d'Orbigny) became established in South East Asia (Hayes et al. 2008; Horgan et al. 2014a). Over their native ranges, most apple snails (i.e., *Pila conica* Wood in the Philippines and *Pila polita* [Deshayes] in Thailand) do not significantly affect rice production and are often beneficial sources of supplementary foods or medicine (Bombeo-Tubaran et al. 1995; Thaewnon-ngiw et al. 2003). In Asia, the native species *Pila polita* (Deshayes), *Pila pilosa* (possibly a misidentification), and *Pila globosa* (Swainson) have been associated with only minor levels of damage to rice (Cowie 2002). Most records of damage from native apple snails (*Lanistes* spp.) in Africa are now over 40 years old, without any further reports of damage or any recent research attention. *Lanistes carinatus* Olivier and *Lanistes ovum* Peters were reported to damage rice in the Nile region and in Sierra Leone (Cowie 2002) and a report from Swaziland in the 1960s indicated that *L. ovum* caused severe damage to rice in an irrigation project (Crossland 1965) possibly due to poor drainage at the site (Tyler 2008). Under certain crop establishment systems, particularly direct seeding (see below), even native apple snails might pose a risk to rice production.

In the Americas, *Marisa cornuarietis* (L.) (a species introduced for biological control purposes) occasionally causes damage to young rice seedlings in the Caribbean (Ortíz-Torres 1962; Donnay and Beissinger 1993; Cowie 2002). Similarly, *Pomacea glauca* (L.) and *Pomacea lineata* (Spix) have been associated with damage to rice in Suriname and Venezuela (Wiryareja and Tjoe-Awie 2006). However, it is likely that some records of these latter two species represent misidentifications of *Pomacea dolioides* (Reeve) (Hayes et al. 2012). In recent years, *P. canaliculata* in its native range in southern Brazil and *P. dolioides* in its native range in Suriname and northern Brazil have become serious pests of wet-direct-seeded rice (also known as pregerminated rice). Whereas damage due to *P. canaliculata* and *P. maculata* has been limited to wet-direct-seeded rice in the Americas, these two species have been associated with severe damage to transplanted rice in South East Asia (Joshi and Sebastian 2006). It is noteworthy that *P. canaliculata* and *P. maculata* in South East Asia were recorded together as a single species (*P. canaliculata*) during the 1980s and 1990s. Therefore, the impact that each of these species (and particularly *P. maculata*) has had on rice production in Asia is still largely unknown. The impact of *P. maculata* on rice in North America seems to be low: Cold winter temperatures in temperate regions may limit snail activity, recruitment, and consequent damage to rice (Burlakova et al. 2010).

15.4 Broad Effects of Climate and Rice Production Systems on Snail Damage Potential

Because of the wide geographical distribution of both rice production landscapes and apple snails (native and invasive), the relative impact of apple snails on different rice ecosystems varies considerably. Understanding the underlying ecology of such variations can be useful to assess crop vulnerability and to choose medium- to long-term strategies for snail management. Figure 15.1 indicates five main categories of interaction scenario under which apple snails encounter rice crops. These can be explained as follows:

Category 1: Regions where management of native apple snails is not required in transplanted and dry seeded crops (i.e., *P. canaliculata* in Argentina (Cazzaniga 2006)) but where potential for damage is high (up to 100 % losses) in wet-direct-seeded crops (i.e., *P. dolioides* in Suriname (Wiryareja and Tjoe-Awie 2006); *P. canaliculata* in Southern Brazil (Sociedade Sul-Brasileira de Arroz Irrigado 2010); and *L. ovum* in Swaziland (Crossland 1965)). Rice pasture rotations, late flooding, and efficient regulation by natural enemies reduce the damage potential of apple snails in most native regions (Cazzaniga 2006).

Category 2: Regions invaded by apple snails that are close to their original distribution range and where natural enemies (e.g., predatory birds and diseases) can expand their distribution range with the snails (i.e., *M. cornuarietis* in the Caribbean (Cowie 2002); *P. canaliculata* in the Dominican Republic (Rosario and Moquete 2006) and in Ecuador (Horgan et al. 2014b); *P. globosa* in south India (Thomas 1975); *Pomacea lattrei* (Reeve) in Panama (Angehr 1999)). In such regions, regulation by natural enemies may be expected to reduce damage after a short time during which natural enemies adapt and accumulate. However, the impact of the snails on rice production in these regions is often similar to category 3 (below).

Category 3: Tropical regions invaded by apple snails that have adequate climatic conditions for maximum snail survival and fitness and few natural enemies (Fig. 15.2). For example, throughout tropical and subtropical Asia, *P. canaliculata* and *P. maculata* cause severe damage to rice under all types of establishment methods and are a major concern for rice farmers (Halwart 1994; Naylor 1996). Heavy damage (50–100 % of seedlings destroyed) has been reported in Taiwan (Yang et al. 2006), the Philippines (Litsinger and Estano 1993; Sanico et al. 2002), and South China (Wu and Xie 2006); however, there is still a paucity of data on damage levels from most regions where the snails have established. A high cropping intensity (≥2 crops per year) and continuous flooding throughout the year contribute to the high snail densities, a high potential for damage to rice, and enormous labor and management costs following invasion (Litsinger and Estano 1993; Halwart 1994; Naylor 1996; Adalla and Magsino 2006).

Category 4: Wet temperate regions where apple snails may cause relatively little damage to transplanted rice, but high damage (>30 % of seedlings destroyed) to direct-seeded rice (Wada 2004). Several detailed studies have been conducted in Japan where the distribution range of *P. canaliculata* approaches its northern limits. Rice in Japan is predominantly transplanted, either mechanically or manually, and crop rotation (mainly with soybean, *Glycine max* [L.] Merr.) is increasingly practiced due to government efforts to reduce rice overproduction (Wada 2004). Winter mortality is a major constraint for the snails and populations must build up from low numbers of overwintering adults at the beginning of the cropping season (Syobu et al. 2001). However, the recovery is often rapid during warm spring and summer months (Wada 2004).

Category 5: Dry temperate and Mediterranean regions recently invaded by apple snails where snail dispersal is likely to be slow due to dry conditions, but where recruitment and population growth are fast due to mild winter temperatures (i.e., Texas (Burlakova et al. 2010); California (United States Geological Survey 2012); Cataluña, Spain (European Food Safety Authority 2012); Chile (Jackson and Jackson 2009)). Damage to rice is often low (<5 %); however, some rice ecosystems in these regions are high value amenity areas that are vulnerable to perturbations; once apple snails have established in these habitats, they become difficult to manage because of continuously favorable conditions for snail survival. Such vulnerable habitats include the winter flooded rice fields of California, USA (Elphick and Oring 1998) and the Ebro Delta of Cataluña (European Food Safety Authority 2012).

Management practices against apple snails in rice can be selected based on the biology of the snails and the effects of local climatic and geographical conditions on their population dynamics, particularly their reproduction and time to sexual maturity. Management approaches can be divided into two groups. The first includes a suite of cultural control methods aimed at reducing snail damage to the rice crop, but without attempting to reduce snail population densities. These methods reduce rice crop vulnerability by restricting snail movements or avoiding vulnerable seedling stages. The second group of management approaches aims at reducing snail population densities through poisoning, mechanically crushing the snails, or using biological control and manual collections. The later methods are often nonselective and also affect beneficial aquatic organisms; they exert selection pressures on the snails toward avoidance and adaptation to management; and they are often short-term solutions, because apple snails, particularly without natural enemies, can rapidly build up numbers. The best approaches to management will often combine several management techniques (Litsinger and Estano 1993; Yanes Figueroa et al. 2014). These management approaches are discussed in the sections that follow.

15.5 Reducing Rice Crop Vulnerability to Apple Snails (Crop Establishment Methods)

In rice paddies, apple snails feed on a range of macrophytes including both the rice plants and their associated weeds (Litsinger and Estano 1993; Sanico et al. 2002; Joshi and Sebastian 2006). The higher nutrient levels of crop plants result in marked feeding preferences by apple snails for some crops over macrophyte weeds (Qiu and Kwong 2009); however, leaf and stem dry matter content ultimately determine macrophyte palatability and hence the vulnerability of plants to snail damage (Wong et al. 2010; Yanes Figueroa et al. 2014). Dry matter content increases with an increase in plants age: Seedling stages of both rice and weeds are most vulnerable to snail attack but resistance to snails increases as plants grow older (Yanes Figueroa et al. 2014).

Table 15.1 Management practices to reduce the vulnerability of rice seedlings to apple snails during crop establishment

Management method	Mode of action	Advantages	Disadvantages	References
Transplant seedlings or sow seed with known resistance or tolerance to snails	Resistant seedlings are nonpalatable whereas tolerant seedling are palatable but recover quickly from damage; some rice varieties have noted tolerance (i.e., some hybrid varieties) but seedling resistance to snails is unknown	Safe, no adverse effects	Little information available to support decisions; Resistance and tolerance both vary according to field conditions	Horgan et al. 2017
Transplant seedlings at >28 days after sowing	Older seedlings have thicker stems that resist snail damage	Safe, no adverse effects; may also result in reduced production costs due to a shorter time for the crop in the field	Late transplanting requires larger seedbeds and for some varieties may be associated with transplanting shock	Litsinger and Estano (1993), Yanes Figueroa et al. (2014), Horgan et al. (2014c)
Transplant at >1 seedling per hill	Unclear, possibly due to feeding capacity of snails	Safe, no adverse effects	Increases input costs	Sanico et al. (2002), Yanes Figueroa et al. (2014)
Sow seeds at ≤ 100 g m^{-2}on wet or dry seedbeds	Seedlings produced on low-density seedbeds are larger and have thicker, resistant stems compared to seedlings from high density seedbeds	Robust rice seedlings also have advantages against insect pests and diseases	Requires larger seedbeds	Yanes Figueroa et al. (2014)
Parachute (seedling broadcast) or transplant seedlings with intact roots and soil plugs	Decreased transplanting shock and faster growth rates increase seedling tolerance	Labor and cost effective	Can produce plastic waste; broadcasting of older seedlings is difficult; not widely accepted by farmers in vulnerable areas because of displacement of seedlings during flooding	Horgan et al. (2014c)

(continued)

Table 15.1 (continued)

Management method	Mode of action	Advantages	Disadvantages	References
Treat paddy field or seedbed soils with silicon	Silicon is taken up by the developing rice plant and increases seedling resistance against herbivores	Safe, no adverse effects	Costly; no proven effects – may decrease growth rates of some varieties	Horgan et al. 2017
Reduce water depth during vulnerable seedling stages	Water is lowered such that snails are immobilized and cannot feed on young rice plants	Easy to implement	Longer drainage periods are better, but result in greater weed problems, also heavy rains can produce standing pools; leveling of the field is important for efficient drainage	Litsinger and Estano (1993), Wada (2004)

Table 15.2 Management practices to reduce apple snail densities in rice fields during crop growth

Management method	Mode of action	Advantages	Disadvantages	References
Application of chemical or biological molluscicides during seedling establishment	Toxic substances act as neurotoxins or stomach poisons to kill snails	Easily applied, rapid response method	Prohibits collection of snails for food; can kill nontarget organisms including fish and frogs; damaging for human health; variable results often due to pest adaptation; products may be phytotoxic; alters size distribution of snails to promote larger individuals	Horgan et al. (2014b), Cowie (2002), Joshi et al. (2004), San (2006), Li and Xu (2012), Chen et al. (2012), Cagauan and Joshi (2002)
Application of calcium cyanamide after harvest	Originally used as a fertilizer containing nitrogen and calcium, calcium cyanamide is toxic to apple snails	Reduces need for fertilizers, 250 kg ha^{-1} corresponds to 50 kg of nitrogen ha^{-1}	Phytotoxic and should be applied 7–10 days before seedlings are transplanted or before seeding - oxygen supplier seed-coating (Calper) can reduce toxicity	Wada (2004), Zhao et al. (2011)
Use of higher fertilizer concentrations at basal applications and with delayed flooding	Snail mortality increases at higher fertilizer concentrations	Easy to implement	Can be phytotoxic; higher fertilizer leads to greater run-off; affects beneficial organisms also; leads to higher plant growth rates and more algae which increases snail recruitment	Stuart et al. (2014)
Application of mixed chemical fertilizers	Apparent higher toxicity of chemical fertilizer over organic and mixed over single type	Easy to implement	Conflicting results from research	De la Cruz et al. (2001) Stuart et al. (2014)

(continued)

Table 15.2 (continued)

Management method	Mode of action	Advantages	Disadvantages	References
Application of chemical fertilizers with delayed flooding	Increased mortality in plots treated with chemical fertilizers possibly due to toxic (poisoning) effects; effects of delayed flooding are unclear, possibly delay the dilution of toxic fertilizers	No change in normal crop management practice	May also harm beneficial organisms in the rice field	Stuart et al. (2014)
Intensified tillage	Snails are crushed	Represents a slight adaptation to regular land preparation	Will kill other beneficial organisms too, including turtles and native snails	Wada (2004), Wada et al. (2004)
Rotation of rice with a dry crop	Snails can aestivate for several months depending on temperature and humidity; however, mortality increases over time	Sometimes required by markets or governments, also controls other pests and diseases	Can reduce mortality from mechanical control, if soils remain friable	Wada et al. (2004)
Blocking of water inlets with wire, plastic, or bamboo screens	Reduces snail dispersion from canals to rice fields	Often simple to install	Can affect dispersal of beneficial organisms	Integrated ‘golden’ kuhol management (1989)
Use of baited traps	Snails are captured in baited traps and are removed from the field or killed	Simple inverted-funnel traps can be constructed from plastic bottles, some companies manufacture traps	Time consuming; not tested for efficacy at field scales	Integrated ‘golden’ kuhol management (1989)
Hand picking or collection using a long-handle sieve. Placing baits overnight in the field can facilitate hand-picking	Removal of largest snails to reduce population densities	Snails can be used as human or animal feed depending on water quality	Labor intensive	Yanes Figueroa et al. (2014), Integrated ‘golden’ kuhol management (1989)

Hand picking of egg masses, particularly after nights of heavy rain	Reduces population densities; stakes placed in the rice field can facilitate egg collection as snails deposit eggs on the stakes	Egg clusters are highly visible and allow destruction of several individuals at the same time	Labor intensive	Integrated 'golden' kuhol management (1989)
Herding of ducks and geese to forage in flooded rice paddies	Direct predation of snails	May also control other pests and weeds	Requires infrastructure and experience in duck rearing; ducks can introduce allergens to the rice fields; often there is only a limited market for ducks or duck eggs	Naylor (1996), Integrated 'golden' kuhol management (1989), Teo (2001), Cagauan and Joshi (2002)
Rice–fish farming with efficient predatory fish such as common carp	Direct predation by fish of hatchling and small juvenile snails	May also control other pests and weeds	Some infrastructure, i.e., pond refuges and antipredator netting, and experience required; often not compatible with modern agricultural practices; fish may sometimes damage seedlings	Halwart (1994), Teo (2001), Teo (2006); Wong et al. (2009), Ichinose et al. (2010)
Installation of perches for predatory birds such as snail kites, and setting-aside natural areas for predators such as turtles and fish	Enhances natural predation of snails	May also control other pests and weeds; promotes biodiversity and ecosystem functioning	Some infrastructure and set-aside land required	Horgan et al. (2014b), Sociedade Sul-Brasileira de Arroz Irrigado (2010), Dong et al. (2012)

There is also a direct relationship between snail size and the maximum age of seedlings that may be consumed: Large snails can feed on rice seedlings across a greater age range, whereas small snails can feed only on young seedlings (Litsinger and Estano 1993; Teo 2003; Wada 2004; Yanes Figueroa et al. 2014). Furthermore, feeding by snails is limited to water that is deep enough to allow snail movement—this is often considered as roughly equal to the height of the snail shell (Litsinger and Estano 1993; Teo 2003). Since smaller snails are less damaging, a depth of 3–5 cm is considered by many researchers as sufficient to limit the movement of larger snails and inhibit feeding damage (Litsinger and Estano 1993; Teo 2003; Wada 2004). Water depths of below 1 cm can eliminate damage entirely (Teo 2003). Therefore, the choice of rice crop establishment method is a key determinant of vulnerability to apple snails because crop establishment is largely defined by rice age at transplanting or broadcasting and by water depth. Rice crop establishment methods can be grouped into six main categories (see below). These methods are adopted by farmers based on labor costs, irrigation costs, and issues of weed management (De Datta 1981). Farmers rarely consider risks from apple snails when choosing a crop establishment method (Horgan et al. 2014b) despite the impacts of apple snails at this vulnerable crop stage. Table 15.1 indicates methods to reduce rice vulnerability to apple snails.

15.5.1 Transplanting

Seedling transplanting consists of sowing rice to wet or dry seed beds and, when the seedlings reach a certain age (usually >20 days), the rice is transplanted by hand or machine to puddled rice paddies. Snail damage to transplanted rice varies considerably depending on snail density, seedling age, the number of seedlings per hill, and water depth. Where snail densities are high (>5 snails m^{-2}), damage to 15-day-old seedlings can reach 100 % (Sanico et al. 2002), and damage to 20-day-old seedlings is between 80 % and 90 % (Litsinger and Estano 1993; Sanico et al. 2002; Teo 2003).

15.5.1.1 Delayed Transplanting

Damage can be avoided by planting older seedlings, for example, delaying transplanting by 7–10 days (28- to 30-day-old seedlings) can reduce seedling mortality by 30–60 % and delaying by 14–20 days (35- to 40-day-old seedlings) reduces seedling mortality by 50–75 % (Litsinger and Estano 1993; Sanico et al. 2002; Teo 2003; Yanes Figueroa et al. 2014). Some rice varieties experience yield-reducing transplanting shock if seedlings are too old at the time of transplanting; this limits the age of transplanting to below 40 days for most varieties. The intensity of transplanting shock may be more severe for younger seedlings; however, older seedlings are thought to recover more slowly from shock (De Datta 1981). For example, Teo (2003) estimated that transplanting of seedlings at 40 days after sowing resulted in significant yield declines (19–22 % reduction) in the variety TR7 despite reducing snail damage to zero. However, Sanico et al. (Sanico et al. 2002) found no effect of transplanting age (up to 35 days) on yield in IR72 under snail-free conditions, but, where snails were present, transplanting older seedlings increased yields by up to 60 % compared to transplanting young seedlings (21 days old).

Despite the improvements gained from transplanting older seedlings, under high snail densities, yield reductions in the wet season can be as high as 20 % when seedlings are transplanted even as late as 35 days—with over 40 % of hills missing (Sanico et al. 2002). Clearly the transplanting of older seedlings will not eliminate significant yield losses due to snails. Planting of more resistant or tolerant varieties could potentially reduce damage, but there is little concrete evidence to indicate varietal differences in seedling resistance or tolerance to snails. Therefore, delayed transplanting must normally be combined with some other damage reduction method.

15.5.1.2 Increasing Seeding Rates and the Number of Seedlings per Hill

Increasing the number of seedlings per hill has been shown to reduce damage (missing hills) and yield losses: For example, in an experiment by Yanes Figueroa et al. (2014) increasing seedlings from one to three per hill increased hill survival of 18-day-old seedlings by up to 25 %. Sanico et al. (2002) found that increasing planting from one to two seedlings per hill reduced damage to 35-day-old seedlings by about 75 % and increased yields by 16 %. Nevertheless, this still represented a loss in yield of nearly 15 % compared to optimal snail-free conditions (Sanico et al. 2002). Improved seedbed management can further reduce losses to apple snails. For example, Yanes Figueroa et al. (2014) suggested that low-density seeding (≤100 g m^{-2}) on raised seedbeds can reduce damage by up to 25 % because the developing seedlings, under conditions of low intraspecific competition will have thicker stems that are difficult for the snails to feed on. By delaying transplanting, planting more than one seedling per hill, and using low sowing densities, damage in snail-infested ponds was reduced to <10 % (Yanes Figueroa et al. 2014).

15.5.1.3 Field Draining

In order to reduce snail damage further, transplanting of older seedlings is generally combined with some period of short-term field draining. Draining paddy fields reduces water levels to below 1–2 cm (although 0 cm is optimal for reducing snail damage, particularly in direct-seeded rice) (Teo 2003). Even under high snail densities (5–6 snails m^{-2}), draining fields for up to 10 days after transplanting can reduce damage to 21-day-old seedlings by 44 % (Teo 2003) to 69 % (Litsinger and Estano 1993). For the best results, the soil should be level to reduce puddles where seedlings can be damaged. There are two important constraints to drainage for snail management—first, rice seedlings may become stressed under dry conditions: Despite reports of drainage for up to 3 weeks reducing snail damage to direct-seeded rice by over 99 % (Japan: Wada 2004), draining for as little as 10 days can cause seedling stress and plant mortality (tropical South East Asia: Litsinger and Estano 1993; Teo 2003); second, during periods where the field is drained of standing water, weeds will germinate and compete with the delicate rice seedlings.

15.5.2 Machine Transplanting

Several mechanical (automated or semiautomated) transplanters are available for rice farmers. Machine transplanting reduces the labor costs of crop establishment and are particularly popular among rice farmers in Korea and Japan; however, mechanical transplanters are often limited in developing countries because of high costs associated with purchasing the machinery (Horgan et al. 2014c). Rice seedlings are specially prepared for machine transplanting by sowing in mat-bed trays. The seedlings are usually sown at high density without soil, making them akin to dapog seedlings (see below). The seedlings are usually transplanted as small clumps at <15 days old (Ghafoor et al. 2008; Horgan et al. 2014c). The restrictions on seedling ages that are suitable for most machines, as well as their production as mats in plastic trays, suggest that machine transplanted seedlings will be vulnerable to apple snails. For example, machine transplanting of 15-day-old rice seedlings from mat beds resulted in 70 % missing hills during a field experiment in the Philippines (Horgan, unpublished). Machine transplanting of older seedlings would be advantageous for snail-infested regions.

15.5.3 Dapog Method for Transplanting

The dapog method is sometimes employed by farmers to reduce time involved in pulling seedlings from seedbeds. In the dapog method, the seedbed is sown on banana leaves or plastic sheets and seedlings are transplanted at 9–14 days after sowing. Litsinger and Estano (1993) found higher damage (about 30 % higher under flooded conditions) from apple snails to dapog-transplanted seedlings compared to using 20-day-old wet bed seedlings in fields in the Philippines. In a study by Horgan et al. (2014c), 100 % of 21-day-old dapog seedlings were damaged after transplanting to snail-infested ponds. Dapog transplanting is now rarely practiced in the Philippines possibly due to nonviability of the system in snail-infested regions.

15.5.4 Seedling Broadcasting

The broadcasting of rice seedlings is now gaining popularity as a rice crop establishment method in China (Tang 2002). There are four principal forms of seedling broadcasting. In the most popular form, seedlings are produced on dry beds with soft plastic trays. The seedlings (usually 2–4 per hill) with some soil are broadcast from about 2 m to puddled soil so that the roots sink by 1–1.5 cm into the mud due to gravity and the weight of the attached soil. Other forms of seedling broadcasting rely on the same broadcasting technique but with seedlings produced on either wet or dry beds, or using machine broadcasting of seedlings produced on dry beds in plastic trays. Seedling broadcasting is designed to reduce labor costs, reduce the land area dedicated to seed beds, and reduce the turnaround time in rice–rice and rice–wheat cropping systems (Tang 2002). In a recent study by Horgan et al. (2014c) broadcasting of 21-day-old seedlings resulted in 80 % better survival and 62 % higher yields than transplanting of seedlings of the same age from a dry bed nursery. The authors suggest that a lower level of transplanting shock likely contributed to the success of the method. Seedling broadcasting is gaining popularity in Asia; however, broadcasting is often carried out with seedlings of <15 days (personal observation). Further research is required to optimize seedling broadcasting for snail-infested regions.

15.5.5 Direct Seeding

In Europe, the United States, Australia, and much of Latin America, rice is generally direct seeded (Farooq et al. 2011). Direct-seeded rice can be sown under wet or dry soil conditions. In *dry direct seeding*, dry seed is sown to dry or moist soil, often with a slight soil covering. The seed germinates in response to flush irrigation or high rainfall. Throughout much of East Asia, conditions are too wet for successful dry direct seeding. However, in regions with marked dry seasons, direct seeding can significantly reduce the costs of labor and irrigation (De Datta 1981; Sociedade Sul-Brasileira de Arroz Irrigado 2010; Farooq et al. 2011). A long period without standing water after sowing can reduce the vulnerability of dry-seeded rice to apple snails. In an experiment by Teo (2003), dry direct seeding resulted in zero seedling damage from apple snails compared to 11 % in wet-direct-seeded rice and 7 % in transplanted rice.

During *wet-direct seeding*, the rice seed is pregerminated by soaking in water for 24–36 h and is then left in shade for the same period of time until the coleoptiles are about 2 mm long before it is broadcast or mechanically seeded to flooded rice fields (Sociedade Sul-Brasileira de Arroz Irrigado 2010). On large rice plantations (as in Suriname and Brazil) pregerminated seed is sometimes broadcast using light aircraft (Wiryareja and Tjoe-Awie 2006). Wet seeding is preferred in some regions because it produces dense competitive rice stands that reduce weed problems (Sociedade Sul-Brasileira de Arroz Irrigado 2010); however, because the developing seeds and seedlings are highly vulnerable to snail damage, even the smallest snails (hatchlings and juveniles) can cause serious damage to the rice stand (Wada 2004; Yanes Figueroa et al. 2014). In a study by Horgan et al. (2014c) wet-direct-seeded rice failed to yield any grain in snail-infested ponds and seedling survival was close to 0 %.

15.5.6 Water Seeding

Water seeding is similar to wet-direct seeding except that the depth of standing water is over 5 cm and the seed is sown dry (not pregerminated) to the water (Sociedade Sul-Brasileira de Arroz Irrigado 2010). The method is likely to be the most vulnerable to snail damage because very few (low densities) and small snails can cause high levels of damage to developing cotyledons in a short time.

15.6 Reducing Apple Snail Densities in Rice Fields

Apple snails have a high reproductive output, producing clutches that range from maximum egg numbers of between 50 (*P. glauca*) and 4700 (*P. maculata*) (Horgan et al. 2014a). Furthermore, depending on climate, body size, and population density, a female snail may lay several clutches during her lifetime (Horgan et al. 2014a). Growth rates are fast and the snails may reach sexual maturity after about 60 days under conditions of high food availability and adequate water temperatures (Lach et al. 2000). In temperate regions, snails such as *P. canaliculata* are semelparous (one reproduction event per lifetime), whereas, in tropical regions, they are iteroparous (more than one reproductive event per lifetime) (Estebenet and Martin 2002; Seuffert et al. 2012). Growth rates and population density are linked: snails at high densities tend to remain relatively small (Tanaka et al. 1999) either due to direct intraspecific competition or regulating pheromones in the water body. Furthermore, apple snails can adapt quickly to ambient conditions (Seuffert et al. 2012), threats from predators, and other mortality factors (Reed and Janzen 1999; Aizaki and Yusa 2010). Plasticity in the apple snail life cycle, together with high reproductive output and adaptability, allows apple snail populations to quickly bounce back from perturbations and hampers management practices aimed at decreasing snail populations in rice paddies (Table 15.2).

15.6.1 Molluscicides

The most popular approach to snail control among rice farmers is the use of chemical molluscicides such as methaldehyde and niclosamide (Schnorbach et al. 2006; Horgan et al. 2014b; Khodabaks and Tjoe Awie 2014), and insecticides (Horgan et al. 2014b). Molluscicides are formulated poisons that directly kill snails either through direct contact or after ingestion. Molluscicides can be very effective and result in >90 % snail mortality within days of application (Litsinger and Estano 1993). However, molluscicides have several associated risks: They are toxic to beneficial organisms including fish and birds (Calumpang et al. 1995; Baumart et al. 2011), they are harmful to human health (Anderson 1993), and some are phytotoxic and can damage young rice seedlings (Joshi et al. 2004). Furthermore, apple snails in molluscicide-treated fields are often notably larger that in nontreated fields because survivors after application have faster growth rates at lower population densities (personal observation). Because apple snails are a perpetual problem in invaded regions and because they are aquatic in nature, the continuous application of molluscicides must be avoided. Several researchers have attempted to develop more environmentally friendly molluscicides to replace damaging chemicals.

A range of plant extracts with molluscicidal properties have been identified to replace toxic chemical products (San 2006; Yang et al. 2006; Chen et al. 2012; Li and Xu 2012). Among these, tea tree meal, a byproduct of oil extraction from seeds of the tea plant (*Camellia sasanqua* Thunb.) has become popular in some countries and is noted to give good snail control with up to 95 % mortality (Yang et al. 2006). Extracts of several other plant species have also been developed to control apple snails: These include quinoa (*Chenopodium quinoa* Willd.), *Solanum* spp., *Eucalyptus* spp., and others (San 2006; Li and Xu 2012). Many of these products are still restricted for use in some countries because of difficulties in registration for agricultural use and because their risks to the environment and human health have not been evaluated. The products have variable success in reducing snail damage: Their efficiency may depend on the conditions of the water, including water temperature and dissolved oxygen. Furthermore, some botanical extracts may have lethal effects on beneficial aquatic organisms, including fish and decomposer invertebrates (i.e., tea saponins: Yang et al. 2006; Chen et al. 2012); however, several botanical products, e.g., quinoa saponins, appear considerably less toxic than chemical molluscicides and represent a step toward improving the sustainable management of apple snails (San 2006).

15.6.2 Fertilizers

Fertilizers, including urea, complete fertilizer and calcium cyanamide have been noted to kill apple snails under laboratory and field conditions (Wada 2004; De la Cruz et al. 2001; Zhao et al. 2011; Stuart et al. 2014). Calcium cyanamide is proposed as a relatively environment friendly approach to snail management that is potentially highly effective, e.g., 100 % mortality at $3gL^{-1}$ (Zhao et al. 2011). Applications of nitrogenous fertilizers have also been noted to cause snail mortality, possibly due to toxic effects after ingestion. Under certain conditions, mortality due to nitrogenous fertilizers can be as high as 60–80 % (De la Cruz et al. 2001; Stuart et al. 2014). To help control apple snails, farmers can increase the concentrations of fertilizer products during basal applications, select the most toxic fertilizers such as complete fertilizer, urea or mixed products, and reduce flooding of the rice fields during application (De la Cruz et al. 2001; Stuart et al. 2014). However, such practices are likely to affect beneficial organisms in the water, alter the structures of animal and plant communities (Vitousek 1994), and must be carefully balanced to avoid run-off and eutrophication. Furthermore, snail population recovery may be accelerated by high plant biomass, including the biomass of periphyton and algae that develops after fertilizer use (Stuart et al. 2014).

15.6.3 Crop Rotation and Fallow Periods

A range of cropping practices has been examined to potentially reduce apple snail densities. Among these are crop rotations and extended, dry fallow periods (Wada 2004; Wada et al. 2004). Apple snails have evolved to inhabit ephemeral water bodies and therefore have a high capacity to survive dry conditions. The snails normally burrow a few centimeters into the mud where they enter aestivation. Aestivation can last for several months; however, mortality increases over time (Yusa et al. 2006a). To cause any appreciable mortality of apple snails, dry fallows should be longer than about 4 months. This can result in >90 % and 50 % mortality of small and large snails, respectively (Yusa et al. 2006a). Long-term drainage will be most effective under hot dry conditions (Yusa et al. 2006a) but can have variable impact on snail populations because of microclimates in the rice fields and the rapid recovery of snail populations after flooding. Land preparation between crops can also cause considerable snail mortality. For example, using an adapted rotary cultivator, 90 % mortality of large *P. canaliculata* and 25 % mortality of smaller individuals has been achieved in Japanese rice fields (Wada 2004). The success of mechanical crushing depends on the soil type and soil conditions, for example, mortality from mechanical crushing can be 14–20 % higher in fields that are compacted after rice harvest (Wada 2004).

15.6.4 Hand Collecting

Manual collection of apple snails is often conducted among small-holder farmers prior to transplanting. During collection, farmers and farm laborers will walk through the fields collecting any snails that they see. These are generally the largest snails with the greatest potential to cause damage. Picking can increase seedling survival by 20–50 % even for singly planted, 18-day-old seedlings (Yanes Figueroa et al. 2014). However, picking is labor intensive, conducted with variable intensity, and is not suitable for large farms. Hand picking is also best conducted during cooler and cloudy conditions because the snails burrow in mud during high temperatures (Wada and Yoshida 2000). There is also some evidence that continuous picking may lead to the selection for cryptic shell colors in snail populations (M Türke 2014, personal communication). Picking can be improved by using baits such as the leaves of sweet potato (*Ipomoea batatas* [L.]) or other plants that attract the snails to one place, or by using drainage canals (Wada 2004). Furthermore, in some regions, farmers use rakes and baskets to facilitate snail collection (Fig. 15.3).

Fig. 15.3 A farmer in Bali (Indonesia) uses a sieve to collect apple snails during land preparation for rice transplanting (Photo: Artzai Jauregi)

The collection and destruction of egg masses may be a more effective way of reducing densities but the success of the method has not been evaluated. The brightly colored eggs of apple snails are easy to find and, by placing wooden stakes in the fields for snails to deposit their eggs, they can be collected quickly. Collection of apple snails and their eggs would benefit from further economic incentives, e.g., selling snail meat as a protein source for farmed fish or poultry (Cagauan and Doria 1989; Bombeo-Tubaran et al. 1995).

15.6.5 *Biological Control on Integrated Farms*

Several biological control methods have been proposed to reduce apple snail densities in rice fields (Joshi and Sebastian 2006). Integrated farms often produce ducks or fish together with rice in flooded paddies. Ducks can be herded through rice fields to feed on snails, other invertebrates, and weeds (Teo 2001). Duck herding is common in many South and East Asian countries with farmers often inviting duck herders to visit their fields. The effectiveness of the method in reducing snail densities is difficult to determine and may depend on the breed of duck (Teo 2001). Hirai (Naylor 1996) claims that ducks consume up to 89 % of apple snails on passing through rice fields; however, this likely refers only to their effects on larger snails.

