Reading 20-2
Rice: The Natural History of Rice

Rice has fed more people than any other crop has for thousands of years. The ancient Indian name for rice, *Dhanya*, means "sustenance for the human race." Especially in much of Asia, life without rice has been unthinkable. Rice feeds more than half of the world population, but most rice is consumed within 10 miles of where it is produced.

Rice is the 2nd largest crop in planting acreage after wheat. Global rice production was 596.5 million tons from 155 million hectares (ha) in 1999. The major rice growing regions are found in more than a hundred countries in Asia, Latin America, and Africa (Table 1). But major rice exporting countries only include Thailand, the United States, Vietnam, Pakistan, and India. About 85% of the total rice production is for human consumption. Rice provides 23% of the global human per capita energy and 16% of the per capita protein (IRRI, 1997). In Asia, where people typically eat rice 2 or 3 times a day, 250 million rice farms (the average rice land per farm is less than 1 ha) produce more than 90% of the world's rice. For example, Myanmar consumes 195 kg of rice per capita per year, whereas the average annual rice consumptions in Europe and America are 3 kg and 7 kg, respectively. The 3 most populous nations, including China, India, and Indonesia, are rice-based countries, which together have 2.5 billion people (about half of the current world population).

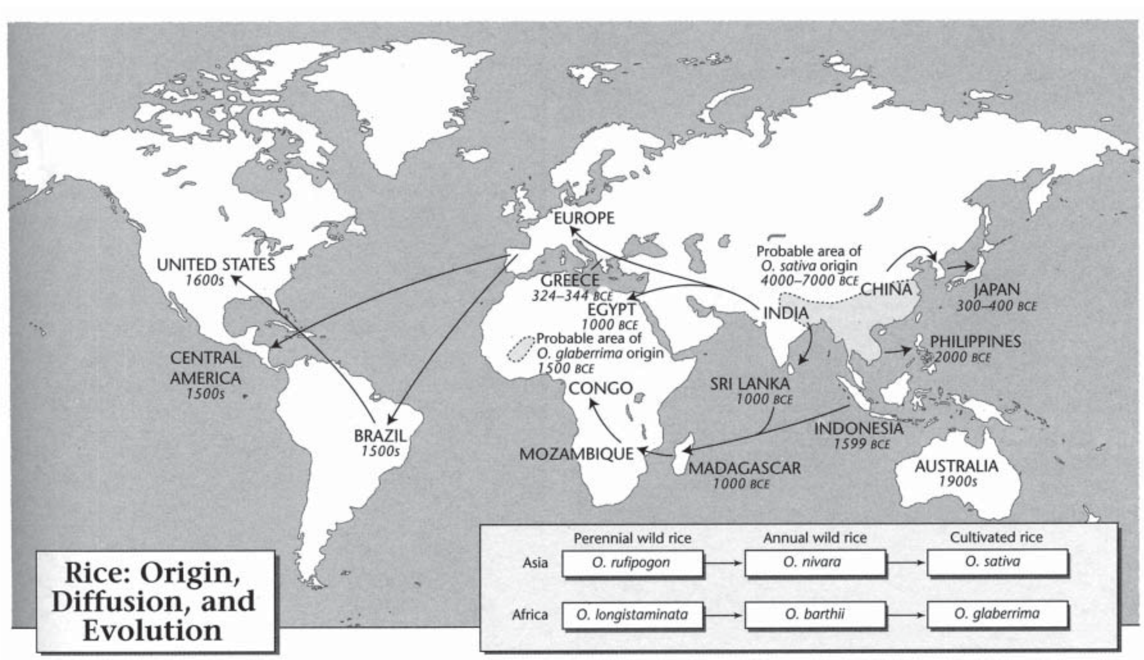
Rice can be processed into rice bran oil, wine, rice cakes, and other foods. Rice flour can be used as the main component of face powders and infant formula or for polishing expensive jewelry. Rice bran oil can be used in cooking, making soap, and as an ingredient in insecticides. Silica-rich rice husks can be used as raw materials for construction materials such as like insulation, as a conditioner for commercial fertilizers, as an ingredient in hand soaps and furfural (a chemical used in synthetic resin manufacture), as mulch, as an abrasives, as a fuel, or as an ingredient to make thermoplastics (Yekani Amonollah: United States Patent: 6,172,144). Rice straw has been used for livestock feed, bedding for livestock, straw mushroom production (in China and Thailand), and in industries for arts and crafts. In the early times, rice straw was also used for thatching roofs in Asia, and to make ropes, mats, paper, baskets, and bags. Now rice straw is mostly used for animal feed or as field manure.

