An Overview of Rice and Rice Quality

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ABSTRACT

Rice is grown over much of the world and provides more calories directly to human beings than any other cereal. Rice production is concentrated in Asia (~90% of total world production), with China and India being the largest single national producers and consumers of rice. Because of its critical role in human nutrition, more rice must be produced annually to provide food for a growing population. Worldwide rice yields increased more than threefold between 1960 and 2019. Much of this production is due to greater yield per hectare of land area rather than increasing land area used in rice production. The increase in yield has been facilitated by genetic improvement of rice varieties through breeding for changing production conditions and improved cropping practices. The development of hybrid rice has also allowed large increases in rice productivity to be achieved. The rice plant is harvested as the rough rice grain, or paddy, which contains approximately 20% husk, 10% bran, and 70% milled rice. The unbroken kernel of rice is the main product of the rice paddy that is consumed by humans. These unbroken (or mostly unbroken) kernels, or head rice, are the largest determinant of rice quality and the primary source of value from the crop. The milled rice kernels or heads are primarily composed of starch, which is mostly amylopectin, and a smaller amount of protein. Critical quality components of the milled rice kernel include percent chalk, protein content, amylose content, cooking properties, and gelatinization characteristics. Optimal timing of harvesting the rice paddy allows head rice yields to be optimized. Since rice is dried after harvest to a safe moisture content for storage, drying practices and conditions must also be optimized to achieve optimal head rice yields. Harvest timing, drying conditions, and storage practices are critical to practical productivity improvements in rice production. Rice is milled after storage, and milling factors dramatically influence overall rice quality. Most rice is consumed directly as milled rice, but many important products, including noodles, puffed rice, flour, and beer, also have critical quality requirements. In the last 60 years, critical improvements in breeding, production practices, harvesting, drying, storage, and milling have enabled a continual flow of more, higher quality rice for the growing global population.

Rice (*Oryza sativa*) is a semiaquatic plant grown in at least 95 countries around the globe (20). Rice can complete its life cycle, from emergence to maturity of the next generation of seed, in either dryland or aquatic environments. Rice produced today is predominantly grown under flooded conditions, with upland or dryland rice accounting for only about 15% of total world acreage (91). In most cases, productivity of upland rice is much lower than that of rice grown under flooded conditions.

Archaeological evidence indicates rice cultivation in Asia began around 3200 to 2500 BC in northern China; around 4530 BC in India; and around 4000 BC in Thailand (14,93,103). Dethloff (26) postulated that the cultivation of rice in China began as early as 10000 BC along the Yellow River.

A very versatile crop, rice is grown in areas as diverse as the highland terraces of Nepal and along the gulf coast of Texas. About 55% of rice is harvested from irrigated lowland ecosystems, 28% from rainfed lowlands, 9% from rainfed uplands, and 7% from deepwater or floating rice ecosystems (30). About 20 species of the genus *Oryza* are recognized, but *O. sativa* L. is the primary species cultivated worldwide (50). A small acreage of the perennial species *O. glaberimma* is grown in Africa. What is called "wild rice" (*Zizania palustris*) is grown in the Great Lakes region of North America and in California. Wild rice is more closely related to oats than to rice per Oelke et al. (74). The two major rice subspecies are indica and japonica. Indica is mostly grown in the tropics and subtropics; it cooks fluffy, dry, and separate and is usually more slender than japonica. Japonica rice is generally cultivated in temperate climates and cooks moist and sticky (15,110). About 90% of rice is produced in Asia. Worldwide, 80% of rice produced is indica; 15% is japonica; aromatic jasmine and basmati rice varieties account for about 1%; and the remainder is constituted by glutinous or waxy rice. Glutinous rice is grown mostly in Southeast Asia, very sticky when cooked, and mainly used in desserts, pastes, and ceremonial dishes (15).

Rice cultivation in the United States began in the Carolina colonies in 1685 with seeds obtained from Madagascar, and by 1700 South Carolina's annual rice export was 400,000 lb (182 Mt) (26). The United States is projected to plant 2.6 million acres in 2020–2021, with long-grain as the dominant class (83). The five leading rice-growing states in the United States are Arkansas, California, Louisiana, Missouri, and Texas, with a combined production of 238 million cwt in 2019.

