Journal of Food Engineering 117 (2013) 304–315

Contents lists available at SciVerse ScienceDirect

Journal of Food Engineering

journal homepage: www.elsevier.com/locate/jfoodeng

Review

The breakage susceptibility of raw and parboiled rice: A review

J. Buggenhout *, K. Brijs, I. Celus, J.A. Delcour

Laboratory of Food Chemistry and Biochemistry and Leuven Food Science and Nutrition Research Centre (LFoRCe), KU Leuven, Kasteelpark Arenberg 20, B-3001 Heverlee, Belgium

ARTICLE INFO

Article history:
Received 8 August 2012
Received in revised form 5 March 2013
Accepted 9 March 2013
Available online 17 March 2013

Keywords:
Rice
Breakage
Head rice yield
Parboiling

ABSTRACT

Rice (*Oryza sativa* L.) is one of the most important cereals in the world. Before it is consumed, it is common to remove the hull, bran and germ from the rough rice kernel which is either parboiled or not. During such processing, rice kernels are subjected to mechanical stresses which cause some rice grains to break. A main challenge of the rice industry is to minimize the quantities of broken rice. We here review the factors impacting the breakage susceptibility of rice kernels. Their tendency to break is primarily determined by fissures, chalkiness, immaturity and rice kernel dimensions, properties which are both cultivar and rice grain history dependent. The intensity of processing of any given rice feedstock determines the actual level of broken rice kernels. If performed properly, parboiling, a three-step hydrothermal treatment consisting of soaking, heating and drying of rough rice, substantially reduces the level of broken kernels.

Contents

Abbreviations: CMC, critical moisture content; DOM, degree of milling; HRY, head rice yield; MC, moisture content; pp, percentage points; RH, relative humidity; T, temperature; T_g, glass transition temperature.

* Corresponding author. Tel.: +32 (0)16321634; fax: +32 (0)16321997.
E-mail address: joke.buggenhout@biw.kuleuven.be (J. Buggenhout).

0260-8774/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.jfoodeng.2013.03.009

1. Introduction

Rice (*Oryza sativa* L.) is one of the leading food crops in the world. In 2010, the global rice production was *ca*. 696 million tons. More than 90% of the world's rice is grown and consumed in Asia by 60% of the world's population on about 11% of the world's cultivated land (FAO, 2010).

Rice, like barley and oat, is harvested as a covered grain, which is called rough rice (also referred to as paddy). Rough rice consists of a white, starchy endosperm surrounded by tightly adhering bran and germ within a hull. The hull surrounds, but is not bound to, the grain and constitutes about 20–25% of the rough rice mass (Champagne et al., 2004; Delcour and Hoseney, 2010c).

Dehulling of *rough rice* separates the hull from the brown rice. The most common dehuller makes use of rubber rolls. In such dehuller, rough rice is fed in a continuous stream at a controlled rate between two rubber rolls rotating at different speed in opposite directions. Because each side of the rough rice attempts to travel at the same linear speed as its corresponding roll, the hull is sheared from the resultant brown rice.

Most *brown rice* is converted into white or milled rice in a process which, in rice technology jargon, is referred to as *milling*. Milling of brown rice kernels involves removing the bran and germ from the underlying endosperm by applying friction and/or abrasion forces. In abrasive milling, a high-speed rotating stone with a rough surface abrades off the bran. In contrast, in friction milling, the rice grains are forced against each other and against a metal screen by a steel-ribbed cylinder rotating inside a metal-plated cylinder. As a result, bran is removed by frictional forces created between individual rice grains on the one hand and between rice grains and the metal screen surface on the other (Bond, 2004; Delcour and Hoseney, 2010a; Kohlwey, 1992). Fig. 1 shows the different steps in the processing of rough rice [Adapted from Delcour and Hoseney (2010a)]. Several unit operations can increase the value of milled rice, such as those targeting a reduced cooking time (from 20 to 35 min to less than 15 min) or an increased nutritional value (i.e. increased vitamin and mineral contents). An important one is parboiling, a hydrothermal treatment consisting of soaking, heating (wet or dry) and drying of the rough or brown rice (Delcour and Hoseney, 2010a).

We here review the different factors impacting the breakage susceptibility of both raw and parboiled rice kernels.