Rice Biology

Classification. Rice has 120,000 varieties, the richest gene bank in the plant kingdom. There has been great progress in rice genome sequencing projects recently by using both *Indica* (9311) and *Japonica* (Nipponbare) varieties. This will greatly enhance rice improvements in the near future. From the taxonomy of rice, Asian rice belongs to the grass (Gramineae) family and genus *Oryza*. Wheat, corn, and barley also belong to the grass family. *Oryza* has 23 species, which can be classified into 4 groups (Table 2, IRRI, 1997). The *O. ridleyi* complex and *O. meyeriana* complex contain species in lowland swamp forests and upland hillside forests, respectively. The *O. officinalis* complex consists of perennial species throughout the tropics. The *O. sativa* complex includes 2 cultigens and the wild relative of these 2 cultigens. Only 2 *Oryza* species, the tetraploid *O. schlechteri* and the diploid *O. brachyantha*, are different from these 4 groups. Based on another classification method for *Oryza* species, the common wild rice or so-called "*O. perennis* complex" includes Asian wild rice (*O. rufipogon*), African wild rice (*O. longistaminata* or *O. bar-*

thii), and Oceanian wild rice (*O. meriodinalis*) (Chang, 1976). *O. rufipogon* is the wild relative of *O. sativa* and a noxious weed in rice-growing countries. This wild rice has the characteristic of easy shedding to facilitate easy dispersal and easy crossing with the Asian cultivars, which results in the degradation of the variety and contamination of red-grained plants. The wild rice (or Indian rice or water oats) of North America (*Zizania palustris* or *Z. aquatica L.*, 2*n* = 30) belongs to a different genera and even a different tribe of the grass family. It was traditionally harvested by native Americans in the Great Lakes region, and now is commercially produced in Minnesota, Wisconsin, northern California, and Manitoba, Canada. It has nutty and rich flavor and boasts a pleasant chewiness. It is high in protein and B vitamins but low in fat. It is also 2 to 3 times more expensive than regular white rice.

Rice has only 2 cultivated species, *Oryza sativa* Linn. (the Asian cultivated species) and *Oryza glaberrima* Steud. (the West African cultivated species). *O. sativa* is by far the more widely utilized of the two. By contrast, *O. glaberrima* has much less diversity because of a relatively short cultivation history and a narrower dispersal than *O. sativa*. The main differences in botanical morphology between these 2 cultivated species are the ligule size and glume pubescence. Most of *O. glaberrima* varieties have fewer hairs, short ligules, and fewer or no branches, and also have red-hulled grains on the shattering panicle. They are generally more resistant to flood, alkaline soils, and blast than *O. sativa* varieties. Another difference is that *O. glaberrima* is strictly annual, whereas *O. sativa* is potentially a perennial. It is generally thought that there are 2 major subspecies in *O. sativa*: *indica* (or *hsien*) and *japonica* (sometimes called *sinica* or *keng*). *Japonica* is generally short, less leafy, and has a strong culm and short grains. *Japonica* varieties are grown in temperate areas such as northern China, Japan, Korea, Spain, Australia, and California. When cooked, *japonica* rice is sticky. *Indica* rice generally has long, slender, and fluffy grains, many tillers, and is tall, leafy, and tolerant of drought. It does not stick when cooked. *Indica* rice is usually grown in hot (tropical or subtropical) climates such as in India, Thailand, Vietnam, and Southern China. The so-called *javanica* can be classified as a tropical *japonica* and is mostly grown in Indonesia and the United States. *Javanica* was originally grown in equatorial areas with abundant



water and is generally vulnerable to drought.

Morphology. Rice has the following 3 main developmental phases: the vegetative phase (from germination to panicle initiation), the reproductive phase (from panicle initiation to flowering), and the ripening phase (from flowering to maturity). A typical rice plant during reproductive and ripening stages has the following organs: roots, a main stem and a number of tillers (or side shoots), leaves, panicles, flowers (or florets) when flowering, and grains when maturing (Fig. 1). The edible part of a rice plant is in the rice grain, which includes glumes, endosperm, and embryo. Some varieties have awns at the tip of the grain. More detail about rice morphology can be found in literature by Chang and Bardenas (1965) and by Grist (1986).

Roots. Rice has a fibrous root system, that is, it has the temporary seminal roots or embryonic roots, then secondary adventitious roots. The fibrous roots only last for a short time after seed germination. An alternative is the classification of rice roots based on the spatial pattern as crown roots (including mat roots) below the soil and nodal roots above the soil. The function of rice roots is to absorb water. It is estimated that it takes 5,000 liters of water to produce 1 kg of irrigated rice. Owing to the greater consumption of water in rice production, the future rice cultivation will face the looming water deficiency in some countries.

Culms. Plant height can range from approximately 0.4m to more than 6m (in floating rice) depending on the rice variety or environmental conditions. The rice culm is round, hollow, jointed, and hairless. A maturing rice plant has a main stem and a number of tillers depending on the variety and cultural conditions. Each stem has a certain number of nodes (generally ranging from 13 to 16 nodes) and internodes under a certain environmental condition for a rice variety.

Leaves. Rice leaves are rather flat. The first rudimentary leaf or prophyllum is at the base of a tiller and, with only a two-keeled bract, has no blade. The uppermost leaf immediately below the panicle is called the flag leaf. The leaf blade and leaf sheath are attached at the node, where there is an auricle (a pair of claw-like appendages encircling the stem), and the ligule (a thin, upright papery and triangular structure) immediately above the auricle. When young, the major difference between rice and a common grassy weed (*Echinochloa* spp.) is the presence of auricles and ligules.