Rice provides more calories in the human than any other cereal in the world. It is a staple for over half the world's population. Among different Asian countries, rice provides 35–80% of calories consumed (86). For almost six decades worldwide milled rice production has increased more than threefold from 150,000 Mt in 1960 to 499,000 Mt in 2019 (83). More than 50% of rice is produced and consumed in China and India (70). The top 20 rice-producing countries are led by China and India (Fig. 1). The largest exporters of rice, in order, are: India, Thailand, Vietnam, Pakistan, and the United States (34).

The Green Revolution

Forecasts of coming famine and rice insecurity in the 1960s led to concentrated research and selection of improved, higher yielding rice varieties. The development of new varieties and breeding advances at the International Rice Research Institute (IRRI) included, most notably, the semidwarf variety IR8 that provided farmers with a yield advantage of 1–2 tons/ha on irrigated lands compared with traditional varieties and a potential yield of up to 10 tons/ha in tropical irrigated lands (25). Dubbed as "miracle rice," IR8 catalyzed the Green Revolution; by the end of the 20th century, more than 60% of the world's rice fields were planted with varieties developed by government and research

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institutions (79). IR8 resulted from a cross of high-yielding 'Peta' and the semi-dwarf variety 'Dee-gee-woo-gen' (DGWG), whose traits include shortened culm, improved lodging resistance, and greater harvest index. Despite a 90% population growth among developing countries from 1966 to 2000, as well as increasing land and water scarcity, rice production grew by 130% during the same period (39,79). Over the past six decades, productivity (rice yield per hectare) increased linearly, while land area devoted to rice production increased only a little (Fig. 2). Advances in breeding techniques have allowed development of high-yielding varieties with a shorter and stronger plant architecture, improved resistance to diseases, and enhanced nitrogen response. Development of short-maturity varieties allowed for planting of two to three cropping seasons in tropical regions (27). Modern mechanized farming operations (including application of effective herbicides, fungicides, and insecticides) have also greatly increased productivity (79).

Hybrid Rice

Hybrid rice development began in 1926 when Jones reported heterosis in rice (58). Heterosis is simply increased plant vigor and yield as a result of crossing two inbred (genetically fixed) varieties that are genetically distant from each other (55). It is common for hybrid rice to have a 20–30% yield advantage over inbred cultivars in commercial production (104). Research has shown that hybrid rice is more sustainable than inbred rice: hybrid cultivar production in Arkansas was 23.2% more efficient in converting greenhouse gas inputs into grain output than conventional cultivars (72). Economic gains associated with hybrid rice adoption in the United States were estimated at an average of \$76.2 million annually from 2003 to 2013 (71). Contributing factors to the cost-saving advantages of hybrids are blast resistance, yield heterosis, efficient water use, and nutrient conversion.

Hybrid rice was commercially introduced in 1976, but hybrid research dates back to 1964 in China (39). In 2000, mechanized hybrid rice was introduced in the United States with the first hybrid, XL6. Two decades later, hybrid rice has grown from 4,000 ha to about 60% (about 1.2 million acres) of the U.S. Mid-South rice-growing area. In 1997, it is estimated that 17 million ha of China's rice-growing area was planted to hybrid rice (50). Hybrid rice adoption is also increasing in many other countries in Asia, including Bangladesh, India, Myanmar, the Philippines, and Vietnam.

Food Insecurity and the Need for More Rice

Food insecurity has become an ever larger issue with rapid population growth projected to exceed 9 billion globally in 2050 (30). Estimates in 2005 required an additional 30% in world rice production by 2025 (44). A study tracked production and consumption trends of four key global crops—corn, rice, wheat, and soybeans—constituting two-thirds of the world food calorie intake from 1961 to 2008 (81). According to the modeling study, the current rice yield increase of 1.0%/year is well below the estimated 2.4%/year required to double global production by 2050.

Rapid Generation Advance Breeding

The conventional breeding cycle of rice requires up to 10 years to develop a variety. There are several breeding methods for self-pollinated crops, such as pedigree, bulk, modified bulk, single-seed descent, and double haploid (62). Rapid techniques in breeding, known as rapid generation advance, enable development of improved, and high-yield varieties in a shorter time (22). Rapid generation advance was first reported in 1939 (22) and was popular in the 1960s and 1970 as a breeding technique for barley, soybean, and oats (52).