2. Breakage of raw rice kernels

Rice grains are subjected to mechanical stresses during several unit operations such as harvesting, threshing, drying, dehulling and milling. When the stresses exceed the rice grain strength, the individual rice grain breaks (Bhattacharya, 1969; Matthews et al., 1970; Matthews and Spadaro, 1975; Raghavendra Rao

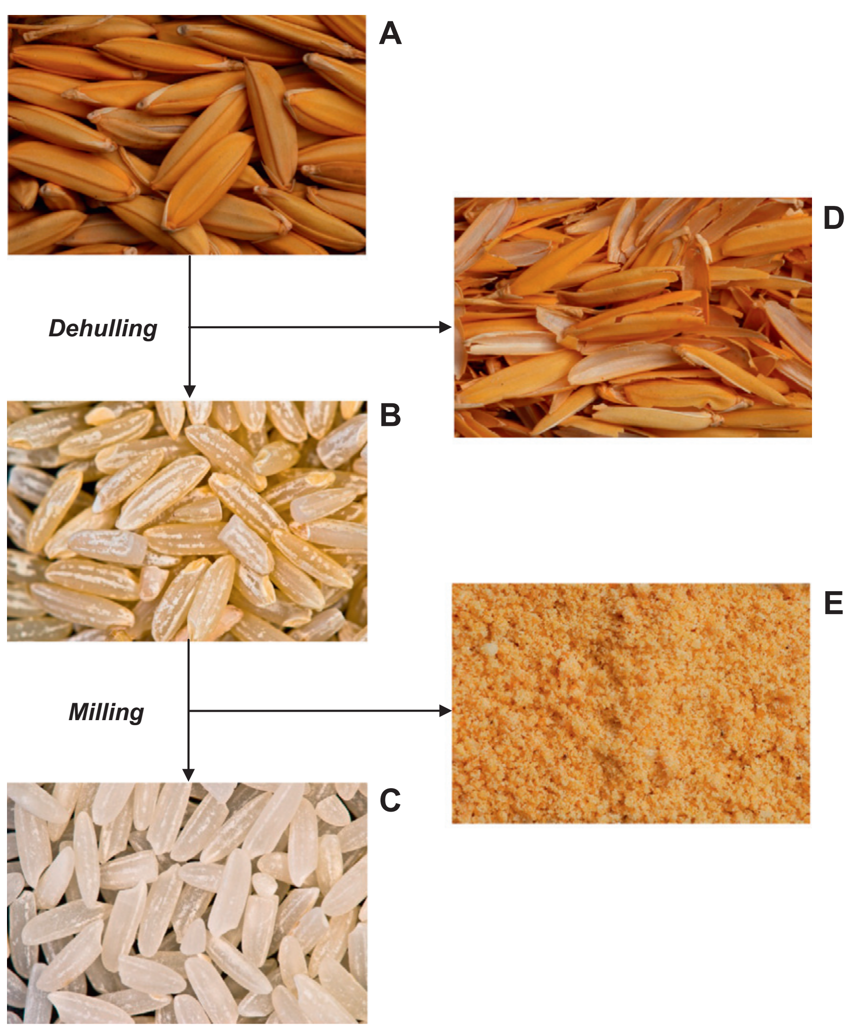

Fig. 1. Photographs of the different products obtained in the conversion of rough rice (A) into white or milled rice (C). First, rough rice is separated into brown rice (B) and hull (D). The brown rice is then milled to give white rice and rice bran (E).

et al., 1967; Rhind, 1962; Smith and Mc Crea, 1951; Swamy and Bhattacharya, 1979; Velupillai and Pandey, 1990). The intensity of processing largely determines the actual level of broken kernels. However, the tendency of rice kernels to break is primarily determined by fissures, chalkiness, immaturity and rice kernel dimensions (see Section 3). We here focus on the impact of dehulling and milling on kernel breakage.