Rice–fish culture is practiced in many lowland rice-growing regions, particularly in Asia. Rice–fish cultures require deep reservoirs to be constructed in the fields as refuges, allowing the fish to forage among the rice plants only during periods of flooding. The effectiveness of fish predation depends on the species of fish and the size (or gape) of the mouth (Ichinose et al. 2010). A number of studies have found common carp (*Cyprinus carpio* L.) to reduce snail densities (Teo 2006; Wong et al. 2009; Ichinose et al. 2010); however, the common carp is also an invasive species and can significantly alter freshwater habitats by reducing macrophyte density and the abundance of native benthic organisms (Wong et al. 2009). The success of several other fish species in reducing snail densities or protecting developing rice seedlings has been generally low (Halwart 1994; Teo 2001; Ichinose et al. 2010). It is possible that the rice–fish systems need to be established for relatively long periods (several cropping seasons) before snail populations are effectively regulated by the fish.

Dong et al. (2012) report that farmers in Zheizhang China have adopted a system of turtle (*Pelodiscus sinensis* [Weigmann])-zazania (*Zizania latifolia* [Griseb] Turcz) culture that reduces apple snail densities. Zezania is a high-value "wild rice" and the turtles can also be sold for meat in local markets. The turtles were noted to reduce snail densities and the system was sufficiently lucrative for farmers to establish large enclosures for the turtles. Biological control using ducks, fish, or turtles has potential, but is limited by marketability of ducks, eggs, or fish meat and is likely to remain small scale.

15.6.6 Classical and New Association Biological Control

Classical biological control of apple snails has received little research attention. There have been a few studies on the potential for using predatory flies (Fu and Meyer-Rochow 2012) and pathogenic bacteria (Chobchuenchom and Bhumiratana 2003) to control snails; however, these ideas have not been implemented among farmers. There is good potential to enhance biological control through new associations between native diseases or predators and exotic apple snails. Predation and regulation of apple snails by native species has been examined in detail in Japan. Several wild animals including crayfish (*Procambarus clarkia* [Girard]), crabs (*Eriocheir japonicas* [de Haan] and *Gerthelphusa dehaani* [White]), turtles (*P. sinensis*, *Trachemys scripta* [Schoepff], *Mauremys reevesii* [Gray] and *Mauremys japonica* [Temminck and Schlegel]), and rats (*Rattus norvegicus* [Berkenhout]) will feed on snails and may play a role in reducing snail densities in natural areas (Yusa et al. 2006b; Yamanishi et al. 2012). Furthermore, it appears that over time, apple snails have accumulated natural enemies in Japan as local wildlife have adapted to feed on and consume the snails. Snail kites, *Rostrhamus sociabilis* Vieillot, in Ecuador and open bill storks, *Anastomus oscitans* (Boddaert), in Thailand have built up populations in response to the invasion of rice fields by apple snails (Sawangproh et al. 2012; Horgan et al. 2014b). Predation is highest in natural habitats including ponds and rivers, but can be low in rice paddies because farming activities will kill or displace natural enemies, particularly at the time of land preparation (Burlakova et al. 2010; Yamanishi et al. 2012).

15.7 Concluding Remarks

Despite widespread knowledge of the risks associated with apple snails, several species, including species known to damage rice, continue to be imported into rice-producing countries, mainly for the pet trade (Coelho et al. 2012). Strict and effective quarantine of apple snails should be a priority in major rice-growing areas that are vulnerable to apple snails, including India, Bangladesh, Sri Lanka, Peru, and Colombia. Furthermore, the feasibility of wet-direct seeding should be reexamined. While crop establishment methods that are suitable for snail-infested or native regions exist, it will be hard to justify continuing research and extension aimed at promoting direct-seeding methods that rely heavily on molluscicides. Research into alternatives to, or adaptations of direct seeding, could greatly improve country and regional preparedness for apple snails.

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Chapter 16
Harvesting, Threshing, Processing, and Products of Rice

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16.1 Introduction

Rice (*Oryza sativa* L.) is one of the most important food items consumed by more than half of the world population as staple diet. Globally, the rough rice (paddy) stands at position second with a total production of 740.9 metric tons from 154 million hectare, almost 90 % of which is grown in developing countries (FAOSTAT 2013), while it stands first at human consumption scale with 85 % utilization compared to wheat (72 %) and maize (19 %). Rice provides 21 % and 19 % of the global human per capita energy and protein, respectively (FAO 2012). It is estimated that 10 billion people will depend on rice as a major source of their meal increasing the demand up to 880 metric tons by 2050 (FAO 2015). In order to cope with the situation, multiple strategies have been adopted to increase the production of rice by developing high yielding, drought, insect, and disease resistance varieties. The increase in rice production due to crop management is hardly compensating in yield reduction on account of urbanization and industrialization persuaded decline in the size of productive agricultural land. Globally, the rate of growth in yields of major cereal crops has been steadily declined from 3.2 % per year in 1960 to 1.5 % in 2000 (FAO 2015). Moreover, postharvest losses of crops range from 10 to 20 % in developed, while 25 to 40 % in developing countries. These losses in rice are particularly

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associated with socioeconomic development of farmers, awareness, and adoption of the latest and improved methods of production, harvesting, milling, and storage. Lack of awareness among farmers on weather forecast, latest methods of harvesting, time of harvesting, milling, and storage conditions due to illiteracy are the major contributors for too high losses of crops in developing countries. Policy makers, scientists, and stake holders associated with production and management have focused on the quantitative losses of rice since the last quarter of the twentieth century giving meager consideration to the qualitative losses of the crops. It is among the reasons that the qualitative losses of rice crop are getting more attention in the most recent era. Many of the research organizations, policy makers, and financial support agencies have already set their targets to achieve the milestone of better production by developing high yielding rice cultivars, improved methods of harvesting, threshing, milling, and storage to curtail postharvest losses. The developed countries although have attained maximum production of rice with the development of high yielding varieties, best agronomic practices, and adoption of good agricultural, harvesting, transportation, and storage practices. However, the developing countries could contribute to significant rise in rice production by improving cropping intensity and expansion of arable land in addition to reduce postharvest losses. Rice production in proper moisture conditions and nutrient availability, harvesting fully matured grains at moisture levels below 26 % and subsequent mechanical drying upto15% moisture level, milling through pneumatic rubber rolls, storage under controlled environmental conditions, and integrated insect and pest management programs are the factors that can reduce quantitative and qualitative losses in rice crop (Bell et al. 2000). Increasing production of rice by putting lot of capital and investment on research is a good sign but a little effort to curtail the postharvest losses of rice can save cost and energy and might further increase the total turnout from the crop. The applications for advanced and latest techniques of rice harvesting, milling, transportation, and storage can reduce the losses up to a compromising level. The current chapter has been written with the objective to discuss the various techniques universally adopted for harvesting, drying, milling, and storage. This chapter discusses methods of milling in detail with a focus to improve the understanding of both the farmer and the rice processor to adopt best crop management practices. Moreover, various factors contributing toward quality of rice are also enlightened in a way that the reader with a little background knowledge may understand how to prepare a better quality of rice and how milling recovery is to be increased.

16.2 Harvesting and Threshing

Rice harvesting is a process of whole grain recovery utilizing a chain of mechanized operations from crop cutting up to threshing. The process involves recovery of matured rice from the field and generally comprises operations like stalk cutting, stacking, handling, and transportation on threshing blades. Threshing of rice involves separating grains from panicles without removing husk. Such methods of harvesting and threshing are adopted universally, which maximize grain recovery, minimize harvesting losses, and improve the straw yield. The straw serves as dry forage for milking and meat animals. The crop harvesting time and procedures are reportedly associated with certain important qualitative attributes of rice. Mechanized harvesting at an appropriate time ensures improved paddy quality and grain yield by avoiding lodging, over drying of grains, shattering, rodent and bird attack, and soil contamination (Van den Berg et al. 2007). Indicators showing the correct timing of rice harvesting include yellowing of panicles, 20–26 % moisture contents of grains, and recovery of at least 80 % matured grains from the panicles (Almera 1997). The method of rice harvesting depends upon many factors such as ecology, size of the field and cultivated area, cultural practices, social and economic status of the farmers, climatic conditions at the time of harvesting, availability of labor, access to the market, market demand, and usage of the straw.

Rice Variety Some varieties are prone to lodging hence their panicles are bowed to ground and cannot be picked up by combine or machine harvesters. Hence to avoid harvesting losses, manual harvesting is preferred over mechanized harvesting for cultivars with poor field standing capability.

Timeliness of harvesting It is the time for which the variety can stay unharvested after ripening. On account of low cost labor availability and higher timeline of the variety, manual rice crop harvesting is preferred over mechanized harvesting.

Environmental conditions If environmental conditions worsen, then quick and mechanized harvesting is preferred over manual harvesting.

Availability of labor In regions with higher availability of cheaper labor, manual harvesting is preferred over mechanical to curtail harvesting expenditures of the crop.

Access to the field or farm If the farm has no access for combined or machine harvesting, then manual method of harvesting is preferred.

Market demand The paddy harvested through manual harvesting is usually cleaner than that mechanically harvested, having less moisture and higher percentage of matured grains. There are reports that higher demands are raised by industry for manually harvested paddy for the sake of better milling and cooking quality attributes; however, highly trained labor is required for manual harvesting to minimize the losses (Khan and Salim 2005).

Demand of straw In developing countries, paddy straw is usually used as fodder and to make silage for animal feed. The waste fraction is also used for making fire in the pottery, brick, and tile industry and as raw material for mats manufacturing. Hence, paddy is harvested manually if there are higher demands to save the straw in its original form.

Following methods are globally used for harvesting and threshing of rice crop.

16.3 Manual Methods

This is an oldest and the primitive method of rice harvesting that involves intensive human resources. Manual harvesting is laborious, very slow, and time consuming; however, it is very cheap compared to the other available harvesting techniques, particularly where cheaper labor is available. The rice crop is manually harvested usually in uplands, small farms, and under developed areas where access to the harvesters is poor. In the manual harvesting, knives, sickles, or cutlasses are used for cutting the crop (Bora and Hansen 2007). In knife cutting, the harvesting is done panicle by panicle that makes harvesting much more laborious and time consuming. Sickle or cutlasses method involves the cutting of whole plant and hence less labor is required in this method than the former one. The paddy harvested manually or with reaper is usually spread on dry earth floor for field drying that have higher risks of contamination with mud, mold, dust, dirt, and stones. In order to avoid postharvest losses and damages to the field crop quality, plastic sheets, tarpaulins, or traditional sheets may be used. The semidried panicles are tied into bundles of around 10 inch diameter by a crew of two to three persons. The bundles are stacked into small piles and collected at a central point of the field where it is threshed by any means. Multiple threshing techniques are deployed for the purpose and the most primitive among these is manually beating freshly cut or semidried panicles onto the solid surface either made of mud, wood or iron (Fig. 16.1). Another manual method of threshing of rice is to beat bundles of rice with a device generally called as flail. In some very under developed regions, rice grains are also been separated by forcing animals to walk on the heaps of semidried harvested panicles. The same technique had also been adopted by the farmers by replacing animals with tractors having rubber tires.

16.4 Mechanical Methods

Mechanical harvesting and threshing has many benefits over manual harvesting on account of managing the crops in a very short period of time, harvesting the crop even at more than 20 % moisture contents, reduced labor involvement, appreciable reduction in spoilage, and higher grain yield or output. However, the crop has to be dried as early as possible after harvesting to avoid losses incurred due to higher rate of respiration of the harvested grains. Following mechanical methods are commonly used globally.

16.5 Harvesting with Reapers

Reapers are an intermediate technology between manual and combine harvesting and are deployed to facilitate crop harvesting. Reapers are of two types including reaper-cutter and reaper-binder. Reaper-cutter is a tractor front driven machine that reaps and

Fig. 16.1 Various stages of manual harvesting and threshing

makes windrows of the harvested crop. The machine comprises a cutting bench, traversing conveyor, reel, reciprocating cutter, crop-lifter, and divider board. The crop passes the divider board and the reel, while reciprocating cutters cut it above the ground level. Traversing conveyor moves it to one side of the reaper in the form of row. The harvested paddy crop is tied into bundles manually after it is dried in the field, provided that the reaper is not combined with binder. The machine is compact and easy to operate and maintain. A single machine can harvest 0.3–0.4 hectare standing crop per hour. The reaper–binder is similar to reaper cutter with the addition of a binder in which the harvested paddy crop is tied into bundles mechanically. The machine has a working capacity of 0.5–20 h per hectare (Khan and Salim 2005). Paddy from the harvested rice stalks is further separated either by manual or mechanical threshing.

16.6 Rice Threshers

Two types of threshers are available on the globe including whole feed and half feed for separating paddy from the panicles. In the whole feed thresher, paddy with straw is fed through the hopper or feed table. The drum containing teeth is rotated through an engine via a V-belt pulley. The spike teeth cylinder and the concave sieve are the main sections of thresher that take part in threshing. The grains passing through concave sieve are collected in the grain collector and are propelled to the outlet elbow by grain propeller. The reflecting plate throws the straw from the rotating cylinder in a tangential direction. In half feed thresher the paddy straw is fed in such a way that only panicle part strikes with the rotating cylinder while keeping the paddy stalks in hand. The grain free stalks are heaped separately. The efficiency of half feed thresher is very low compared to the full feed threshers; however, they consume less power for their working.

16.7 Combine Harvester

Combine harvester is a multipurpose machine that carries all necessary makeup to execute crop harvesting and threshing operations including cutting, conveying, threshing, separation, and cleaning processes spontaneously (Fig. 16.2). Combine harvesters have higher working efficiency and are less laborious. However, it is quite complicated and expensive technique for illiterate and small farmers having meager resources to manage harvesting operations and poor access to on field equipment services. Combine harvester operates mainly on hydraulic system and some controllers and, regulators. It is classified into wheel and claw combine harvesters depending on the type of mechanism for its mobility while straight-through and head-feed combines on the basis of feeding pattern. In the straight-through machine, the cut crop with stem is fed into the cylinder for threshing, cleaning, and

Fig. 16.2 A typical combine harvester for harvesting and threshing of rice crop

separation. While in head-feed combine, the cut straw is held by a clamping mechanism and only the panicle part is fed into the thresher for threshing. The former has a higher efficiency, while the latter can generate whole straw that may be utilized as farm feed or industrial raw material for multiple purposes. Straight-through harvester is commonly used in developing countries and its working may be divided into following six sections.

Cutting Section This unit cuts the crop and delivers it to the feeding section through a conveyor system. The section comprises of a reel for supporting the grain part of the rice stalk against the cutter bar. The cutter bar cuts the crop just below the grain part, i.e., heads; hence, this section is also called as head section. The dividers separate the standing crop and bind the swath to be cut by the cutter bar.

Feeding Section This part comprises of a conveyor system that carries the harvested crop from the cutter bar to the threshing cylinder.

Threshing Section This section comprises of a cylinder, concaves, and grates. The grains are separated from the straw while passing in between the cylinder and concaves. The concaves are the stationary bars and are extended across the full width and surrounded about one-quarter of the cylinder. The grates are the openings or perforations in between the concaves to separate the threshed grains. The threshed grains are collected in the grain pan beneath the basement of threshing section, while the straw traveling to full length of rack is discharged at rear end of the machine.

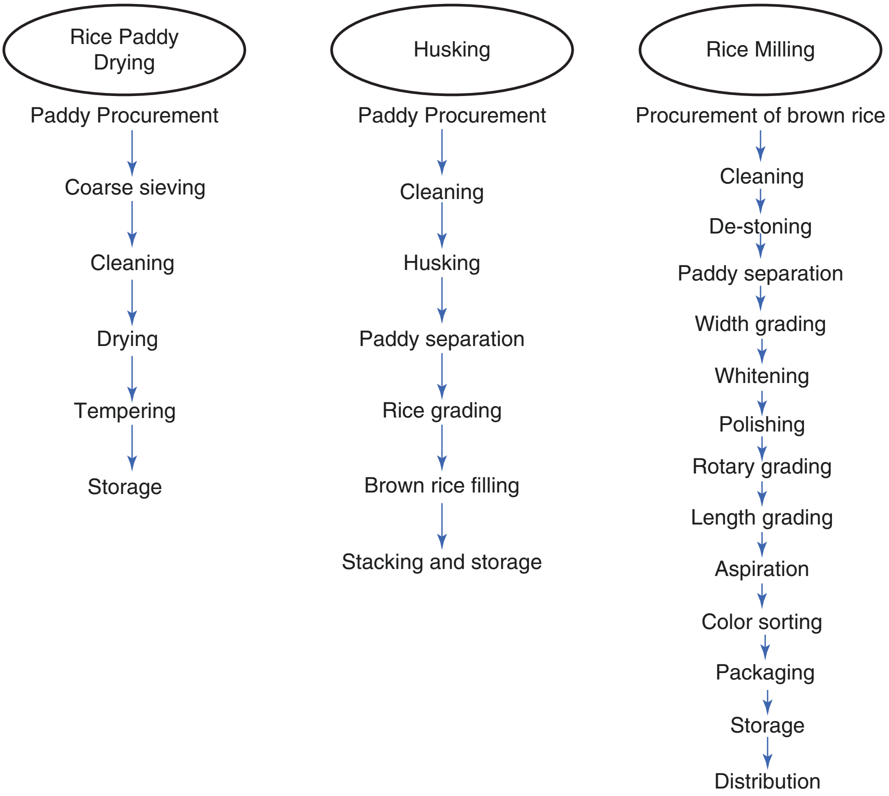
Separating Section Small pieces of straw are mixed with grains and pass through the grates particularly at the rear end of the threshing section. The mass of straw is separated from the grains by the straw-rack, which tosses and tumbles straw and propels it to the rear end.

Cleaning Section This section removes chaff and fine residues from the threshed grains collected at the end of the concave and the straw walker by the combined action of the sieve installed above the grain pan and the blower.

Grain Collecting Section This section conveys the grain to the point from where it is taken out for packing at the grain tank. A clean grain auger is the extended part of the grain pan at the bottom of the threshing section that conveys the grains to auger elevator. The auger elevator elevates the cleaned grains and throws into the grain tank. The grain tank is then emptied and the grains are packed in the desired packaging material.

16.8 Rice Processing

Rice processing includes a series of operations from crop harvesting to the finished rice product ready for onward marketing or consumption (Fig. 16.3). Rice processing generally involves paddy drying, dehusking, milling, and packaging. However,



Note: For Parboiled milling, paddy is soaked before drying while all other steps remain unchanged

Fig. 16.3 Flow diagrams of paddy drying, husking and rice milling

a high degree of variability exists in rice processing depending upon type of the product developed from paddy. Rice milling and cooking qualities are primarily dependent upon a rapid and efficient method of drying.

Paddy Drying Rice grains at harvesting may have a moisture content ranging from 20 to 26 % (Siebenmorgen et al. 2007). Harvesting at high moisture levels is aimed at avoiding grain shattering and crop loss. Delay in harvesting results in field drying of standing crop generating cracks in the grains that further results in a higher broken kernel output. Process of paddy drying preserves innate quality attributes of rice. It is therefore recommended that the rice crop after harvesting and threshing may be dried up to the safe moisture contents. Paddy having moisture contents up to 15–16 % may be stored for 3–6 months while for longer period of storage, moisture contents can further be lowered to 12 % (Genkawa et al. 2008). Paddy having 12–13 % moisture contents is considered to be the best for milling and head rice recovery, while moisture contents beyond this limit may cause high breakage and low yield consequently a significant economic loss to the miller (Ali et al. 1990; Siebenmorgen et al. 1998; Surek and Beser 1998; Hossain et al. 2009).

Quantity of the stock, initial moisture contents, storage temperature, relative humidity, speed and volume of the air passing thorough the paddy, drying method, type of the drier, and drying efficiency of the driers are the major factors that can affect paddy drying process. Paddy being hygroscopic in nature may gain and loose moisture; therefore, tempering of paddy is required to equilibrate the moisture contents of the grain. Tempering is the process in which the paddy grains are collected together to equalize the moisture contents between the grains. Various methods have been employed to dry the paddy including sun drying and mechanical drying. The most common, cheaper and primitive method for paddy drying particularly employed in temperate and tropical areas is sun drying. Freshly threshed paddy is spread over the water proof floor in thin layers early in the morning and collected on sunset each day and the process is continued until moisture contents reduce to the desired level. It is better to spread the paddy in thin layers of 6 cm. One acre (4000 m^2) dry insulated field can handle 60 ton of paddy for drying at one time, and drying may be completed in 2–3 days depending upon the initial and desired final moisture contents, exposure hours, intensity of heat, and humidity in air. In the developing countries, roofs of the houses are used for the purpose at home scale, while leveled and mud-varnished dried fields are used for drying at the industrial scale. The cost of the method is dependent on the availability of the labor, socioeconomic conditions, and climatic conditions of the region. Sun drying is advantageous on account of initial and operational cost.

Adverse climatic conditions are barrier to the sun drying process; hence, mechanical drying is employed as alternate to sun drying and, for holding the paddy, heating and blowing the dried air through the mass of moistened grains. A range of mechanical dryers are used for the purpose. These may be divided into three groups including batch-in-bin, recirculating batch, and continuous flow dryers.

Batch-in-bin is the simplest small-scale mechanical drying technique applicable at village or farm level as well as at large scale for industrial paddy drying. Paddy drying in this technique is carried out in a bin equipped with perforated base that allows dried air to pass from the bottom through the entire stored stock. The bin is emptied for refilling with fresh stock when desired level of moisture of paddy is gained. The recirculating batch is like the batch-in-bin type dryer with the exception that it has a system for circulating the paddy in the bin. Recirculating batch drying is more efficient on account of better milling quality of paddy.

In the continuous flow type dryer, the paddy is dropped from the top of the dryer column, while hot air enters at the bottom of the drying chamber. Baffles in continuous flow type dryers are constructed in such a way that they create hurdle in free fall of the paddy in drying chamber. The speed of the paddy falling through the dryer chamber may be controlled by tilting the baffles up to the desired angle. The dryer is designed in such a way that paddy takes around 15–30 minutes to reach from top to the bottom. The paddy after drying is sent to a temporary storage bin for 48–72 h for tempering (Taechapairoj et al. 2007). Continuous flow dryers have a holding bin at the top of the drying chamber, a flow control system to control the passage of paddy, and systems for heating and blowing the dried air. This method is employed when a large volume of wet paddy is to be dried. The initial cost for installation of continuous flow dryers is too high but working efficiency compensates its cost.

16.9 Paddy Cleaning

Foreign matters like sand, stones, straw, mud, weed seeds, iron particles, and stitching ropes may become part of paddy during harvesting, threshing, and transportation. Removal of such material is called paddy cleaning. Paddy is passed through precleaner and destoner for the purpose of removal of such foreign debris. The process of precleaning not only cleans rice but also reduces the risk of wear and tear of the milling machinery. There are various types of globally used precleaners that work on the basic principle of aspiration for the removal of lighter particles from the paddy, sieving for separation on the basis of size and shape and gravity separation. Impurities like sand, dust, small stones, soil particles, and weed seeds are separated by aspiration. Larger and smaller particles than paddy grains may be separated by sieves having grooves of various sizes. Particles having same size but heavier than paddy grains can be separated by gravity separation. Iron particles are separated by gravity separation, by sieving or by permanent or electromagnets (Dhankhar 2014). Three major types of precleaners used in industry include open double-sieve precleaner, single-action aspirator-precleaner, and single-drum precleaner.

Open double-sieve precleaner Paddy is inserted from the top of the machine on the upper sieve having larger perforations than paddy size. Paddy along with small foreign particles is dropped on the lower screen having perforations smaller than the paddy grains. This action removes straw and chaff fractions from the paddy; however, particles smaller than paddy are further separated and dropped through the lower screen. Open double screen precleaner is too simple to be handled but still there exists risk of clogging of perforations with dust that is needed to be monitored adequately for higher throughput of the cleaner.

Single-action aspirator precleaner It comprises of a stationary section, oscillating section, and a suction fan connected to a cyclone. The stationary section is fixed in wooden or iron frame housing with a suction fan connected to a cyclone. Paddy is inserted from the top near the housing and dust is removed by suction fan. The flow of the grain in aspirator cleaner and speed of suction air are adjusted to their maximum efficiency for removal of dust and lighter particles. The remaining two sieves of aspirator cleaner have the same function as of open double sieve precleaner. This is a closed type precleaner having minimum risks of clogging of sieves.

Single-drum precleaner It consists of a vibrating inclined screen, a horizontal rotating cylinder covered with a wire screen of larger mesh size, air suction fan connected to cyclone, and double oscillating sieves fixed in iron or wood frame. Paddy is inserted via vibrating inclined screen into the rotating cylinder from the top to remove larger impurities. Paddy along with smaller impurities passes through upper sieve in the form of a film. The suction fan removes the dust from the film and delivers it to the cyclone. The upper screen removes larger impurities, while paddy grains along with smaller impurities are dropped to bottom screen. The smaller impurities are dropped to the bottom screen while overflowing the cleaned paddy to the destoner. Magnets are installed to remove iron particles at the inlet or outlet housing of the precleaner.

Destoner Stones similar in size to paddy grains are difficult to remove through paddy cleaners; hence destoners having a perforated deck mounted with an angle and aspiration facility are used. The air stratifies the particles while the reciprocating motion of the deck removes the stones at lifted back end and cleaned paddy is separated at the lower end of destoner.

16.10 Dehulling

The process of removal of paddy husk is called dehulling or dehusking. Various types of hullers or huskers are used with the objective to remove husk from paddy. The most common types are steel huller, under-run disc huller, and rubber rollers. The steel huller is the first mechanical type of huller having disadvantages like higher percentage of breakage, lower head rice recovery, and requirement of high electric power.

Under-run disc huller also called as disk huller is made of two horizontal iron discs. One of the disc housing of dehuller is fixed in iron case, while the second one rotates. The paddy grains are dropped from the hopper to the center of hullers under gravitational force and husk is removed from the surface of paddy while passing between the two roller under the centrifugal pressure and friction of the discs. The space between the two discs can be adjusted by the rotating disc according to the moisture contents, type, size, and condition of the paddy with the objective of minimum breakage and maximum recovery. The disc shellers although have many advantages over steel hullers including low operational cost, cheaper maintenance, and operational simplicity. However, due to high breakage rate, requirement of high electric power, lower capacities of hulling, excessive removal of germ, damage to the bran layer, and, requirement of an extra step of sieving make them rather less economical compared to the rubber rollers.

Rubbers rollers are widely used in the rice industry now-a-days. The rubber roll paddy husker comprises of two rolls rotating in opposite directions but with differential speed. The husk from the paddy grains is easily removed by shearing action of the rolls. The speed and space between the two rolls are adjustable to get maximum recovery of the head rice. The rubber rolls have many advantages over all other types of rollers including lower rate of breakage, lower rate of germ removal, and minimum loss to the bran layer, improved hulling efficiency, and negligible brew production that eliminates needs of sieving. Only disadvantage of rubber rollers is the cost of their replacement on account of faster wear and tear of rubber compared to steel or disc hullers.

16.11 Husk Separation

Huskers produce a mixture of brown rice, unhusked paddy grains, husk, brew, and germ. Husk is separated by the process of aspiration. The dehusking process generates broken kernels, brew, and germs from the paddy. If paddy is hulled through steel or disk type hullers then these products are separated from each other in three different steps. These fractions are passed through the plane sifter consisting of a set of two screens and a blower at the bottom. The top screen separates the husk, unhulled paddy, and head rice into a hopper at the bottom of the plane sifter. The aspirator at the bottom pulls air through the mixture and throws husk outside the blower. The immature and lighter grains while moving with the air are dropped into a hopper due to negative air pressure. The broken kernels move through the upper screen, while the brews and germs are separated by the bottom screen. The unhulled paddy and head rice are passed onto the paddy separator. Since housing of rubber rollers carry blower, husk is separated just after dehusking while the remaining products including unhulled paddy grains, head, and broken rice are moved to the paddy separator (Tangpinijkul 2010).

16.12 Paddy Separation

The unhulled paddy grains are compulsory to be separated from the rice before milling. Mixture of paddy grains, broken, and brown rice are sent to the paddy husker that separates the paddy grains from the other fractions. Paddy grains having larger volume to mass ratio possess less specific gravity compared to brown rice. Moreover, due to coarse surface of husk, paddy grains have high resistance in mobility. Hence, the paddy grains are separated from hulled rice by the to and fro motion in tilted position of paddy separators. Two types of paddy separators are being employed in rice processing industry.

Compartment type separator These are prototype mechanical separators made of steel or wood having 10–80 compartments housed in 2–4 decks. The mixture of unhulled paddy and rice is fed on the top through the hopper to a channel that distributes it evenly in the compartments. Unhulled paddy as a result of oscillating motion is separated and fed to the hullers for dehusking again while the rice along with broken kernels is transferred to a width grader for the separation of head rice. Efficiency comparison of different separators confirms the compartment-type separators as the cheaper ones, requiring less energy and operating cost; however, they need large space and strong foundation for installation.

Tray Separator It consists of a set of trays housed one above the other, and all fixed in a frame made of steel. The assembly is attached in a tilting position to a base operated by an electric motor. The paddy grains are dropped onto the screens through an inward hopper. The tray section moves up and forward making a slight jumping movement. The brown rice having smooth surface and larger density moves toward the upper and forward end while paddy to the lower forward end. The brown rice separated is moved toward plane sifter for separation of broken rice, brew, or germs. The head rice is separated while the mixture of broken and head rice is sent to the length grader (Van Ruiten 1976).

16.13 Length Grading

Broken grains have smaller length as compared to whole grains or head rice and are separated through length grader, also called as trieurs, rotating cylinders, and drum graders. A length grader comprises of two half-circled indented screens fitted in such a way as to make a cylinder, a catch trough having a screw conveyor, and a rotation controller. The length grader is installed in an inclined position to add a slight push to the head rice for easy removal from the grader. The broken kernel packed in indents reach the top with the rotation of the cylinder, dropped in the trough, and pushed out of the cylinder by screw conveyor. Length graders on the basis of number of stages may be classified as single stage, two stage, and three stage length graders. The broken percentage in the final rice may be reduced up to a desired level by controlling the rotation speed of the cylinder and type of the length grader.

16.14 Width Grading

Width graders are the circulating cylinders made with a perforated iron or steel sheet housed over a rotating shaft. These graders are used to separate rice on the basis of width and are installed in slightly tilted position. Width graders are used for separating rice grains and foreign particles having size greater than normal rice. The oversized width graders have screens with perforations of size slightly more than the normal rice width (Gariboldi 1974). Rice fed into the rotating cylinder while passing through the perforations drops into a trough at the bottom. A screw conveyor in the trough pushes rice outside of the trough while oversized rice retained in the cylinder is pushed outside due to tilted rotation of the cylinder. Undersized width graders are used to remove thin and shriveled rice grains from the normal and healthier grain. The perforation size of these cylinders is slightly less than the width of the normal rice. The under sized rice is dropped in the trough at the bottom and is carried away through the screw conveyor while normal sized rice retained in the cylinder is pushed by tilted rotation of the cylinder.

16.15 Rice Whitening

Partial or complete removal of rice bran layer is carried out through a process referred as rice whitening or polishing. In industrial rice processing, polishing is considered as an essential segment of rice milling. The outer layer of rice comprises of aleuron layers which do not allow the rice to expand during cooking. In most parts of the word, polished rice is consumed for its better cooking properties, ease in digestibility, better volume expansion ratio, and good aesthetic value. The bran layers from rice are removed by abrasion or frictional force (Wimberly 1983). Various types of rice whiteners are used for rice milling.

Single machine mills Single machine mills are primarily used for small scale milled rice production owing to their low milling capacity and greater susceptibility to damage rice grains. Single machine mill is powered by electric motors and in some regions via tractors, generators, or diesel engines. The machine comprises of steel or iron made rotating cylinder covered with a perforated steel sheet, a motor to derive steel cylinder, and a hopper. The paddy is fed from hopper to the space between rotating cylinder by rotational direction of the flutes and perforated steel cover. Husk and upper bran layer is removed and converted into powder-like small pieces by the frictional force, and pushed out of the huller through the perforations of the outer covering. Some husk and bran part are included in whitened rice, which is further removed by sieving. Single machine mill can also separate broken kernels up to a desired level by sieving. Irrespective of its simplicity to handle paddy, steel-based single milling machine causes huge losses to the rice grains in the form of breakage. The modern single mills having rubber rolls for improved husking and steel whiteners are available now-a-days, which have higher raw material handling capacity with lower energy requirement and reduced breakage risks (Singhagajen and Thongsawang 1982).

Multiple machine mills Large capacity multiple machine mills are used at a commercial scale. These mills comprise of a machine for each process like cleaning, dehusking, destoning, paddy separation, whitening, polishing, color sorting, and other necessary processing operations. They have varying milling capacities starting from 1 to 10 or even more tons per hour. If the machines are installed at multiple floors then conveyor or bucket elevators are used to transfer the product of one machine as raw material to the other machine. If machines are installed on the same floor then the difference between them is fixed in such a way that there should be no resistance in the flow of the rice grains through the pipes to a machine. This machine has higher milling capacity and operates more efficiently than single steel machine.