Panicles. Rice has a terminate panicle having the following structures: the base, axis, primary, secondary, and sometimes tertiary branches, pedicel, rudimentary glumes, and spikelets. Each panicle generally bears from 50 to 300 flowers or spikelets.

Flower. The rice panicle is a perfect and determinate inflorescence. A rice spikelet has 2 sterile lemmas, the rachilla and the floret. A

Horses threshing rice in the Italian Veneto. From a copper engraving in Gian Battista Spolverini's *La Coltivazione del riso* (The Cultivation of Rice) printed at Verona in 1758. Roughwood Collection.

rice floret includes 6 stamens and a pistil having stigmas, styles, and ovary, enclosed by the lemma and palea, sometimes with an awn. Even though rice is pollinated by wind, the natural crossing rate is low (less than 3-4%) because of the floral characteristics. The stigma (a plumose structure) functions to catch pollen for fertilization. This function is important for the out-crossing rate in hybrid rice seed production.

Grain. The rice grain generally refers to rough rice or paddy consisting of brown rice (or caryopsis) and the hull. As Figure 2 indicates, brown rice consists of the endosperm, embryo, and several thin layers of differentiated tissues-the pericarp (the ovary wall), the seed coat, and the nucellus. The seed coat consists of 6 layers of cells, with the aleurone layer the innermost. The rice embryo is small and contains the embryonic leaves (plumule) enclosed by a sheath (coleoptile), embryonic primary root (radicle) ensheathed by the coleorhiza, and the joining part (mesocotyl). Rice endosperm consists mostly of starch granules in a proteinaceous matrix, together with sugar, fats, crude fiber, and inorganic matter. Hull weight is about 20% of the total grain weight. The hull of a typical indica rice variety has the palea, lemmas, and richilla, but the hull of japonica rice usually only includes rudimentary glumes and perhaps a portion of the pedicel. The lemma is usually tough, archmenlike, sometimes awned, and bigger than the palea. Generally, pigmentation in rice does not cause any problems except for the pigmented apiculus or hull, which may stain the endosperm during parboiling, thus affecting the marketing value. Grain ripening stages (15–65 days) can be subdivided into milky, dough, yellow-ripe, and maturity stages based on the texture and color of the growing grains.

Nutritious Value (USA Rice Federation, May 2002). Half-cup servings of white rice and brown rice contain 103 calories and 108 calories of energy, respectively. The composition of a typical brown rice, milled rice, rice bran, and germ or embryo are indicated in Table 3. Although the nutritional value varies with different varieties, soil fertility, fertilizers applied, and other environmental conditions, the following trends still exist by comparison with other cereals: lower fat content after the removal of the bran, lower protein content (about 7–10%), and higher digestibility of proteins. Fresh harvested rice grains contain about 80% carbohydrates, including starch, glucose, sucrose, dextrin, fructose, galactose, and raffinose. Polished rice grains have an insufficient supply of iron, considerable Vitamin E content, rich pantothenic acid, and pyridoxine of Vitamin B complex, low riboflavin content, negligible vitamin A and D content, and an unfavorable calcium to phosphorus ratio.

Milling, rinsing before cooking, and boiling reduce the nutritional value of rice. For example, milling removes about 80% of thiamine from brown rice, and thus causing beriberi and other dietary deficiencies. However, most rice consumers still prefer well-milled rice since brown rice has an unfavorable chewier texture and flavor.

Protein. Crude protein content in rice can be measured using micro-Kjeldahl analysis and other methods. In addition to varietal differences, protein content is affected by environmental conditions, such as soil and nitrogen fertilizer application. Protein is mainly distributed in the bran and periphery of the endosperm. The central part of the rice grain only contains a small proportion of rice's protein. Rice protein has all essential amino acids, in rather a well-balanced proportion, for the human body. Though the amount of protein is not high, the quality of rice protein is one of the highest. Rice protein has a biological value of 86, compared to 75–90 of the biological value in fish fillet protein. Rice is unique in the richness of alkali-soluble proteins or glutelin (about 70%), whereas the other cereals are rich in alcohol-soluble proteins or prolamin (rice has only about 3% prolamin in its gross protein content). The other components of rice proteins include 4–9% water-soluble proteins or albumins and about 10% salt-soluble proteins or glubulins. Rice proteins are rich in arginine and contain tryptophan and histidine, but are poor in lysine and threonine. However, by comparison with other cereals, rice protein is one of the most nutritious because it contains about 4–5% lysine (higher than that in wheat, corn, or sorghum). Efforts have been made to improve protein content through conventional breeding, but so far, it has not been successful. Rice varieties with high protein contents tend to have worse flavor, are less tender, less cohesive when cooked in the same amount of water, and longer cooking times are needed because of lower water absorption.