2.1. Rice grain dehulling and milling

2.1.1. Dehulling

In a rubber roll dehuller, the distance between the rolls determines the stress applied to the rough rice kernels. As the distance increases, the kernels experience less stress. While this results in less broken kernels, it can also reduce dehulling efficiency such as determined with the McGill dehuller (Matthews et al., 1970; Swamy and Bhattacharya, 1979). Swamy and Bhattacharya (1979) observed that, at a dehulling efficiency of 50%, about 4.6–18 percentage points (pp) less rice kernels break than at a dehulling efficiency of 90–95%. This was confirmed by Matthews et al. (1970). They showed that kernel breakage was 5 pp lower at a dehulling efficiency of 70% compared to dehulling at 95% efficiency.

2.1.2. Milling

Dehulled whole brown rice kernels can still break during milling (Bhattacharya, 1969; Liang et al., 2008; Matthews et al., 1970; Raghavendra Rao et al., 1967; Swamy and Bhattacharya, 1979; Takai and Barredo, 1981; Yadav and Jindal, 2008). Interestingly, most brown rice kernel breakage occurs at the beginning of milling (Bhattacharya, 1969; Matthews et al., 1970; Smith and Mc Crea, 1951; Swamy and Bhattacharya, 1979; Takai and Barredo, 1981; Yadav and Jindal, 2008). However, some authors suggest that during extended milling rice kernels also break as a result of heat generation (Bhattacharya, 1969; Liang et al., 2008; Raghavendra Rao et al., 1967).

The amount of rice kernels that break during milling is influenced by the type of mill. Abrasive mills operate at a relatively low and uniform grain-to-grain pressure, and consequently produce less broken rice grains than friction mills (Bond, 2004; Kohlwey, 1992). Factors such as rice kernel moisture content (MC), temperature (*T*), and kernel surface topography affect the ease with which bran is removed from the rice kernel during milling. Under otherwise standardized conditions, higher initial MC and *T* result in an increased degree of milling (DOM), i.e. the extent to which germ and bran are removed during milling (Andrews et al., 1992; Banaszek et al., 1989; Bhashyam and Srinivas, 1984; Cooper and Siebenmorgen, 2007; Reid et al., 1998).

After milling, broken rice grains are often separated from whole rice grains. Depending on the level of broken grains allowed by the customer's specification, these broken kernels may then be blended in a precise ratio with the unbroken kernels to maximize the profitability of the mill (Bond, 2004).

2.2. Head rice yield

The primary parameter used to quantify rice dehulling and milling efficiency is the head rice yield (HRY). HRY is defined as the mass percentage of rough rice that remains after milling as head rice (Cnossen et al., 2003), i.e. kernels that are at least three-fourths of the original kernel length (USDA, 2005). HRY can range from 0% to 75% (Andrews et al., 1992; Schluterman and Siebenmorgen, 2007) and is evidently of great importance in commercial operations, which are continuous, multi-break, sequential systems that mill several tons of rice per hour. HRY can also be determined by dehulling and milling a small quantity of sample in a single-break, batch laboratory dehuller and mill. Although milling such a limited amount of sample is assumed to be representative for commercial milling, there is a lack of evidence to support this statement. Differences in HRY between commercially and laboratory milled rice are mainly determined by mill settings (Graves et al., 2009).

HRY is often used to compare dehulling and milling quality of rice lots. However, it is evidently influenced by their DOM. Indeed, as milling duration increases, DOM increases and HRY decreases linearly (Reid et al., 1998; Wadsworth, 1994). The impact of the initial rice grain MC and *T* on HRY may be due to their impact on DOM rather than to their impact on kernel breakage as such (Archer and Siebenmorgen, 1995; Banaszek et al., 1989; Webb and Calderwood, 1977). In general, under standardized conditions (including milling duration), HRY increases when the initial MC decreases from 14% to 10%, (Andrews et al., 1992; Banaszek et al., 1989; Bennett et al., 1993; Pominski et al., 1961; Webb and Calderwood, 1977). In addition, milling at lower initial *T* (0 °C) produces greater HRY than milling at higher *T* (25 °C) (Archer and Siebenmorgen, 1995).

However, the bending strength (i.e. the maximum bending stress a rice grain can sustain before it is ruptured by a flexural load) of intact brown rice kernels, which is well related to HRY (Lu and Siebenmorgen, 1995), decreases from 57.8 MPa to 19.2 MPa with increasing MC from 10.4% to 20.4% (Zhang et al., 2005).