Vertical abrasive whitener Vertical abrasive whitener consists of a cone made of steel or stone directed by an electric motor from top or bottom. The cone is covered with a perforated screen housed in a frame and fixed to a strong base. The screen is divided into segments by adjustable 30–50 mm rubber brakes at regular intervals around the cone. These brakes extend the full length of the cone with 2–3 mm clearance from the cone. The hulled rice is fed from top through a hopper and is moved to the clearance zone between screen and cone. The abrasive surface of the revolving cone removes the bran layer of the hulled rice. The bran powder is pushed through screens and is collected separately while white rice is collected at the bottom. The degree of milling is directly linked with the milling and cooking quality of rice. Lesser the clearance zone, the higher will be the degree of milling, keeping other factors including revolutions per minute of cone and feed rate as constant. Intended increase in degree of milling, however, may increase the breakage percentage. It is therefore advisable that complete bran removal should be avoided and hulled rice should be passed through multiple whiteners to reduce loss in the form of breakage. Any vibration in the cone may cause a great loss due to uneven polishing and increases breakage. It is therefore suggested that the whitening machines should be fixed on very solid and compact base. Damage to the rice grains during milling may be due to very high heat of resistance that may develop cracks in rice and increase the breakage percentage (Banaszek and Siebenmorgen 1990). In order to avoid frequent losses from rice, air is continuously passed through the whiteners to remove heat of resistance and dust fraction.

Horizontal abrasive whitener The abrasive roll in horizontal abrasive whitener consists of an emery stone attached to a steel shaft rotated by an electric motor, and is covered with a metallic perforated cylindrical screen. The unhulled rice fed from one side travels along abrasive roll and bran is removed through abrasive action and is passed through the perforated sheet. The degree of milling is adjusted by the feed rate controlled at the intake hopper and pressure developed on account of adjustable weighted discharge gate. Breakage is increased if the feed rate is very low or the discharge rate is very high or very low. Breakage percentage has been controlled in horizontal abrasive whiteners by replacing the compact steel shaft with a hollow shaft having many small openings to dissipate heat developed in abrasion. Air is passed through these openings to rice and escapes through perforated screens. Multiple advantages have been gained through this mechanism including heat control, removal of dust and powder, low breakage, and low perforation clogging risks. The disadvantage of this machine is that clearance between the screen and emery is not adjustable which is overcome by adjustable weighted discharge gate. Horizontal abrasive whiteners are more beneficial in parboiled rice milling where higher risks of screens clogging exist due to sticky and thick bran powder of parboiled rice.

Horizontal friction whitener The horizontal friction whiteners consist of a steel roller with a steel perforated sheet covering housed in casing. A feeding worm is used to force the grains in the clearance zone between the roll and the screen. Bran layer is removed by frictional force instead of abrasive action and is pushed out through perforations with the air entered through very small openings of the revolving roll in the center. The pressure on the rice during whitening is controlled by a weight adjustment valve at the outlet spout. Milling capacity and recovery is compromised when single pass horizontal frictional whitener is used. It is better to use multistage frictional whiteners to get maximum recovery and minimize breakage percentage. Power requirement of horizontal whitener is about the same as that for vertical and horizontal abrasive polishers.

16.16 Rice Polishing

Rice polishing is the mechanism of making rice glossy or shiny. Physical appearance of rice depends on the degree of milling and polishing. Polishing of rice is characterized as single polished, double polished, touch silky, and silky polished.

Single and double polished rice is prepared on abrasive or friction whiteners discussed above, while polishers are used for silky or touch silky rice.

Polisher consists of a steel roller having very small holes mounted on a shaft that is connected to an electric motor. The roller is encompassed in perforated screens and the whole assembly is housed in a steel or iron casing. If the roller is covered with leather, then it is called as leather polisher. The leather gives a smooth surface and shine to the rice when grains pass through the clearance area between roller and screens. The leather strips roll the whitened rice over and over against the screen. The pressure on rice in the clearance area is controlled by the weight adjustment at the outlet cover. The uniform removal of the bran layers from the rice surface makes it shiner, brighter, and glossy. However, negative attributes like risks of off flavors development and aflatoxins contamination during rest period make polishers as less adoptable technique for rice polishing. Due to this reason the leather polishers have been replaced with water polisher around the globe. Water polishers, like leather polishers, have a steel roller or drum connected to a shaft operated by an electric motor, water control system, and weight adjustment at outlet. The roller is encompassed in a perforated sieve and the entire assembly is housed in a steel cylinder. Rice is fed into the clearance zone between rotating roller and sieve. Air passed through the roller to the clearance area escapes through the perforated sheets along with the fine powder of rice removed from rice surface during polishing. Air is used to dissipate heat from milling system to avoid heat-associated quality losses in rice. A fine mist of clean water is continuously sprayed on the rotor surface to make the rice surface glossy and shiny. This also helps to lower down the temperature of milled rice. Water polishers are very useful and widely used due to their high efficiency, less breakage, and production of high quality rice. Degree of polishing is directly dependent upon the retention time of rice in the clearance area, number of revolutions per minute of the rotor, quantity of the water sprayed, and feed rate (Satake 1990).

16.17 Rice Grading

Milling and polishing under abrasive and frictional forces may produce breakage of various sizes including broken, brews, germs, bran, and head rice. Separation of these particles after polishing or whitening is called grading. The degree of grading is dependent on the choice of the consumers or the rice market. Many markets do not require grading, while others demand a sophisticated grading system to be implemented in order to improve product quality. The demand of graded rice is directly linked with the economic condition of the consumers. A large part of the bran is removed from the screens of the whiteners or polishers and collected separately. However, remaining bran is removed by the process of aspiration for which the blowers are installed at length graders and before final packing. The mixture of broken, brews, germs, and head rice is sent to the plane or rotary sifter. The rotary sifter comprises of a set of two to three screens installed one above the other and fixed in a frame. Screens of various mesh size are installed starting from lower to higher mesh size from top to bottom. The head rice is separated by the top screen, while the fine tips are separated by the bottom screen. Similarly, broken grains of various sizes are separated by central screens (Kour and Singh 2013). In large industries, two to eight sets of these screens are installed one above the other to increase the efficiency and production of more sophisticated product. The vibratory and oscillatory movements of the screens do not efficiently separate broken having length longer than the width of the rice. Hence, this head rice containing broken is passed through the length graders, which have already been explained above.

16.18 Color Sorting

The head rice may have pecky, damaged, yellow, green, chalky, amber, or red-colored grains. The presence of these various colored or damaged grains in export grade rice is considered to be a quality mark in international trade. It is, therefore, recommended to remove these contaminants before the rice is sent to the market. Before 1980s, it was considered very difficult to remove these grains from the head rice. The rice used to pass on a conveyor belt in front of the workers who had to manually pick these grains from the final marketable rice. However, now color sorters of various capacities are available and widely used around the globe for sorting rice (Lisin et al. 2011).

A color sorter consists of a hopper for intake of rice connected with chutes in an inclined position. Each chute is further divided into four channels. Rate of feed is controlled by a feeder device installed at the top of the chutes. The rice in thin layers falls through the channels by gravitational force. Colored grains while passing through the reflector panel are assessed by a high-resolution charge couple device (CCD) optical camera. A sensor connected with the camera passes a signal to the jet valve or ejector to push the undesired grain by a blow of air. The disqualified grains are separated, while qualified grains are collected in the packaging material or stored temporarily in the final storage vessel.

Color sorters of various capacities and efficiencies are available in the market. These have revolutionized the rice export industry since its invention in the second last decade of the twentieth century. It has reduced substantial labor involvement for color sorting. The installation cost of the machine is too high and requires a huge capital but operational cost compromises its purchase. One of the biggest disadvantages of the machine is that qualified grains are also rejected along with the disqualified grains. However, color sorters advantages are beyond its disadvantages, as the rejected grains may be recovered by a second pass through the machine. The machine also requires a skillful person for its proper functioning and maintenance.

16.19 Parboiling

The word “parboiling” refers to partially boiled. Parboiling of rice means partial boiling of rice in the form of paddy. Parboiling is a hydrothermal technique for the treatment of rough rice (paddy) before drying and milling (Miah et al.

2002). Generally, rough rice is soaked in hot water or steamed before drying and milling. Since how long the process of parboiling exists, nobody knows; however, this process was recognized in the early nineteenth century to cope with *beri beri* and vitamin B_1 (thiamine) deficiency (Heinemann et al. 2005). A group of researchers observed a direct linkage of *beri beri* with the consumption of raw milled rice, and parboiled rice was reported to be a remedial technique in *beri beri*.

16.20 Parboiled Rice Has Many Advantages and Disadvantages as Follows Over Raw Milled Rice

16.20.1 Advantages

Milling recovery of parboiled paddy is better compared to raw. During parboiling the starch is partially gelatinized, becomes stiff, harder, and fishers or cracks in rice are filled thus milling recovery and head rice yield is increased (Nguyen and Kunze 1984).

1. The rice texture is improved and it becomes more translucent during milling.
2. Postharvest losses are reduced on account of inactivation of enzymes during boiling or steaming.
3. Hull can be removed very easily compared to raw rice milling.
4. Expansion in volume mass ratio, hence less amount is required per serving.
5. Better cooking quality due to reduction in breakage, bursting, or curling during cooking.
6. Nutritional quality is improved due to the transportation and fixation of vitamins from bran layer to the starchy portion.
7. Inferior rice varieties come at par with superiors.
8. Simplicity of the process.

16.20.2 Disadvantages

1. The risk of development of off flavors in parboiled grains due to fermentation, particularly in cold water.
2. Rice turns light yellow to black depending on the duration of soaking or steaming.
3. Removal of bran layer is difficult and requires higher electric power; hence cost of milling is higher compared to raw rice milling.
4. It requires high initial capital for installation of a parboiling plant.
5. Parboiled rice cannot be used in starch or brewing industry.

16.21 Parboiling Process

In addition to all other steps taken for rice milling, paddy is soaked in water until moisture content reaches to 30 %. Heat treatment is applied to the paddy particularly by steam for the development of some important physicochemical changes followed by drying. Initial investment on paddy drying and rewetting can be saved by using fresh paddy just after threshing and cleaning for parboiling. Usually, the rice crop is harvested when the grain moisture contents are higher than 20 %; hence, high moisture contents will require less energy and time to gain desired moisture level, i.e., ~30 %. Paddy grains are passed through following steps for the manufacturing of parboiled rice.

16.21.1 Soaking

Freshly harvested, matured paddy grains are soaked in warm water to get water to be absorbed until 30 % moisture content. Water absorption by paddy depends upon the time of soaking, temperature, mineral contents, and pH of water. Cold water is absorbed very slowly by the paddy and hence higher soaking time is required for getting desired moisture level that may initiate fermentation. Prolonged fermentation may also lead to the growth of molds and development of aflatoxins on paddy. It has been estimated that soaking is completed in just 2–4 h at a temperature of 60–65 °C compared to 36–48 h in a water having temperature of 30 °C. Similarly, higher salt contents, minerals, and pH of water will slow down absorption of water in paddy. Soaking under vacuum has been reported to reduce soaking time and avoid problems like fermentation (Bello et al. 2008).

16.21.2 Steaming

Gelatinization of rice starch is one of the major objectives of parboiling that makes the rice grains harder and stiffer compared to the raw rice grains thus causing less breakage, improved milling recovery, fixation of biomolecules like vitamins, minerals, etc., and improvement in organoleptic properties of rice. Steaming of soaked paddy is one of the improved methods available in the recent era for gelatinization of rice. The condensed moisture contents of steam have higher capability to increase the moisture contents of paddy up to 38 %. Starch at this high temperature and moisture is gelatinized (Sareepuang et al. 2008). This method has many advantages over primitive sun drying or dry heat:

1. Steam has higher capacity to carry excessive heat.
2. It carries moisture and increases the rate of condensation.
3. It has the capacity to increase the moisture contents of soaked paddy.

4. It improves the gelatinizing properties of starch.
5. It helps to minimize losses like burning or blackening of paddy grains as a result of dry heat.
6. It helps to evaporate extra moisture from paddy leaving concentrated molecules in the grain.
7. The excessive heat of steam helps to kill the microorganisms particularly pathogens and to some extent degradation of toxins.
8. Heating of soaked paddy with steam under pressure will help to open the husk indicating the completion of the process consequently the dehulling of the paddy will be easier.
9. Steaming retains better color and flavor of rice compared to dry heat.
10. It improves the cooking quality of rice, including separation of grains, volume expansion, and decreased chances of bursting, curling, and breakage.

A range of utensils, structures, and equipment have been used for soaking and steaming of paddy on pilot plant and commercial units.

16.21.3 Concrete Soaking Tanks

Fixed structures with all four walls and floor made of bricks, mortar, and/or cement having no roof is used for soaking of paddy in hot or cold water. The size of the tank is made according to the requirement and may be rectangular or square. A typical soaking tank 2.4 m wide, 3 m long, and 2.1 m deep is considered to be suitable for pilot plants. Paddy is filled up to 1.7 m depth in order to accommodate swelling during soaking. Concrete soaking tank has less initial cost; however, it has many disadvantages.

1. The tank cannot be inverted and paddy is removed from the tank manually and labor faces problems in handling hot paddy.
2. Cleaning of the concrete soaking tank is difficult and extra water and labor are required for the purpose.
3. Cracks may be developed in the concrete walls due to intensive use of water; hence, continuous maintenance is required.
4. Greater chances of microbial, pest, and rodent attack; hence, a higher contamination rate.
5. Being open roof, its working depends upon environmental conditions.
6. More heat loss if soaking is in hot water.

16.21.4 Drying of Steamed Paddy

Handling of steamed paddy is more sensitive compared to rough rice. Steamed paddy is dried by the same methods as discussed for rough rice paddy with the exceptions that it requires higher initial temperature. Moreover, if the paddy is dried in a single stage, chances of cracks and fishers in the grain are increased; hence less recovery with more breakage and poor cooking quality has been observed (Siebenmorgen and Meullenet 2004). It is advisable to dry the steamed paddy in two to three stages on mechanical dryers and tempering duration of 12–36 h for each stage. The tempering time facilitates aging and equalizes the moisture content uniformly among the paddy grains.

16.22 Postharvest Losses

Postharvest losses of cereal grains account for 10–40 % losses in grains quantity and/or quality from farm to fork. Developing countries are particularly more susceptible to these losses on account of poor access to innovative harvesting, storage, transportation, drying, and milling techniques. Being a major field crop, postharvest losses of rice cannot be avoided but can be curtailed to an appreciable extent. Paddy, like other crops respires and hence loss of energy in the form of heat dissipated to the storage environment results in excessive loss of grain quality if not properly managed (Tyler and Gilman 1979). Sizeable reduction in postharvest losses reduces the cost of rice harvesting, drying, and milling. It helps to cut down the prices on trade distribution, improves the livelihood of the farmer and increases the purchasing power of the consumer as well (Panhwar 2006). Losses in rice can be curtailed by the application of advanced postharvest techniques in entire rice production and processing chain. Following parameters are helpful to cut down the postharvest losses to their minimum.

1. *Identification of maturity stage:* Harvesting at maturity is necessary to avoid losses from shattering and in the form of immature, slender, or chalky grains. Over maturity leads to shattering of the grains in the field, while under ripening results in slender and chalky grains.
2. *Rapid harvesting*: The use of combine harvesting is helpful to manage the crop very rapidly. The losses due to rains, thunder storms, attack of fungus and pests, and inclusion of mud, dirt, and dust can be avoided. The combine harvesting should therefore be preferred over conventional methods of harvesting of rice crop.
3. *Timely threshing*: The crop after harvesting should be threshed very rapidly. Keeping crop untreated after harvesting increases the chances of fungus attack, discoloration, yellowing, and shattering.
4. *Quick drying:* Quick drying after harvesting and threshing reduces the chances of heat burn during fresh crop storage.
5. *Mechanical drying—preferred drying technique:* Mechanical drying compared to sun drying is helpful to manage the crop produce rapidly. It reduces the chances of inclusion of dockage, fungal, and pests attack. Wise mechanical drying avoids the development of cracks and fissures, hence curtailing the milling and quality losses.

6. *Adequate cleaning*: Cleaning of paddy before drying and milling can avoid losses induced in the form of wear and tear of machines. It also improves the milling recovery. It is, therefore, advisable to use precleaners before drying and milling.
7. *Advanced rice milling*: Advanced methods of rice milling can reduce the grain losses to an appreciable extent. It has been estimated that head rice recovery at village level husking-cum-milling machines is around 40 %, while it is 70–80 % at advanced milling machines. It is, therefore, recommended to use pneumatic huskers and rice polishers to avoid conventional methods of milling.
8. *Milling moisture*: Proper moisture contents of paddy grains before milling is vital to avoid excessive losses. The moisture content between 13 and 14 % is considered ideal for maximum recovery of head rice.
9. *Storage*: Storage of rice at 12 % moisture decreases the chances of mold attack. Moreover, losses due to heat of evaporation are minimized if the paddy crop is stored below 16 % moisture content. Proper aeration, control of pests, management of relative humidity, and temperature are the key factors to avoid losses during storage.
10. *Insects, pest management*: Storage losses due to insects can be reduced by the application of spray of piperonyl butoxide, tetrachlorovinfos, fenithrothion, etc., or a suitable fumigant like methyl bromide, phosgene, carbon tetrachloride, hydrogen cyanide, etc., after fixed intervals.
11. *Packaging and transportation*: Poor transportation and defective packaging can lead to quantitative losses of the product (Kiaya 2014). It is, therefore, recommended to use packaging bags of various sizes and proper transportation vehicles to avoid losses during traveling and storage.

16.23 Rice Storage

Paddy, if not immediately milled, is dried for storage. Likewise, milled rice needs to be stored until it is delivered to the market for sale. Paddy and rice can be stored for a few years if storage conditions are appropriate. Grain moisture is one of the important factors to be considered critically while planning for short term or long term storage. Higher the moisture of the commodity during storage, lesser will be the storage stability. It has been estimated that at 12 % moisture contents and optimum relative humidity, paddy, and rice can be stored for years (FAO 2008). Digital portable and desktop grain moisture meters are available in local markets with a knob to put into heap or bag of rice or paddy grains. However, digital moisture meters are necessary to be calibrated with hot air ovens; a most reliable method for the determination of moisture in any commodity. Insect infestation during paddy or rice storage is a major concern that can be controlled by implementing an integrated pest management program. Need-based storage facilities can be constructed to store paddy and rice at industrial and home scale levels. Generally, at home scale levels, paddy and rice are stored in bins made of mud, cement, and bamboo, or cement and bricks, or iron and steel. However, extended facilities in the form of temperature and atmosphere controlled large silos and or warehouses with stacked sacks and bags of commodity are deployed at the industrial scale.

16.24 Nutritional Composition and Significance of Rice in Human Health

Globally, rice stands third in a list of 30 highly produced and consumed food crops of the world with an estimated production of ~479 million metric tons of milled rice (IGC.int 2015). In Asian perspectives, rice is a staple diet of 15 countries where the crop provides around 715 kcal per capita daily. On energy and nutrient scale, this much amount of rice consumption adds up ~27 % dietary energy and 20 % daily protein intake. It is likely that in countries like Bangladesh, Viet Nam, Laos, Cambodia, and Myanmar rice consumption is responsible for 50 % per capita dietary energy and protein requirements (FAOSTAT 2011). Before marketing, rice grains are milled to produce brown rice, white rice, hull, and bran nutritional composition of which varies with cultivars and milling extent. Despite the valuable nutrition of brown rice, globally higher intake is recorded for white polished rice. The milling and or polishing process destroys at least 50–90 % of rice B vitamins, essential minerals, fatty acids, and fiber (Ensminger and Ensminger 1986).

16.25 Nutritional Composition of Rice

Milled rice is referred to be a good source of carbohydrates, predominately starch, whereas appreciable amounts of macro and micronutrients that exists in bran fraction are leached down with mill-fractions. B vitamins are concentrated to a greater extent in bran layer and 65 % of thiamine, 39 % of riboflavin, and 54 % of niacin contents are reported in the same. It is due to these reasons that brown rice is recommended for consumption as edible grain as compared to milled rice that is devoid of pericarp, testa, embryo, and aleurone layer. Distribution of energy yielding compounds, i.e., carbohydrates, protein, and fats varies with different rice fraction. Maximum protein (7.1–8.3 %) and fat (1.6–2.8 %) contents are anticipated in the brown rice, whereas maximum carbohydrates (77–89 %) are attributed to the milled rice. As far as some fractions are concerned, maximum protein, fat, and fiber contents are found in rice bran, i.e., 11.3–14.9 %, 15.0–19.7 %, and 7.0–11.4 %, respectively (Julino 1993).

16.26 Micronutrient and Phenolics Contents

Micro and macroelemental composition of rice varies with its various forms and processing conditions, e.g., those of parboiled, milled, and brown rice. The studies show higher ash contents (~18 %) in parboiled rice as compared to the milled rice proclaiming higher contents of K and P (Heinemann et al. 2005). Nutritional assays on various cultivars reveal more or less similar as proximate composition including moisture, protein, fat, ash, and fiber; however, some minor differences exist for the micronutrients particularly vitamin E, thiamine, and iron. These exist in higher amounts in Chinese wild rice compared to the American wild rice (Zhai et al. 2001). Well-versed genetic diversity exists in rice as far as nutritional composition is concerned. A study carried out on unpolished rice reveals an intravarietal difference in proteins (9 g), zinc (3.34 mg), thiamine (1.6 mg), iron (5.65 mg), niacin (7.2 mg), and riboflavin (0.39 mg) (Kennedy and Luo 2015). A recent update on nutritional quality of commercial rice available in Malaysia proclaims nondetectable levels of cholesterol and very low level of trans fatty acid. The study estimates appreciable levels of vitamin B1, A, C, and E to exist in all commercial rice brands (Fairulnizal et al. 2015). Higher acceptability levels have been recorded for black rice in Korean culture where rice is consumed as staple food. Black rice is a good carrier of anthocyanin and associated antioxidant activity and hence have very important role of not only providing dietary energy but also functional health features to its ultimate consumers. Forty-two pigmented rice cultivars were analyzed for their micronutrient contents and radical scavenging activity. The study identifies iron to be the most prevalent mineral element as compared to Zn, Cu, and Mn. Antioxidant activity associated with their good pool of polyphenols was reported to be of 31.9–98.5 %, whereas tocotrienol contents were comparatively higher than tocopherol (Ha and Lee 2015).

16.27 Rice Nutrition and Consumer's Health

Rice is not a primary food crop among most of the children and adolescents of America. Whereas, high and low rice consumers of non-Hispanic and Indo-Asian mixed racial children and the adolescents are reported to meet maximum of their caloric requirements from rice and hence have significantly higher body reserves of certain micronutrients, e.g., iron, folates, copper, magnesium, vitamin B6, vitamin C, thiamine, and niacin (Luo and Kennedy 2015). A significant difference exists in dietary pattern and energy intake of rice and non rice consumers that can be evaluated in the form of saturated fat consumption. Rice consumers are generally referred to be good in micronutrient pool, low in saturated fats, and physically possess lower waist circumference, skinfold, and body mass index, i.e., less than 25 kg/m^2 (Kennedy and Luo 2015). Higher household expenditure on rice in countries where it is cultivated as staple food crop is highly associated with multiple micronutrient deficiencies due to poor diet diversification and low expenditure on non rice foods. Torlesse et al. (2003) suggested reduction in the underweight children population of rice grown regions might be anticipated by more expenditure on non rice foods.

16.28 Recent Innovative Approaches to Improve Nutritional Quality of Rice

A very significant role of nutritional genomics has been observed to cope with the situation of multiple micronutrient deficiencies in health and economic status of malnourished populations. Staple crops including wheat, rice, and maize that are not adequate or good source of vital nutrient like iron, vitamin A, iodine, and zinc were engineered owing to their maximum acceptability as staple food grains by the undernourished populations. In order to address ever increasing burden of anemic population from socioeconomically weaker communities, transgenic iron fortified rice has been introduced that has been developed by adopting approaches like improving grain iron reserves, enhancing iron translocation, and improving its flux into the endosperm (Masuda et al. 2012). The study referred further endorses multiple transgenic technologies to be the more effective approach in addressing micronutrient deficiencies compared to single gene manipulation for some particular micronutrient. Genetically engineered rice cultivar 'Golden Rice' was produced aimed at addressing vitamin A deficiency and associated disorders. Genetic modifications were made to produce β-carotene—pro-vitamin A in the endosperm, i.e., ~31 μg/g of 37 μg/g carotenoids. Despite more than normal reserves of vitamin A as carotenoids, a debate still exists on golden rice incompetency to address severe deficiencies of vitamin A in underprivileged populations (Dawe et al. 2002; Paine et al. 2005). Zinc biofortification of rice is in practice by its foliar spray irrespective of environmental conditions, cultivars, and crop management practices. The biofortified rice crop is reported to significantly affect zinc deficiencies and cut down burden of immune dysfunction, growth retardation, and cognitive losses (Bashir et al. 2013).

16.29 Rice Based Edible Products

Cooked rice is taken as a staple diet by more than 50 % of world population. The major by-products during milling are rice bran, husk, brews, germ, and polish. These by-products are primarily used in the feed industry. In addition, following food products are manufactured for human use.

16.29.1 Rice Pudding

Rice pudding is usually prepared by addition of water or milk in the rice along with other desired flavoring agents. Rice pudding makes delicious desserts for dinners equally liked by people of all ages in different cultures. Rice puddings being prepared as dessert are made with added sugar alongside cinnamon, ginger, flavor, and egg. Variants of rice puddings are reported from various parts of the world depending on regional food habits and cultures. Rice puddings being consumed as desserts in South Asian countries like India and Pakistan are known as *Kheer* and *Firni*.

Rice puddings are considered instant energizers as they contain high contents of carbohydrates as rice starch and simpler sugar. The presence of milk in rice puddings makes them rich in calcium and vitamin D that are beneficial for stronger bones and healthy teeth. Moreover, the fibers in the rice pudding help in regulation of bowel movement and relieve constipation. Rice puddings are also well known for their usage in human experimental studies related to bowel movements and blood glucose levels along with other ingredients (Hlebowicz et al. 2009; Pritchard et al. 2015). Rice pudding does not contain gluten, so people allergic to gluten may rely on rice puddings for their energy requirements in addition to other gluten free diets. Depending upon the type of ingredients used, a serving of 5–6 ounces may provide 130–230 kcal energy (Corleone 2015).

16.29.2 Rice Bread

Rice flour is used in some regions replacing wheat flour for the preparation of rice bread. Rice bread being gluten free is suitable for individuals allergic to gluten. For the preparation of gluten free breads, the rice flour may also be used in various proportions with other gluten free starch sources that include corn and potato for better volume and crumb structure (Sanchez and Osella 2002). Rice flour supplementation has shown better sensory performance in gluten free bread preparation compared to corn and cassava flours (López et al. 2004). Rice flour is considered to be highly suitable for production of gluten free breads as it is colorless, easily digestible and hypoallergenic with no off flavors. Other basic ingredients required for the production of rice bread include yeast, sugar, oil, water, and salt (Kadan et al. 2001). Rice flour is also low in sodium, fat, and fiber (Gujral and Rosell 2004a, b). Kadan at al. (2001) showed stronger tendencies of rice starch to retrogradation compared to whole wheat bread. However, due to lack of elasticity and plastic properties in rice proteins like those attributed to wheat gluten, application of rice flour in baking is limited (Juliano 1985). Gluten replacers such as hydroxy propyl methyl cellulose are used in addition to the basic ingredients to enhance the rheological properties of bread dough to obtain the bread with better crumb and textural properties (Sivaramakrishnan et al. 2004).

16.29.3 Rice Cakes

A rice cake is made from the rice, shaped, condensed, or combined into a single object. Rice cakes are becoming popular as a snack food among people because of their low caloric value and low fat contents. Rice cakes may be made from rice flour, ground rice, or from whole grain rice compressed or combined together with some binding substance. The preparation of rice cakes is based upon their popping characteristic under heat and pressure. The balance between the ingredients, moisture, time, and temperature is of foremost importance as their imbalance can result in the breakage of rice cakes during production decreasing their value.

Rice cakes prepared from rice grains are prepared in popping machines in which they are exposed to heat and high pressures. The rice should be subjected to ideal temperature and time combinations for its desired expansion. The additives such as flavors and sweeteners are sprayed onto the cakes after their preparation as early addition of additives increases the risk of cake breakage. Sticky rice varieties are preferred, while the long grain varieties do not expand much during cooking.

Stabilizers and to some extent emulsifiers are used in rice cake preparation to improve viscosity and stability of batter. A study showed that the addition of xanthan and xanthan-guar gum blends showed increased viscosity of the batter. The addition of emulsifier blend resulted in softer and porous final product (Turabi et al. 2008). However, the baking methods also affect the microstructures of cake. Conventional baking methods tend to deform the starch structure more as compared to the cakes baked through combination of IR-MW (infrared-microwave) ovens (Turabi et al. 2010).

16.29.4 Rice Noodles

Rice noodles are prepared using rice flour and water. Noodles from rice flour are very popular traditional foods in the South China. The production processes used for a particular type may differ from region to region to meet local demand; however, the basic production principles are usually the same. Rice noodles are classified on the basis of molding methods as well as the moisture contents. On the basis of molding method, rice noodles are classified into cutting noodles (1 mm thick, 4–6 mm wide, and 200 mm long) and spreading noodles (rice noodle wrapper rolls containing different fillings) (Li et al. 2015).

On the basis of moisture contents, rice noodles are further classified as dehydrated and fresh noodles. The amount of moisture in fresh rice noodles ranges between 40 and 65 %, while that of dehydrated noodles ranges between 15 and 25 %. Moisture content plays an important role in flavor and texture of the noodles. However, higher moisture contents compromise shelf-life of the finished product. On the contrary, dehydration can improve shelf-life of the rice noodles for extended period of time (Chen et al. 2012).

16.29.5 Rice Bran Oil

Rice bran oil (RBO) is extracted from the hard outer brown layer well known as bran of the rice. Crude form of rice bran oil is obtained using solvent extraction followed by distillation. RBO is considered to be very useful for salads and cooking purposes due to high smoke point as compared to other oils along with slight flavor

(Ghosh 2007). The smoke point of RBO is up to 213 °C and its saponification value ranges between 180 and 195 (Orthoefer 2005).

In its crude form, RBO comprises of 2–4 % free fatty acids (FFA) that can initiate lipids hydrolysis if FFA are not extracted immediately. The FFA develops at a rapid pace of ~5–7 % per day in the rice bran. Therefore, it is important to stabilize the rice bran before extraction to obtain good quality rice bran oil (Saunders 1985).

During recent years, RBO has gained significant popularity on account of its health benefits. RBO and its essential fatty acids composition have shown an ability to improve plasma protein patterns of rodents, rabbits, and humans through reduction of plasma cholesterol and concentration of triglycerides along with an increase in high-density lipoprotein (HDL) levels (Cicero and Gaddi 2001). A study revealed that RBO exhibits cholesterol lowering ability in healthy and moderately hypercholesterolemic adults, decreasing LDL concentration ~7 %. This activity may be attributed to unsaponifiable components of RBO (Most et al. 2005). Other beneficial effects of RBO include anti-inflammatory properties (Nagasaka et al. 2007). Other than consumption, researchers have been working on the utilization of RBO as biodiesel fuel through transesterification for the production of RBO methyl (Sinha et al. 2008).

16.29.6 Rice Vinegar

Rice vinegar has been in use with the Chinese people for almost 3000 years. Rice vinegar is made by fermenting rice into alcohol and then further into acid. Sometimes rice vinegar may be confused with rice wine. However, they both are different products. Rice wine is prepared through a fermentation process that involves yeast for the transformation of sugars from rice into alcohol. While for the preparation of rice vinegar, another step is required that involves the addition of bacteria for the conversion of alcohol into acid (Xu et al. 2010). Rice vinegar is sodium free making it beneficial for hypertension patients (Corleone 2015).

16.29.7 Edible Rice Films and Wrappers

Rice flour is usually prepared from broken rice that is not fit for further processing. Therefore, in many cases it proves to be cheaper than other sources of starch. Use of rice flour for the edible films and coatings is becoming popular. Different methods are being developed to reduce its levels of permeability. A study revealed that the rice flour or rice starch coating with sorbitol as a plasticizing agent decreased the permeability of water and resulted in more rigid structure (Dias et al. 2010). Rice protein concentrate was also used to prepare edible films with addition of polysaccharides complex (pullulan) along with the incorporation of oils for enhanced resistance against water vapors (Shih 1996). In another study, rice wax up to 46.4 % was used in addition to pullulan to obtain compact film structures. Addition of rice wax is also reported to improve moisture barrier properties (Shih et al. 2011).

16.29.8 Other Products

Other products of rice that are accepted by a large number of consumers include rice cereals, rice fudge, rice cookies, and crackers. Some of the products like rice milk are not very common among the people but are in use due to certain health complications in particular individuals. Most of the rice products are used as an alternative due to shortage of other available raw material or by the individuals having certain disorders related to consumption of some food stuff.

16.30 Rice Quality

Rice quality is a difficult term to define as it depends upon the acceptability of the consumer to a greater extent. However, on broader term, rice quality may be divided into two categories, i.e., milling and cooking. Milling quality of rice determines the final yield during milling, while cooking quality determines the acceptability of the consumer. Both cooking and milling quality of rice depend upon the type of the variety, environmental factors involved during production and methods of harvesting, drying, and milling of rice (Siebenmorgen and Meullenet 2004).

16.30.1 Milling Quality

Paddy having high head rice yield, low broken, bran, and polish is considered good for milling. Milling quality of paddy is dependent on the following interrelated factors:

Moisture content Moisture contents at harvesting and subsequent storage before or after drying of paddy are one of the most important factors contributing toward the storage, milling, and cooking quality of rice. The optimum temperature at harvesting may reduce the losses due to shattering on account of less moisture contents and unripened paddy grains due to high moisture contents. The ideal moisture contents for harvesting are 20–26 %. Maximum milling yield of rice can be obtained at 13–14 % moisture contents of paddy. The broken percentage below and above this optimum moisture contents may increase due to pulverization and stiffness of grains. Control of moisture contents during drying is also a critical factor to ensure the milling and cooking quality of rice, as cracks and fissures are the characteristics attributed toward improper paddy drying.

Degree of purity Purity is related to the presence of dockage, i.e., materials other than paddy including hay, chaff, stones, seeds of weeds, soil, and mud, etc., included from the field or drying floor. Impurities increase the cost of paddy cleaning or some time wear and tear of the machines. Milling yield is also influenced by these impurities.