Carbohydrates. More than 90% of the energy in rice comes from carbohydrates. Rice contains both simple and complex carbohydrates. Simple carbohydrates or sugars include glucose, fructose, lactose, and sucrose. Complex carbohydrates in rice are starch and fibers. As for fiber, ½ cup cooked brown rice and the same volume of cooked white rice have 1.6 grams and 0.3 grams of dietary fiber, respectively. About 85% of the rice grain weight is starch. Amylose is the linear fraction of the rice starch, and is negatively correlated with the cohesiveness, tenderness, color, and the gloss of the cooked rice. The rice starch has to be gelatinized during cooking or else rice is too firm to be eaten comfortably. Glutinous or waxy rice, sometimes referred to as “sweet” or “mochi,” contains 1–2% amylose, has white and opaque kernels, and often is used for such ethnic foods as mochi cake and crackers, desserts, puffed rice, and parboiled rice flakes. The non-glutinous rice varieties can also be classified as low-amylose (8-20%), intermediate (21–25%), and

Nutrients in rice

Nutrient	Brown rice	Milled rice	Rice bran	Rice embryo	Polished rice
Percentage of total					
Protein (%N × 5.95)	7.1–8.3	6.3–7.1	11.3–14.9	14.1–20.6	11.2–12.4
Crude fat	1.6–2.8	0.3–0.5	15.0–19.7	16.6–20.5	10.1–12.4
Crude fiber	0.6–1.0	0.2–0.5	7.0–11.4	2.4–3.5	2.3–3.2
Crude ash	1.0–1.5	0.3–0.8	6.6–9.9	4.8–8.7	5.2–7.3
Available carbohydrates	72.9–75.9	76.7–78.4	34.1–52.3	34.2–41.4	51.1–55.0
Starch	66.4	77.6	13.8	2.1	41.5–47.6
Free sugar	0.7–1.3	0.22–0.45	5.5–6.9	8.0–12	
Micrograms per gram					
Vitamin A	0.1	Trace	4.2	0.3	0.95
Thiamine	2.1–4.5	Trace–1.8	10–28	45–76	16–30
Riboflavin	0.4–0.9	0.1–0.4	1.7–3.4	2.7–5.0	1.4–3.4
Niacin	44–62	8–26	241–590	15–99	228–385
Pyridoxine	1.6–11.2	0.4–6.2	10–32	15–16	10–31
Pantothenic acid	6.6–18.6	3.4–7.7	28–71	3–13	26–92
Biotin	0.06–0.13	0.005–0.07	0.16–0.47	0.26–0.58	0.14–0.66
Folic acid	0.20–0.60	0.06–0.16	0.50–1.46	0.9–4.3	0.4–1.90
Vitamin B_{12}	0.0005	0.0016	0.005	0.0105	0.003
Vitamin E (tocopherols)	13	Trace	149	87	63

high-amylose (>25%) types. Generally japonica has low amylose content and the amylose content of indica varies widely. Environmental conditions can greatly influence amylose content as much as 6% for the same variety in the different seasons. Intermediate amylose content is preferred by the major world rice market. For high-amylose rice varieties, a gel consistency test can complement the amylose test by separating these varieties into three categories: hard gel consistency for very flaky rice (< 40mm for the length of gel), medium gel consistency for flaky rice (41–60 mm), and soft gel consistency for soft rice (> 60 mm).

Fat. Rice contains a trace of fats (0.9 and 0.2 grams of fats in ½ cup of cooked brown rice and ½ cup of cooked white rice, respectively). Rice is a health food because it does not contain any cholesterol, but it does contain linoleic acid, accounting for 30% of the total rice fats that cannot be converted from carbohydrates, proteins, or other fats.

Vitamins. Rice contains several kinds of vitamins (Table 1). Thiamin (vitamin B_1) has positive health effects for the brain and heart, but unfortunately it cannot be stored in a human body and must be supplied in the daily diet. One half cup of cooked brown rice and ½ cup of cooked white rice contain 7% and 6% of the U.S. Daily Value (D.V.) for thiamin, respectively. Riboflavin (vitamin B_2) is important for energy production and the health of skin and eyes. Rice has a very small amount of riboflavin, about 1% of the D.V. in ½ cup of cooked brown rice. Niacin (vitamin B_3) is essential for healthy skin, digestive, and nervous systems. One half cup of cooked brown rice and the same amount of cooked white rice have 8% and 6% of the D.V. for niacin, respectively. Pyridoxine (vitamin B_6) indirectly helps to control amino acids in the body. A shortage of pyridoxine has negative effects on the central nervous system. The folate or folic acid is important for the manufacture of DNA and hemoglobin. Rice also has traces of vitamin E that protects vitamin A and essential fatty acids from oxidation. Recently, scientists in Switzerland and Germany developed "Golden Rice™" through genetic engineering and could substantially increase vitamin A content in rice (Ye et al., 2000).

Minerals. Iron is important in humans for oxidation and other enzymatic reactions. One half cup serving of cooked brown rice and ½ cup serving of cooked white rice have 8% and 7% of the D.V. for iron, respectively. Phosphorus is critical for healthy bones and teeth and other metabolisms. Phosphorus in rice can be best absorbed when supplemented with milk or vegetables. One half cup of cooked brown rice and ½ cup of cooked white rice have 8% and 3% of the D.V. for phosphorus, respectively. Rice also has traces of calcium, potassium, and sodium.