3. Factors determining rice kernel breakage

The tendency of rice kernels to break is primarily determined by rice kernel fissures, chalkiness, immaturity and dimensions, properties which are both cultivar and rice grain history dependent (Bergman et al., 2004; Bhattacharya, 1969; Deepa and Singh, 2010). We here review these factors and the underlying reasoning on their influence. It has been suggested that the chemical composition (e.g. amylose or protein content) and physicochemical properties (e.g. starch gelatinization or pasting properties) impact the extent of breakage during dehulling and milling (Juliano et al., 1993; Patindol and Wang, 2002; Proctor and Goodman, 1985; Wang et al., 2002). However, there is little literature available on the relation between chemical composition and physicochemical properties of rice on the one hand, and HRY on the other. Rice flour from broken kernels exhibits significantly lower peak and setback viscosities than that from whole kernels, indicating that flour and starch of broken rice do not swell as easily or to the same extent as those of head rice, while the lower setback viscosities suggest that starch of broken rice grains associates to a lower extent than that of head rice (Proctor and Goodman, 1985; Wang et al., 2002). Starch isolated from flour from either whole or broken rice shows similar pasting properties (Wang et al., 2002). This indicates that non-starch components such as protein may be responsible for the different rheological properties of flour from either whole or broken rice kernels. However, it is also possible that during starch isolation, part of the starch is removed together with the protein.

3.1. Fissures

Rice grains of a same panicle can differ up to 10 pp in MC. MC of rice grains on the same plant and/or on the same field can vary even more (Kunze and Calderwood, 2004; Li et al., 2003; Siebenmorgen et al., 1990, 1992). During harvest, kernels with both high and low MC are mixed. Those with high MC desorb moisture into the air, while grains with low MC adsorb moisture (Bautista and Siebenmorgen, 2004; Kunze, 1977). Indeed, due to their hygroscopic nature, rice grains adsorb or desorb moisture from or into the air until an equilibrium state is reached. This equilibrium state is a function of both relative humidity (RH) and *T* of the surrounding air (Choi et al., 2010; Hogan and Karon, 1955; Kachru and Matthes, 1976; Ondier et al., 2012b; Siebenmorgen et al., 2009). The MC gradients in the rice kernels resulting from moisture sorption cause hygroscopic stresses in the kernel. These MC gradients are frequently calculated by mathematical models (Dong et al., 2009; Sarker et al., 1996; Yang et al., 2002, 2003). When the MC gradients exceed the rice kernel mechanical strength, fissures can develop (Jia et al., 2002; Kunze, 2001; Kunze and Choudhury, 1972; Sarker et al., 1996; Yang et al., 2002). Such fissures are large internal fractures, usually perpendicular to the longitudinal axis of the rice grain (Hwang et al., 2009; Jia et al., 2002; Kunze, 1979; Kunze and Calderwood, 2004; Sharma and Kunze, 1982). Rice grain kernels primarily break during dehulling and milling because of weakness caused by these fissures (Bhattacharya, 1969; Matthews et al., 1970; Nguyen and Kunze, 1984; Qin and Siebenmorgen, 2005; Rhind, 1962; Sarker et al., 1996; Siebenmorgen et al., 1998b; Swamy and Bhattacharya, 1979; Velupillai and Pandey, 1990; Zhang et al., 2005). The effect of moisture adsorption and desorption on fissure formation during different stages of rice handling, i.e. cultivation, harvest, drying and storage, is discussed below.

Of further note is that each rice cultivar has its own susceptibility to fissuring (Bautista et al., 2009a; Bergman et al., 2004; Bhashyam et al., 1984; Juliano et al., 1993; Srinivas et al., 1977; Velupillai and Pandey, 1990). This cultivar dependence may be attributed to differences in rice grain dimensions (see Section 3.4) (Dong et al., 2010; Fan et al., 2000; Kunze and Lan, 2004; Nguyen and Kunze, 1984) or physicochemical properties (Bhashyam et al., 1984; Dong et al., 2010).

3.1.1. Moisture adsorption induced fissures during cultivation

From seeding to harvest, rice grains go through different developmental phases. During grain-filling, dry matter is formed and moisture is transferred from vegetative tissues into the developing seeds. Elevated cultivation Ts during critical grain-filling stages can affect rice kernel development. The impact hereof on kernel breakage will be discussed in more detail in Sections 3.2 and 3.4. At the end of the grain-filling phase, the rice grains dry down. At this point, the MC is no longer controlled by moisture transfer within the plant, but varies in response to the environment (Counce et al., 2000; Kunze, 2001; Kunze and Calderwood, 2004; Siebenmorgen, 1994).