Admixture Seeds of contrasting varieties may be mixed during handling at farm or may be added as adulterant during paddy drying. Grains of various sizes and shapes make it difficult to adjust hullers, huskers, whiteners, and polishers to produce whole grains; hence head rice yield is reduced. In addition to milling recovery, cooking quality of rice and hence consumer's acceptability is influenced.

Cracked grains Exposure of paddy grains with shocks of high temperature and moisture may result in the development of cracks and fissures in the rice. These fissured and cracked grains cannot withstand high pressure of frictional forces of milling. Hence, broken percentage is increased with low head rice yield.

Immature grains Immature grains that have not developed properly are thinner, slender, chalky, and opaque on milling. The higher the percentage of these grains in the paddy, the lower will be the milling recovery. After milling, these are converted into broken, brew, and polish and ultimately reduce the head rice yield.

Damaged grains High moisture, insect attack, and high temperature during storage may cause physical and biochemical changes in the grains. The grains have less tensile strength and cannot withstand milling resulting in increased broken percentage and reduced milling yield.

Discolored grains The grains of various colors including yellow, amber, chalky, red, and green may be present in the paddy that might come from the field due to environmental factors or high moisture during temporary storage before drying. Various biochemical reactions and microbiological activity may generate excessive heat during temporary storage of the paddy and partly gelatinize the rice starch, hence changing the color of rice from white to amber, yellow, brown, or black. This discoloration may not influence the milling yield but influences the consumer acceptance.

16.30.2 Cooking Quality

Cooking quality of rice in addition to above factors is also dependent on the following factors:

Variety of rice Variety is one of the major factors of rice contributing toward its cooking quality. Starch is 90 % of the dry matter content of rice. It is composed of linear (amylose) and branched (amylopectin) polymers of glucose units. The amylose has the lesser tendency to hold moisture. Rice having high amylose contents dries at cooking, absorbs less water, and becomes hard upon cooling (Bhattacharya 2011). On the other hand varieties having higher contents of amylopectin absorb more water, become sticky, and do not become dry on cooling. Rice having amylose content 1–2 %, 3–9 %, 10–20 %, 21–25 %, 26–30 % is considered as waxy, very low, low, intermediate, and high amylose content rice, respectively.

Degree of milling Degree of milling is the measure of percentage of bran removed from the brown rice. It is the degree of milling that determines the color of the rice, milling yield, broken percentage, absorption of water, volume expansion of rice grain during cooking, and consumer's acceptance (Champagne 2004). The bran layer on the surface of brown rice allows poor absorption of water hence does not allow starch to expand properly. Moreover, complete removal of bran layer again causes excessive absorption of water and its seepage in rice starch from the grains, hence causing stickiness of rice. Proper degree of milling is compulsory for the rice having good cooking and consumer's acceptance qualities. It is considered that 75 % bran removal may result in rice of good cooking qualities (Rodriguez-Arzuaga et al. 2014).

Gel consistency It measures the tendency of cooked rice to harden on cooling. Rice varieties having softer touch on cooling within the same amylose contents have higher degree of tenderness, and are preferred around the globe. Rice varieties having higher amylose contents are harder. Gel consistency is measured by heating rice in small quantity of dilute alkali (Bergman et al. 2004).

Gelatinization temperature The time required for cooking milled rice is called gelatinization temperature. The gelatinization temperature is influenced by environmental factors particularly temperature during rice production. Higher the temperature during rice production, greater is the gelatinization temperature of the rice (Waters et al. 2006; Shu et al. 2006).

16.31 Conclusions

Mechanical methods of drying, improved versions of hullers, and advancement in the milling machinery have resulted in high yield and better cooking quality of rice. In addition, better storage techniques and advancement in the means of transportation curtailed the postharvest losses to certain extent. However, socioeconomic limitations, lack of awareness, and poverty are the major hurdles to adopt innovative techniques and machinery in the developing countries. Research-based strategies to develop cost-effective techniques for harvesting, drying, storage, hulling, and milling of rice are further required, particularly for small farmers of the developing economies to curtail postharvest losses and to impart better quality to rice.

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Chapter 17
Rice Physiology

Ahmad Nawaz and Muhammad Farooq

17.1 Introduction

Rice (*Oryza sativa* L.) is the staple food for millions across the globe. Major consumption of rice takes place in the tropical and subtropical Asia. Globally, rice is grown either as upland and/or lowland crop. Although, the irrigated lowland rice covers about 57 % of the land under rice cultivation but that contributes nearly 76 % of the global rice production (Papademetriou 2000).

The rice growth cycle can be divided into three distinct growth stages, viz., (i) germination and stand establishment, (ii) vegetative stage, and (iii) reproductive and grain-filling/grain ripening stage (Fig. 17.1; Fageria et al. 2006). Rice plant enters from one phase to the other one after a specific period of time (Tables 17.1 and 17.2). Tillering, root growth, stem growth, and leaf development are the major events of vegetative growth phase. Booting, heading, flowering, and panicle development (panicle size and spikelets per panicle) are the main events of reproductive growth phase. During grain-/spikelet-filling stage, the grain weight/spikelet weight is determined (Fageria et al. 2006). In this chapter, the physiology of different growth stages, aerenchyma formation, and stomatal development of rice is discussed.

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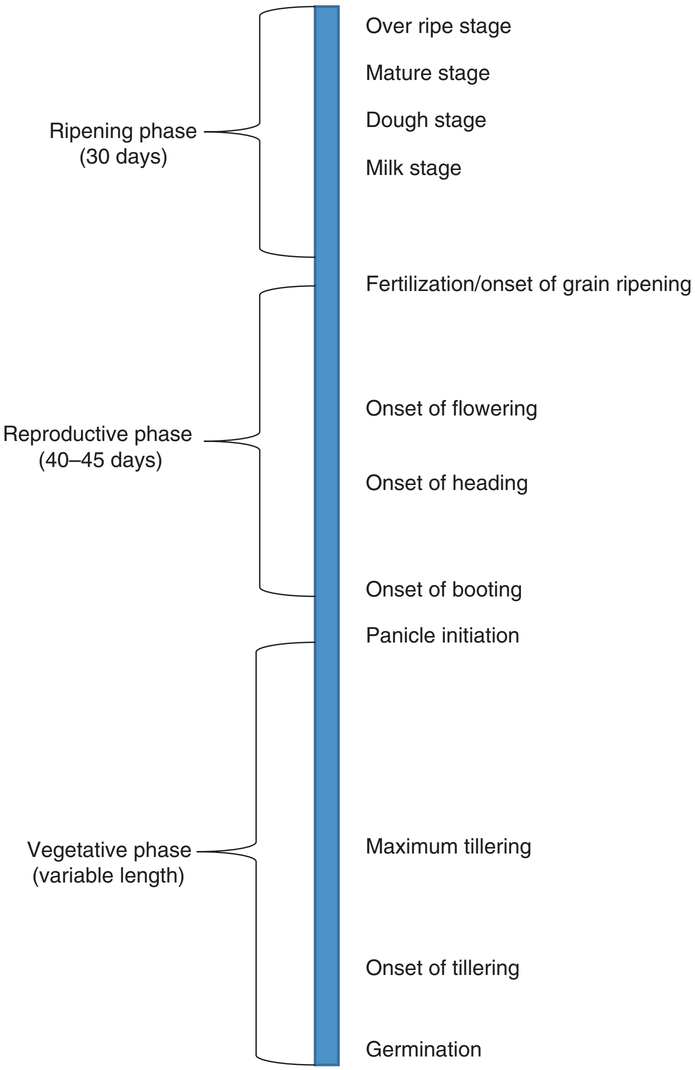
Fig. 17.1 Growth stages of rice



Moreover, the impact of drought, heat, and salinity on growth, development and yield formation, and resistance mechanisms are also described.

17.2 Rice Growth and Development

17.2.1 Germination and Stand Establishment

Seed germination is a crucial stage in rice life cycle which starts from the water uptake by dry seeds and ends with radicle protrusion (Bewley 1997). For nutrient storage, rice seed has dominant endosperm enriched with starch. The endosperm is

Table 17.1 Various developmental stages of rice

Seedling growth stage	Code	Vegetative development stage	Code	Reproductive development stage	Code
Dry, imbibed seed	S0	Collar formation on first complete leaf on main stem	V1	Panicle development has started	R0
Emergence of coleoptile	S1	Collar formation on leaf 2 on main stem	V2	Panicle branches have formed	R1
Emergence of radical	S2	Collar formation on leaf 3 on main stem	V3	Flag leaf collar formation	R2
Emergence of prophyll from coleoptiles	S3	Collar formation on leaf 4 on main stem	V4	Panicle exertion from boot, tip of panicle is above collar of flag leaf	R3
		Collar formation on leaf 5 on main stem	V5	One or more florets on the main stem panicle have reached anthesis	R4
		Collar formation on leaf 6 on main stem	V6	At least one caryopsis on main stem panicle is elongating to the end of hull	R5
		Collar formation on leaf 7 on main stem	V7	At least one caryopsis on main stem panicle has elongated to the end of hull	R6
		Collar formation on leaf 8 on main stem	V8	At least one grain at the main stem panicle has a yellow hull	R7
		Collar formation on leaf 9 on main stem	V9	At least one grain at the main stem panicle has a brown hull	R8
		Collar formation on leaf 10 on main stem	V10	All grains which reached R6 have brown hull	R9
		Collar formation on leaf 11 on main stem	V11		
		Collar formation on leaf 12 on main stem	V12		
		Collar formation on leaf 13 on main stem	V13		

Source: Counce et al. (2000, 2003)

Table 17.2 Description of different growth stages of upland rice

Growth stage	DAS	Description
Germination	5	The stage at which coleoptile tip first became visible
Tillering initiation	19	The crop growth stage at which first tiller is visible from the main shoot
Active tillering	45	Development stage when maximum tillering rate per unit time occurs during crop growth
Panicle primordia initiation	61	The stage at which panicle initiation starts
Booting	85	The development stage at which panicle is within uppermost leaf sheath
Flowering	95	The development stage when flowers become visible on the panicles
Physiological maturity	120	The stage when grains become ripen and the panicles become ready to harvest

Source: Fageria (2007)
DAS days after sowing

surrounded by an embryo and aleurone layer. Scutellum, a metamorphous of cotyledon, lies between the endosperm and embryo. The endosperm and embryo have differential role in seed germination in rice. Most of the genetic information is encoded within the embryo. Seed germination takes place in three phases in rice (Yang et al. 2007). In the first phase, rapid uptake of water occurs which initiates the mRNA synthesis (Howell et al. 2009). Upon imbibition of water in the phase I, the embryo produces various types of phytohormones [mainly gibberellic acid (GA)], which initiates a signaling cascade after diffusing through the aleurone layer and leads toward the synthesis of hydrolytic enzymes (α-amylase being the most important). These enzymes are secreted in the endosperm, which initiates the hydrolysis of food reserves for further development of rice seedlings (Jacobsen et al. 1995; Bethke et al. 1997). Phase II is vital for metabolism reactivation, reserve mobilization, repair of cell structure, loosening of cell wall, and elongation of coleoptile. During the phase III, rapid water uptake induces the aerobic respiration, initiates cell division, and pushes the radicle protrusion – initiation of the seedling establishment (Yang et al. 2007). This is followed by emergence of prophyll from the coleoptile. Following this, the first complete leaf emerges. The seedling development continuous and follows the order as (i) leaf initiation, (ii) leaf elongation, (iii) leaf blade maturation, (iv) collar formation, (v) leaf sheath elongation, (vi) node formation, and (vii) internode elongation (Counce et al. 2000). Internode elongation occurs for the final five internodes of the rice main stem.

Various external and internal factors such as light, water, temperature, level of phytohormones, and circadian rhythm regulate the rice seed germination (Penfield et al. 2005; Holdsworth et al. 2008). Among these factors, water status is the most important; its deficiency may affect the seed germination (Hundertmark et al. 2011). Rice seed can also germinate under anaerobic conditions via rapid coleoptile elongation (Menegus et al. 1991; Perata et al. 1997), and the radicle continues to elongate when switched toward aerobic conditions. This suggests that availability of oxygen is another factor controlling the true germination of rice seed (Howell et al. 2009). Temperature has a strong impact on germination of rice seed. The imbibition in rice seeds occurs at an adequate temperature in the presence of oxygen (Yoshida 1981). The minimum, optimum, and maximum temperatures for rice seed germination are 6, 37, and 41 °C, respectively, while the minimum, optimum, and maximum temperatures for seedling development are 8, 37, and 44 °C, respectively (Chaudhary and Ghildyal 1969; Alocilja and Ritchic 1991).

17.2.2 Vegetative Stage

17.2.2.1 Tillering and Shoot/Root Growth

Tiller initiation in rice starts when rice seedlings are at 3–4 leaf stages. Tillers are the secondary shoots which appear on the main shoot. The formation of tillers is completed over a period of 2–3 weeks. In rice, tillering proceeds without any restriction when the plant nitrogen contents are ≥3.5 % in the presence of sufficient light energy (Murata and Matsushima 1975). Phosphorus (P) concentration in the rice stem below than 0.25 % may restrict the tillering (Counce et al. 2003). For tiller emergence, optimum water temperature during the day is 31 °C while that for night is 16 °C. Water temperature above 31 °C affects the tiller emergence. The tillering continues if the light reaches the base of the rice plant (Counce et al. 2003).

Some tillers may die during the rice growth cycle, and surplus amount of nutrients in dying tillers may be translocated to other healthy tillers (Murata and Matsushima 1975). Li et al. (2003) isolated and characterized a gene *MONOCULM 1* (*MOC1*), which controls tillering in rice. This *MOC1* gene encodes reputed GRAS nuclear protein families, which are expressed in axillary buds, thus initiating the formation of axillary buds and facilitates their outgrowth.

Various hormones are involved in tillering, e.g., cytokinins (CK), auxins, and strigolactones (SL) which play the key role (Kebrom and Richards 2013). Auxins suppress the outgrowth of the axillary bud. These auxins are produced in young developing leaves and are transported actively but basipetally through the shoot (Agusti and Greb 2013), and this is termed as polar auxin transport (PAT). Zazímalová et al. (2010) reported that PAT relies on the PIN-FORMED (PIN) protein families and auxin efflux carriers of ATP-binding cassette B (ABCB). The auxins travel through the outermost shoot apex epidermal layer and reach to plant organ initiation sites. From here, auxins move toward the basipetal stream of the main shoot via the developing primordia. The PIN1 proteins, which are present in parenchyma cells of xylem, sustain the supplementation of auxin toward the basipetal stream of main shoot, thus playing key role in PAT (Petrásek and Friml 2009). Underexpression of *OsPIN1b* (previously known as *REH1*) enhances tillering in rice (Table 17.3; Xu et al. 2005; Chen et al. 2012). Overexpression of *OsPIN2* enhances tillering but reduces the stature (Chen et al. 2012). Some members of the miR393 miRNA family also impact tillering in rice by regulating the expression of

Table 17.3 Gene expression and mutants identified at various developmental stages of rice

Developmental stage	Genes expressed	Reference	Mutants	Reference
Embryogenesis	OSH1	Sato et al. (1996)	gle1, gle2, gle3, cle1	Hong et al. (1995)
	OsVP1, OSEM	Miyoshi et al. (2002)	shl1, shl2, shl4, shl3	Satoh et al. (1999)
	RAB16A, RAB16A, REG2	Miyoshi et al. (1999)	sho1, sho2	Itoh et al. (2000)
	RAmy1A	Itoh et al. (2005)	riv1, riv2	Miyoshi et al. (2000)
Inflorescence	–	–	pla1	Itoh et al. (1998)
	–	–	lax	Komatsu et al. (2001)
	–	–	Sp	Iwata and Omura (1971b)
	–	–	ri, Dn1, sp	Nagao and Takahashi (1963)
	–	–	Dn2, Dn1	Jones (1952)
	–	–	Dn3, Dn2	Futsuhara et al. (1979)
	–	–	pap1, Dn3	Takahashi et al. (1998)
Leaf	OSH1, OsPNH1,	Nishimura et al. (2002)	sho1, sho2	Itoh et al. (2000)
	OsSCR	Kamiya et al. (2003a)	lsy	Obara et al. (2004)
	DL,	Yamaguchi et al. (2004)	Lg	Maekawa (1988)
Crown root	QHB, OsSCR	Kamiya et al. (2003b)	cr/1, crl2	Inukai et al. (2001)
Spikelet	FZP	Komatsu et al. (2003)	fzp	Komatsu et al. (2003)
	LHS	Jeon et al. (2000)	ur2	Iwata et al. (1983)
	RAP1, OsMADS2, RAG,	Kyozuka et al. (2000)	lhs	Jeon et al. (2000)
			bd1, bd2	Misro (1981)
	SPW1	Nagasawa et al. (2003)	An1, An2	Nagao and Takahashi (1963)
	OsMADS45	Greco et al. (1997)	dp1	Iwata and Omura (1971a)
	DL	Yamaguchi et al. (2004)	spw1, dl, msp1	Nonomura et al. (2003)
	MSP1	Nonomura et al. (2003)	dp2	Iwata and Omura (1971b)
	OsMADS13	Lopez-Dee et al. (1999)		

Table 17.3 (continued)

Developmental stage	Genes expressed	Reference	Mutants	Reference
Ovule	OsMADS13	Lopez-Dee et al. (1999)		
	SPW1	Nagasawa et al. (2003)		
	MSP1	Nonomura et al. (2003)		
Anther	MSP1	Nonomura et al. (2003)	msp1[d]	Nonomura et al. (2003)
	Osc4, Osc6	Tsuchiya et al. (1994)	aid1	Zhu et al. (2004)
	AID1	Zhu et al. (2004)	oscp1	Lee et al. (2004)
	OsCP1	Lee et al. (2004)	rf1	Kazama and Toriyama (2003); Komori et al. (2004)
	Rf1	Kazama and Toriyama (2003)		
Meiosis in rice anther	PAIR1 PAIR2	Nonomura et al. (2004a)	pair1	Nonomura et al. (2004a)
			pair2	Nonomura et al. (2004b)
			as	Katayama (1963)
			ds1	Chao and Hu (1960)
			ds2~d, s11	Kitada and Omura (1983)
Stomata	OsSCR	Itoh et al. (2005)		

auxin receptors. The plants which overexpress *OsmiR393* show less expression of both the auxin receptors (OsTIR1 and OsAFB2), successively repressing the expression of *OsAUX1* (auxin transporter) (Xia et al. 2012). This results in the downregulation of *OsTB1* (a tillering repressor), thus explaining the improved tillering in OsmiR393 overexpressing plants. Zhang et al. (2009) reported another auxin-dependent pathway involving an indole-3-acetic acid (IAA)-amido synthetase (i.e., TLD1) which conjugates with amino acids to convert active form of auxin into inactive, thus regulating tillering in rice.

The root system of rice is comprised of crown roots, lateral roots, and seminal roots which corresponds to root-borne, stem-borne, and pole-borne roots, respectively. Like other monocots, the rice is characterized with fibrous root system possessing many crown roots. The rice plant grown under field conditions may have several hundred crown roots (Kawata et al. 1978; Kawashima 1988). The expression of *QHB* gene takes place in central cells of quiescent center within the apical meristem of root, while the expression of *OsSCR* gene takes place in the root endodermis (Table 17.3; Kamiya et al. 2003a, b). The crown root primordium during crown root development initiates from the innermost cells of ground meristem, neighboring the peripheral cylinder of stem vascular bundles. These cells progressively differentiate into several tissues, e.g., epidermis, cortex, endodermis, root cap, and stele (central cylinder), in succession to form a full organization of the apical meristem of the crown root. When the preclinical division of endodermal cells forms the cortex, the expression of the *OsSCR* becomes downregulated within the cells of daughter cortex (Kamiya et al. 2003a). At the next stage, regulated cell division in each tissue enhances total cell number. Further, two periclinal divisions of the innermost cell of ground meristem form few layers of initial crown root primordium cells. These initial crown root primordium cells and their nuclei become enlarged, and a gradual increase in their protoplasm density takes place. Later on, inner cell layers of the initial crown root primordium divide periclinally and anticlinally to form a central cylinder initial and an epidermis–endodermis initial. After that, the outer layer cells of the initial crown root primordium begin to divide anticlinally to give rise to root cap initial. Specific cell layer divides periclinally, and epidermis–endodermis initial is separated into epidermis and endodermis, while root cap and central cylinder initials undergo anticlinal and periclinal divisions to enhance their own size. The endodermal cells undergo various asymmetrical periclinal divisions to form different layers of cortical cells (Kawata and Lai 1965). Periclinal divisions in cells of root cap initial result in the formation of columella. At this stage, a big metaxylem vessel is visible in center of stele. The central cylinder initial cells (stelar initial) become dome-shaped after periclinal and anticlinal divisions. During the same time course, cells constituting various vascular bundle tissues are progressively differentiated. Later on, all tissue cells turn out to be elongated and vacuolated simultaneously, and the crown root emerges from the stem in the basal region of the primordium. Cells in cortex show vacuolation, while those that are in the basal region of the stele show vacuolation as well as elongation (Kawata and Harada 1975).

Abscisic acid (ABA) and auxin promote while cytokinin suppresses the lateral development of roots. Ethylene also plays a role in lateral root development by interacting with auxin through cortical cell breakdown. Gibberellic acid promotes the growth of adventitious roots in flooded rice in combination with ethylene. High concentration of zeatin in root exudates favors the stronger root activity within rice hybrids, thus proposing that the cytokinin contents in roots could be considered as an important trait of root physiology. In another study, the use of an antisense transgenic predicted that cytokinins play a crucial role in rice root development (Liu et al. 2003). Besides improving the lateral development of roots, ABA promotes the root hair formation, tip swelling, and root water permeability in rice (Chen et al. 2006). Ethylene mediates the formation of aerenchyma and growth of adventitious roots in flooded rice (Rzewuski and Sauter 2008). Auxins modulate the gravitropism and the nodal and seminal root growth (Nakamura et al. 2006).

Cytokinins (CKs), the key regulators of several developmental processes of plants (Mok 1994), are synthesized within roots and are transported in upward direction with plants along the xylem (Wang and Li 2006). In the transgenic rice, overexpression of the isopentenyl transferase (*OsIPTs*) enhances the axillary bud activity and minimizes the root formation activity, and these are typical of CK overexpression. Until now, eight *OsIPT* genes are identified in the rice genome (Sakamoto et al. 2006). GAs also have strong influence on several developmental processes, especially the root and stem development (Lo et al. 2008).

17.2.2.2 Leaf Development

Rice produces ≥ ten leaves prior to initiation of reproductive phase (Itoh et al. 2005). The leaf development events occur in the following order for each rice node: (i) leaf initiation, (ii) leaf elongation, (iii) leaf blade maturation, (iv) collar formation, (v) leaf sheath elongation, (vi) node formation, and (vii) internode elongation. The intermodal elongation takes place for only five internodes of the main rice stem (Counce et al. 2003). The leaves are formed continuously. Cell division/expansion, tissue differentiation, axis determination, and tissue specification are the main events taking place during the leaf development (Itoh et al. 2005). The mature leaf of rice is strap-like, which can be easily distinguished into three regions along the proximal–distal axis. Leaf blade is distal region and is the major photosynthetic site. Leaf sheath is the proximal region and thus encloses the shoot apex while protecting the younger from physical damage. The boundary of the leaf sheath and leaf blade is comprised of three distinct parts, viz., ligule, auricle, and the lamina joint (collar) (Itoh et al. 2005). The ligule is acuminate and membranous, which is usually divided into two segments within the mature leaves. The collar or lamina joint is a whitish region within the leaf blade base which assists leaf blade to bend toward the abaxial side. The auricles (two in number) are the small appendages having long hairs and are situated at the margins of rice leaves (Itoh et al. 2005).

Rice leaves are polarized along the adaxial–abaxial axis. Several papilla and two different kinds of trichrome are present over the entire surface of leaf excluding the leaf sheath adaxial surface. Bulliform cells, organized in vertical rows, stuck between vascular bundles in the leaf blade adaxial epidermis. Both small and large types of vascular bundles are present in leaves (Itoh et al. 2005). The xylem and phloem are located at the adaxial and abaxial sides of vascular bundles, respectively. These vascular bundles are enclosed by bundle sheath cells. The leaf blade vascular bundles on adaxial/abaxial side possess the sclerenchymatous fiber cells. The leaf sheath and leaf blade margins vary in shape, the margin of the leaf sheath being pointed and membranous (Itoh et al. 2005).

Leaf primordium looks like a small bulge present at the edge of shoot apical meristem. It grows toward opposite side of the shoot apical meristem and toward apex and after protrusion; it forms a crescent-shaped primordium. Cell division in leaf primordium is several times more than that take place in shoot apical meristem (SAM), as confirmed by histone *H4* expression (Itoh et al. 2000). Leaf founder cell stage can be distinguished from leaf primordium stage through using several markers. The expression of *OsSCR* is initiated in the epidermal layer of the leaf primordium which gradually becomes specific to several epidermis files (Kamiya et al.

2003a). The *DROOPING LEAF* (*DL*) gene, which is a regulator of carpel specification and formation of midrib, is firstly expressed within leaf primordium central region (Table 17.3; Yamaguchi et al. 2004).

In apical and marginal regions, rapid cell division/elongation causes the leaf primordium to become hood shaped, and the commencing of procambial strand can be seen at the center of leaf at this stage. Further, both leaf primordium margins overlap with each other and surround the shoot apical meristem (Itoh et al. 2005). At this stage, leaf primordium shape seems to be cone-like, and the boundary of blade (lamina)–sheath becomes visible. At the boundary of adaxial surface of blade–sheath, a protrusion of ligule primordium originates from epidermal cells after periclinal divisions (Itoh et al. 2005). Progressively, the commencement of different plant tissues takes place at this stage. Cell file-specific expression of *OsSCR* gene within epidermis can be found at ligule primordium (Table 17.3; Kamiya et al. 2003a). The xylem/phloem is recognized in midvein, when the large vascular bundles surround the whole leaf width. On the other hand, the formation of small vascular bundles starts between large vascular bundles, and differentiation of macro hairs takes place at leaf-tip epidermis at this stage. At the distal region, the formation of stomata proceeds basipetally, while the epidermis proximal region remains immature (Itoh et al. 2005).

After ligule primordium differentiation, the leaf blade extends very fast and attains its maximum length, but elongation of leaf sheath remains inhibited. This elongation of leaf blade is attributed to the enhanced activity of intercalary meristems which are housed in leaf blade basal region (Kaufman 1959). At this stage, the expression of genes (e.g., *OsPNH1*, *OsSCR*, and *DL*) associated with cell differentiation becomes downregulated (Table 17.3; Nishimura et al. 2002; Kamiya et al. 2003a; Yamaguchi et al. 2004).

The leaf sheath elongation becomes rapid after the completion of elongation of leaf blade. Epidermis-specific cells such as silica cells, bulliform cells, and stomata cells from apex become visible. At this time, sclerenchymatous cell differentiation occurs on the external side of vascular bundles. When leaf blade tip appears out of the preceding leaf sheath, the leaf epidermal and internal structures are nearly complete excluding those which are found in the proximal region. Special air spaces (the lacunas) are also formed in the inner tissue of midrib and leaf sheath, basipetally. Unequal elongation, in the adaxial and abaxial cells, forces the leaf blade to bend toward lamina joint (Maeda 1961).

17.2.2.3 Aerenchyma Formation

After flooding, within 24 h, the supply of oxygen (O_2) becomes limited due to usage by soil bacteria (Ponnamperuma 1972). The rice roots require oxygen to stay alive and function properly. The roots become coated with ferrous iron in most of the flooded mineral soils. This iron is associated with sideraphores and the conversion of ferric form of iron to ferrous needs oxygen. The rice leaves may die within three to six phyllochrones of their elongation, so they cannot provide conduit for oxygen.

The nodes and internodes persist and conduit oxygen from the above floodwater into the roots. Aerenchyma, the tissue capable to conduit oxygen, is developed from the orderly killing (programmed cell death) of several plant tissues to produce large intercellular spaces (Counce et al. 2003). Three decades back, Kawai et al. (1998) reported that acidification of cytoplasm and loss in the integrity of plasma membrane are the preceeders of cell death in rice, with the gas space spreading radially. The cell death in roots and coleoptiles is usually very rapid. Rupture of tonoplast is the first step in the initiation of aerenchyma cells, which is followed by swelling of cytoplasm, rupture of plasma membrane, degradation of walls, and damaging of cellular contents (Inada et al. 2002). Aerenchyma in rice are well developed in leaf sheath, internodes, roots, and in leaf midrib (Colmer and Pedersen 2008; Steffens et al. 2011), which facilitates inner aeration among the roots and shoots (Colmer and Pedersen 2008). Indeed, the submerged leaves have gas films, which facilitate the exchange of carbon dioxide (CO_2) and O_2 between plant leaves and water, and thus enhance the underwater net photosynthesis by improving the uptake of O_2 for respiration during night and supplying CO_2 during the day (Raskin and Kende 1983; Pedersen et al. 2009). These leaf gas films thus help in sugar production within leaves by promoting photosynthesis when underwater and thus encourage the shoots and roots to work properly (Pedersen et al. 2009).

Aerenchyma formation is vital for the plants (e.g., rice) to survive and function in submerged conditions. Aerenchyma cells not only supply O_2 from shoots to roots but also help in ventilation of various gases such as methane and CO_2 from soil to the aerial environment (Colmer 2003; Evans 2003). This ventilation is mainly caused by diffusion of gases (Armstrong et al. 1996). In rice, the developed aerenchyma cells are called lysigenous aerenchyma (Jackson et al. 1985), which may be developed in root cortex, pith cavity, and stem cortex (Armstrong 1979).

In rice, the formation of aerenchyma cells initiates at the root apical parts and then expands gradually to the basal parts (Ranathunge et al. 2003). Fully developed aerenchyma cells, present on basal parts of the roots, separate the outer cell layers from the inner root stele (Armstrong and Armstrong 1994; Ranathunge et al. 2003). The constituents of remaining cell walls and cells form the radial bridges thus differentiating the gas spaces present in cortex. These gas spaces play important role in maintaining the root structural integrity and nutrient transport (apoplastic and assymplastic) (Drew and Fourcy 1986). During aerenchyma formation, cell death within the rice roots begins in the mid-cortex and then spreads toward the neighboring cortical cells radially (Kawai et al. 1998). The epidermis, endodermis, stele, and exodermis remain unaffected (Yamauchi et al. 2011).

In roots, the lysigenous aerenchyma formation may be enhanced through ethylene application under aerated conditions and can be suppressed with silver ions under stagnant (0.1 % agar) deoxygenated conditions (Wiengweera et al. 1997). Cell wall degradation takes place during aerenchyma formation, and this process is mediated by modification in the degradation of cell wall enzymes. Subsequently, the further degradation of cell will take place through various enzymatic actions, viz., xylanolytic, pectolytic, and cellulosolytic (Jackson and Armstrong 1999; Evans 2003).

During, lysigenous aerenchyma formation, the death of root cell cortex takes place in five major steps (Joshi and Kumar 2012). Firstly, the perception of hypoxia and initiation of biosynthesis of ethylene takes place. Secondly, perception of ethylene signaling takes place by mid-cortex cells. Thirdly, the ions are loosed to the neighboring environment, followed by invagination of plasma membrane, thus initiating cell death and small vesicle formation. Fourthly, the condensation of chromatin takes place which is followed by enhanced activity of hydrolytic enzymes of cell wall, and cell organelles are enclosed by membranes. At final step, the final degradation of cell wall takes place followed by cell lysis (Joshi and Kumar 2012). The surrounding cells absorb the cell contents and water.

17.2.2.4 Stomatal Formation

Stomata are microscopic aperture structures present on epidermis of plant leaves. In rice, the stomata are distributed on surface of leaf in vertical rows. The stomata present on the leaf sheath adaxial surface are rudimentary. In rice leaf epidermis, the distribution of cell rows of stomata is not random, and these cells are situated on vascular bundle boundaries. These rows are further differentiated into two different adjacent files (Itoh et al. 2005). In stomatal cell rows, uniform and specific expression of *OsSCR* gene is uniformly and specifically expressed in the stomatal cell rows (Table 17.3). The rice stomata have two narrow and thick-walled guard cells, having two subsidiary cells in neighborhood. During the formation of leaf ligule primordium, on leaf epidermis, the formation of stomatal cells occurs basipetally. Firstly, nonspecialized epidermal cells (NEC) and guard mother cells (GMCs) are formed through asymmetric divisions within the stomata cells. The NEC is large and weakly stained, while GMC is small, strongly stained cell (Itoh et al. 2005). In GMC, the expression of *OsSCR* gene is retained. In other cells of epidermis of stomata cell row, the expression of this gene is downregulated. At later stage, the polarized expression of this gene (i.e., *OsSCR*) can be observed on subsidiary mother cells (SMC) on GMC. The second asymmetric division takes place in the two lateral epidermal cells (subsidiary mother cells), adjacent to the GMC, to form subsidiary cells, which results in the formation of a three-cell complex (GMC + two subsidiary cells) (Itoh et al. 2005). The expression of *OsSCR* takes place in GMC as well as two subsidiary cells. Final symmetric transverse divisions in GMC form a pair of guard cells. At this stage, expression of *OsSCR* becomes very low. The subsidiary cells become ellipsoidal, while the guard cells enlarge and become dumbbell shaped at maturity (Luo et al. 2012; Itoh et al. 2005).