Genetically Modified Rice

No genetically modified rice is currently commercially cultivated in the United States, primarily because of consumer resistance (40). Golden rice, which was genetically engineered through biosynthesis of β-carotene in the edible parts of rice, was first developed around 1999 and aimed to alleviate vitamin A deficiency in the poorer economies of Asia (110). In 2019, the Philippines became the first Asian country to approve Golden rice for human consumption. It contains up to 35 µg of β-carotene/g of rice (2,98)—a 100–150 g bowl of Golden rice can provide about 60% of daily vitamin A recommended for children.

Another genetically modified rice was developed as a source of raw materials for additives in products, including yogurt, pro-

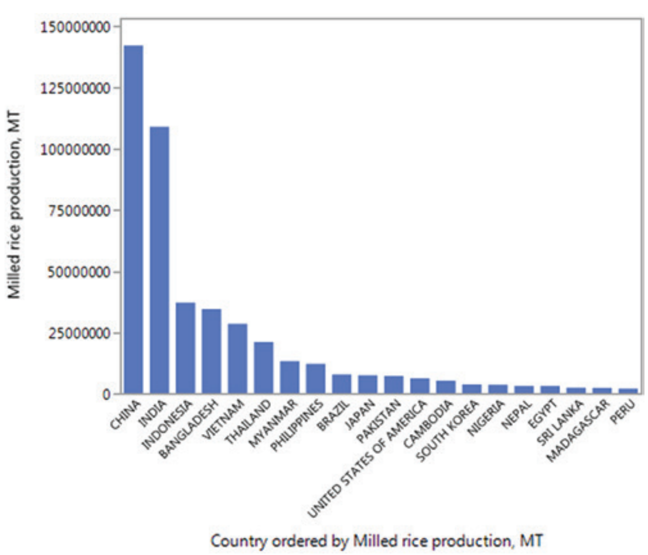

Fig. 1. Total milled rice production for 20 countries in 2018: 487,800,000 tonnes (Rice Outlook [83]).

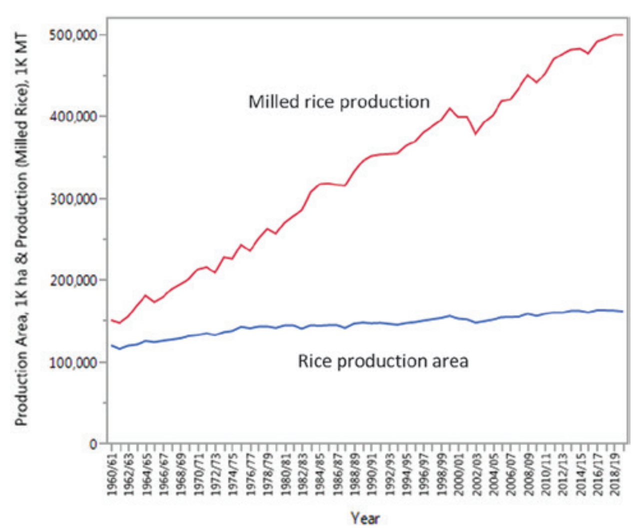

Fig. 2. Global rice production (milled rice) and land usage by year. (Source: U.S. Department of Agriculture, Economic Research Service, using data from the Foreign Agricultural Service, 2020).

tein bars, sports drinks, and oral rehydration products to treat diarrhea in children. The U.S. government approved Ventria, a biotechnology company, to plant genetically modified rice for pharmaceutical purposes. The rice strains produce lysozyme, lactoferrin, and human serum albumin in its seeds (65).

Rice Production Challenges

Sustainable rice production requires that diverse challenges be met, including climate change, reductions in arable land, pressure from pests and diseases, and limited water resources (114). For example, 2,500 L of water are required to produce 1 kg of rice (9). Underground irrigation water in the U.S. Mid-South has suffered alarming depletion from aquifers as a result (108).

Rice kernel appearance, kernel dimension uniformity, milling properties, and cooking characteristics are grain qualities that are usually genetically and environmentally related. Abiotic stresses are aggravated in rice and can impede yield and grain quality, such as milling properties and chalky appearance. High nighttime air temperature, drought, salinity, and submergence are potential causes of damage to rice plants and grain. For instance, elevated temperatures reduce rice yields and, in combination with rainfall during pollination, can cause grain sterility. High nighttime air temperature has been found to affect grain development and increase chalkiness in rice endosperm through impeded starch assimilation (4,23,57,59).