Rice grain quality. The aroma of rice can be detected in rice leaf tissue, rice kernel, and cooked rice. It was reported that 2-acetyl-1-pyrroline was a major aroma component in aromatic rice. There is an excellent description about the evaluation of rice grain quality in a book chapter by Webb (1985). Grain quality is determined by the appearance (milling quality), texture and ease of cooking (cooking quality), flavor and smell (eating quality), nutritive characteristics, cleanness, and purity. For parboiled rice, light-hulled (straw-colored) rice is preferred and bran color should have uniform light color. Rice can be classified, based on the grain length on the traditional U.S. market, as follows: extra long (>7.50 mm), long (6.61–7.50 mm), medium (5.51–6.60 mm), and short (<5.50 mm). Rice also has the following classification based on the grain shape (measured as length/width ratio): slender (>3.0), medium (2.1–3.0), bold (1.1–2.0), and round (<1.1) .

Endosperm is preferred to be bright, clear and translucent by the market, with the exception of waxy rice having an opaque endosperm. Excessive chalkiness is undesirable because chalkiness greatly affects the milling yield and milling quality. Chalkiness can be categorized as white belly, white core, and white back depending on the location of the chalkiness on the rice endosperm. Chalkiness is influenced both by the variety and by environmental factors such as weather conditions when harvesting, and by different agronomic or field managements.

Milling quality is determined by the following factors: size and shape of the grain, ripeness, drying method, age, moisture content, and the method of storage. High head rice and high milled rice are critical for the commercial success of a rice variety. To determine the milling quality, the rough rice percentage is measured after removing the foreign materials (dockages). After removing hulls and most of the bran layers and germs, total milling yield and head (or whole-grain) rice yield can be measured. Total milling yield includes the whole (head) rice and broken rice yield from total unclean rough rice.

The economic value of rice depends on its cooking and processing quality, which can be measured in terms of major methods: amylose content, alkali spreading value, gelatinization temperature, gel consistency, and protein content. Sometimes, parboiling-canning stability and specific brewing cookability with malt diastase need to be measured for specific purposes. The gelatinization temperature is the temperature at which 90% of the starches in the rice have gelatinized or turned liquid and lost their crystalline structure. Gelatinization temperature can be evaluated by measuring alkali spreading value (ASV). Gel consistency is used to differentiate among the high-amylose rice varieties with different amylograph pasting viscosities. The major factors affecting gel consistency are fat (lipid) content and degree of milling.

History

Origin and diffusion. Origin and diffusion of rice are still unsettled issues (Huke and Huke, 1990). Asian cultivated rice originated in the region from south China to the Ganges in South and Southeast Asia, including the river valleys and deltas of the Brahmaputra of northern India, the Irrawaddy of Burma, the Mekong of Vietnam, and the Yangtze of China. Based on the number of wild rice species and the evidence of rice glumes in the burnt clay from the late Neolithic period, Ting (1949) concluded that rice might have originated in South China and then spread northwards. Copeland (1924), Chang (1975) and some Japanese rice scientists asserted that rice might have originated from South or Southeast Asia, including India, China, Thailand, and Indonesia. Thermoluminescence and carbon-14 tests of the pottery shards with the imprints of rice grains in Thailand indicate that rice could be dated back to at least 4000 BCE (IRRI, 1997). The 3 oldest pieces of archaeological evidences for rice origin are from Maharaga of India (6500–4500 BCE), Non-Nok-Tha of Thailand (about 6000 BCE), and Pen-tou-shan of China (7150–6250 BCE) (Abrol and Gadgil, 1999; Chang, 1998). Great diversity of rice and linguistic evidence support the argument for Southeast Asia as the origin of rice cultivation. It was believed that the early spread of rice was from southern China or northern Vietnam to the Philippines about 2000 BCE, and then to Indonesia about 1599 BCE by Deutero-Malayans. Most likely, the techniques of rice cultivation radiated outward from the Yangtze delta of China towards Korea and then Japan. Japan became known as *Mizumono kuni* ("the Land of Luxurious Rice Crop") about 300–400 BCE, but rice did not become the staple Korean dish until the 1930s. Sri Lanka had rice as a crop as early as 1000 BCE. Rice was introduced to Greece and the neighboring Mediterranean ca. 344–324 BCE, and then gradually to Europe and Africa (IRRI, 1997). There have been debates about the introduction of Asian rice into

Africa. *O. sativa* was believed to have been introduced to Africa primarily from Malayo-Polynesia a few centuries BCE or from Sri Lanka and Indonesia. It was postulated that at different times *O. sativa* was introduced to Egypt from India, to Madagascar from Indonesia as early as 1000 BCE, to Mozambique and East Africa from Madagascar, and finally to West Africa by Portuguese spice traders between the 15th and 17th centuries, or by traders or Muslim missionaries in the 9th or 10th centuries. Lu and Chang (1980) argued that Asian rice entered into the Congo from Mozambique in the 19th century. The other possibilities for the introduction of rice into Europe are from Persia, central Asia, or directly from China. Later the Portuguese brought rice to Brazil, and the Spanish introduced rice to Central and South America. The Malays brought rice to Madagascar. The United States might have been 1st introduced to rice from the Malagasy Republic, Europe, or the Far East. It was often cited that a storm-battered ship from Madagascar had brought rice seeds "Golde Seede Rice" to South Carolina in 1694. Not until 1888 did the first large-scale growing of rice plants occur in Louisiana and Texas, although rice was introduced to Virginia as early as in 1609. Later the Gulf Coast grew rice because of the popularization of mechanical farming. The current major rice-producing states in the United States include Arkansas, California, Louisiana, Texas, Mississippi, and Missouri. Rice was first commercialized in Australia in 1924, even though in as early as in 1892 experimental planting of rice took place in New South Wales.