17.2.3 Reproductive Development

The reproductive phase starts with panicle initiation during the development of internodes (Leonards 2010). Initially, the panicles are microscopic in size wrapped within the stem. After the start of internode elongation, the buildup of chlorophyll takes place between the nodes. This chlorophyll imparts green color and forms green ring/band, which surrounds the developing internode. As panicle and internode formation continues, the differentiation of panicle is started. The newly forming panicle becomes visible at this stage, having an approximate length of 2 mm (Leonards 2010). The panicle growth and development continues inside the stem, and developmental stage is called booting. This stage can be classified further on the basis of panicle length. When panicle length is up to 2.5 cm, the growth stage is referred to as early boot. When the panicle length is 5–12 cm and ≥12 cm, the growth stage is called as middle boot and late boot, respectively. The identification of the rice developmental stages up to this point needs the dissection of the stem (split in half) (Leonards 2010). The development of panicle is completed during the late boot stage, and the panicle becomes visible outside the stem. The growth stage is referred as heading stage when panicle becomes visible from the flag leaf. The heading stage can also be classified further and is identified by percentages, e.g., the crop is said to be at 50 % heading stage when panicle is visible on 50 % rice stems (Leonards 2010).

The flowering and grain-filling stages start within 1–5 days after heading stage. The grain-filling stages can further be divided into milk stage (7–10 days after heading), dough stage, and physiological maturity stage. At milk stage, the white substance starts to accumulate. One week after the start of milk stage, dough stage is initiated where milky stuff becomes the texture of bread dough. At physiological maturity stage, the grains achieve maximum dry matter accumulation and become firm. The crop cannot be harvested at this stage as the grain moisture contents are ≥30 %. It may take two more weeks to drop the grain moisture contents to 20 % (harvest maturity), depending on weather conditions (Leonards 2010). Physiology of various reproductive and grain-filling processes has been discussed in the following lines.

17.2.3.1 Spikelets

After producing two sterile glume pairs (i.e., empty and rudimentary glumes), the floret meristem is formed from the spikelet meristem. The spikelets in rice consist of a single floret. Rice florets are consisted of palea, lemma, six stamens, two lodicules (known as petals), and one pistil. Only a single carpel constitutes this pistil. After production of lateral branches, the spikelet meristem is formed from the branch/inflorescence meristems. Later on, two sterile glumes are formed from the spikelet meristem in 1/2 alternate arrangement. These glumes have rudimentary shape with no axillary buds. In rice, two empty glumes are also formed in contrast to other grasses. The expression of *FZP* gene, vital for the formation of floret meristem, takes place at this stage (Table 17.3; Komatsu et al. 2003). Further, spikelet meristem forms floret meristem with two kinds of glumes (palea and lemma) and other floral organs. The palea and lemma identity is regulated by *LHS* genes (Jeon et al. 2000). Expression of RAP1 genes also occurs in lemma and palea primordium (Kyozuka et al. 2000).

The two empty glumes formed in rice are much smaller than lemma but larger than rudimentary glumes. The six glumes (two empty and two rudimentary glumes, palea and lemma) are organized in 1/2 alternate phyllotaxy. Three floral organs, viz., lodicules (two), stamens (six), and pistil (one), are shaped after the formation of palea (Itoh et al. 2005). The lodicules oriented at lemma side are whitish and smaller in size and are called petals. The expression of genes such as *OsMADS45*, *OsMADS2*, *RAP1*, and *SPW1* takes place in lodicules (Kyozuka et al. 2000, Nagasawa et al. 2003).

All the stamens in rice are formed in a whorl. The expression of genes such as *SPW1*, *OsMADS45*, and *RAG* takes place in stamens (Table 17.3; Kyozuka et al. 2000, Nagasawa et al. 2003). From the lemma side of floral meristem, one carpel primordium is differentiated, which afterward encloses this floral meristem. At this stage, the stamen primordium is transformed into a filament and an anther (Itoh et al. 2005). The expression of genes such as *RAG*, *OsMADS45*, and *DL* takes place in carpel primordium (Kyozuka et al. 2000; Yamaguchi et al. 2004).

Sepals are lacking in rice flower as against the other monocot and dicot flowers. Interestingly, only two lodicules biased to the lemma side are present in rice, which suggests that one lodicule present on palea side has probably been lost in the past during evolution (Itoh et al. 2005). The identity of carpel in rice is principally regulated by the *DL* gene (Nagasawa et al. 2003).

17.2.3.2 Megasporogenesis and Megagametogenesis

Carpel primordium spreads toward palea side with the downregulation of *OSH1* expression of floral meristem and thus is transformed into ovule primordium. The carpel encloses the ovule at this stage. Later on, female gamete is formed in the ovule, followed by production of pollen grains within anther. In the ovule, the *OsMADS13* and *OsMADS45* genes are expressed (Lopez-Dee et al. 1999). The expression of *MSP1* gene takes place in the surrounding tissues of female and male sporocytes (Nonomura et al. 2003). The proximal end of ovule primordium is attached to the palea-side carpel.

Later on, the formation of integument primordium occurs from ovule primordium base. The ovule is enclosed by carpel to form an ovary locule (Itoh et al. 2005). At this stage, *AINTEGUMENTA* gene expression starts in integument primordium.

The outer and inner integuments are formed from the single integument primordium. The expression of *SUPERWOMAN1*/*OsMADS16* genes take place (Nagasawa et al. 2003) on abaxial side of the outer integument. The expression of multiple sporocyte1 (*MSP1*) gene takes place in the whole carpel and ovule (Nonomura et al. 2003). The archesporial cell enlarges and is then distinguished into the megaspore mother cell (MMC). Although, the elongation is taking place in both inner as well as outer integuments, however, it is significant in the inner integument and encloses most of the nucleus excluding micropyle area near MMC (Itoh et al. 2005). After that, the ovule ascents toward receptacle side, and embryo sac (polygonum type) is formed in the nucleus. The meiotic division in MMC forms four different megaspores, which are arranged linearly in direction of micropyle–chalaza. Just chalazal megaspore functions while other three degenerate (Itoh et al. 2005).

Following meiosis, the mitotic nuclear division in the functional megaspore forms two nucleate cells, which gradually degenerate, and the enlargement of megagametophyte occurs. Later on, this megagametophyte forms a large vacuole. Second mitotic division occurs in each of the two nuclei. Sequentially, third mitotic division in megagametophyte occurs and it becomes eight nucleated (Itoh et al. 2005). Cellularization occurs when each (out of eight) nuclei drifts toward its respective positions. Thus, the completion of the hemianatropous ovule occurs consisting of an embryo sac, which is composed of one egg cell, two synergids, one central cell (formed from the fusion of two polar nuclei), and antipodal cells (Itoh et al. 2005). In rice, the antipodal cells continue to divide at chalazal end by forming antipodal cell cluster (Huang and Sheridan 1994).

17.2.3.3 Microsporogenesis and Microgametogenesis

The anther initial is ovoidal and takes place in transverse section, which successively becomes four cornered in shape. In rice, the formation of stamens starts in the third flower whorl. The anther primordium is composed of three distinct layers, viz., L1, L2, and L3 (Satina et al. 1940; Goldberg et al. 1993). The L1 layer in rice anther primordium forms the stomium and epidermis, which have vital role in the dehiscence of anthers. On the other hand, the L2 layer forms the primordial germ/archesporial cells from which the microsporangium and pollen are developed. The L3 layer forms vascular bundles, connective cells, and circular cell cluster, which are very near to the stomium (Raghavan 1988; Nonomura et al. 2003). The connective cells, present between vascular bundles and microsporangia, degenerate during gametogenesis.

The hypodermal anther cells are equipped with cylindrical rows, which can segregate into ACs. These ACs have slightly enlarged cytoplasm and nucleus, which distinguish them from other cells. After differentiation, continuous cell divisions in these cells result in the formation of primary parietal cells (PPCs) and primary sporogenous cells. Repeated periclinal divisions in PPCs form endothecium, a tapetum layer, and a middle layer. Mitosis in PSCs forms the pollen mother cells (PMCs) (Itoh et al. 2005).

Anticlinal divisions cause the expansion of each four-walled layer. The tapetal cells, being binucleated, provide materials for pollen wall and also the nutrition to gametophytes (Scott et al. 2004), thus serving as a nurse tissue. With the completion of anther wall, the PMCs undergo the premeiotic synthesis of DNA and enter meiosis (Nonomura et al. 2004b). In meiotic events, the spores are first developed into haploid gametophytes, which form gametes (haploid). When the free microspores are released from the tetrads, these become enlarged and spherical, but no mitotic cell division has been observed at this stage. In most of flowers, male gametophyte uninucleate status retains until heading. Although, the length of anther is highly correlated with the development of microsporangia, the most of the anthers attain elongation when uninucleate stage is at the end. First mitosis inside the pollen forms two types of nucleus, viz., vegetative and generative. Subsequently, the generative cells are distinguished into two sperm cells.

17.2.3.4 Fertilization and Grain Development

Grain development, in rice, starts with double fertilization. After the pollination, pollen grain germinates to develop into pollen tube, which elongates to reach ovaries (Fig. 17.2; Farooq et al. 2014). The pollen grain growth requires the energy, which is provided by the acid invertase action in the developing pollen tube. Upon fertilization, the endosperm and the developing embryo need nutrients primarily provided by sucrose through assimilate transport in phloem. The cell expansion causes the caryopsis to elongate to the maximum space of lemma and palea (the "hull" for rice).

After the elongation of caryopsis, the process of grain filling starts. There is no deposition of starch at the end of cell elongation. Most of the synthetic biochemistry takes place in two cell organelles, viz., plastid and cytosol. The route of carbon in the cytosol is from the imported sucrose. During grain filling, the sucrose is broken down into UDP-glucose and UDP-fructose by the action of sucrose synthase. The primary sucrolytic enzyme in the endosperm of rice is one or more of the isoforms of the sucrose synthase (Avigad and Dey 1996). For rice, three sucrose synthase isogenes have been identified, which code for various enzymes taking part in different tissues and various development phases (Counce et al. 2003). In the next step, the UDP-glucose

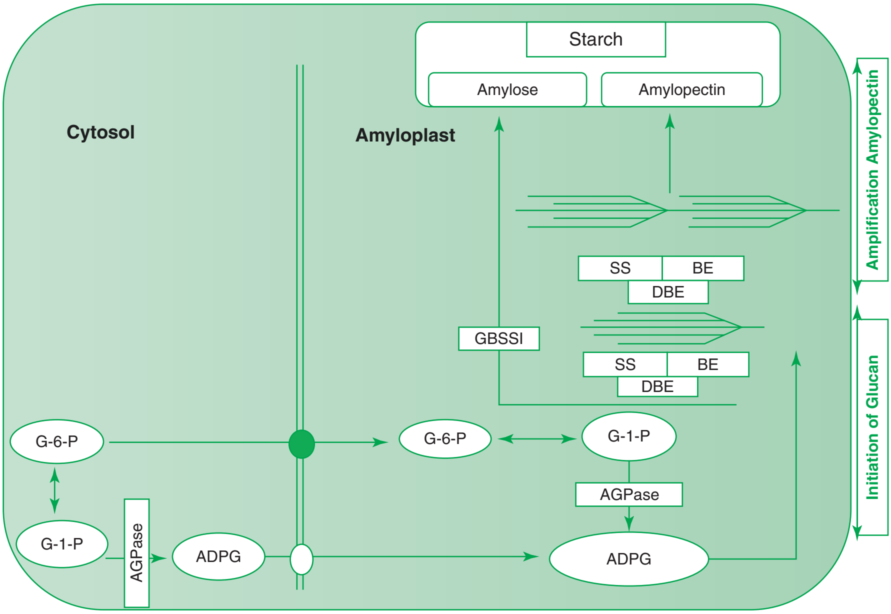


Fig. 17.2 Starch biosynthesis in the developing rice grain. Biosynthesis of starch, in rice, starts with the conversion of glucose-1-phosphate to glucosyl donor ADP-glucose (*ADPG*). The reaction is catalyzed by AGPase (ADP-glucose pyrophosphorylase). Synthesis of of α-1,4 linkages during elongation of amylopectin is mediated by soluble starch synthase (*SS*). Starch-branching enzyme (*BE*) catalyzes the formation of α-1,6 linkages in glucose polymer creating the branched amylopectin. Starch debranching enzyme (*DBE*) isoamylase removes some of the α-1,6 linkages and forms the crystalline shape of amylopectin. Filled circle indicates G-6-P transporter and open circle is ADPG transporter (Modified from Farooq et al. (2014))

is converted into glucose-1-phosphate. The enzyme involved is UDP-glucose pyrophosphorylase. The action of various enzymes may convert the fructose into glucose phosphates and progressively into starch. In the next step, the G-1-P is either converted into G-6-P via phosphoglucose isomerase or is transported into plastids. At this point, the synthesis of starch starts either in cytosol or in amyloplast via the ADP-glucose pyrophosphorylase. The production of starch in plastid is limited by AGP (situated in cytosol) (Shannon et al. 1998; Farooq et al. 2014). ADP-glucose is the starting point of synthesis of starch and the further synthesis of starch takes place in the plastid. Once the starch synthesis has been started, the single glucosyl unit add to either straight or branched chains accomplished with starch synthase. Starch-branching enzyme is also involved in the branching of starch chains for further starch synthesis. Branching, resizing, and debranching of the starch are important for progressive shaping, assembly, reassembly, and disassembly of the developing endosperm. The enzymes involved in these events are starch-branching enzyme, starch debranching enzyme, starch synthase, and D-enzyme (Myers et al. 2000). These events form highly structured granules in which the starch is packed in alternating zones of less and more branched amylopectin (Myers et al. 2000). In rice and other cereals, the starch structure is highly variable and may fluctuate greatly with temperature regimes. The starch granules of rice are smaller than the other cereals. The most sensitive enzyme to temperature is starch synthase as compared to other starch synthesis enzymes (Keeling et al. 1994). During grain filling, high temperature may cause chalkiness owing to decrease in the activity of starch synthase (Chaudhary and Hara 1977). Potassium is also required by the starch synthase for the proper activity (Marschner 1995). Thus the first step in grain development is the formation of individual starch molecules. Later on, these starch molecules assemble to form the starch granules (Myers et al. 2000).

After the filling of endosperm cells with starch, the cells of aleurone layer are filled with protein and lipds. The sub-aleurone cells have lipid, protein, and starch. The starchy endosperm cells not only contain starch but a little amount (6–7 %) of protein (Juliano and Bechtel 1985). The genes involved in the grain filling in most of cereals are common and well documented (Counce et al. 2003).

17.3 Resistance to Abiotic Stresses

Productivity of rice is constrained by several biotic and abiotic stresses. Among the abiotic stresses, submergence, drought, salinity, and heat stress are more devastating. In the following lines, mechanism of resistance to above stresses in rice is discussed.

17.3.1 Submergence

Several key physiological traits help rice plant to perform well under submergence stress (Setter et al. 1997). These traits include the high carbohydrate concentration before and during submergence, increase in alcoholic fermentation rate, and conservation of energy by reduction in the elongation growth (Setter et al. 1997). During submergence, the capacity of plants to produce carbohydrates depends on several factors including the shading or dark treatments before/during submergence (Palada and Vergara 1972), time of day during submergence (Setter et al. 1997), carbon dioxide supply and pH (floodwater) which impacts the underwater plant photosynthesis (Setter et al. 1989), irradiance before plant submergence, seedling age, and seed size (Ella and Setter 1996). Increase in the rate of alcoholic fermentation under submergence may be attributed to increase in the activity of alcoholic fermentation enzymes, dying of mutants without alcohol dehydrogenase, and increase in sugar (Waters et al. 1991). Thus resistance against submergence in rice is a complex physiological adaptation. A single putative gene encodes a trans-acting/transcription factor (i.e., RNA or a protein) (Ferl 1990; Ricard et al. 1994), which either binds to unique regulatory sequences of DNA (Singer and Berg 1991) or impacts the pathway of transduction of signals (Dolferus et al. 1994). Submergence may lead toward the induction of more than ten major anaerobic genes in rice (Rivoal et al. 1989; Setter et al. 1997). Furthermore, aerenchyma formation in rice facilitates the diffusion of oxygen from aerial to the submerged plant parts (discussed above), thus helping for resistance against submergence. The resistance against submergence in completely submerged rice is also linked to the presence of a gene Submergence1 (*Sub1*), which is located on chromosome 9 (Xu and Mackill 1996) in rice. FR13A Sub1 region encodes three different transcription factors (*Sub1A*, *Sub1B*, and *Sub1C*), which correspond to the B-2 subgroup of the ethylene response factors (Xu et al. 2006). The *Sub1A*/*Sub1C* transcription is strongly upregulated while that of *Sub1B* is slightly upregulated upon submergence, however, downregulated by de-submergence (Xu et al. 2006).

17.3.2 Drought

Drought stress is very detrimental to rice as it affects the morphological, physiological, and yield-related parameters of rice (Table 17.4). Several studies have identified the physiological basis of drought resistance in rice. For instance, Ji et al. (2012) reported that the activity of Rubisco activase, chloroplastic superoxide dismutase, peptidyl-prolyl *cis-trans* isomerase, Cu-Zn, and dehydroascorbate reductase was upregulated under drought stress. Rabello et al. (2008) identified genes, which were related to maintenance of cell integrity and cell turgor during drought stress in rice. They also identified L-ascorbate peroxidase 1, superoxide dismutase [Cu-Zn], cytosolic malate dehydrogenase, and ascorbate peroxidase as dominant protein conferring drought tolerance in rice. Rice plants possessing the water-channel protein, i.e., RWC3, had better root hydraulic conductivity and leaf water potential (Lian et al. 2004). Accumulation of proline, polyamines (spermidine and spermine), soluble sugars, sucrose, glycinebetaine, and other solutes also help in improving resistance against drought (Pandey and Shukla 2015). Among these solutes, proline is of vital importance. Besides acting as an excellent osmolyte, proline also acts as a metal

Table 17.4 Impact of different abiotic stresses on morphological, physiological, and yield-related parameters of rice

Stress type	Stage of imposition	Trait	Cultivar	Decrease over control (%)	Reference
Drought	Reproductive, grain filling	Photosynthetic rate	Super Basmati	21.9	Akram et al. (2013)
Drought	Reproductive, grain filling	Photosynthetic rate	Shaheen Basmati	15.0	Akram et al. (2013)
Drought	Seedling stage	Transpiration rate	Mahsuri	173.3	Cabuslay et al. (2002)
Drought	Reproductive, grain filling	Transpiration rate	Super Basmati	36.0	Akram et al. (2013)
Drought	Reproductive, grain filling	Transpiration rate	Shaheen Basmati	30.3	Akram et al. (2013)
Drought	Reproductive, grain filling	Grains per panicle	Super Basmati	3.3	Akram et al. (2013)
Drought	Reproductive, grain filling	Grains per panicle	Shaheen Basmati	3.9	Akram et al. (2013)
Drought	Seedling stage	Chlorophyll contents	IR-29	113.4	Basu et al. (2010)
Drought	Seedling stage	Chlorophyll contents	Pokkali	33.1	Basu et al. (2010)
Drought	Reproductive stage	Chlorophyll contents	KDML105	9.3	Cha-um et al. (2010b)
Drought	Seedling stage	Chlorophyll contents	Pusa basmati	120.5	Basu et al. (2010)
Drought	Seedling stage	Shoot weight	Mahsuri	33.9	Cabuslay et al. (2002)
Drought	Seedling stage	Leaf area	Mahsuri	211.6	Cabuslay et al. (2002)
Drought	Seedling stage	Sugar in leaf blade	Mahsuri	22.8	Cabuslay et al. (2002)
Drought	Seedling stage	Starch in leaf blade	Mahsuri	125.6	Cabuslay et al. (2002)
Drought	20 d before heading	Grain yield	Gangyou 527	22.1	Wang et al. (2010)
Drought	20 d before heading	Grain yield	Yixiangyou 9	46.7	Wang et al. (2010)
Drought	Whole cycle	Grain yield	Yangdao 6	3.14	Yang et al. (2001)
Drought	20 d before heading	Grain yield	Gangyou 188	31.0	Wang et al. (2010)
Heat	–	Grain weight	L-204	92.8	Prasad et al. (2006)
Heat	–	Grain yield	L-204	89.1	Prasad et al. (2006)
Heat	Booting	Grain yield	Hovaze	18.3	Aghamolki et al. (2014)
Heat	Booting	Grain yield	Fajr	37.5	Aghamolki et al. (2014)
Heat	Booting	Grain yield	MR219	24.0	Aghamolki et al. (2014)

(continued)

Table 17.4 (continued)

Stress type	Stage of imposition	Trait	Cultivar	Decrease over control (%)	Reference
Heat	Booting	Grain yield	Hashemi	30.4	Aghamolki et al. (2014)
Heat	Post heading	Grain yield	S-NMLYtz	1.5	Shi et al. (2015)
Heat	Post heading	Grain yield	S-SWP	6.2	Shi et al. (2015)
Heat	Post heading	Grain yield	DE-SMLYtz	9.7	Shi et al. (2015)
Heat	Post heading	Grain yield	DE-SC	4.6	Shi et al. (2015)
Salt	–	Root length	SS	13.2	Cha-um et al. (2007)
Salt	–	Root length	RD6	28.8	Cha-um et al. (2010a)
Salt	–	Leaf area	SS	80.8	Cha-um et al. (2007)
Salt	–	Leaf area	ST	43.4	Cha-um et al. (2007)
Salt	–	Leaf area	RD6	494.9	Cha-um et al. (2010a)
Salt	–	Chlorophyll contents	SS	237	Cha-um et al. (2007)
Salt	–	Chlorophyll contents	ST	259.0	Cha-um et al. (2007)
Salt	–	Chlorophyll contents	RD6	268.0	Cha-um et al. (2010a)
Salt	–	Photosynthetic rate	RD6	40.7	Cha-um et al. (2010a)
Salt	–	Number of tillers	BR-11	5.5	Gain et al. (2004)
Salt	–	Plant biomass	BR-11	4.32	Gain et al. (2004)
Salt	–	Tiller per plant	M-202	161.7	Zeng and Shannon (2000)
Salt	–	Plant height	BR-11	11.6	Gain et al. (2004)
Salt	–	Plant height	BBRI dhan44	16.7	Hasamuzzaman et al. (2009)
Salt	–	Relative water contents	BBRI dhan44	28.8	Hasamuzzaman et al. (2009)
Salt	–	Panicle number	BBRI dhan44	42.4	Hasamuzzaman et al. (2009)
Salt	–	1000-grain weight	BBRI dhan44	44.8	Hasamuzzaman et al. (2009)
Salt	–	1000-kernel weight	IR-28	25.2	Abdullah et al. (2001)
Salt	–	1000-grain weight	M-202	80.5	Zeng and Shannon (2000)
Salt	–	Grain yield	BBRI dhan44	44.4	Hasamuzzaman et al. (2009)
Salt	–	Seed per panicle	IR-28	14.8	Abdullah et al. (2001)

chelator, a signaling molecule, and an antioxidative (Hayat et al. 2012) and thus imparts resistance against drought. Proline accumulation also enhances the antioxidant activities. Exogenous application of polyamines improved water relations, net photosynthesis, proline accumulation and anthocyanin and soluble phenolic accumulation and helped alleviating the oxidative damage to cellular membranes (Farooq et al. 2009a). Moreover, improvement in the antioxidant defense system of plant may help to cope drought stress in rice (Pandey and Shukla 2015). With increasing levels of drought stress in rice, the activities of ascorbate, glutathione, ascorbate peroxidase (Selote and Khanna-Chopra 2004), superoxide dismutase, monodehydroascorbate reductase, dehydroascorbate reductase, glutathione reductase (Sharma and Dubey 2005), phenylalanine ammonia-lyase, and catalase (Shehab et al. 2010) consistently increase which are very beneficial for drought resistance. Abscisic acid can help in inducing resistance against drought in rice by improving the status of antioxidant enzymes (Latif 2014; Li et al. 2014) and improving transport of proteins and carbon metabolism and expression of stress proteins (Zhou et al. 2014). Overexpression of C_4 photosynthesis enzymes such as phosphoenolpyruvate carboxylase and pyruvate orthophosphate dikinase (Zhou et al. 2011; Gu et al. 2013) may also help rice plant to withstand with drought.

Drought stress in rice reduces grain size, grain weight (Venuprasad et al. 2011; Mostajeran and Rahimi-Eichi 2009), and seed-setting rate (Ji et al. 2012), increases the spikelet sterility (Kumar et al. 2014), and thus taxes the grain yield. This reduction in grain yield may also be attributed to shortening of grain-filling period, disturbance of leaf gas exchange, reducing of source and sink size, and impaired loading of phloem and assimilate translocation (Farooq et al. 2009b, c), reduced CO_2 assimilation, decreased stomatal conductance/photosynthetic pigments, and disturbed and reduced activities of sucrose and other starch synthesis enzymes (Farooq et al. 2009b, 2014).

17.3.3 Salt Stress

Salt stress strongly affects the productivity of rice (Table 17.4). Resistance against salt stress, in rice, may be attributed to various antioxidant enzymes such as peroxidases (Mittal and Dubey 1991; Wu et al. 2005). Wu et al. (2005) also identified four genes in rice conferring the resistance against salt stress. These genes include *Asr1*, *LIP9*, *salT*, and *GRP*. In rice, Kawasaki et al. (2001) also reported the induction of stress ribosomal proteins under salinity. Chen et al. (2007) also reported that resistance against salinity, in rice, may be improved by increasing expression level of a vacuolar Na^+/H^+ antiporter gene. Gong et al. (2006) reported that silicon deposition in the roots of rice may help in decreasing the sodium uptake by reducing bypass flow. In rice, *OsHKT2* is rapidly downregulated to reduce the influx of potentially toxic Na^+ at higher external sodium concentrations. *SKC1* gene, expressed in parenchyma cells, was related with salt resistance owing to its role in the K^+/Na^+ homeostasis under salt stress (Ren et al. 2005). In a recent study, rice cultivars with better resistance against salt stress had higher catalase activity and accumulation of proline and hydrogen peroxide (Chunthaburee et al. 2016). In another study, Igarashi et al. (1997) reported that the accumulation of proline helped the plants to produce higher green leaf area under salt stress (Pongprayoon et al. 2008). Roychoudury et al. (2008) further documented involvement of anthocyanin production in salt resistance in rice. Indeed, anthocyanins under salt stress reduce the oxidative damage (Hughes et al. 2005) and function as antioxidants by detoxifying the reactive oxygen species (ROS) (Kytridis and Manetas 2006).

17.3.4 Heat Stress

Like drought, heat stress is also very detrimental to rice as it strongly affects the morphological, physiological, and yield-related traits of rice (Table 17.4). Antioxidant enzymes play important role in thermotolerance by scavenging the ROS and protect the membranes from oxidative damages (Ali et al. 2013). Ye et al. (2012) identified four different single-nucleotide polymorphisms in rice, which were associated with resistance against heat stress. They used selective genotyping as well as single marker analysis techniques to find these nucleotide polymorphs. They also found four putative QTL, which were linked with resistance against heat stress in rice F2 population. In another study, Cao et al. (2008) reported that resistance against heat stress in rice was attributed to strong antioxidative defense system, little ethylene synthesis, high RNA contents, and reduced malondialdehyde content during meiosis.

The expression of various protective proteins (HSP90, Cpn60, HSP70) and thiamine biosynthesis protein (THI1) was enhanced (Scafaro et al. 2010). Jagadish et al. (2010) also reported that accumulation of heat-shock protein in rice may confer resistance against heat stress. Another NAC gene, viz., *SNAC3* (ONAC003, LOC_Os01g09550), which is stress responsive, has been reported to confer resistance against heat and drought stresses in rice by quenching the ROS (Fang et al. 2015).

17.4 Conclusions

The growth cycle of rice can be divided into three distinct growth phases including germination/seedling, vegetative, reproductive, and grain development. The reproductive phase, in particular the grain development, is the most important stage, which dictates its yield potential. Floral development, gametogenesis, and grain development are regulated by expression of specific genes and homeostasis of plant hormones. Understanding the plant physiology may help to improve the yield formation and crop productivity. The differences within different species of rice for gene expression during the reproductive phases need to be investigated. Moreover, the expression of these genes under various growth environments may be a topic of future scientific debates.

Rice may produce well in a variety of environments. However, several biotic and abiotic stresses impede its productivity. Among the abiotic stresses, submergence, drought, salinity, and heat stress are more devastating. Although physiological mechanisms of resistance against abiotic stresses in rice are relatively well understood, further studies to determine the physiological basis of assimilate partitioning from source to sink; plant phenotypic flexibility, which leads to resistance against abiotic stresses; and factors that modulate stress response in rice are needed. The genomic resources combined with ecophysiological research may be helpful to understand the genotypes and environment interactions and to develop rice genotypes better able to produce well under less than optimum conditions.

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Chapter 18
Role of Biotechnology in Rice Production

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18.1 Introduction

Rice is the most important cereal crop and a firmly established model plant for scientists. Recent advances in molecular biology and omics research have dramatically changed our capability for gene discovery and functional genomics of rice. A holistic "snapshot" of a rice cell can be obtained with transcript and metabolite profiling. With the recent advances in phenomics research, one can easily expose a germplasm to diverse field environments in a more integrative approach capturing whole-plant adaptation and trait diversity. Ultimately, the genetic control for specific component traits can be investigated with a reductionist approach in controlled environments (Dingkuhn et al. 2015). With revolutionary progress in systems biology and molecular techniques, functions of cohorts of genes and their regulation are being predicted, validated, and implemented for improvement of rice cultivars.

Rice provides 31 % of all food energy consumed in Asia, 8 % in Africa, and 11 % in Latin America (ILSI International Food Biotechnology Committee 2008). Rice cultivation is a major socioeconomical and even political activity in many Asian

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countries. More than 50 % of the population of China, Thailand, and Vietnam directly or indirectly depend on rice for their food and livelihood.

Demand for rice continues to increase due to the ever increasing rice consumer base. However, the present rate of increase in rice production (2000–2009) has slowed down (1.21 %) when compared to previous decades (2.49 % in 1970–1990, 1.7 % in 1990–2000) due to various biotic and abiotic stresses (Khush and Jena 2009). The integration of recent molecular tools to classical rice breeding programs offers substantial opportunities toward breaking the yield barrier. Molecular markers have been utilized for long time through (i) marker-assisted selection (MAS) strategies for germplasm improvement and novel cultivar development, (ii) gene pyramiding for accumulating multiple genes for resistance to specific or family of pathogens and pests, (iii) examining allelic diversity in natural populations or breeding material and association mapping of genomic regions related to the desired traits, and (iv) providing DNA fingerprinting barcodes to diverse genotypes for plant variety protection. Candidate gene-based functional markers can be used for precision breeding. The "advanced backcross QTL analysis" and "exotic libraries" are other approaches that increase the efficiency of harnessing natural biodiversity to improve yield, adaptation, and quality of elite germplasm.

The exponential development in genomics, next-generation sequencing (NGS), and associated DNA technologies in recent years represents a quantum leap in our molecular understanding of important plant breeding traits. Advanced marker technologies, such as single-nucleotide polymorphisms (SNPs) or more recently the paradigm shift with microarray, RNA sequencing (RNA-Seq), and chromatin immunoprecipitation sequencing (ChIP-Seq) techniques, open a totally new horizon to improve the efficiency of breeding programs. Powerful reverse genetic strategies allow the detection of induced point mutations in individuals of the mutagenized populations. It can address the major challenge of linking sequence information to the biological function of genes and can also identify novel variation for plant breeding. Multiple rice mutant resources that are key tools for functional analysis of genes have been developed and are available in public domain (Hirochika et al. 2004). A searchable FST database, which contains 55,000 mutant lines with functions of gene trap and gene knockout and activation tagging, is available at the Taiwan Rice Insertional Mutant (TRIM) website (http://trim.sinica.edu.tw/). The available mutant seeds are provided upon request (Hsing et al. 2007).

DNA markers have enormous potential to improve the efficiency and precision of conventional plant breeding via MAS. DNA markers have been used in almost all aspects of rice improvement. Application of MAS in rice breeding can be broadly classified into marker-assisted evaluation of breeding material, marker-assisted backcrossing, pyramiding, early generation selection, and combined MAS (strategical combination of phenotypic screening with MAS), although there may be overlap between these categories (Collard and Mackill 2008).

Various plant tissue culture techniques have been applied for crop improvement for more than 30 years. While in vitro fertilization can be used to avoid physiological incompatibility in both interspecific and intergeneric crosses, embryo rescue technique has been utilized against post-zygotic embryo abortion due to poor endosperm development (International Rice Research Institute 2013). Unique hybrid plants, which cannot be produced by conventional sexual hybridization methods, can be generated using protoplast fusion. These techniques provide opportunity to utilize genetic resources from distant relatives of rice. Similarly double haploid plants are highly important for geneticists to study the recessive gene functions and for plant breeders in terms of generating homozygous breeding lines within no time.

Genetic engineering, an important avenue for enhancing sustainable productivity in agriculture, transcends the reproductive or phylogenetic barriers facilitating precise transfer of traits. Several transgenic rice lines have been developed for biotic/abiotic stress resistance, herbicide tolerance, and improvement of nutritional value as well as to improve the quality of rice grains (Endo et al. 2007). Rapid improvement in the genetic engineering techniques such as "marker-free transgenics" and targeted genome engineering using TALENs and CRISPR/Cas9 system provide better scope for introduction of new genetic material to the targeted location in the genome. Modern biotechnology tools have complemented to conventional trait-based selection approach to accelerate the rice improvement in several programs which are discussed below.

18.2 Improving Nutrition and Quality

Micronutrient malnutrition or hidden hunger is a serious health problem worldwide, particularly in the developing countries. Micronutrients, often referred as vitamins and minerals, are required in minor quantities to produce enzymes, hormones, and other substances that are essential for growth and development. Absence of these micronutrients poses severe consequences in the overall growth and development of the human body. Humans obtain micronutrients from the food chain. Deficiencies occur when people do not get access to micronutrient-rich food items such as fruits, vegetables, animal products, and fortified food due to their high costs. With a large part of the world's population living on less than two dollars a day, staple crops such as rice play the key role in providing the daily micronutrient needs. Rice is the predominant dietary energy source for 17 countries in Asia and the Pacific, 9 countries in North and South America, and 8 countries in Africa (Hegde and Hegde 2013). It supplies 30 % of the total dietary energy supply in the world. The milled rice grains contain low levels of iron, folate, zinc, provitamin A, and vitamin E. Previous attempts tried supplementation and fortification-based interventions to furnish the much needed micronutrients in cereals and other crops. In spite of the sizable success, such interventions failed to eradicate the problem because of laborious undertaking and expensive distribution logistics. Other factors such as mismanagement, underfunding, and poor compliance that arises due to economic crisis and political turmoil make such type of interventions unsustainable.