Rice grain quality is defined differently for different users and processors. The definitions of rice quality depend on the needs of the buyer. Rice quality can be based on physical appearance, uniformity of kernel dimensions, cooking and textural properties, aroma, and derivable nutrition. The primary determinant of rice quality in most types of rice and markets is head rice yield (86). Chalk percentage is also an important consideration in rice quality. Head rice yield and chalk both affect physical appearance, but head rice yield also greatly affects flavor and value in other ways. Overall, rice physical appearance greatly influences the market price (32). Grain appearance and size uniformity (kernel length, width, and thickness) influence both appearance and milling turnout. Chalky kernels are usually undesirable compared with translucent kernels (Fig. 3). In a few cases, however, chalky kernels are actually preferred (e.g., paella and risotto applications) (48,59). Chalk in rice kernels (Fig. 3) refers to white, opaque, discolored areas of the endosperm, which occur when starch and protein particles become loosely packed during the critical grain filling stage (67). It is believed to weaken kernel strength, allowing kernels to break easily during milling, thereby reducing head rice recovery (4,33,48,62).

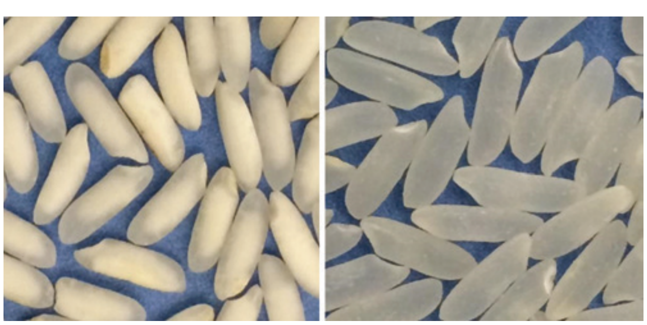

Fig. 3. Chalky milled rice (left) and translucent rice kernels (right). (Photo: R. Bautista, RiceTec, Inc.)

Botanical and Chemical Composition of the Mature Rice Grain

Understanding the rice grain requires an appreciation of the genetic, developmental, and environmental antecedents of the mature grain. The grain starts with the rice flower. Within the rice flower, several pollen grains land on the stigma of the female flower, a few germinate, and one completes fertilization (112). The male gametes from the pollen fertilize the ovule and the polar nuclei, and these, respectively, form the embryo and the endosperm of the caryopsis. Over approximately 32 days, in good conditions, most rice grains normally mature within a crop (94). The rice grains mature sequentially, as rice grains within the panicle and crop are usually pollinated over the course of 7–10 days. The grains pollinated earlier develop earlier and faster than the grains pollinated later (67). During the grain-filling portion of this development, critical environmental conditions, especially night temperatures, strongly influence the yield of the crop and the physical and chemical characteristics of the grain (19,23,57,58,75,76,105). At maturity, the rough rice grain (the paddy) has developed and is harvested in combination with millions of its cohorts in the same field. These grains are harvested in bulk and have variations in size, weight, and moisture content.

The paddy consists of a hull and a brown rice kernel (Fig. 4). The rice is dehulled prior to milling, leaving the brown rice kernel, which is botanically defined as the caryopsis. Various sections of the rice grain are defined differently by botanists and