It was believed that *O. glaberrima* originated in the central Niger river delta of Mali about 1500 BCE. (Portères, 1956). Two secondary centers of diversity are located to the southwest near the Guinean coast. *O. glaberrima* has 2 ecotypes, deepwater and upland, and is now only grown in the flooded area of the Niger and Sokoto River basins. *O. glaberrima* in some parts of the Africa was gradually replaced by *O. sativa*. The ongoing WARDA rice improvement project is also targeting to these regions by substituting new varieties for *O. glaberrima* with new varieties through *glaberrima-sativa* interspecific crossing.

Domestication: Chang (2000) made exhaustive descriptions on the evolution and early spread through several routes for rice, especially the Asian rice. In his review the pattern for rice evolution was suggested as from perennial wild to annual wild and then to cultivated. Therefore, the evolution for *O. sativa* is *O. rufipogon* to *O. nivara* to *O. sativa* in Asia. In parallel, the evolution for *O. glaberrima* is *O. longistaminata* to *O. barthii* to *O. glaberrima* in Africa. It is believed that rice originated in the marsh areas and spread toward the dry lands and hills. The domestication of rice, including such cultural practices as puddling and transplanting, might have first taken place in China. The ancient Chinese cultural practices for rice then shifted to Southeast Asia and other parts of the world (De Data, 1987). Only until in the 20th century did systematic rice improvement start. For example, IRRI scientists Peter R. Jennings, Te-Tze Chang, and Henry M. Beachell developed the semi-dwarf variety "IR8" in 1966, which initiated the "green revolution" (Lang, 1996). China also successfully developed hybrid rice

These Vietnamese rice paddies are not only used for growing rice, they are sometimes flooded for fish farming, and ducks can be raised in the paddies while the rice is young. Photo courtesy of the National Archives and Records Administration.

in 1973. These achievements have greatly increased the rice yield so as to feed the increasing world population, especially in Asia.

Oka (1988) indicated that domestication of rice involves the decreased seed dormancy, increased seed shattering and selfing rate, and other adaptive characteristics. Wild rice usually has one month or more of seed dormancy resulting in non-synchronous germination. This is an adaptive characteristic to increase the probability of regenerating success under changing environments. Seed maturity on a panicle also does not synchronize and the flowering for wild rice can last more than one month instead. Grain dormancy protects rice grains from sprouting on panicles because of frequent raining during ripening. Generally, *japonica* has little dormancy, but *indica* has some degree of dormancy. The tropical *indica* in particular has quite strong dormancy. But grain dormancy is affected by the weather. For the same variety, the sunny and dry weather will make the grain less dormant than the humid weather. It was deduced that the substance(s) for grain dormancy exist mainly in the flowering glumes and the hull (palea and lemma) because dormancy was broken by simply removing the hull from the seed. Grain dormancy can be broken by chemicals, such as fungicides or diluted nitric acid, or by heat treatment (50°C for 4 to 6 days or even longer).

Grain shattering is affected by the strength of the spikelet attachment to its pedicel. The requirements for the resistance to grain shattering vary with the environmental and cultural conditions in the modern rice cultivation. Regions with strong winds at rice maturity require non-shattering varieties. Intermediate-shattering types should be grown for mechanical harvesting using a combine. If harvested by hand harvest and threshing, the intermediate type with resistance to shattering is preferred. In Asian rice, *japonica* is highly resistant to shattering, but most of *indica* varieties have intermediate resistance to shattering. Wild rice has easy shedding or shattering and thus easy dispersal. Also, some wild rice has awns on the tip of the grain. Some rice varieties are either fully awned or partially awned among spikelets on the same panicle. This characteristic might be favorable for the dispersal through water. The cross-pollinated feature of wild rice (similar to that of like wild barley) might be favorable for rice evolution.

Hybrids: Before the 1970s, rice breeders extensively studied the utilization of rice heterosis after they realized the great potential of using by heterosis to improve crops such as corn. Generally speaking, hybrid rice has more than 15–20% yield advantage over the best conventional rice varieties in China, Bangladesh, Brazil, Colombia, Ecuador, India, Indonesia, Malaysia, Myanmar, the Philippines, Sri Lanka, and Vietnam. Unfortunately, no large-scale planting of hybrid rice was successful until China developed a three-line (cytoplasmic male sterile line, male sterile maintainer line, and restorer line) system hybrid rice in 1973 and commercialized this technology in 1976. This was because of the very small reproductive organs and difficulty in finding or developing a cytoplasmic male sterile line in rice. China has greatly increased its rice production by the utilization of hybrid rice technology and therefore has been able to feed its rapidly growing population in the last quarter of the 20th century. Now China is trying to increase the rice yield by employing the two-line system hybrid rice (male sterile line and restorer line) and intersubspecific heterosis (i.e., the heterosis between indica and japonica) utilization. By following China's success, other countries, including India, Vietnam, Myanmar, and Bangladesh, are currently learning to use the hybrid rice technology to boost the rice yield. FAO is also providing financial support to activities of networks on hybrid rice such as the International Task Force for Hybrid Rice (INTAFOHR) and the Working Group on Hybrid Rice in Latin America and the Caribbean (GRUTHA).