Biofortification takes advantage of the regular daily intake of staple food by all family members. It targets low-income household and hard to reach areas with limited access to commercially available fortified foods. Biofortification aims to develop rice cultivars with abundant vitamin and mineral nutrients through traditional plant breeding methods and transgenic approaches. Genomic-based strategies have been applied to identify functional profile of candidate genes that will allow the development of nutrient-rich rice cultivars. Multiple genes associated with production and storage of micronutrients into the rice endosperm can be integrated into a single rice cultivar to produce a high micronutrient density variety. Biofortification can also give rise to superior rice varieties with combined high micronutrient density and high yield traits. Recent advancement in the field of gene discovery and biotechnology makes such interventions feasible and cost effective. Once biofortified crops are developed, there are no other recurring costs except those involved in maintenance breeding.

18.2.1 Iron and Zinc Content

Iron, zinc, and vitamin A deficiency are recognized as the most common forms of micronutrient deficiency. Iron deficiency alone affects about 2 billion people, and vitamin A deficiency affects at least 100 million children each year, of which 1.3–2.5 million die and over 0.25 million suffer permanent health defects such as blindness. Nearly 30 % of the world's population may face the risk of iodine deficiency. Inadequate diet owing to poverty is the most important reason for zinc deficiency that diminishes appetite and adversely affects the immune response. The polished rice contains an average of only 2 parts per million (ppm) iron (Fe) and 12 ppm of zinc (Zn) (International Rice Research Institute 2006). Several screening studies have been undertaken to identify rice cultivars with higher iron and zinc content (Anuradha et al. 2012; Sardar et al. 2015; Jahan et al. 2013).

18.2.1.1 Marker-Assisted Breeding

Initial germplasm screening and field evaluation of breeding lines from Korea, Bangladesh, Indonesia, India, and the Philippines has shown that iron and zinc content in polished rice can be increased by a factor of 2–4 (International Rice Research Institute 2006). Jalmagna, a traditional floating rice variety of Eastern India, has almost double the iron concentration of IR64 as well as nearly 40 % more zinc. Madhukar, a popular variety in some rainfed and deepwater areas of Eastern India, had slightly high iron density and very high zinc density. Other known zinc-efficient rice varieties that can be exploited for zinc or iron content through breeding include Kuatik Putih, Bille Kagga, Getu, Zuchem, and Xua Bue Nuo.

Three groups of genes were found to be associated with the high-iron trait. These groups of genes were located on chromosomes 7, 8, and 9 and explained 19–30 % of the variation in iron content. Permanent mapping populations of F8 recombinant inbred lines (RILs) were developed to map high-iron and high-zinc traits.

18.2.1.2 Transgenic Research

Iron concentration was observed to be significantly correlated with zinc concentration (Anuradha et al. 2012). Although concentration of these trace minerals is moderately affected by soil properties and weather, breeding for higher iron and zinc content can be done side by side (Vasconcelos et al. 2003).

The entire coding sequence of soybean endosperm-specific ferritin gene was transferred into *Oryza sativa* (L.) cv. Kitaake to improve iron content in rice (Goto et al. 1999). Ferritin is an intracellular protein present in all organisms responsible for storing iron and releasing it in a controlled manner when needed (http://www.chemistry.wustl.edu/). In a different study, the human lactoferrin gene was expressed in rice for higher bioavailability (Nandi et al. 2002). Human lactoferrin is the major iron-binding protein in breast milk. Its expression in transgenic rice was stable for more than five generation. However, expression of lactoferrin was able to only double the iron content in rice grains unlike two- to threefold increase observed in the soybean ferritin expression (Lonnerdal 2003).

In another attempt, the ferritin (*pfe*) gene from *Phaseolus vulgaris* (common bean) was introduced into rice along with two other genes – *Aspergillus fumigatus* phytase (*phyA*) and an endogenous cysteine-rich metallothionein-like (*rgMT*) protein (Lucca and Hurrell 2001). Cysteine peptides formed in the digestive system enhance iron absorption, while the enzyme phytase hydrolyzes phytic acid. Phytic acid present in plant seeds chelates multivalent metal ions such as iron and zinc forming insoluble salts with low bioavailability (Zhou and Erdman 1995). Resulting seeds of the transgenic rice showed sevenfold increase in cysteine residues and 130-fold increase in phytase level. Further study by Hong et al. (2004) in Taiwan showed the potential of increasing phytase in transgenic rice by the incorporation of two bacterial genes derived from ruminal bacterium *Selenomonas ruminantium* (*SrPf6*) and *Escherichia coli* (*appA*). The expressions of these genes produce phytases highly active under broad pH ranges of 3.0–5.5 and 2.0–6.0 and with optimal temperature at 55 and 60 °C, respectively. Overexpression of MxIRT1, a ferrous transporter from an iron-efficient genotype of the apple tree, *Malus xiaojinensis*, showed active transport of iron (Tan et al. 2015a). Concerted expression of *AtIRT1*, *AtNAS1*, and *PvFERRITIN* synergistically increased iron in both polished and unpolished rice grains (Boonyaves et al. 2015).

18.2.2 Vitamin A

Many countries with a high prevalence of vitamin A deficiency (VAD) rely on rice as a major source of energy. Rice does not contain β-carotene, the direct precursor of vitamin A. Existing rice cultivars are not capable of accumulating provitamin A in the grain. Germplasm screening conducted by various rice institutions and private companies showed that there are no cultivars of rice that can be used as parental line for vitamin A biofortification using traditional breeding methods. Key pathway enzymes in β-carotene synthesis are only expressed in the vegetative tissues of rice plants. However, immature rice endosperm is capable of synthesizing the early intermediate of β-carotene called geranylgeranyl diphosphate. While this isoprenoid precursor is synthesized in the endosperm, conversion of this to β-carotene requires the enzyme phytoene synthase along with three other plant enzymes – phytoene desaturase and ξ-carotene desaturase, each catalyzing the establishment of double bonds, and lycopene β-cyclase, encoded by the *lcy* gene.

The engineering of biosynthetic pathway of provitamin A (β-carotene) into the rice endosperm was first reported by Xudong Ye and his colleagues in 2000 (Ye and

Al-Babili 2000) (Table 18.2). Since immature rice endosperm is capable to produce the precursor of β-carotene, geranylgeranyl diphosphate, genetic engineering was used to introduce other key enzymes needed in β-carotene synthesis pathway. The phytoene synthase (*psy*) gene was introduced through *Agrobacterium*-mediated transformation to convert geranylgeranyl diphosphate to phytoene, the immediate precursor of β-carotene in plants. In Golden Rice 1, the phytoene desaturase and ξ-carotene desaturase, involved in catalyzing the introduction of two double bonds, were replaced by a bacterial carotene desaturase (*crtI*), which was capable of introducing all four double bonds. Golden Rice 2 was developed with homologs of the same genes that were used in Golden Rice 1 and encode enzymes with similar activities. The *psy* gene for Golden Rice 2 was isolated from maize, while it came from daffodil (*Narcissus pseudonareissus*) for Golden Rice 1 (Paine et al. 2005).

Golden Rice 2 had an increase in total carotenoids of up to 23-fold (maximum 37 μg/g) compared to Golden Rice 1 and a preferential accumulation of β-carotene, resulting to a deep orange color (Paine et al. 2005). With significantly higher level of β-carotene, the consumption of Golden Rice 2 in typical quantities may provide adequate daily intake of vitamin A in countries in which rice is a staple food, assuming cooking losses of β-carotene are not excessive. If approved for human consumption, Golden Rice 2 could provide adequate levels of vitamin A to large populations that are currently at risk for VAD. Golden Rice 2 may also be useful even for populations where rice is a smaller dietary component.

18.3 Improvement of Abiotic Stress Resistance

Global environmental changes (GEC) have posed a threat to rice production. Various abiotic stresses such as drought, flooding, soil salinization, extremely low and high temperatures, and other adverse environmental conditions result in major loss to rice yield. Though high-yielding varieties are mostly susceptible, wide variation exists in rice gene pool, which is being utilized to improve the cultivated varieties.

18.3.1 Drought

Drought is a complex physiological phenomenon of widespread significance for agriculture. It is among the most severe factors which affect rice yield and grain quality. It has been termed as the single most common cause of severe food scarcity in developing countries. From agronomic point of view, drought is a period when soil moisture is inadequate to meet the demands for crops to initiate and sustain plant growth. In rainfed areas, upon failure of rain or a long interval between two rains, drought stress can occur at the seedling, vegetative, or reproductive stage of the rice crop, and it can also be intermittent depending upon the rainfall pattern and distribution. In fact, drought often has neither a distinct start nor end. The reproductive stage drought has been identified as the most detrimental to grain yield (O'Toole 1982) and a short period of drought during this stage can lead to substantial yield loss.

Poor water management, increased competition for limited water resources, and the uncertain threats associated with global warming all highlight the looming water crisis that threatens agricultural productivity worldwide. More than 23 million ha (20 %) of the total rice area in Asia is subjected to drought of different intensities (Pandey and Bhandari 2009; Pandey et al. 2007). Development and dissemination of a climate-smart drought-tolerant rice varieties can increase the annual rice production up to 6 million tons worth US$ 3.3 billion (Mottaleb et al. 2016). Hence, there is an urgent need to develop climate-resilient rice cultivars, which can give higher yield under drought and boost the income of resource poor farmers.

Drought resistance includes drought escape (DE) via a short life cycle or developmental plasticity; drought avoidance (DA) via enhanced water uptake and reduced water loss; drought tolerance (DT) via osmotic adjustment (OA), antioxidant capacity, and desiccation tolerance; and drought recovery (DR) mainly through high vegetative vigor (Chang et al. 1986) (Fig. 18.1). Different rice varieties use different physicochemical methods that again vary at different developmental stages (Tripathy et al. 2000).The ability to maintain water uptake during drought appears to be a major attribute that confers increased drought resistance on traditional rice varieties, and hence increased rooting depth and density would increase the capacity to extract available water. Chang et al. (Chang et al. 1986) found that rice cultivars with deep root systems avoided drought better than those with more shallow root systems. The ability to resist the adverse effect of drought has also been reported to be directly proportional to the density and concentration of root development in wheat (Hurd 1964). Application of molecular markers and high-density SNP genotyping array to look for parental polymorphism and root-specific gene expression can be exploited for drought tolerance of rice (Chen et al. 2014).

18.3.1.1 Marker-Assisted Breeding

Progress in breeding for drought resistance has been slow mainly due to a wide range of water stress environments found in rice-growing areas, difference in time, intensity, and hydrology of drought. Furthermore, drought stress is accompanied by other stresses like high temperature and nutrient deficiencies, which further complicate the breeding efforts. Traditional varieties, N22, Laloo 14, Brown gora, Birsa gora, Dular, etc., are known to have high drought tolerance. However, most of these lines are early in duration and carry unfavorable linkage drag. On the other hand, some released varieties, such as Annada and Vandana in India and Apo and PSBRc82 and PSBRc68 in the Philippines, possess good drought tolerance.

Conventional breeding for drought tolerance in rice has met with little success (Fukai and Cooper 1995) due to the polygenic nature of the phenomenon with low heritability and high G×E interaction (Zhang and Creelman 2004; McWilliam 1989;

Ingram and Bartels 1996). With recent advances in marker-assisted selection, several international and national programs working on rice have generated systematic programs to develop effective drought-tolerant cultivars. Over the past decade, many drought researchers have shifted to direct selection of large-effect QTLs for higher grain yield (GY) under drought stress against the earlier thought that heritability (H) of yield under drought stress might be low. Most of these programs evaluate advanced lines under both drought stress and irrigated control situations to select lines combining high yield under both situations. However, proper drought-phenotyping protocols for inducing an appropriate level of drought stress in screening experiments that result in a clear differentiation of drought-tolerant and drought-susceptible lines still need improvement and standardization.

Drought is an ideal trait for improvement through MAS though it has been difficult to be managed through conventional phenotypic selection. The recent progress made in the field of genomics offers new opportunities to dissect QTLs for drought tolerance. Initial approaches included the secondary physiological traits as the targets for selection. Significant genetic variability has been found in the root-associated traits, especially root morphology and ability to penetrate compact soil layers (Nguyen and Joshi 1994). Several QTLs associated with different parameters of rice root morphology, i.e., root length, thickness, root/shoot ratio, root dry weight per tiller, deep root dry weight per tiller, maximum root length, and root penetration

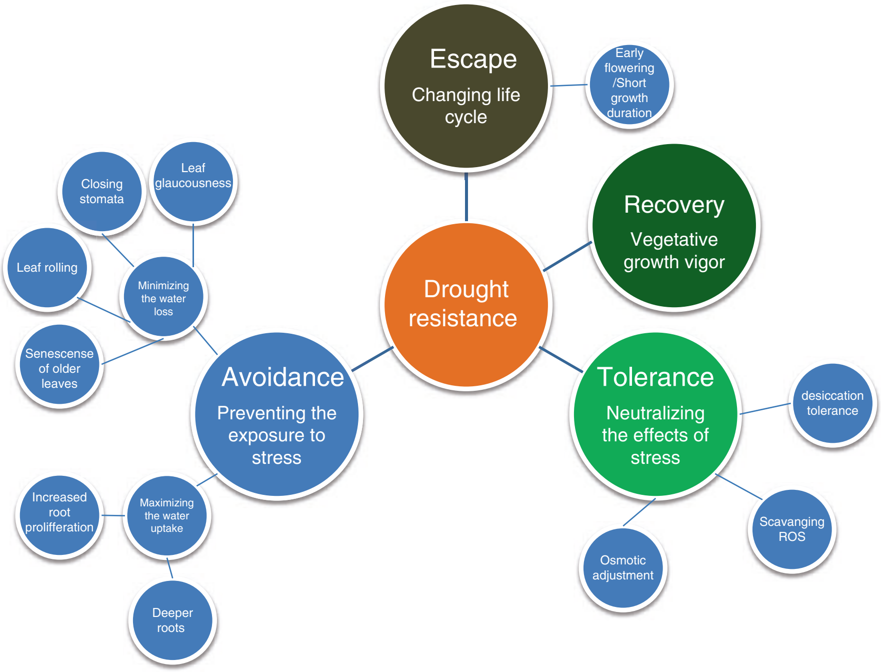

Fig. 18.1 Schematic mechanism of drought resistance in rice

ability, have been identified (Champoux et al. 1995; Price et al. 2000; Steele et al. 2006). A study on RILs developed from a cross between Co39 and Moroborekan showed that osmotic adjustment and dehydration tolerance were negatively connected with root morphological characters associated with drought avoidance (Lilley et al. 1996). Shen et al. (2001) conducted a marker-assisted backcross breeding program to transfer the deeper root alleles of Azucena into the elite high-yielding cultivar IR64. QTLs for drought avoidance using other traits have also been explored. Courtois et al. (2000) also identified 42 QTLs for drought-related traits in rice among which 11 were for leaf rolling, 10 for leaf drying, 11 for relative water content, and 10 for relative growth rate under stress. Due to the complex polygenic nature of drought resistance, major QTLs have been considered for effective tolerance. Obara et al. (2010) mapped a major QTL qRL6.1 for root length, on chromosome 6 in rice seedlings. Steele et al. (2006) improved the root morphological traits of Indian upland rice cultivar Kalinga III through marker-assisted backcross breeding with Azucena, an upland japonica variety from the Philippines.

The identification of QTLs with a major effect on grain yield raises new hopes of improving grain yield under drought through marker-assisted breeding (Table 18.1). The first large-effect QTL, *qDTY12.1*, for grain yield under reproductive-stage drought was reported in the Vandana/Way Rarem population explaining nearly 51% of the genetic variance (Bernier et al. 2009, 2007; Dixit et al. 2015). Major QTLs have also been reported for grain yield under lowland drought stress explaining 32 and 36 % of the genetic variance (Kumar et al. 2007; Venuprasad et al. 2009). Another major QTL for grain yield under reproductive-stage drought stress (qDTY1.1) showed an additive effect of 29.3 %, 24.3 %, and 16.1 % on mean yield in N22/Swarna, N22/IR64, and N22/MTU1010, respectively (Vikram et al. 2011). It also showed a positive effect on GY in non-stress situations. The grain yield under reproductive-stage drought stress of popular rice varieties Vandana and IR64 has been successfully improved through identification of large-effect QTLs (qDTY2.2, qDTY4.1, qDTY9.1, qDTY10.1, and qDTY12.1) and marker-assisted backcross breeding (Mishra et al. 2013; Swamy et al. 2013). Direct selection of GY under drought has led to the successful development and release of 17 high-yielding drought-tolerant rice varieties in South Asia, Southeast Asia, and Africa as well as 14 QTLs showing a large effect against high-yielding drought-susceptible popular varieties (Kumar et al. 2014).

18.3.1.2 Transgenic Research

While molecular biologists are gathering more and more information about the mechanism of drought tolerance, information regarding transgenic rice lines that show increased drought stress tolerance is being generated fast (Table 18.2). However, molecular basis underlying the improved drought tolerance of these transgenic rice plants remains largely unclear. Most of the transgenic lines have been developed by expressing transcription factors or other genes targeting secondary traits like root system architecture (RSA), water use efficiency (WUE), antioxidants and other metabolites, etc.

Table 18.1 List of QTLs that have been used in rice crop improvement

QTL	Function	Cross	References
Abiotic stress tolerance			
qDTY12.1	Controls grain yield under reproductive-stage drought stress	Vandana and Way Rarem	Bernier et al. (2009), Bernier et al. (2007)
qDTY1.1	Controls grain yield under reproductive-stage drought stress	N22 crossed with Swarna, IR64, and MTU1010	Vikram et al. (2011)
qDTY2.2, *qDTY4.1*, *qDTY9.1*, and *qDTY10.1*	Major-effect QTL for improved grain yield under drought stress	IR64 and Aday Sel	Swamy et al. (2013)
qSKC-1	Controls rice salt tolerance	Nona Bokra and susceptible *japonica*, Koshihikari	Lin et al. (2004)
qSNC-7	Controls rice salt tolerance	Nona Bokra and susceptible *japonica*, Koshihikari	Lin et al. (2004)
Saltol	Controls Na/K ratio and seedling-stage salinity tolerance	Pokkali and IR29 (*indica*)	Gregorio (1997)
Sub1	Controls submergence tolerance	Submergence-tolerant *indica* line (IR40931-26) and susceptible *japonica* line (P1543851)	Xu et al. (2006)
qRL6.1	Major QTL for root length; promoted root elongation under a range of NH4+ concentrations	Koshihikari (*japonica*) and Kasalath (*indica*)	Obara et al. (2016)
QTL 2	Increased root penetration and deep root weight under well-watered conditions	Bala/Azucena RIL	Steele et al. (2013)
QTL 7	Increased root weight parameters and maximum root length	Bala/Azucena RIL	Steele et al. (2013)
QTL 9	Increased deep root thickness under both well-watered and drought conditions	Bala/Azucena RIL	Steele et al. (2013)
QTL 11	Increased root length and root penetration	Bala/Azucena RIL	Steele et al. (2013)

Biotic stress tolerance			
pif	Rice blast resistance	Lemont and Jasmine 85	Jia and Liu (2011)
qSB-11	Sheath blight resistance	Lemont and Jasmine 85	Liu et al. (2009)
qStv1, *qStv 7*, and *qStv11*	RSV resistance	Kinmaze and DV85	Ding et al. (2004)
qSTV7	RSV resistance	Nipponbare/Kasalath/Nipponbare	Zhang et al. (2011)
qSTV11KAS	RSV resistance	Nipponbare/Kasalath/Nipponbare	Zhang et al. (2011)
qBph4.2	Brown planthopper (Bph) resistance	Zhenshan 97 and IR65482-17 (*Oryza australiensis*)	Hu et al. (2015)
Yield trait improvement			
pn4	Controls panicle number	Junambyeo and introgressed *indica* IR71033-121-15	Rahman et al. (2008)
pn6	Controls panicle number	Junambyeo and introgressed *indica* IR71033-121-15	Rahman et al. (2008)
qPN2	Controls panicle number	Three MAGIC populations from elite *indica* lines (DC1, DC2, and 8 way)	Meng et al. (2016)
Ghd7	Controls grain per panicle, plant height, and heading date	Zhenshan 97 and ZS(tq7) near-isogenic lines	Xue et al. (2008)
Ghd8	Controls grain per panicle, plant height, and heading date	Zhenshan 97 (ZS) and HR5	Yan et al. (2011)
DTH8	Controls yield, plant height, and flowering time	CSSL61 and Asominori	Wei et al. (2010)
GW2	Controls rice grain width and weight	WY3 (*japonica*) and Fengaizhan-1 (high-quality elite *indica*)	Song et al. (2007)
GS3	Major QTL for grain length and size; minor QTL for width and thickness in rice	Minghui 63 (large grain) and Chuan 7 (small grain)	Fan et al. (2009)
GIF1	Controls grain filling	*gif1* and Zhenshan97 (*indica*)	Wang et al. (2008)

Table 18.2 List of genes characterized or used for rice improvement

Gene	Category	Source species	Phenotype	Function	References
Nutrition and quality					
Soybean ferritin	Ferritin	*Glycine max*	High iron content	Increased iron content in the rice endosperm	Goto et al. (1999)
HLF	Human lactoferrin	Human	High iron content	Increased iron content in the rice endosperm	Nandi et al. (2002)
Pfe	Ferritin	*Phaseolus vulgaris*	High iron content	Increased iron content in the rice endosperm	Lucca and Hurrell (2001)
*phy*A	Phytase	*Aspergillus fumigatus*	Decreased phytic acid in simulated small intestine condition	Increase iron bioavailability	Lucca and Hurrell (2001)
rgMT	Cysteine-rich metallothionein-like protein	*Oryza sativa*	Increase in content cysteine residues	Increased iron absorption	Lucca and Hurrell (2001)
SrPf6	Phytase	*Selenomonas ruminantium*	High phytase activity over broad pH ranges	Hydrolyzes phosphate from phytate	Hong et al. (2004)
appA	Phytase	*Escherichia coli*	High phytase activity over broad pH ranges	Hydrolyzes phosphate from phytate	Hong et al. (2004)
MxIRT1	Ferrous transporter	*Malus xiaojinensis*	High iron content	Active transport of iron	Tan et al. (2015b)
AtIRT1	Iron-regulated transporter	*Arabidopsis thaliana*	High iron content; accumulation of Cu and Zn, but not Mn	Active transport of iron	Boonyaves et al. (2015)
AtNAS1	Nicotianamine synthase	*Arabidopsis thaliana*	High iron content	Biosynthesis of phytosiderophores (mugineic acid family) for iron uptake	Boonyaves et al. (2015)
PvFERRITIN	Ferritin	*Phaseolus vulgaris*	High iron content		Boonyaves et al. (2015)

Psy	Phytoene synthase	*Narcissus pseudonarcissus*	Increased provitamin A	Conversion of geranylgeranyl diphosphate to phytoene	Paine et al. (2005)
crtI	Bacterial phytoene desaturase	*Erwinia uredovora*	Increased provitamin A	Introduction of double bonds to phytoene	Ye and Al-Babili (2000)
pinA, *pinB*	Puroindolines	Chinese spring wheat	Grain texture	Grain softness	Krishnamurthy and Giroux (2001)
Abiotic stress tolerance					
SNAC1	NAC transcription factor	*Oryza sativa*	Drought and salinity tolerance	Water use efficiency	Hu et al. (2006)
OsbZIP23	Basic leucine zipper (bZIP) transcription factor	*Oryza sativa*	Drought and salinity tolerance	Transcriptional regulator through an ABA-dependent regulation pathway	Xiang et al. (2008)
DREB1A	Transcription factor	*Arabidopsis thaliana*	Drought tolerance	Drought-responsive element	Datta et al. (2012)
DREB1C	Transcription factor	*Arabidopsis thaliana*	Drought tolerance	Drought-responsive element	Ishizaki et al. (2013)
OsLEA3-1	LEA protein	*Oryza sativa*	Drought resistance for yield in the field	LEA	Xiao et al. (2007)
MnSOD	Manganese superoxide dismutase	*Pisum sativum*	Drought tolerance	Antioxidant enzyme	Wang et al. (2005)
ZmPPDK	Kinase	*Zea mays*	Drought tolerance	C_4 photosynthesis	Gu and Qiu (2013)
ZmPCK	Kinase	*Zea mays*	Drought tolerance	C_4 photosynthesis	Gu and Qiu (2013)
OsCPK4	Calcium-dependent protein kinase	*Oryza sativa*	Drought and salinity tolerance	Protection of lipid peroxidation	Campo et al. (2014)
OsSIK1	Receptor-like kinase	*Oryza sativa*	Drought and salinity tolerance	Abiotic stress and the senescence process	Ouyang et al. (2010)

(continued)

Table 18.2 (continued)

Gene	Category	Source species	Phenotype	Function	References
OsSIK2	Receptor-like kinase	*Oryza sativa*	Drought and salinity tolerance	Abiotic stress and the senescence process	Chen et al. (2013)
CodA	Choline oxidase	*Arthrobacter globiformis*	Salt stress tolerance	Conversion of choline to glycine betaine	Mohanty et al. (2002)
OsCDPK7	Calcium-dependent protein kinase	*Oryza sativa*	Salt stress tolerance	Ca^{2+}-stimulated protein phosphorylation	Saijo et al. (2000)
*HVA*1	LEA protein	Barley	Salt/drought tolerance	Confers cell membrane protection from damages caused by water limitation	D et al. (1996)
OsSOS1	Plasma membrane Na+/H+ exchanger	Oryza sativa	Salt tolerance	Proton pumps, antiporters, and ion transporters	Martinez-Atienza et al. (2007)
pdc1	Pyruvate decarboxylase	*Oryza sativa*	Submergence tolerance	Conversion of pyruvate to acetaldehyde during alcohol fermentation; enhanced metabolic capacity under anaerobiosis	Rahman (2001)
adh1, *adh2*	Alcohol dehydrogenase	Cotton	Submergence tolerance	Conversion of acetaldehyde to ethanol during alcohol fermentation	Rahman (2001), Xie and Wu (1989)
NtPT1	Phosphate transporter	Rice	Phosphate acquisition	Proton pumps, antiporters, and ion transporters	Park et al. (2007)
Biotic stress resistance					
Pi-d2	Transmembrane receptor protein kinase	Rice variety Digu	Wide-spectrum resistance to rice blast strains	Rice blast resistance gene	Chen et al. (2010)

Pi54	Coiled-coil, nucleotide-binding site and leucine-rich repeats	Indian rice cultivar HR22	Resistance to blast	Class of *R* genes and the protein activates several downstream defense-related pathways upon pathogen attack	Wang et al. (2014a)
Cht-2 and *Cht-3*	Chitinase	Rice	Enhanced resistance against *Magnaporthe grisea*	Chitin breakdown; PR protein; rice blast resistance gene	Nishizawa et al. (1999)
StSy	Antitoxin gene	*Vitis vinifera*	Resistance to blast	Stilbene synthase; phytoalexin trans-resveratrol synthesis	Stark-Lorenzen et al. (1997)
Alfalfa glucanase and rice basic chitinase	Chitinase-glucanase	Alfalfa and rice	Resistance to blast	Glucan and chitin breakdown; enhanced resistance to *Pyricularia oryzae*	Daorong et al. (1999)
Trichosanthin	Type I ribosome-inactivating protein (RIP)	*Trichosanthes kirilowii Maxim*	Resistance to blast	Protein synthesis inhibitor	Ming et al. (2000)
WT1	Phytoalexin	*Wasabia japonica*	Resistance to blast	Antimicrobial peptide	Kanzaki et al. (2002)
Dm-AMP	Defensin	*Dahlia merckii*	Rice blast/sheath blight resistance	Antimicrobial peptide	Jha et al. (2009)
Tlp	Thaumatin-like protein	Rice	Rice blast/sheath blight resistance	PR protein	Kalpana et al. (2006)
Xa21	Serine-threonine kinase	*Oryza sativa*	Rice blast/sheath blight/bacterial blight resistance	Confers resistance to *Xanthomonas oryzae pv. oryzae* (Xoo)	Zhai et al. (2004), Zhai et al. (2000)
N	RHBV nucleocapsid protein	Rice hoja blanca virus (RHBV)	RHBV resistance	RNA-mediated resistance to RHBV	Lentini et al. (2003)

(continued)

Table 18.2 (continued)

Gene	Category	Source species	Phenotype	Function	References
CP	RTBV coat protein	Rice tungro bacilliform virus (RTBV)	RTBV/RTSV resistance	Confers RTBV/RTSV resistance in rice with integrated transgene	Ganesan et al. (2009)
cryIA(b), *cryIA(c)*, and *cry1Ab/Ac*	Cry group endotoxin	*Bacillus thuringiensis*	Resistance to insect pest (leaf folder and yellow stem borer)	Endotoxin-mediated disruption of apical cell membrane and osmotic process of insect pests	Tu et al. (2000), Chen et al. (2011)
*OC-I*ΔD86	Oryzacystatin-IΔD86	Rice	Resistance to Meloidogyne	Cysteine proteinase inhibitor	Vain et al. (1998)
Chi11	Chitinase	Rice	Resistance to sheath blight and BLB	Chitin breakdown	Maruthasalam and Kalpana (2007)
Ace-AMP1	ns-LTP-like protein	*Allium cepa*	Resistance to both fungal and bacterial pathogens	Antimicrobial protein	Patkar and Chattoo (2006)
Dm-AMP1	Antimicrobial protein	*Dahlia merckii*	Resistance to sheath blight	Antifungal activity	Jha et al. (2009)
Yield traits					
OsTB1	Putative HLH TF	Rice	Increased no. of tillers	Negative regulator of lateral branching	Takeda et al. (2003)
OsmiR393	MicroRNA	Rice	Increased no. of tillers	Targets auxin receptor homologs	Xia et al. (2012)
OsmiR397	MicroRNA	Rice	Increased no. of tillers	Targets auxin receptor homologs	Zhang et al. (2013)
LRK1	Leucine-rich repeat receptor-like kinase 1	Dongxiang wild rice	Higher grain number per plant	Plasma membrane protein; regulates rice branch number by enhancing cellular proliferation	Zha et al. (2009)

OsLSK1, *OXOsLSK1-t-3*, and *OXOsLSK1-t-4*	Large spike S-domain receptor-like kinase 1 and truncated large spike S-domain receptor-like kinase 1	Rice	Improved grain yield	Plasma membrane protein	Zou et al. (2015)
OsSPL14	Squamosa promoter-binding protein-like 14	Rice	Increase in branch and grain number	Promotes panicle branching and higher grain yield in rice; controls shoot branching in the vegetative stage	Miura et al. (2010)
Herbicide resistance					
Bar	Bialaphos resistance	*Streptomyces hygroscopicus*	Herbicide tolerance	Detoxification of glufosinates	Kumar et al. (2008)
EPSPS	Enolpyruvylshikimate-3-phosphate synthase	*Agrobacterium* sp. CP4	Glyphosate tolerance	Aromatic amino acid biosynthesis via shikimate pathway	Kumar et al. (2008)
Protox	Protoporphyrinogen oxidase	*Bacillus subtilis*	Diphenyl ether (DPE) herbicide tolerance	Heme and chlorophyll biosynthesis; oxyfluorfen detoxification	Jung et al. (2004)
CYP1A1, *CYP2B2*, and *CYP2C19*	Cytochrome p450	Human	Enhanced chlorotoluron and norflurazon metabolism	Metabolizes xenobiotics in mammals; enhanced herbicide metabolism in plants; soil detoxification by phytoremediation	Kawahigashi et al. (2007), Kumar et al. (2012)
Other traits					
PEPC, *PPDK*, *NADP-ME*, and *NADP-MDH*	C_4 enzymes	Maize	Improvement in photosynthesis	C_4 photosynthesis	Kajala et al. (2011)

There are several reports that transgenic rice plants show higher grain yields than their wild relatives under drought treatment. The increase in grain yield of the transgenic plants has mainly been attributed to larger panicle sizes and higher tiller numbers (Todaka et al. 2015).Transcription factors have been suggested to play important roles in the regulation or reprogramming of the gene expression associated with plant stress responses. Overexpression of a NAC (NAM, ATAF and CUC) transcription factor *SNAC1* significantly enhanced drought resistance in transgenic rice (22–34 % higher seed setting than control) in the field under severe drought stress conditions at the vegetative and reproductive stage without showing any phenotypic changes or yield penalty (Hu et al. 2006). Similarly, overexpression of *OsNAC6* in rice plants was observed to increase tolerance to drought and salinity stresses (Nakashima et al. 2007). Overexpression of transcriptional regulators *OsbZIP23* and *OsbZIP16* that function through an ABA-dependent regulatory pathway resulted in transgenic rice plants with enhanced tolerance to drought and salinity stresses (Chen et al. 2012; Xiang et al. 2008). Transgenic rice plants expressing *AtDREB1A* under the control of the stress-inducible *RD29* promoter and *AtDREB1C* driven by a stress-inducible rice lip9 promoter showed higher tolerance to dehydration (Datta et al. 2012; Ishizaki et al. 2013).

Late embryogenesis abundant (LEA) proteins are important stress-inducible proteins involved in cellular protection against stresses (Hong and Uknes 1988). Transgenic rice plants expressing different LEA proteins showed increased tolerance to drought and salinity stresses (Xu et al. 1996; Xiao et al. 2007; Duan 2012). ABA-signaling unit composed of *OsPYL/RCAR5*, *OsPP2C30*, *SAPK2*, and *OREB1* was also used for the transgenic purpose in different rice varieties and found better adaptation under drought stress (Todaka et al. 2015).