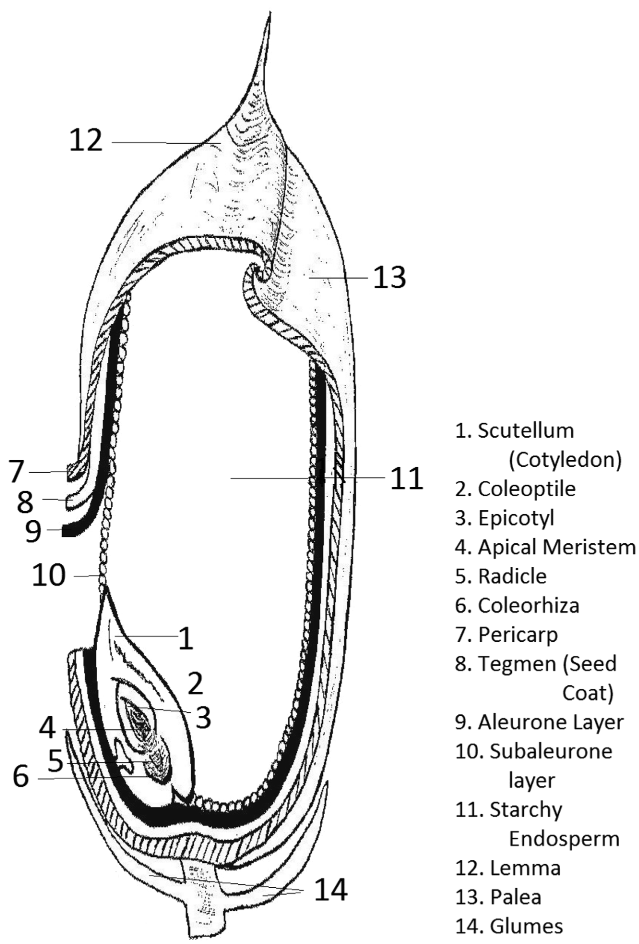

Fig. 4. The rough rice grain (paddy). (Drawing used with special permission of the artist, Dr. Karen Moldenhauer, with labels added by the authors.)

food scientists. For food scientists, the brown rice kernel consists of the bran and the white rice kernel. It is useful to understand what tissue types are included in the bran and the kernel. The various parts of the mature brown rice kernel (by weight) are 1) the pericarp (1–2%); 2) the seed coat, aleurone, and subaleurone layers (5%); 3) the starchy endosperm (89–91%); and 4) the embryo (2–3%) (60). The starchy endosperm (with varying traces of the aleurone and sub-aleurone layers) form the milled rice kernel, while the pericarp, seed coat, most of the aleurone layer, and embryo are the botanical components of the bran.

The primary product of milling is the whole milled kernel, which, in turn, is made up entirely (or almost entirely, depending on degree of milling) of the endosperm cells. The endosperm cells divide and develop with typical plant cell organelles. Many of the initial organelles are degenerated, stretched, or transformed during kernel development and are absent or greatly amended by grain maturity through the process of programmed cell death (24,53).

The milled rice kernel has been reported to contain 87–91% starch on a dry basis (47,49), but two sets of authors have reported a starch content of 77.6% (13,60). Over the course of development, the starch granules within the plastids develop individually and collectively to compose the bulk of the rice kernel by maturity and harvest. The starch in rice grains contains a preponderance of amylopectin, which forms the ring structure of the rice granules, while the amylose is distributed within the amylopectin ring structure (45). The starch granules of japonica rice are larger and more "fluffy" than those of indica rice (51). Some waxy rice varieties have starch that contains very little or no amylose (typically nearly 0 to 1.2% or less), whereas some lines naturally contain as much as 30% amylose. The amount of amylose relative to amylopectin in rice varies greatly depending on seasonal variations (year to year, and within planting dates in the same year). Higher temperatures, especially night temperatures, during grain filling impact amylose content in rice, with amylose content decreasing as temperatures increase (3,56). As a result, rice will typically contain around 90% starch, with 6–25% of that starch being amylose and the remainder being amylopectin. The nature of the amylopectin also fluctuates, with varying degrees of branching observed within the amylopectin molecules. The structure of the amylopectin also varies with night temperatures, with warmer nights resulting in more long-chain (more glucan units per chain) branches (75).

The protein content of milled rice is quite variable across varieties and within varieties from year to year (36). It is highly dependent on solar radiation during grain filling. Milled rice protein is increased by late-season nitrogen fertilization (1). Gomez (36) noted that milled rice protein contents tend to decrease with increasing solar radiation during the rice-growing season. Elevated CO_2 also decreases milled rice protein contents (109). One likely conclusion from the negative responses to increased radiation and CO_2 levels would be that with increased photosynthesis, grain filling is more complete, and the protein content, therefore, is lower. Kernels from smaller, poorly filled grains often have higher protein contents than well-filled, larger grains. Storage proteins rather than functional proteins predominate in milled rice, and these storage proteins are present in aggregations within the endosperm cells called protein bodies. The protein bodies are distinguished by their location within endosperm cells and by their composition (11,51,69,105). Most of the protein (prolamins) in the mature rice kernel is deposited in larger protein bodies (type I), while smaller amounts of protein (glutelins and globulins) are deposited in smaller protein bodies (type II) (96). The larger type I protein bodies are deposited on the inner surface of the plasma membrane, while the smaller type II protein bodies are distributed throughout the endosperm cells (69,97). Extensive information on rice and other cereal protein bodies has been published and is relevant to cereal nutritional and processing qualities (37). There are small amounts and activities of functional proteins (enzymes) in the milled rice kernel, including amylase, proteases, lipases, sucrose synthase, and sucrose phosphate synthetase (92,100).