Outside China, the planting acreages under hybrid rice in Vietnam, India, and Bangladesh in 1998 were 250,000 ha, 120,000 ha, and 20,000 ha, respectively.

Production & Processing

Distribution: Generally speaking, rice paddy is adaptable to regions that have sufficient rainfall, high temperature, and prolonged solar radiation. Rice has evolved into 4 major ecosystems based on different ecological or environmental conditions: irrigated (53% of the total rice crop area, exemplified by China), rain-fed lowland (23%), deepwater (11%), and upland (13%, exemplified by Latin America). Rice is cultivated on all continents except Antarctica. Recent estimates list 112 rice-growing countries, including all the countries in Asia and most of the countries of West and North Africa, some countries of East and Central Africa, most of the South and Central America countries, and Australia (De Datta, 1987). Geographically, the current rice cultivation regions ranges from latitudes 53°N in Moho, China, to latitudes 35°S in central Argentina and New South Wales, Australia, from sea-level in Bangladesh to an altitude of 3,000m in Nepal. Asia produced 90.6% out of the total rice production in 1999; Latin America, 4%; Africa, 3%; Europe, 0.5%; Australia, 0.2%; and the United States, 1.6%. The top 10 countries with the largest rice production in 1999 were China, India, Indonesia, Bangladesh, Vietnam, Thailand, Myanmar, Brazil, Japan, and the Philippines, in descending order. Outside Asia, rice is consumed as a staple food in Guyana, Guinea, Liberia, Sierra Leone, and Madagascar. Based on the above geographical distribution of rice, currently there are 3 major international rice research centers from Consultative Group on International Agricultural Research (CGIAR), including the International Rice Research Institute(IRRI) in the Philippines, Centro Internacional de Agricultura Tropical (CIAT) in Columbia, and West Africa Rice Development Association (WARDA) in the Ivory Coast.

Cultivation. Rice can be grown in many eco-systems from upland (Fig. 4) to deepwater conditions (Fig. 5). For irrigating a rice system, fields are plowed with a wooden plow, and then a harrow drawn by a docile and reliable water buffalo in most of the Asian countries (Fig. 6). Some Asian countries, such as India and China, are still practicing transplanting the rice seedlings to suit for the double cropping or multiple cropping systems (Fig. 7). Developed countries in Europe and America, such as the United States, employ direct seeding cultivation without transplanting, to avoid the cost of expensive labor and take advantage of the advances in the mechanization of rice production. There are 2 methods for direct seeding: (1) dry seeding before sprouting, followed by a flow of water in Louisiana and Texas, and (2) wet seeding by low-flying aircraft in California and Arkansas because rice is unique, among cereals, in being able to germinate when submerged in water. In rice cultivation, the most serious pests include stem borers and leaf hoppers. The most dangerous diseases are rice blast, bacterial blight, sheath blight, and seedling blight. These pests and diseases can be controlled at the proper stage by chemicals or other measures. Now more efforts are being focused on breeding for the resistant rice varieties through conventional approaches or through modern biotechnology, such as Bt. Rice. The most persistent weeds in rice cultivation are barnyard grass (Echinochloa spp.), water hyacinth (Eichhornia crassipes), Eleocharis acidularis, Typha spp., and red rice. These weeds can be controlled by the cultural approaches or by herbicides.

Harvesting & Post-harvest Operations. Rice is considered to be a photoperiod or daylength sensitive crop, although there are daylength-insensitive rice varieties. Short photoperiods or daylengths (less than 11 hours) will shorten its growth duration, which ranges from 90 to 160 days or even longer depending mainly on the photoperiod sensitivity, the basic vegetative phase, and the temperature sensitivity. The approximate duration from flowering to maturity is 30 days. Photoperiod-insensitive rice varieties, such as most of the current rice varieties in tropical Latin America, are increasingly preferred because of their greater adaptability to a wide region and the flexibility in planting dates. But in some rice growing regions, the strong photoperiod sensitivity of rice is used to grow rice in the rainy season; it is then harvested after the rainy season and before the dry-season water shortage. The maturity of rice is also influenced by air temperature, planting methods, and nitrogen fertilization. The best time for mechanical harvesting is when panicles become yellow but the stem and leaves still have green color. At that time the moisture contents of grains should be 20–25%. By visual inspection in the field, rice can be harvested when the kernels on the upper part of the panicle are fully ripe and the ones in the lower part reach a hard-dough stage. For some rice growing regions with some extra time beyond one rice-growing region, ratooning of the 1st rice crop is possible by using the varieties with high ratooning ability for maximizing the annual rice yields without too much investment. Currently, harvesting can be done with a combine in the more developed countries. However, most Asian and African countries are still harvesting rice by hand sickles, scythes, or knives, because of scarcity of capital, availability of inexpensive labor, and the topographical limits, such as small rice fields, mountainous fields, or deep-water rice (Fig. 8). A rice combine threshes the harvested paddy after cutting. Hand threshing or threshing by animals or simple foot- or gasoline-powered threshing machines are still being used in some countries.