Wang et al. (2005) used the pea manganese superoxide dismutase (*MnSOD*), an important antioxidant enzyme, under the control of a stress-inducible SWPA2 promoter to generate transgenic rice lines which showed improved drought tolerance. Gu et al. (2013) developed a transgenic rice lines with maize-specific pyruvate orthophosphate dikinase (*PPDK*) independently and in combination with the maize C4-specific phosphoenolpyruvate carboxylase (*PCK*) which exhibited higher grain yields than wild-type (WT) plants under soil drought conditions.

Changes in membrane integrity and modulation of lipid synthesis are important factors in the primary sensing of abiotic stress (Kader 2010). Transgenic rice plants overexpressing *OsCPK4*, a calcium-dependent protein kinase, exhibited stronger water-holding capability and reduced levels of membrane lipid peroxidation and electrolyte leakage under drought or salt stress condition (Campo et al. 2016). Similarly, transgenic rice plants, overexpressing *OsSIK1* and *OsSIK2* [putative receptor-like kinase (RLK)], showed enhanced tolerance to drought and salinity stresses (Ouyang et al. 2010; Chen et al. 2013). Transgenic rice plants expressing many other candidate genes such as lipid transfer protein gene *OsDIL* (*O. sativa drought-induced LTP*), (Guo and Ge 2013), heat shock protein gene *OsHsp17.0* or *OsHsp23.7* (Zou et al. 2012), and *Arabidopsis* glycine-rich RNA-binding protein *AtGRP2* or *AtGRP7* genes (Yang et al. 2014) have been reported to show enhanced drought tolerance. Disruption of squalene synthase (*SQS*) gene function by RNA interference has also been found to improve drought tolerance in rice plants (Manavalan et al. 2012).

Although several studies have reported transgenic rice plants with improved drought tolerance during field trials, further research is needed to uncover the regulatory mechanism of drought response and tolerance under field conditions. Such investigations should lead to the discovery of new genes that increase drought tolerance without yield penalty under well-watered as well as drought conditions.

18.3.2 Salinity

Salinity is one of the major impediments for enhancing production in rice-growing areas worldwide. Rice shows varied level of tolerance to salinity at different developmental stages. Though rice is relatively tolerant to salinity during germination, active tillering, and maturity, it is highly sensitive during the early seedling stage and reproductive stage (Ismail et al. 2007; Munns 2008; Singh and Redoña 2010). Thus, the seedling and reproductive stages are the most vulnerable to salt stress, with considerable impacts on survival and grain yield. One-fifth of irrigated arable lands in the world have been reported to be adversely influenced by high soil salinity (Negrão and Courtois 2011). Over 800 million ha of land is severely salt affected worldwide, while approximately 20 % of irrigated areas (about 45 million ha) are estimated to suffer from salinization problems of various degrees.

18.3.2.1 Marker-Assisted Breeding

Salinity is particularly a major problem in coastal regions in the tropics because of the intrusion of brackish water during the dry season and at the start of the wet season into rice field. Salt stress is also worsening due to buildup of salinity as a consequence of excessive use of irrigation water with improper drainage and poor-quality irrigation water. Rice shows wide genetic variation with respect to salinity tolerance. Landraces such as Pokkali, Nona Bokra, Damodar, Dasal and Getu, etc. are well adapted to grow in saline environments, while modern rice varieties show high sensitivity. The salinity tolerance at different growth stages seems to be managed by independent genes. A number of mapping studies have identified QTLs associated with salinity tolerance in rice (Table 18.1). A cross between tolerant *indica* landrace Nona Bokra with the susceptible japonica Koshihikari led to identification of several QTLs such as qSKC-1 for shoot K^+ concentration on chromosome 1 and qSNC-7 for shoot Na+ concentration (Lin et al. 2004). The *SKC1* gene was subsequently cloned and found to encode a sodium transporter that helps control K^+ homeostasis under salt stress (Ren et al. 2005). Saltol, a major QTL associated with the Na^+/K^+ ratio and seedling-stage salinity tolerance, was identified from a RIL population developed from *indica* varieties IR29 and Pokkali (Gregorio 1997). This QTL explains 43.2 % of the phenotypic variance and confers salinity tolerance at the vegetative stage (Bonilla et al. 2016). The availability of the large-effect QTL Saltol for salinity tolerance in rice, a theoretical framework for MABC, and the existence of intolerant varieties that are widely accepted by farmers provide an opportunity to develop cultivars that would be suitable for larger areas of submergence-prone rice (MacKill 2008). One highly salt-tolerant RIL from this population, FL478 (IR 66946-3R-178-1-1), has been used to improve the salt tolerance of BT7 variety by using marker-assisted backcross (Linh et al. 2012). Lang et al. (2008) applied MAS to improve salt tolerance in OMCS2000 rice cultivar, a widely grown cultivar in North Vietnam. However, there is no report of robust QTLs for salt tolerance at the reproductive stage. The main reason for this is time-consuming and laborious phenotyping protocols needed for the reproductive stage as compared with the relatively easy phenotyping protocols for the seedling stage (Jena and Mackill 2008).

The best known and seemingly most robust QTL is *Saltol/SKC1* on the short arm of chromosome 1 (Lin et al. 2004). QTLs have been identified in this region in a number of populations derived from several donors (Ahmadi et al. 2011; Ul Haq et al. 2010), and the candidate gene has been identified to a high degree of confidence (Ren et al. 2005; Platten et al. 2006). Hossain et al. (Hossain et al. 2015) reported that genomic regions on chromosomes 1, 7, 8, and 10 affect salinity tolerance at the reproductive stage through alterations in Na^+ uptake, pollen fertility, and Na^+/K^+ ratio, and these loci are good targets for marker-assisted selection aimed at improving salinity tolerance. The notable association of some QTLs with other QTLs for different traits suggests that they have a causal relationship. This would help to improve rice varieties for salinity-prone areas where reproductive-stage salt stress is a major impediment to rice production especially during the dry season. Mechanisms such as Na^+ exclusion, Na^+/K^+ ratio, and pollen fertility may be responsible for reproductive-stage salt tolerance. Recently, a novel cross was made using embryo rescue technique between the exotic wild rice species *Oryza coarctata* and cultivated rice variety IR56 (*O. sativa.*), spawning a new generation of rice that has double the salinity tolerance of other rice varieties (International Rice Research Institute 2013).

18.3.2.2 Transgenic Research

Genes for aquaporins (water channel proteins) and late embryogenesis abundant (LEA) proteins have been tested in transgenic studies addressing drought and salinity, but much more work is necessary before we know whether they will be useful to breeders and farmers (Table 18.2). Transgenic rice plants harboring the choline oxidase (*codA*) gene from *Arthrobacter globiformis* were highly tolerant to salt stress (Mohanty et al. 2002). Choline oxidase catalyzes conversion of choline to glycine betaine, which is known to provide tolerance against a variety of stresses. The protective function of glycine betaine has been predicted to be more efficient when produced in a photosynthetic organelle (Sakamoto and Murata 1998). Transgenic rice with chloroplast-targeted *codA* gene were more tolerant than the transgenic plants with the protein localized in the cytosol (Kathuria et al. 2009). The potential role of superoxide dismutase (SOD) in the protection against salt stress was examined through overexpression in rice (Tanaka et al. 1999). Transgenic rice plants expressing *HVA*1, driven by the constitutive promoter from the rice *actin*1 gene, showed significant increase in tolerance to salt (Xu et al. 1996). The overexpression of calcium-dependent protein kinase *OsCDPK*7 gene, which performs the Ca^{2+}-stimulated protein phosphorylation, in rice resulted in higher salt tolerance (Saijo et al. 2000). Barley LEA protein genes expressed in two rice varieties enhanced growth under either salt or drought stress (Rohila and Jain 2002; Chandra Babu et al. 2004).

18.3.3 Flood and Submergence

Flooding and submergence are recurring problems for rice farming, especially in the lowlands of South and Southeast Asia. Since most of the economically high-yielding varieties are intolerant to flooding, farmers in these areas depend on traditional low-yielding varieties that can tolerate flooded conditions. In the rainfed lowland areas of Eastern India, submergence is the third most important limitation to rice production among 42 biotic and abiotic stresses, and it is surpassed only by drought and weeds (Widawsky and O'Toole 1996). The expression of submergence tolerance genes is known to be environmentally dependent and genetically complex (Setter et al. 1997). One of the ways that has enabled rice to adapt to flooding has recently been identified as a "quiescence strategy" (Bailey-Serres and Voesenek 2008). It is characterized by reduced plant elongation during submergence associated with regrowth when the water recedes. An ethylene-responsive factor (ERF), *Sub1A*, is the key determinant of this survival mechanism (Xu et al. 2006). *Sub1A*-1 is induced by ethylene, a gaseous plant hormone that becomes entrapped by water submergence (Perata 2007).

18.3.3.1 Marker-Assisted Breeding

Genetic studies suggest both simple and quantitative inheritance for submergence tolerance. Breeding of improved varieties to overcome the problem of submergence has mainly relied on FR13A, a tolerant landrace from Odisha, India that can tolerate complete inundation for 10–14 days (Mackill et al. 1993). Using population derived from a cross between a submergence-tolerant *indica* line (IR40931-26) and a susceptible *japonica* line ("P1543851"), a major QTL was finely mapped near the centromere of chromosome 9, designated as *Submergence 1* (*Sub1*). The locus showed 70 % of phenotypic variation in submergence tolerance. There are a cluster of three genes at *Sub1* locus, encoding putative ethylene response factors (ERFs)/ethylene-responsive element-binding proteins/APETALA2-like proteins (Xu et al. 2006; Perata 2007). All three *Sub1* region genes fall in the B-2 subclass of ERF proteins, which contains a single 58- to 59-residue ERF domain. Two of these genes, *Sub1B* and *Sub1C*, are invariably present in the *Sub1* region of all rice accessions analyzed. In contrast, the presence of *Sub1A* is variable. A survey identified two alleles within *indica* varieties that possess this gene: a tolerance-specific allele named *Sub1A-1* and an intolerance-specific allele named *Sub1A-2*. Overexpression of *Sub1A-1* in a submergence-intolerant *O. sativa* ssp. *japonica* conferred enhanced tolerance to submergence, downregulation of *Sub1C*, and upregulation of *Alcohol dehydrogenase 1* (*Adh1*), indicating that *Sub1A-1* is a primary determinant of submergence tolerance. The molecular mechanism behind the deepwater rice responses through the identification of the genes, viz., *SNORKEL1* (*SK1*) and *SNORKEL2* (*SK2*), which trigger deepwater response by encoding ethylene response factors involved in ethylene signaling (Hattori et al. 2009). The products of *SK1* and *SK2* trigger remarkable internode elongation via gibberellin. The deepwater rice C9285 possesses *SK1* and *SK2*, although both genes are absent in the non-deepwater rice T65. *SK1* and *SK2* possess a putative nuclear localization signal and a single APETALA2/ethylene response factor (AP2/ERF) domain. The *SK* genes were significantly expressed under deepwater conditions, whereas these expressions were low under dry conditions in C9285. Overexpression of *SK1* gene drove elongation one to three internodes, and *SK2* overproducers elongated one to seven internodes, even under dry conditions (Hattori et al. 2009). The *Sub1* gene, derived from the tolerant variety FR13A, has been transferred to a number of widely grown varieties, allowing them to withstand complete submergence for up to 2 weeks. The IR64-Sub1 cultivar carrying QTL/*Sub1* gene was successfully used in backcross breeding programs to alter the submergence tolerance of improved high-yielding Vietnamese rice cultivars (Lang et al. 2013; Lang and Buu 2011; Submergence et al. 2013).

Four QTLs were identified in a cross between two moderately tolerant varieties IR72 and Madabaru, on chromosomes 1, 2, 9, and 12. The largest QTL on chromosome 1 which had a LOD score of 11.2 and R^2 of 52.3 % was found in a non-Sub1 locus and had the tolerant allele from IR72 which suggests that an alternative pathway may be present in this variety that is independent of the ethylene-dependent pathway mediated by the *Sub1A* gene (Septiningsih et al. 2012). These novel QTLs can be combined with Sub1 using marker-assisted backcrossing in an effort to enhance the level of submergence tolerance for flood-prone areas (Table 18.1).

18.3.3.2 Transgenic Research

Two different approaches have been used to try and identify limiting factors in response to waterlogging (Table 18.2). First is the under-expression of single candidate genes, e.g., for ethanol synthesis, using sense and antisense constructs. Second is the overexpression of transcription factors (Dennis et al. 2000). It was anticipated that both approaches may have a beneficial effect in switching on the longer-term adaptation response to low oxygen stress. Quimio et al. (2000) found that Taipei 309 transformed with pyruvate decarboxylase (*pdc1*) linked to a constitutive 35S promoter had up to threefold higher PDC activities and ethanol synthesis rates when exposed to anoxia compared to non-transformed controls. They also reported that increasing ethanol production up to sixfold in a range of transgenic lines exposed to anoxia was correlated with an eightfold increase in percentage survival of lines during submergence under hypoxic conditions. In contrast, Rahaman et al. (2001) studied Taipei 309 transformed with *pdc1* and found that two transgenic lines had over twofold greater PDC activity and they had up to 43 % greater rate of ethanol synthesis; however, survival of seed lines exposed to anoxia was even less than that of non-transformed plants. They observed similar results for transgenic rice expressing the cotton alcohol dehydrogenase *adh2*cDNA. Therefore, the results of transgenic rice need to be repeated for its potential extrapolation.

18.4 Improvement of Biotic Stress Resistance

On average, farmers lose 37 % of their rice yield to pests and diseases, and these losses can range between 24 and 41 % depending on the production situation (Sparks et al. 2012). While many of these can be handled with management practices, often it is not the viable option due to financial and educational status of the farmers and unavailability of the pesticides.

18.4.1 Disease Resistance

18.4.1.1 Blast Disease

Rice blast is among the diseases that cause highest damage to the grain yield among all diseases (Lee 1983). The fungus *Magnaporthe oryzae* is the causal agent of rice blast. It is a haploid filamentous ascomycete with a relatively small genome of ~40 Mb divided into seven chromosomes (Dean 2005). The fungus causes disease at seedling and adult stages on the leaves, nodes, and panicles. Sesma and Osbourn (Sesma 2004) reported a new facet of the *M. oryzae* life cycle, where the fungus can undergo a different and previously uncharacterized set of programmed developmental events that are typical of root-infecting pathogens.

Marker-Assisted Breeding

Conventional genetic analyses of identified donors with resistance, availability of pure isolates of the blast pathogen, and advanced molecular analysis techniques have resulted in identification of more than 100 genes for resistance to *M. oryzae* (Sharma 2012) and have been designated as *Pi1-Pi62*, *Pii*, *Pia*, *Pib*, *Pik*, *Pi-kh* (*same as Pi54*), *Pit*, *Pita*, *Pita 2*, *Pitp*, *Pish*, etc. (Wang et al. 2014a). A genome-wide association study based on genotyping 0.8 million single-nucleotide polymorphism variants across 366 diverse *indica* accessions identified thirty associated loci (Wang et al. 2014b). Marker-assisted backcross breeding (MABB) approach was employed to incorporate blast resistance genes, viz., Piz-5 and Pi54, from the donor lines C101A51 and Tetep into the genetic background of PRR78 to develop Pusa1602 (PRR78 + *Piz5*) and Pusa1603 (PRR78 + Pi54), respectively (Singh et al. 2012).

Transgenic Research

Homozygous transgenic rice lines harboring rice blast resistance gene *Pi-d2* showed high resistance to disease incidence of neck blast (Chen et al. 2010). Microarray analysis of transgenic rice Taipei 309 (TP) carrying Pi54 gene indicated activation of defense response and transcription factor-related genes and a higher expression of key enzymes involved in the defense response pathway (Gupta et al. 2012). Asghar et al. (2007) attempted to improve basmati rice against fungal infection through gene transfer technology. Transgenic plants with rice class-I chitinase genes, *Cht-2* or *Cht-3*, showed significantly higher resistance against the rice blast pathogen *Magnaporthe grisea* races *007.0* and *333* (Nishizawa et al. 1999). Other reports include plant antitoxin gene (Stark-Lorenzen et al. 1997), chitinase-glucanase gene (Daorong et al. 1999), trichosanthin gene (Ming et al. 2000), wasabi phytoalexin gene (Kanzaki et al. 2002), and rice blast resistance genes Pi-ta, Pi-9, Pi-2, etc. (Table 18.2).

18.4.1.2 Sheath Blight (ShB)

Rice ShB pathogen produces toxin that induces characteristic symptoms on rice leaves and wilting of seedlings and inhibits rice radicle growth. Over the past decades, studies on resistance to ShB have been conducted by many researchers who have had diverse objectives, including screening of the germplasm of cultivated rice and its wild relatives, assessment of genetically engineered plants with genes for resistance, and phenotyping for QTL mapping or validation (Table 18.1). Sources of ShB resistance have been sought for in different rice-growing regions. These studies resulted in the identification of genotypes with moderate to high levels of resistance.

Marker-Assisted Breeding

Both wild species and landraces of the *Oryza* genus possess under-exploited alleles that may have a strong potential for the improvement of Asian rice (*Oryza sativa* L.) and African rice (*Oryza glaberrima* Steud.). Over the years, a very large number of accessions from different species of *Oryza* have been tested at IRRI to identify sources for ShB resistance. From a total of 233 accessions tested, 76 were found to contain a high level of resistance to ShB, and 29 showed moderate resistance. The latter accessions belonged to the African rice, *O. glaberrima* (2*n* = 24 AA), a close relative of *O. sativa* (2*n* = 24 AA). The relatively high-resistant accessions belonged to mixed genetic groups. In addition to the studies mentioned above, several other groups also explored wild accessions or their derivatives for ShB resistance (Amante et al. 1990; Lakshmanan 2016; Prasad and Eizenga 2008). Ram et al. (2016) screened 11 different species of *Oryza*, identifying the accessions of *O. latifolia* Desv., *O. grandiglumis* (Doell) Prod, *O. nivara*, and *O. rufipogon* as having a higher level of resistance. Li et al. (1995) identified six QTLs for sheath blight resistance in an F4 population of Teqing/Lemont.

Transgenic Research

Pathogenesis-related (PR) proteins are produced in response to attack by pathogens and are known to play key roles in the plant defense mechanisms. Overexpression of PR proteins, including chitinase (PR-3), β-1,3-glucanases (PR-2), thaumatin-like proteins (PR-5), and other plant- or microbe-derived antifungal proteins, has been used to develop transgenic plants against fungal infection. Chitinases that hydrolyze the β-1,4 linkages of N-acetylglucosamine ("chitin") have been well characterized. Overexpression of different chitinases in rice cultivars has been found to result in enhanced resistance against ShB (Datta et al. 2001). The expression of *Ace-AMP1* (Patkar and Chattoo 2006) and *Dm-AMP1* (Jha et al. 2009) genes resulted not only in enhanced resistance against ShB but also against other rice diseases. There have been efforts to combine resistance genes to generate plants with increased resistance to ShB. To date, more than 12 rice cultivars, including IR72, IR64, Chinsurah Boro II, Basmati 122, Swarna, and IR58, have been transformed with different genes for ShB resistance. Kalpana et al. (2006) engineered the different lines of elite *indica* rice cultivars, ADT38, ASD16, IR50, and Pusa Basmati1, by constitutively overexpressing rice *tlp* encoding a thaumatin-like protein. The putative transformants and their progenies expressing *tlp* showed enhanced resistance against the sheath blight pathogen, *Rhizoctonia solani*, when compared to the non-transformed plants. The combination of rice *chi11*, encoding a chitinase, along with *tlp* showed enhanced resistance against *R. solani* than the ones that express either *tlp* or *chi11* transgene alone (Table 18.2).

18.4.2 Bacterial Disease

18.4.2.1 Bacterial Leaf Blight (BLB)

Bacterial leaf blight or bacterial blight (BB) caused by the pathogen *Xanthomonas oryzae pv oryzae* (Xoo) is one of the most destructive diseases of rice throughout the world (Rao and Lakshminarasu 2002). Twenty-six genes conferring resistance to various races of the pathogen have been identified and used in rice breeding programs (http://www.knowledgebank.irri.org). Fourteen of these [*Xa1*, *Xa2*, *Xa3*, *Xa4*, *Xa7*, *Xa10*, *Xa11*, *Xa12*, *Xa14*, *Xa16*, *Xa17*, *Xa18*, *Xa21* and *Xa22* (t)] are dominant while six (*xa5*, *xa8*, *xa13*, *xa15*, *xa19* and *xa20*) were also found to be recessive (Khush 1991; Kinoshita 1995; Lin 1996). At least ten races of the bacterium have been identified in the Philippines and two other in India. Each race has specific virulence to varieties with different resistance genes, showing a gene-for-gene relationship in the host-pathogen interaction (Mew 2016; Vera Cruz 1989).

Marker-Assisted Breeding

Four *Xa* genes have been cloned and six others have been tagged with molecular markers and employed for marker-assisted selection and release of resistant cultivars in several countries. Huang et al. (1997) pyramided four resistance genes into IR-24 background. The resistance gene *Xa-1,* conferring resistance to the Japanese Xoo race I, was first reported by Sakaguchi (Sakaguchi 1967). The*Xa-1* gene was extensively studied and mapped to chromosome 4 by RFLP markers (Yoshimura et al. 1996). Positional cloning of the gene in the rice genome project in Japan revealed that it encodes a nucleotide-binding site leucine-rich repeat (NBS-LRR) type of protein. A broad spectrum bacterial blight resistance gene *Xa-21* was introgressed from the wild species *O. longistaminata* into *O. sativa* background (Khush and Mackill 1989). This gene was tagged by RAPD and RFLP markers and was later cloned by map-based cloning strategy. Marker-assisted selection was used by Sanchez et al. (2000) to transfer three bacterial blight resistance genes *Xa-5*, *Xa-13*, and *Xa-21* into three promising new plant types. The same set of genes were also pyramided into PR106, a widely grown variety in Punjab, India and Samba Mahsuri (BPT5204), a very popular variety with farmers and consumers across India because of its high yield and excellent cooking quality (Sundaram and Vishnupriya 2008; Singh et al. 2001). The Xa3/Xa26 family is a potential disease resistance gene reservoir. In addition to Xa3/Xa26, the MRKa, a paralog of Xa3/Xa26 in rice cultivar Minghui 63, can mediate Xoo resistance (Cao et al. 2007). Datta et al. (2002) stacked the *Bt* fusion gene (for insect resistance) and the chitinase gene (for tolerance of sheath blight) in rice by reciprocal crossing.

Transgenic Research

Maruthasalam et al. (2007) generated *indica* rice cultivars, co-transformed with genes rice chitinase (*chi11*) and a thaumatin-like protein (*tlp*) conferring resistance to fungal pathogens, and a serine-threonine kinase (*Xa21*) conferring bacterial blight resistance through particle bombardment. The transgenic Pusa Basmati1 line pyramided with *chi11*, *tlp* and*Xa21* showed an enhanced resistance to both sheath blight and bacterial blight. Zhai et al. (2004, 2000) transformed *Xa*21 into five widely used Chinese rice varieties through an *Agrobacterium*-mediated transformation system and obtained transgenic plants highly resistant to bacterial blight disease (Table 18.2).

18.4.2.2 Virus Resistance

The detrimental effects of viruses in rice yield have posed a challenge in the past years. In fact, , 828,000 tons of rice amounting to US$120 million was lost due to rice grassy stunt virus (RGSV) or co-infection by RGSV and rice ragged stunt virus (RRSV) that severely infected more than 485,000 hectares of paddy fields in southern Vietnam during 2006–2007 (Cabauatan and Cabunagan 2009; Sasaya et al. 2013). Thus, it is important to control viral diseases in rice to maintain global food security and rice supply.

Marker-Assisted Breeding

Some *indica* paddy varieties, such as Modan, have a resistance allele Stvb-i, which is incompletely dominant and allelic with Stv-b on chromosome 11 (Washio et al. 1968). In the 1960s, Stvb-i from Modan was introduced into many japonica varieties, including St. No. 1, Chugoku 31, Aichi 6 and Aichi 97 for the control of rice stripe virus (RSV) (Toriyama et al. 1966; Maeda et al. 2006). Thereafter, the derivative varieties harboring Stvb-i were widely cultivated in Japan and in the Jiangsu province of China with stable resistance to RSV (Wang 2006).

In the variety Milyang 23, a QTL for RSV resistance was detected in the interval between markers XNpb202 and C1172 on chromosome 11 (Maeda et al. 1999), which was reported to be allelic with Stvb-i. Subsequently, the same research group using both RFLP and SSR markers reported two QTLs in the Japanese upland rice variety, Kanto 72. The QTL on chromosome 11 corresponding to Stv-b exerted a greater effect than the other on chromosome 2 by reducing the infection rate of RSV (Maeda et al. 2006, 2004). Ding et al. (2004) also detected two major QTLs for RSV resistance in the *indica* variety, DV85 (Table 18.1). One was mapped to the same chromosomal region as Stvb-i and the other was mapped on chromosome 7. More recently, three QTLs were detected in the Indian landrace Dular, one on chromosome 3 and the other two in the RM287–RM209 and RM209–RM21 intervals on chromosome 11, respectively (Wu et al. 2009).Romero et al. (2014) identified one major QTL on the short arm of chromosome 4 for resistance to rice hoja blanca virus (RHBV) in two populations. Two major QTL on chromosomes 5 and 7 were also identified for resistance to *T. orizicolus* in the Fd2000 · WC366 and Fd50 · WC366 crosses, respectively. This comparative study using two distinct rice populations allowed for a better understanding of how the resistance to RHBV and its vector are controlled genetically. Zhang et al. (2011) performed QTL analysis for RSV resistance using 98 backcross inbred lines derived from the cross between the highly resistant variety, Kasalath and the highly susceptible variety, Nipponbare. Under artificial inoculation in the greenhouse, two QTLs for RSV resistance, designated qSTV7 and qSTV11KAS, were detected on chromosomes 7 and 11 respectively, whereas only one QTL was detected in the same location of chromosome 11 under natural inoculation in the field. The stability of qSTV11KAS was validated using 39 established chromosome segment substitution lines (CSSLs). Fine mapping of qSTV11KAS was carried out using 372 BC3F2:3 recombinants and 399 BC3F3:4 lines selected from 7018 BC3F2. Resistance to RSV has been studied in Japanese upland rice varieties and two loci, Stv-a and Stv-b, have been reported (Washio et al. 1968). Stv-a and Stv-b are complementary dominant genes. The former was linked with the glutinous endosperm (wx) and photosensitivity-1 (Se-1) loci on chromosome 6 and the latter was located on chromosome 11. Encabo et al. (2009) developed near-isogenic lines from Utri Merah and Taichung Native 1 (TN1), which were evaluated for reactions to rice tungro spherical virus (RTSV) and rice tungro bacilliform virus (RTBV). TW16 is an NIL (BC5) resistant to rice tungro disease (RTD). RTBV was able to infect both TN1 and TW16 but the levels of RTBV were usually significantly lower in TW16 than in TN1. Infection of RTSV was confirmed in TN1 by a serological test but not in TW16. However, the global gene-expression pattern in an RTSV-resistant NIL (BC6), TW16-69, inoculated with RTSV indicated that RTSV can also infect the resistant NIL. Infection of RTSV in TW16 was later confirmed by reverse-transcription polymerase chain reaction (RT-PCR) but the level of RTSV was considerably lower in TW16 than in TN1. Examination for virus accumulation in another NIL (BC6), TW16-1029, indicated that all plants of TW16-1029 were resistant to RTSV, whereas the resistance to RTBV and symptom severity were segregating among the individual plants of TW16-1029. Collectively, these results suggest that RTD resistance of Utri Merah involves suppression of interacting RTSV and RTBV but the suppression trait for RTSV and for RTBV is inherited separately.

Transgenic Research

Transformation of rice with the RHBV nucleocapsid protein (*N*) gene showed a significant reduction in disease development (Lentini et al. 2003) (Table 18.2). Reactions were observed that ranged from susceptible to completely resistant plants (immunity). The resistant reactions were characterized by the production of local lesions like a hypersensitive reaction or a recovery phenotype with the emergence of symptomless new leaves. These transgenic RHBV-resistant rice lines expressed the *N* gene RNA at low levels that were below the detection limit by Northern blots and only resolved by RT-PCR. The nucleocapsid protein could not be detected in any of the transgenic plants either by Western or ELISA tests. These results suggest that the resistance encoded by the *N* gene in these plants appears to be mediated by RNA. When challenged with RHBV, the resistant transgenic lines showed a significant increased performance for important agronomic traits including the number of tillers, the number of grains per plant and the yield as compared to the susceptible control. Furthermore, upon inoculation some of the most resistant transgenic lines showed agronomic traits similar to the uninoculated, non-transgenic Cica 8 control. Using both agronomic traits and disease severity as criteria, several of the most resistant lines demonstrated that the *N* gene and RHBV resistance were inherited in a stable manner. These transgenic rice lines could become a new genetic resource in developing RHBV-resistant cultivars. Verma et al. (2012) transformed rice using

DNA constructs designed to express an untranslatable sense or anti-sense RTSV RNA. Progeny of primary transformants, showing low copies of the integrated transgenes and accumulating the corresponding transcripts at low levels, were challenged with viruliferous green leafhopper (GLH). Three out of four transgenic plant lines expressing untranslatable RTSV RNA in the sense orientation and two out of the four lines expressing an RTSV gene in the anti-sense orientation showed delayed buildup of RTSV RNA over time. Transmission of RTBV from the above lines was reduced significantly.

Biotechnological approaches have also been employed to develop transgenic plants for resistance against RTBV and RTSV (Dai and Beachy 2009). Ganesan et al. (2009) transformed *indica* rice cultivar Pusa Basmati-1 with coat protein (CP) gene of an Indian isolate of RTBV. Rice plants containing the transgene integrated in low copy numbers were obtained, in which the CP was shown to accumulate in the leaf tissue. The progenies representing three independent transformation events were challenged with Indian isolates of RTBV using viruliferous GLH and the viral titers in the inoculated plants were monitored using DNA dot-blot hybridization. As compared to non-transgenic controls, two independent transgenic lines showed significantly low levels of RTBV DNA, especially towards later stages of infection and a concomitant reduction of tungro symptoms. The transgenic strategies for RTD resistance are promising although pathogen derived resistance for RTD has been reported as being only partially effective. Recently, some research on the development of transgenic resistance to RTD have been done targeting RTBV, as it is the causative agent of tungro symptoms (Ganesan et al. 2009; Dai et al. 2008; Tyagi et al. 2008). These reports showed considerable resistance against the disease in controlled laboratory conditions. Tyagi et al. (2008) developed a transgenic rice line by RNA interference (RNAi) for the control of RTBV infection. In the two transgenic lines expressing ds-RNA, different resistance responses were observed against RTBV. In one of the above lines (RTBV-O-Ds1), there was an initial rapid buildup of RTBV levels following inoculation, comparable to that of untransformed controls, followed by a sharp reduction, resulting in approximately 50-fold lower viral titers, whereas the untransformed controls maintained high levels of the virus till 40 days post-inoculation (dpi). In RTBV-ODs2, RTBV DNA levels gradually rose from an initial low to almost 60 % levels of the control by 40 dpi. Line RTBV-O-Ds1 showed symptoms of tungro similar to the untransformed control lines, whereas line RTBV-O-Ds2 showed extremely mild symptoms.

18.4.3 Nematodes

About 300 nematode species belonging to 35 genera have been reported infesting rice. Among them, nematode species from about ten genera are economically important in relation to rice production. Rice grown in different environments is attacked by different nematode species. *Ufra* (*Ditylenchus angustus*) and root-knot (*Meloidogyne* spp.) nematodes are major pests of deepwater rice. In irrigated rice, infections by *Hirschmanniella* spp. and *Aphelenchoides besseyi* are common, whereas upland rice is invariably infested by *Meloidogyne* and *Pratylenchus* species. Among the important nematode species that attack rice, ufra and white tip nematodes find a place in regulatory pest lists of several countries (Varaprasad et al. 2006). In India, yield losses due to ufra were reported as 5–50 % in UP (Singh 1953), 10–15 % in West Bengal, and 30–100 % in hot spots for this nematode in Assam (Panwar and Rao 1998). In southern region of Thailand, 10–90 % loss was observed (Hashioka 1963). Khuong (1983) observed most severe and conspicuous damage by *D. angustus* in 50,000 ha flooded fields with 50 % yield loss in the Mekong Delta and Dong-Thap Province of Vietnam.

Nematode problems have received relatively less attention in the past due to incipient damage in vast areas and difficulties in investigations. Most of the times, the losses caused by the parasitic nematodes in rice are just accepted mainly due to unawareness, poor economic condition of the rice growers, and subsistence farming of the crop. However, importance of nematode pests has increased in the recent years due to the changes in cropping systems and introduction of new production technologies that favor nematode multiplication and spread to new ecosystems in several rice-growing countries. More than 200 species of plant-parasitic nematodes (PPNs) have been reported to be associated with rice (Prot 1994). Rice root-knot nematodes (*Meloidogyne* spp.), rice root nematode (*Hirschmanniella oryzae*), white tip nematode (*Aphelenchoides besseyi*), and stem nematode (*Ditylenchus angustus*) are the important PPNs associated with rice-based cropping systems (Sharma and Rahaman 1998). Among these, the rice root-knot nematodes (*Meloidogyne* sp.) are considered as the major problem in rainfed, upland, and lowland rice fields, whereas the rice root nematodes (*Hirschmanniella* sp.) are problematic on lowland rice-growing areas of South and Southeast Asia (Prot 1994). Among *Meloidogyne* sp., the rice root-knot nematode (*M. graminicola* Golden and Birchfield) attacking rice and wheat is considered the most serious nematode in upland rice cultivation (Panwar and Rao 1998) and causes economic losses in upland, lowland, and deep-water rice and also in rice nurseries (Bridge et al. 1990).