Although starch and storage proteins make up the greatest parts of the rice grain, other components include soluble carbohydrates, fiber, and various minerals (13,60). The soluble carbohydrates include mainly sucrose (92). Fiber makes up a small part of the milled rice grain (13). There are some minerals and vitamins of nutritional importance in small quantities (13). Most milled rice components affect nutritional, milling, and processing properties. The nature of the starch composition, especially amylopectin structure, have profound consequences for all the various attributes of rice destined for human consumption. Protein content and nature also have important consequences for the nutritional and processing qualities of rice. Dietary deficiencies, such as low iron and vitamin A, which are a relatively small percentage of total milled rice mass, can have profound implications and considerations for human health. Appreciation of the overall composition of milled rice provides an important base of understanding for the direct practical implications on rice harvest, milling, processing, and nutrition.

Harvesting and Processing

Rice harvesting is done either manually or mechanically. Quick (81) reported that most of the world's rice is still hand-harvested. In recent years, mechanical harvesting has become a popular practice in many countries in southeast Asia with the development of small- to medium-size combines that fit well with small farmland holding sizes. In industrialized countries, rice is harvested mechanically with large self-propelled combines. Postharvest losses from harvesting to market range from 15 to 25%, which has remained a challenge that requires continuing research to mitigate (38). A continual goal in postharvest processing is to minimize quantities of broken rice (10). Small rice growers in Southeast Asia incur greater postharvest losses than mechanized farms in Asia, Australia, and the Americas. Climatic patterns during monsoon season in tropical regions may delay harvesting, and the shortage of suitable processing technologies can cause rice degradation.

The timing of harvest is critical to achieve good rice quality and returns (7,73,87). In general, the timing of harvest depends on many field considerations, including the size of the crop, harvesting capacity, and, especially, weather. Moreover, the field harvest strategy seeks to optimize maximum harvested yield and quality. Harvesting too early often reduces yield and quality by effectively excluding many grains that have not completed development and including partially mature grains that mill poorly. Harvesting too late can allow the first grains to mature to dry out excessively and potentially be exposed to environmental rewetting, thus greatly decreasing head rice yield. Sometimes the only choice that permits any useful harvest is dictated more by weather than by optimum yield or quality. Individual kernel moisture content (MC) distribution in rice panicles varies widely and is multimodal until the average harvest MC of about 16% is reached (7). Variation in kernel maturity in a rice panicle is shown in Figure 5. Kernel MC variation is attributed to differences in the timing of panicle initiation, flowering, and kernel development and maturity within panicles and tillers (7). The existence of individual kernel MC variation at harvest has implications for grain quality, particularly milling recovery. Harvesting rice at high average MC (e.g., greater than 22% for long grain) could result in a head rice yield reduction because of the high proportion of immature kernels. Conversely, low-MC kernels (~15%) are susceptible to grain fissuring in the field prior to harvesting when they are exposed to moist environmental conditions, such as rainfall or dew in the morning. Research has shown that head rice yield is a quadratic function of harvest MC (86). To maximize head rice yield of long-grain rice grown in the U.S. Mid-South, Nalley et al. (73) recommend harvesting long-grain rice at 17–22% MC, whereas Siebenmorgen et al. (87) recommend a harvest MC range of 22 to 24% for medium-grain rice.

Rice Drying. Rough rice must be dried immediately after harvest to an MC level that is safe for storage and milling; it is a common practice to dry rice to 12.5% MC. High-MC rice respires and, if not dried immediately, can cause discoloration, typically called yellowing or stackburn of rice. This may lead to eventual spoilage due to mold growth if respiration is not prevented over an extended period. Respiration rates increase with MC and temperature. Thus, removal of excess moisture as safely and quickly as possible by drying is crucial to maintain the integrity of the kernel. Improper removal of excess moisture can create fissures in the kernel that affect the relative weight of head rice to brokens (17). Rice fissuring has been researched extensively and occurs with rapid moisture loss or rewetting (6,18,54,89). The fissuring response to moisture desorption or adsorption varies according to grain type; medium-grain cultivars (inbred) fissure more than long-grain cultivars (6). There is no difference in kernel fissuring behavior between hybrid and inbred cultivars (99).

Fig. 5. Individual kernels of rice in a single panicle vary in development and maturity, affecting grain properties at harvest. (Photo: R. Bautista, RiceTec, Inc.)