Storage. Before storage, the moisture content of rice grains should be reduced to below 14%. The most convenient method is sun-drying if the weather permits—drying rice grains in the open air and under strong sunshine for 1 to 2 days. But the sun-drying method can produce “sun checks,” which reduce the head rice and increase the rice bran%age; also, this method requires intensive labor. Therefore, artificial drying such as batch dryers in Japan and the hot air dryers in the United States became an alternative to sun-drying. The artificial drying can avoid the rapid dehydration, which causes reduced head rice. The cleaning of rice grains is important to remove foreign seed and trash before storage. There are 3 major cleaning methods: air cleaning by using a hand winnower, mechanical cleaning by using sieves, and gravity cleaning. In rice mills, all impurities, odds and ends such as stones, and pieces of soil and straw, must be removed by a screening or riddling process and a fan. Further removal of nails or bits of iron can be done with a magnet. Since ageing through storage increases water absorption and paste viscosity and reduces solids dissolved in cooking water, cooked fresh rice tastes worse than rice with 6 to 12 months of storage because rice grains cooked immediately after harvesting tend to disintegrate and to be more cohesive. The curing process can be completed through keeping the rice in heaps of straw for several days or through domestic curing methods. However, long storage time should be avoided, especially for the undermilled rice. Cooked rice, after several months of storage, becomes less sticky and more flaky. In addition to moisture, metabolisms of grain tissues, micro-organisms, insects, and mites also causes storage losses.

Milling. Milling in the rice industry can refer either to the overall operations that include including cleaning, hulling, pearling, polishing, and grading; or simply to one operation, removal of the rice bran or outer layers. Typically, the pericarp accounts for 1–2% of the weight of the whole rice caryopsis, seed coat and aleurone 5%, embryo 2–3%, and endosperm 89–91% (Wadsworth, 1994). The edible part of rice grain is enclosed in the glumes, which need to be first separated by hulling. The most primitive implement for hulling is the system with wood mortar and pestle or a treadle (Fig. 9) or watermill. These hulling methods are still used in some of rice growing regions in Asia and Africa. Now mechanical hulling or milling is popular in most of the rice growing countries (Fig. 10). The hulled rice grains are then winnowed in order to remove the chaff and bran. Rice with the hulls removed but the bran left on is called "brown rice." "Milled rice" refers to the rice after removing all hulls, bran layers, and germ. After hulling, the removal of germs or outer coats—the so-called "polishing" —is necessary by using mechanical hulling or milling for better appearance to meet the market's need, with sacrifice of the flavor and healthy constituents in rice grains. Rice is generally marked either as polished rice or as coated rice with talc and glucose. Rice grains after polishing contain portions of broken grains that have to be separated and sorted to meet the market standards. This separation can be accomplished by passing through a series of sieves or cellular cylinders or trieurs. Some discolored rice grains can be removed by electric sorting.

Enrichment. For restoration of vitamins and minerals lost during milling, the enrichment of rice is important for better nutrition. There are 2 major approaches: powder enrichment and coated kernel enrichment. For pre-blended powder enrichment, mixes include thiamine, riboflavin, niacin or niacinamide, and ferric orthophosphate (white iron), ferrous sulfate (yellow iron), or reduced iron. This is an easy and less expensive approach for enrichment of rice. But the disadvantages of the powder enrichment are that the nutrients are easily washed off by rinsing, less stability of vitamins and minerals, and their reaction with the food components. An alternative approach is the coated kernel enrichment. This method integrates the powder-blended enrichment with the insoluble food-grade coating. This coating is broken down and the enriched vitamins and minerals are released when the coating reacts with the acid environment of the stomach. This method has the advantages of more efficient use of the enriched vitamins and minerals.

Global & Contemporary Issues

In the 1st 20 years of the 21st century, another 1.2 billion new rice consumers will be added in Asia. Currently, less than 5% of world rice production is traded internationally. Therefore, rice production in Asia must be increased by one third from today's 320 million tonnes to 420 million tonnes, even though the rice land is decreasing.

For the future rice production, there are also the following challenges: (1) genetic erosion because of the popular adoption of the high-yielding varieties (HYVs). For example, *javanica* rice germplasm suffered significant losses in Java and Bali, Indonesia, (2) water pollution by chemical pesticides, herbicides, and air pollution, (3) less cultural managements afforded to rice because of more and more rice farmers, especially the young farmers, moving to work in industry and metropolitan areas, particularly in such countries as China and Japan, and (4) decreasing water resources and increasing land salinity.

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