Rice root-knot nematode, *M. graminicola*, was reported to reproduce on all the ten wild *Oryza* species tested. *O. australiensis* Domin and *O. brachyantha* Chev and Rochr showed by far the greatest infestation (5855 and 10,235 juveniles/g root, respectively) compared with *O. officinalis* Wall., which recorded the lowest infestation (240 juveniles/g root). *O. latifolia* Desv., *O. ridleyi* Hook. f., and *O. rufipogon* Griff. recorded <500 juveniles/g root (Gergon and Prot 1993). Efforts have been initiated to screen for rice cultivars with resistance to *M. graminicola.* Srivastava et al. (2011) identified Achhoo, HPR2373, and Naggardhan as rice cultivars with appreciable resistance to *M. graminicola*. In these cultivars only up to ten galls were observed per 5 g root sample in a 3-year consecutive field testing. In contrast, Ranbir Basmati and Hasan Sarai were found to be highly susceptible. These contrasting phenotypes would be helpful in breeding efforts as well as marker development for MAS-breeding approaches. There are other reports on screening for resistant rice cultivars (Ravindra et al. 2015; Sharma-Poudyal et al. 2004). However, due to differences in the screening procedures, it has become challenging to come up with a list of truly *M. graminicola*-resistant rice cultivars. Pokharel et al. (2012) noted that the absence of a uniform resistance evaluation procedure has taken a toll on the progress of the development of resistant lines.

18.4.3.1 Marker-Assisted Breeding

M. graminicola does not show any significant effect on yield of *indica* rice variety Bala, but causes a yield reduction of almost half in *japonica* rice variety Azucena, suggesting that the partial resistance to nematode establishment was related to nematode tolerance. Shrestha et al. (2007) identified QTLs for partial resistance to *M. graminicola* using a mapping population based on Bala (tolerant) × Azucena (susceptible). A total of six putative QTLs for nematode tolerance were detected. For two of the QTLs detected, Azucena was the donor of the tolerance alleles, suggesting it may be possible to breed plants with greater tolerance than Bala. Evaluation of advanced backcross populations developed for water stress environment and *M. graminicola* resistance revealed that Teqing and the donors cvs Type 3, Zihui 100, and Shwe Thwe Yin Hyv were resistant to the nematode (Prasad and Vijayakumar 2006). Furthermore, the study revealed that the resistance to *M. graminicola* is most likely multigenic in nature.

While Soriano et al. (1999) have identified resistant wild rice accessions of *O. glaberrima* (TOG7235, TOG5674, TOG5675) and *O. longistaminata* (WL02), success of introgression into *O. sativa* has been very limited. Using the rice diversity panel 1 with 332 accessions, Dimkpa et al. (2016) found accessions Khao Pahk Maw and LD 24 to be resistant to *M. graminicola* and identified 11 QTLs through a genome-wide association study. It is noteworthy that 6 of the 11 QTLs contain genes annotated as containing lectin domains. QTL11.1 contains genes that have been associated with powdery mildew resistance in barley and also genes with strong homology to stripe rust resistance (Dimkpa et al. 2016). Fine mapping these regions should yield molecular markers and perhaps mine new resistance genes for molecular breeding and/or the generation of resistant transgenic lines.

18.4.3.2 Transgenic Research

There are several possible approaches to develop transgenic plants with improved nematode resistance, such as anti-invasion and migration strategies, feeding-cell attenuation, and anti-nematode feeding and development strategies (Atkinson et al. 2003). Plant proteins (cystatins) that prevent digestion of dietary plant proteins by the feeding nematodes have been exploited for rice nematode resistance. Expression of an engineered cysteine proteinase inhibitor (oryzacystatin-IΔD86) for nematode resistance in transgenic rice plants resulted in a significant (55 %) reduction in egg production by *Meloidogyne incognita* (Vain et al. 1998) (Table 18.2). However, more research is required to understand the plant-nematode interaction and to develop smart plants that can resist nematodes.

18.4.4 Insect Pest

Among the biotic stresses, next to diseases, yield losses due to insect damages are considered as major cause for the decline in rice production and productivity worldwide. Losses due to pests and diseases have been estimated at 37 % of agricultural production worldwide, with 13 % due to only insect pests (Gatehouse 1992). Yield loss due to insects in Asia has been estimated at nearly 25 % (Heinrichs and Institute 1985). The losses due to egregious pests like stem borers, gall midge, green leafhopper, rice hispa, brown leafhopper, and thrips are quite high (Kalode et al. 1986). Brown planthopper (BPH) is a destructive insect pest to rice in Asian countries. It directly damages the plant phloem by using its piercing-sucking mouthparts, resulting in "hopper burn" in the most serious cases. It is also a vector for rice grassy stunt virus and ragged stunt virus, which cause further yield losses in many Asian countries (Zhang and Xie 2014). At least six species of stem borer attack rice. These are the yellow stem borer, white stem borer, striped stem borer, gold-fringed stem borer, dark-headed striped stem borer, and pink stem borer. Stem borers can destroy rice at any stage of the plant from seedling to maturity. At the vegetative stage, the insect larva feeds inside the stem resulting in death of the young leaf whorl causing "deadheart," and during reproductive stage, it feeds inside the panicle stalk leading to unfilled grains causing "white heads" (Biswal 2010). The average yearly yield losses caused by above insects are estimated at about 10 million tons worldwide (Herdt 1991). Enhancing the host plant resistance is considered as the most desirable approach to combat insect/pathogen attack. Hence improvement of rice cultivars by identification and incorporation of new resistance genes into modern rice cultivars are important breeding strategies to control the damage caused by different insect pests.

18.4.4.1 Marker-Assisted Selection

Brown planthopper (BPH) is one of the major insect pests of rice in the temperate rice-growing regions. A resistant gene *bph2* was successfully mapped between SSR markers RM7102 and RM463 on the long arm of chromosome 12, in a cross between resistant parent ASD7 and susceptible cultivar C418, a japonica restorer line (Sun et al. 2006). Three other QTLs for seedling resistance and feeding rate to BPH were identified in a cross between Zhenshan 97 (ZS97) and IR65482-17 (derived from the wild rice species *Oryza australiensis*) (Hu et al. 2015). Other derivatives of *O. australiensis* were also used to identify QTLs and the genes *Bph10* and *Bph18(t)* (Jena et al. 2006; Nguyen Thi Lang 2003). Three other QTLs controlling BPH resistance were detected on chromosomes 2, 10, and 12 in a cross between Nipponbare (japonica) x Kasalath (indica) where all of the resistance QTLs came from Kasalath, the moderate resistance parent (Su et al. 2002). Du et al. (2009) cloned *Bph14* gene which encodes a coiled-coil, nucleotide-binding, and leucine-rich repeat (CC-NB-LRR) protein. QTLs associated with resistance to white-backed planthopper (WBPH) (*Sogatella furcifera*) have been identified using a doubled-haploid (DH) mapping population derived from the cross IR64/Azucena in rice (Geethanjali et al. 2009). QTLs associated with sucking pests have also been identified in a RIL population derived from a cross between japonica rice variety Kinmaze and indica DV85 (Wang et al. 2004). Screening of a F_2 population derived from a cross between an introgression line, IR71033-121-15, from *O. minuta*, and a susceptible Korean japonica cultivar, Junambyeo, resulted in identification of two major QTLs for BPH resistance.

Attempts have been made to identify rice germplasm with resistance to stem borer. ANOVA and linear regression involving the SSR marker data and the phenotypic data associated with YSB resistance resulted in the association of SSR marker RM104 on chromosome 1 with deadheart incidence under both glass house and field conditions (Palanivel et al. 2014).

18.4.4.2 Transgenic Approach

Conventional efforts have been made for the development of rice varieties with moderate level of resistance to stem borer for two decades (Kalode et al. 1986). The results were not convincing. The identification of donor varieties with high level of resistance still remains a challenge for breeders. Even the effort of screening more than 30,000 rice accessions for the stem borer resistance genes was not successful in identifying sufficient degree of resistance in any of the accessions (Teng 1995). However, great progress has been made in developing insect-resistant rice by the transformation of *Bacillus thuringiensis (Bt)* genes (Table 18.2). Numerous independent transgenic events have been generated by using different genes and combination of genes or genes and promoters (Biswal 2010; Fujimoto and Itoh 1993; Ju et al. 1998; Loc and Tinjuangjun 2002; Ramesh et al. 2004; Tang et al. 2006; Jouanin and Bonadé-Bottino 1998; Xu et al. 1996). Transgenic elite rice lines expressing a *Bt* fusion gene derived from *cryIA(b)* and *cryIA(c)* under the control of rice actinI promoter showed high protection against two lepidopteran insects, leaf folder and yellow stem borer, without reduction in yield (Tu et al. 2000). Similarly, many other lines have been field tested with positive results (Tang et al. 2006; Ye et al. 2001; Shu et al. 2000; Bashir et al. 2004; Chen et al. 2005; Ye et al. 2003; Oard et al. 1996). In October 2009, the Chinese Ministry of Agriculture issued biosafety certificates for commercial production of two *cry1Ab/Ac* (*Bt*) lines (Chen et al. 2011). Rigorous testing has shown that these transgenic rice lines are safe for the environment and also for use as food. Laboratory and field tests have confirmed that these two *Bt* rice lines can provide effective and economic control of the lepidopteran complex on rice with less risk to the environment than present practices (Chen et al. 2011). Field evaluation of *Bt* rice is under progress in many other countries which may result in release of transgenic rice in other countries shortly.

18.5 Boosting the Rice Yield

Since the beginning of cereal cultivation, there has been a continuous challenge to increase grain yield. The green revolution almost doubled the rice production that sustained the simultaneous increase in global population from 3 billion in 1961 to 7 billion within five decades. In today's rapidly increasing population that is expected to reach 9.1 billion by the year 2050 (Fao 2009), the demand for rice simultaneously increases as well. Therefore, considerable efforts are now being undertaken to develop strategies in boosting rice yields. These strategies include the elucidation and engineering of the traits that govern rice yield, herbicide tolerance, and C_4 photosynthesis.

18.5.1 Yield Traits

Yield is one of the most important and complex traits in the genetic improvement of rice. Over the past years, tremendous efforts have been done in functional genomics research in rice. Cloning and functional characterization of genes that may be associated to or directly related to yield traits have led to considerable progress in the understanding of molecular and biological processes underlying yield traits in rice.

Rice varieties differ greatly in their grain yield. This variability is influenced by their vast genetic diversity, environmental conditions, field management practices, and the interactions between genotypes and environment that confer adaptation to a specific environmental condition. As a complex trait, grain yield of a rice plant is determined by three component traits: number of tillers/panicles per plant, number of grains per panicle, and grain weight. In the recent years, advances in the molecular marker, genome mapping, and quantitative trait loci (QTL) analysis technologies have greatly facilitated the studies on the genetic bases of these quantitative traits.

18.5.1.1 Number of Tillers/Panicles per Plant

The first of the three component traits that is significant to the improvement of rice grain yield is the number of tillers/panicles. Rice panicles arise from the fully developed tillers. Rice tillers are produced at the late vegetative phase of rice growth and develop through the process of shoot branching. Axillary meristems are formed in each leaf axil which subsequently generates a few lateral leaves to form the axillary bud. Axillary buds may be subsequently activated to form shoot branches called tillers. Secondary and higher-ordered tiller arise through subsequent development if environmental conditions permit. Once fully developed, tillers will give rise to the development of panicles and the subsequent development of grains after pollination. The activity of the axillary buds is mediated by a network of systemic signals through the complex interactions of phytohormones. The production and signaling via phytohormones are influenced by genetic, developmental, and environmental signals (Leyser 2003; Shimizu-Sato and Mori 2001; Xing and Zhang 2010). These phytohormones which include that of auxins (Aux), cytokinins (CKs), and strigolactones and its derivatives allow for the integration of information between different plant organs necessary for plant development (Domagalska and Leyser 2011). A well-known concept in apical dominance had shown the role of CK and Aux in the regulation of shoot apical meristem in rice (Azizi et al. 2015). CKs have been observed to promote branching, leading to an increase in the numbers of spikelet in rice, while Aux, provided by the primary shoot apex, suppresses axillary bud growth (Xing and Zhang 2010; Azizi et al. 2015). CK reduces the inhibition and leads to the outgrowth of lateral branches, and the decreased level of CK results in the increase of apical dominance and repression of axillary bud growth (Azizi et al. 2015).

Grain yield is predominantly contributed by the primary tillers and some secondary tillers. Tertiary and higher-ordered tillers usually make little contribution to grain yield despite its consumption of water, nutrients, and photosynthetic products (Mohanan and Mini 2008). Thus, breeding strategies for the development of rice varieties with optimum numbers of primary and secondary tillers should be a priority. From an agronomic point of view, it is suggested that strategies to regulate axillary bud activity through biotechnology and genetic engineering would be advantageous in the effort to increase rice yields (Xing and Zhang 2010).

Marker-Assisted Breeding

In the recent years, several major QTLs have been identified to influence the number of panicles (Table 18.1). In a cross between Junambyeo and an introgressed indica IR71033-121-15, two QTLs affecting the number of panicles on chromosomes 4 and 6 in both populations were identified and designated as *pn4* and *pn6*, respectively (Rahman et al. 2008). It was found in the same study that an increasing effect on chromosome 4 was imparted by IR71033; on the other hand, there was a decreasing effect on chromosome 6. In addition, a recent genome-wide association study (GWAS) has employed three multi-parent advanced generation intercross (MAGIC) populations from elite *indica* lines (DC1, DC2, and 8 way) to identify QTLs for several yield traits and has revealed a QTL for panicle number designated as *qPN2* (Meng et al. 2016).

Transgenic Research

Some phytohormones also influence tillering and branching, and several genes acting downstream of these phytohormones have been identified. One of these is the rice *OsTB1* (*Oryza sativa* Teosinte Branched 1). *OsTB1* encodes for a putative transcription factor carrying a helix-loop-helix DNA-binding motif, and it was found to be a negative regulator of lateral branching in rice (Takeda et al. 2003). In a recent study, this gene had been overexpressed in rice through

Agrobacterium-mediated transformation, and it was observed that compared to wild-type plants, the number of tillers and panicles was reduced and increased in overexpressed and RNAi-mediated knockdown OsTB1 rice plants, respectively (Choi et al. 2012) (Table 18.2).

Additionally, microRNAs (miRNAs) have been shown to play a vital role in the regulation of plant development by targeting complementary RNAs for cleavage or translational repression (Jones-Rhoades et al. 2006). Recent studies showed that miRNAs were involved in rice tillering and the number of panicles by regulating a number of target genes. In fact, transgenic rice overexpressing an miRNA, *OsmiR393,* displayed a 30 % increase in the number of tillers compared to the control plants (Xia et al. 2012). This was attributed to the hyposensitivity to auxin signals of auxin receptor gene homologs (*OsTIR1* and *OsAFB2*) targeted by the *OsmiR393*. In addition, the increase in tillering was also owed to the downregulation of expression of the auxin transporter *OsAUX1* and *OsTB1*. In a similar study, it was reported that the overexpression of the *OsmiR397* miRNA in rice promotes panicle branching, leading to an increase in overall grain yield of up to 25 % in a field trial (Zhang et al. 2013). In summary, all of these suggest that manipulation of these regulatory genes may prove to be useful in achieving the optimum number of panicles/tillers in an effort to increase rice yield.

18.5.1.2 Number of Grains per Panicle

The number of grains per panicle is a complex quantitative trait in rice and is one of the most important component traits for rice yield. Furthermore, it has been positively correlated with grain yield per plant (Khan et al. 2009) highlighting its significance in the improvement of rice yield potential (Table 18.1). The number of grains per panicle is divided into three subcomponent traits: panicle development, rate of spikelet formation, and duration of panicle differentiation (Tripathi et al. 2012).

Panicle development marks the transition from the late vegetative phase to reproductive phase and is influenced by an interplay of phytohormones and a number of genetic factors. Mutant analyses have revealed two main regulatory genes of axillary meristem formation in rice. These include the LAX PANICLE1 (*Lax1*) and SMALL PANICLE (*SPA*) genes (Komatsu et al. 2003). *Lax1* and *SPA* were demonstrated to play an overlapping function in axillary meristematic formation, which is significant in the transition from vegetative phase to reproductive phase. In *Lax1* mutants, indeterminate growth of rachis branches and a constrained initiation and/or maintenance of lateral and terminal spikelets have been observed (Komatsu et al. 2001). Molecular cloning and sequence analysis of *Lax1* revealed that it encodes for a basic helix-loop-helix (bHLH) transcription factor involved in the formation of all types of axillary meristems throughout the ontogeny of a rice plant (Komatsu et al. 2003).

Genes associated with the control of the rate of spikelet formation include *DEP1* (Huang et al. 2009), SP1 (Li et al. 2009), APO1 (Ikeda-Kawakatsu et al. 2009), LOG (Kurakawa et al. 2007), and cytokinin degradation enzyme (*OsCKX2*)

(Ashikari et al. 2008). All are known to be positive regulators of the rate of spikelet formation except *OsCKX2*. Among these, *DEP1* was highly expressed from the tillering to the heading stage, while the expression of *SP1* was higher until the flowering stage (Tripathi et al. 2012). On the other hand, the expression of OsCKXR encoded by the *Gn1a* gene was found to have a negative correlation with the grain yield per plant. This supports the positive influence of CKs on the grain number per plant. The decreased expression of *OsCKX2* thus leads to an increase in the number of reproductive organs and spikelets due to the accumulation of CK in the inflorescence meristems. This, in turn, leads to an improvement in the grain yield (Azizi et al. 2015; Ashikari et al. 2008).

Marker-Assisted Breeding

The duration of panicle differentiation is influenced by QTLs that control heading date. Gene/QTLs that regulate heading date usually increase the duration of panicle differentiation to increase spikelet number per panicle and, in turn, enhance grain yield potential (Tripathi et al. 2012). Among these are the Ghd7 (Weng et al. 2014; Xue et al. 2008), Ghd8/DTH8 (Wei et al. 2010; Yan et al. 2011), RCN1 (Nakagawa et al. 2002), and RFL (Kyozuka et al. 1998; Rao et al. 2008). Ghd7 encodes for a CCT motif family of protein and functions as one of the major regulators in the pleiotropic control of several traits, including the number of grains per panicle, plant height, and heading date (hence the name Ghd). A recent study has suggested that Ghd7 positively regulates both tiller and panicle branches in a density-dependent manner, indicating that Ghd7 influences the control of branch development in response to environmental conditions (Weng et al. 2014). In addition, elevated Ghd7 expression levels repress Hd3a expression which prolongs panicle differentiation. Ghd7-1, Ghd7-3, and other Ghd7 functional alleles with strong effects allow rice to utilize light and temperature by delaying flowering under long-day conditions in areas with long growing seasons, thus producing large panicles and increasing grain yield (Xue et al. 2008). In a similar fashion, Ghd8/DTH8 is able to repress the expression of early heading date 1 (Ehd1) and Hd3a under long-day conditions leading to a delayed heading date and an increased number of grains per plant (Wei et al. 2010; Yan et al. 2011).

Transgenic Approach

Several studies have employed transgenic approach in the functional characterization of some genes that may influence the number of grains per panicle. The LRK1 (leucine-rich repeat receptor-like kinase 1) has been reported to contribute to a higher grain number per plant (Zha et al. 2009). The overexpression of this gene resulted in an increased number of panicles, spikelets per panicle, weight per grain, and cellular proliferation that led to a 27.09 % increase in total grain yield per plant. In another transgenic study in rice, the use of transgenic expression of a dominant negative form of SRK (S-domain receptor kinase) called *OsLSK1* (*large spike S-domain receptor-like kinase 1*) was observed to improve grain yield components in rice (Zou et al. 2015a). In the same study, the overexpression of a truncated version of *OsLSK1* improved the primary branches per panicle and grains per primary branch which resulted to an increase in grain number per panicle in *OXOsLSK1-t-3* and *OXOsLSK1-t-4* transgenic lines generated (Zou et al. 2015b). Additionally, in a study on another gene *OsSPL14* (squamosa promoter-binding protein-like 14, also known as IPA1) encoded by the WFP (wealthy farmer's panicle), QTL has been reported to increase grain productivity in rice (Miura et al. 2010). It was observed that *OsSPL14*$^{\mathrm{WFP}}$ allele on chromosome 8 was associated with an increase of about 40 % in the primary branch and grain number. These studies underscore that the manipulation of these genes may be a viable and practicable way to improve grain yield in rice and other crops.

18.5.1.3 Grain Weight

Grain weight is a significant trait related to grain yield potential and grain quality of rice. Three parameters are commonly used to determine grain weight. These include grain length, grain width, and grain filling. Recent studies in QTL mapping and cloning have made significant progresses on identification of genes and major QTLs regulating grain weight (Table 18.1). The major genes/QTLs reported to regulate these parameters are GW2, GS3, and the grain incomplete filling 1 (GIF1) (Tripathi et al. 2012).

GW2 encodes a RING-type ubiquitin E3 ligase that was previously suggested to negatively regulate grain width and cell division by targeting its substrates to degradation via ubiquitin-proteasome pathway (Song et al. 2007). On the other hand, GS3 was found to influence grain size and length. The activity of GS3 to influence grain size has been detected in a diverse range of rice varieties (Fan et al. 2009; Takano-Kai et al. 2009) and was found to have lower expression levels throughout the stages of development (Tripathi et al. 2012). Comparative sequence analysis of the gene has identified a nonsense mutation, shared among all the large-grain varieties sequenced in comparison with the small- to medium-grain varieties (Xing and Zhang 2010; Takano-Kai et al. 2009). This mutation causes a 178-amino acid truncation in the C terminus of the protein product itself, suggesting that GS3 may function as a negative regulator for cell division and integument elongation.

GIF1 gene was observed to influence grain filling. It encodes for a cell wall invertase required for carbon partitioning during early grain filling (Wang et al. 2008). In contrast to the GW2 and GS3 genes, GIF1 functions as a positive regulator and had higher expression in the flowering and milk stages of the reproductive phase (Tripathi et al. 2012).

All of these highlight the role of biotechnology in increasing rice yield potential. Knowledge and control of these agronomically important genes that regulate major yield traits offer strategies in an effort to boost rice yields.

18.5.2 Herbicide Tolerance

Herbicide tolerance (HT) is a significant agronomic trait that has been used to control weeds efficiently for several decades. Considerable efforts have been made to produce HT crops to simplify weed management and to alleviate problems that arise from herbicide residues. Several techniques have been used to develop HT crops which include cell culture, in vitro selection, and genetic engineering approaches. Substantial efforts are being made to develop herbicide-tolerant rice using genes that confer resistance to herbicides. Three major HT systems, currently commercialized, are based on resistance to herbicides inhibiting amino acid biosynthesis. These include imidazolinone (IMI), glyphosate, and glufosinate resistance (Duke 2005). In rice, all the three HT rice systems have been developed (Scarabel et al. 2012; Tsai et al. 2006; Wang et al. 2014c).

IMI-resistant rice conveys resistance to the imidazolinone group of potent herbicides (imazethapyr, imazapyr, imazamox, imazapic), which control a broad spectrum of grass and weeds and have favorable environmental profiles (Tan et al. 2005). Imidazolinone herbicides control weeds by inhibiting the acetolactate synthase (ALS) enzyme. As such, ALS has been the target for conventional mutation breeding and transgenic protocols. One of the herbicides that inhibit ALS activity is bispyribac sodium (BS). BS tolerance was found to be associated with two point mutations in the ALS gene: a tryptophan-to-leucine change (W548 L) and another serine to isoleucine (S627I) (Endo et al. 2007). In the same study, a highly efficient T-DNA-mediated gene-targeting (GT) system was developed to introduce W548 L and S627I mutations into the ALS gene which resulted in the generation of hypertolerant rice plants against BS.

Transgenic approach has also been used to introduce herbicide-resistant genes into rice from other organisms. It includes the *bar* gene, isolated from *Streptomyces hygroscopicus*, responsible for the metabolic detoxification of glufosinates and the enolpyruvylshikimate-3-phosphate synthase (EPSPS) gene isolated from *Agrobacterium* strain CP4 that detoxifies glyphosate herbicides (Kumar et al. 2008). Considerable efforts have been made to find other sources of genes that could be used to develop HR transgenic rice. For example, transgenic rice plants expressing *Bacillus subtilis* protoporphyrinogen oxidase (an enzyme that is vital to heme and chlorophyll biosynthesis) were found to be resistant against the herbicide oxyfluorfen (Jung et al. 2004). Another example is the expression of human cytochrome P450s in rice. Transgenic rice plants that contain CYP1A1, CYP2B6, and CYP2C19 genes were found to be more tolerant to several herbicides than non-transgenic plants (Kawahigashi et al. 2007; Kumar et al. 2012). However, rice plant expressing human genes may have ethical issues (Kumar et al. 2008).

Furthermore, herbicide resistance by metabolic detoxification can confer phytoremediating capabilities to transgenic plants which can mitigate the debilitating effects of chemical residues in the environment. However, these advantages should be weighed against potential risks and consequences that are brought about by large-scale adoption of HR technologies in rice.

18.5.3 Other Value-Added Traits

18.5.3.1 Lodging Resistance

High-yielding varieties with natural plant height generally suffer from lodging though dwarf plants have relatively less lodging problem. In addition to plant height, lodging resistance also depends on the physical strength of culms (Ookawa and Ishihara 1993). Recent development of the disomic derivatives of *Oryza latifolia* in the background of *O. sativa* has shown high culm strength, and these are being considered as lines with potential to improve lodging resistance in cultivated rice stem (Angeles-Shim et al. 2014).

18.5.4 C_4 Rice

C4 photosynthesis is one of the most remarkable adaptations within the flowering plants. In fact, C4 photosynthesis is estimated to account for 20–30 % of terrestrial carbon fixation despite being used by only approximately 3 % of the total angiosperm species (Kellogg 2013). The maximum energy conversion efficiency of C4 photosynthesis mainly depends upon its CO_2 concentration mechanism in contrast to the common C3 photosynthesis systems of the most of the terrestrial plants including rice.

In all plants, CO_2 is fixed by the enzyme ribulose-1,5-bisphosphate carboxylase/oxygenase or Rubisco. It catalyzes the carboxylation of ribulose-1,5-bisphosphate (RuBP) into an unstable 6-carbon intermediate that is subsequently hydrated and cleaved to produce two molecules of a three-carbon compound, 3-phosphoglycerate (3-PGA), as the first stable product (hence the name C3). In C3 plants, this process occurs in the mesophyll (M) cells located on the surface of the leaf. The deviant interaction of Rubisco with oxygen elicits Rubisco's oxygenase activity, in which O_2 is covalently bound to RuBP at carbon 2, producing a molecule of 3-PGA and 2-phosphoglycolate (2-PG). 2-PG is toxic for the plant at higher concentrations and has to undergo detoxification in the peroxisome and mitochondria in a process called photorespiration. In the photorespiratory cycle, 2-PG is regenerated to 3-PGA. However, it involves the release of formerly assimilated CO_2 and NH_3, consumption of energy and reducing equivalents (Peterhansel et al. 2010), and, consequently, a reduction of photosynthetic efficiency by up to 30 % (Mallmann et al. 2014). For this reason, photorespiration is often viewed as a wasteful process. In C4 plants, the CO_2 is initially fixed by the cytosolic enzyme phosphoenolpyruvate carboxylase (PEPC) to form a four-carbon compound oxaloacetate (OAA) (hence the name C_4). The PEPC is insensitive to O_2 and specifically reacts with only CO_2. Several attempts have been made either to understand the molecular mechanism of C4 photosynthesis or to introduce C4 photosynthesis into rice.

18.5.4.1 Marker-Assisted Breeding

In fact, C4 photosynthesis has been proposed as a polygenic quantitative trait (Westhoff & Gowik 2010) because of stepwise transition from C3 to C4 and the presence of C3–C4 intermediates (Westhoff and Gowik 2010). Attempts have been made to map the QTL between closely related species from the 1970s. In one of the early crosses made by Malcolm Nobs and Olle Björkman between *Atriplex prostrata* (C3) and *Atriplex rosea* (C4), an F2 population was generated which showed segregation of individual C4. It could not proceed further due to aneuploidy. Similarly crosses have been made between C3, C4, and C3–C4 intermediates of *Flaveria* species through genetic engineering efforts.

18.5.4.2 Transgenic Research

Initially, it was thought that a single-cell C4 system could be faster to develop in C3 plants, and there have been previous attempts to engineer single-cell C4 system in rice (Miyao et al. 2011). However, the earlier attempts have only produced futile cycle (Zhu et al. 2010). In an effort to incorporate the more efficient Kranz-type C4 system into rice, the C4 rice consortium spearheaded the discovery of genes and engineering of already known genes into rice. C4 genes including CA, *PEPC*, *PPDK*, *NADP-ME*, and *NADP-MDH* have been cloned from maize and transformed into rice (Kajala et al. 2011). Several studies have employed comparative transcriptomics in maize and several closely related C3, C4, and C3–C4 intermediate species (Wang et al. 2013; Gowik et al. 2011; Wang and Czedik-Eysenberg 2014) to identify candidate genes related to C4 syndrome and Kranz anatomy. Cohorts of genes have been identified and being validated through genetic transformation into rice (Table 18.2).

Currently, the phase III of the C4 Rice Project is underway. This will allow for a more refined genetic toolkit that has been assembled in the previous stages and a greater understanding of the regulatory mechanisms that establish the pathway in C4 plants. These efforts are geared toward the full realization of engineering the C4 pathway into rice.

18.6 Limitation of Molecular Breeding

Main problems encountered in these studies were that the QTLs having a minor effect on the phenotype pose a great challenge for the breeders to select improved lines in the field condition and discovery of major QTLs functioning independent of their genetic background underlies extensive efforts (Gowda et al. 2011). Secondly, most of these QTL mapping studies in rice have been conducted using progenies derived from intraspecific crosses. Much needed efforts are still required to go for interspecific crosses to explore novel alleles and with their effective incorporation into the breeding programs for drought tolerance in rice. Thirdly, availability of uniformly distributed molecular markers for fine mapping of large-effect QTLs has never been sufficient. Exploitation of 3 K genome sequence and the use of high-density SNP genotyping platform along with next-generation sequencing (NGS) may help to accelerate molecular breeding for improved rice cultivars.

18.7 Controversies Over GM Rice

Several controversies regarding the possible repercussions that genetically modified (GM) rice may bring have been raised. Though many of these are fictitious, some of these issues concern about its environmental and ecological safety, food safety, and ethical and economic issues, among others.

On an environmental and ecological perspective, the evolution of resistant pests and weeds termed as *superbugs* and *super weeds* raises an issue on the consequences of GM rice (Bawa and Anilakumar 2013). This is based on the uncertainty of whether the pest-resistant characteristic of these transgenic crops can escape to their weedy relatives causing resistant and increased weeds. Similarly, herbicide-resistant transgenic crops are also speculated to cause the surrounding weeds to develop resistance as well, thus nullifying the effects of the transgenics. This has led to the topics regarding prevention of gene flow from transgenic crops to wild type. In a study conducted to assess gene flow from herbicide-resistant rice to that of the wild type, it was found that gene flow frequency decreased exponentially with increasing isolation distance and is dependent on the main wind direction during flowering (Han et al. 2015). These highlight the importance of crop management and agricultural laws if large-scale adoption of transgenic varieties is to be carried out.

Another major concern of GM crops, such as rice, is in its safety for human health. Health risks associated with GM foods are concerned with toxins and allergens (Bajaj and Mohanty 2005). Transgenic rice has been developed to overexpress 2S albumin from sesame to increase its cysteine and methionine content (Lee et al. 2003). Despite the fact that sesame has been used as a food additive in many Asian countries, the 2S albumin from sesame seeds has been previously demonstrated to be allergenic (Pastorello et al. 2001). While it is justifiable to conduct allergenicity studies on all transgenic rice, like all other allergenic food items, allergenic transgenic products can be separately labeled and barred from people who are sensitive to it.

Rice is a staple food and is the primary source of energy for more than half of the world's population. There is still a great amount of uncertainties, especially in the large-scale adoption of GM rice. Thus, it is understandable that the incorporation of GM rice into agricultural production is continuously being debated. All of these show the significance of weighing the immense potential benefits of GM rice in food supply and the possible risks that it entails.

Nevertheless, genetic engineering has already shown the potential of plant biotechnology for crop improvement. As a result, transgenic plants with high agronomic and environmental value have been developed for several crop species such as maize, soybean, cotton, tomato, potato, tobacco, papaya, and wheat (http://www.isaaa.org/). However, it suffers from onerous regulatory obstacles. Nevertheless, new methods of precisely transferring genes through targeted genome editing method may simplify the process of commercialization of transgenic crops with less severe regulations. Similarly transfer of genes from the same or related species through cisgenic approach can also be exploited though it limits the potential of genetic engineering to deliver genetic material from any species.

18.8 Future Research and Conclusions

There is a broad scope of biotechnology in modern-day agriculture. Apart from genetic understanding of important traits, biotechnology has a key role in product development. Marker-assisted breeding and transgenic deployment are the two potential areas. Marker-assisted rice breeding has made remarkable progress. Varieties improved through MAS can be used to study gene function and resistance mechanisms by using modern biotechnological tools. The application of tissue culture technology, as a central tool or as an adjunct to other methods, including recombinant DNA techniques, is at the vanguard in plant modification and improvement for agriculture, horticulture, and forestry. Implementation of targeted genome editing technologies such as TALENs and CRISPR/Cas system can be harnessed to modify defunct alleles of useful genes or to knock out unwanted genes in plants without any trace of transgene. Biotechnological tools and techniques provide a unique opportunity to create novel useful variation which is instrumental for the rice breeders.

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