Rice dryers vary in size and mode of action; many small farm holders in Southeast Asia and China sun-dry rice along the side of the highway and drying pavements, while some use stationary flatbed batch dryers. On-farm, in-bin dryers are common in the United States and use natural aeration with supplementary heating and stirring mechanisms. Large commercial processors utilize continuous flow-column dryers that dry rice fast using high air temperature with tempering treatments. The application of glass transition (T_g) theory was a significant advancement in rice drying (17,18,77,78,88). Rice, considered a partially crystalline, partially amorphous polymer, undergoes state transition from glassy to rubbery during drying (90). Various material properties affect drying, such as specific heat, enthalpy, specific volume, expansion coefficient, dielectric constant, and diffusivity change with temperature. Amorphous materials are in a glassy state below T_g, characterized by high viscosity and density but low expansion coefficient, whereas, at temperatures above T_g, the material is in a rubbery state, with a higher expansion coefficient and lower density (18). Application of T_g theory in multipass drying allows for a faster drying rate using higher air temperatures with tempering cycles in continuous flow dryers without creating significant fissures in the kernels that cause breakage in milling. Multipass drying allows a few percentage points of MC removal during each pass in a column with tempering. About 5–6 percentage points of MC can be removed per drying pass without damaging the rice kernel provided sufficient tempering is applied (17). Cnossen et al. (18) explained that tempering allows for a MC gradient relaxation within the kernel, thus preventing material failure due to a residual desorption stress gradient (54). Research indicated that a 60 minute tempering time is adequate to maintain milling quality (17). This concept in rice drying further clarified the intermittent drying of rice as a drying treatment capable of reducing grain fissuring and eventual breakage during milling.

Rice Storage. Rough rice is stored after drying with the purpose of providing a year-round supply for end-use processing (41). During storage, rice must be protected from the environment, insects, mold and other fungal growth, and rodents. Intact hulls in rough rice provide added protection from environmental and physical damage, as well as fungal infection, while in storage. Brown rice must be kept under refrigerated conditions to minimize oxidation and fermentation of fatty acids in the bran layer. Milled rice, in bags or in bulk, is stored in warehouses for marketing and distribution. Because rice is largely used in whole or intact form, the integrity of the kernel must be maintained using sound storage techniques (41,42). In Japan, controlled environment storage of rough rice is a common practice believed to preserve the eating quality of cooked rice. Research has shown that milling, starch properties, and pasting properties are affected by storage (43). Aging of rice during storage is triggered by fat rancidity (50). Storage temperature and MC can affect the physicochemical properties of rice. During 3–4 months of storage, rice stored above 15°C has shown increased total and head rice yield, increased grain hardness, and greater volumetric expansion and water adsorption during cooking (50). Neither starch molecular weight and components (amylose and amylopectin) nor gelatinization temperature are significantly affected by storage (16).

Rice Milling. Milled rice is the portion of the rice kernel that remains after removal of the hull, bran layer, and germ. Rough rice or paddy undergoes a sequential mechanical process to produce milled rice. Before milling, rough rice is dried to about 12.5% MC after harvest and cleaned of impurities. Subsequently, hulls are removed with rubber rolls to produce brown rice. The next steps are bran removal followed by polishing and removal of broken grains. Bran layers and the germ are removed by abrasion or friction to produce milled or white rice. After milling, brokens and grits are removed from the head rice. Modern rice mills include a fine mist of water that is used to remove dust remaining on the milled rice from polishing to improve the luster and translucency of the kernels before packaging and marketing. In large commercial mills, milled rice is sorted to remove discolored kernels caused by insect, fungal, and heat damage, as well as weed seeds and red rice contamination.

In general, 100 lb of rough rice yields 20 lb of hulls and 80 lb of brown rice. Milling the brown rice yields 10 lb of bran and polish and 70 lb of milled rice. Milled rice is a mixture of head rice and brokens. Head rice is whole kernels that remain intact after milling. U.S. premium grade milled rice requires that no more than 4% of head rice consists of brokens (102).

Rice Products, Consumer Preferences, and Uses

Rice consumption varies among unprocessed forms (e.g. brown rice, head rice, or brokens) and processed forms (e.g., parboiled, instantized, puffed and crisped, flour, milk, noodles) (106). Rice is largely consumed as an intact or whole grain. A large portion of rice is consumed as cooked milled rice, a staple among Asian populations. Higher head rice content and more translucent rice is a common consumer preference. For cooking quality, preferred types are grouped according to amylose content (AC); generally, intermediate-AC rice is preferred in Southeast Asia, and high-AC rice is preferred in South Asia (50). Low-AC (short and medium grain) japonica rice is preferred in Japan, China, Taiwan, Korea, Nepal, Australia, Russia, Spain, and the United States. Long-grain rice with intermediate and high AC are consumed primarily in the United States, South America, and some African countries.

Desired rice texture is more a factor of culture and regional or personal preference, and not necessarily determined by economic development. Asian consumers' preferences for table rice are diverse; consumers in Japan, Korea, Taiwan, and parts of China usually dislike a dry and crisp texture (akin to a loose and fluffy texture) (96). In developed countries such as Japan, a soft, sticky, and chewy texture and translucent, almost glassy appearance in cooked rice are particularly favored, such as in Koshikari rice. Aromatic jasmine and basmati are two popular rice varieties that command higher prices (12). They are preferred in Asian countries because of their popcorn-like flavor. Thailand is the biggest producer and exporter of jasmine rice, whereas India and Pakistan are known for producing basmati rice. Western markets prefer fluffy cooked rice, with medium to high AC.

Whole or head rice is consumed in other forms as well, such as sticky or waxy rice made into sweetened cake snacks. In processed form, waxy rice is made into cakes (e.g., *puto* and *mochi*) by kneading and steaming waxy rice flour.

Rice Consumption and Health. A multiyear study among U.S. men and women showed higher intake of white rice (milled rice) was associated with a higher risk of type 2 diabetes; in contrast, a lower risk of type 2 diabetes was associated with high brown rice intake (95). Glycemic properties of rice have been investigated in relation to digestibility and increasing incidence of diabetes, especially with improved living standards among rice-consuming Asian countries (111). Glycemic indices of waxy and low-AC rice are higher than those of intermediate- and high-AC rice (50,111). Brown and parboiled rice have lower glycemic indices than that of regular milled rice (50). Rice bran added to the diet lowers plasma cholesterol levels and triglycerides (85). A separate study on defatted rice bran and rice bran oil suggests that it is the rice bran oil, not the fiber, that lowers cholesterol in moderately hypercholesterolemic adults (68).

Parboiled Rice. About 20% of rice produced worldwide is made into parboiled rice (10). It is the major staple throughout South Asia (the Indian subcontinent), where 90% of the world's parboiled rice is produced and consumed (8). Western and Central Africa have a growing market for parboiled rice. The benefits of parboiling include lowered glycemic indices, maintenance of resistant starch content, and greater vitamin B content (46).

Parboiling involves a three-step hydrothermal treatment of soaking, heating, and drying of rough or brown rice (10). Techniques vary from traditional parboiling, using artisanal methods of boiling rice, to a more sophisticated mechanical process. Commercial processes involve soaking the rough rice until the grains absorb moisture to achieve 30% MC on a wet basis, draining excess water, and heat treating (steaming under pressure) to gelatinize the rice starch in the kernels (8). Parboiling produces physical, chemical, and sensory modifications, improves grain quality, maintains nutritional content, improves milling recovery by sealing fissures in kernels, and alters texture and cooking properties (8,35,63).

Brewing. The high starch content of rice makes it suitable for brewing different kinds of alcoholic beverages. Sake, a popular Japanese rice wine, uses a culture of *Aspergillus oryzae* called *koji* on steamed rice grains (113). The short-grain variety 'Yamadanishiki' is a famous cultivar characterized by a loose endosperm cell arrangement (white core) that allows for quick water absorption, It steams well and has a high rate of sugar reproducibility upon saccharification (113). In beer brewing, rice is used as an adjunct ingredient (main mash supplement), with malt, hops, and water as raw materials. Adjuncts in beer create a lighter color and flavor.

Conclusions

Rice grain is a food staple for more than half of the world's population. Rice sustains life throughout the world, especially in Asia and particularly among some of the less developed economies. Improvements in selection, growing, harvesting, drying, and milling of rice have led to overall improvement of the well-being of millions of people directly and many more indirectly. Development of new rice cultivars is ongoing to allow sustainable, resilient production in a variety of situations, including changing weather patterns and adaptive changes in weed, disease, and insect populations. New rice production, harvesting, drying, milling, and processing challenges continually occur and must be solved in order for farmers to maintain production at or above the rate of consumption. Most challenges facing rice quality are local rather than global, and sound responses require meaningful knowledge of the entire rice production continuum, from beginning production practices through to consumption.

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