When it rains, dew falls, or when the grain MC is lower than that of the equilibrium state of the surrounding air, the rice grain adsorbs water. This moisture sorption can induce fissures when the rice grains are dried to a MC below a critical MC (CMC), which ranges from 12% to 15%. Indeed, above the CMC, rice grains do not fissure when suddenly exposed to an environment in which the rice grain adsorbs moisture. While the different authors (Bautista et al., 2009a; Jodari and Linscombe, 1996; Kunze, 2001; Kunze and Calderwood, 2004; Kunze and Choudhury, 1972; Siebenmorgen et al., 1992, 1998b; Siebenmorgen and Jindal, 1986) do not explain why fissuring only occurs upon moisture uptake by rice of sub-CMC, it seems justified to speculate that too steep moisture gradients could cause fissuring of such rice.

Traditionally, rough rice is cultivated under flooded field conditions. At a given time point, the fields are drained to facilitate grain drying and mechanical harvest. Earlier field draining leads to lower rice MCs at a given harvest time. As a result, more rice grains have a MC lower than the CMC and become susceptible to moisture adsorption induced fissuring (Counce et al., 1990; Jongkaewwattana and Geng, 1991). Highly fertilized rice produces more panicles and is harvested in greater yields. It requires a longer period to mature, dries slower, and has higher MC and less moisture adsorption induced fissures at a given harvest time than less fertilized rice (Kunze and Calderwood, 2004; Kunze et al., 1988). Cultural practices like drain time and fertilization rate both may indirectly impact the incidence of moisture adsorption induced fissures, as they influence rice grain maturation and field drying process (Champagne et al., 2005; Kunze et al., 1988; McCauley and Way, 2002).

3.1.2. Moisture adsorption induced fissures during harvest

While harvest generally starts when the rice grains are mature (Kunze and Calderwood, 2004), rice grains in a field and even on the same panicle do not reach maturity at the same time. Hence, at harvest, some kernels are mature, while others may still be immature. As a result, individual kernel MCs vary widely (Chau and Kunze, 1982; Siebenmorgen et al., 1992). Whenever harvest is delayed, and, as a consequence, rice grain MC declines, an increasing number of kernels reach the CMC for fissures to develop due to rapid moisture adsorption (Bautista et al., 2009a; Jodari and Linscombe, 1996; Jongkaewwattana et al., 1993a; Nangju and Dedatta, 1970; Siebenmorgen, 1994; Siebenmorgen et al., 1992).

3.1.3. Moisture desorption induced fissures during drying and subsequent cooling

Rough rice grains are harvested at MCs ranging from 16% to 26%. To avoid microbial contamination and respiration processes which can cause quality losses, they are dried to a MC of 12–13% (Ondier et al., 2010; Perdon et al., 2000; Siebenmorgen et al., 2006; Siebenmorgen and Meullenet, 2004). Conventional rice drying is performed by forcing heated air through the grains. As the air moves through the grains, it transfers heat to the grain, while adsorbing moisture present at the rice grain surface (Mossman, 1986). It is generally accepted that *T* gradients within the rice grains can be neglected after the first few minutes of drying (Aguerre et al., 1986; Yang et al., 2002). In contrast, MC gradients are present in the rice grains during the entire drying process. Initially, MC declines fast. However, after a brief time, the moisture removal progressively slows down due to the inability of the internal moisture to diffuse to the surface at a rate comparable to that of its removal from the surface. The MC gradients depend on the drying rate, which is determined by both rice grain MC as well as drying air conditions, i.e. air T, RH and flow rate (Ece and Cihan, 1993; Mossman, 1986; Ondier et al., 2012a). As mentioned before, such MC gradients cause stresses within the rice grain which may result in fissuring. However, no or at least very limited fissure formation is observed during rice drying. The fissures seem to arise after drying, i.e. when the rice grains are cooled (Kunze, 1979; Li et al., 1999; Nguyen and Kunze, 1984; Sharma and Kunze, 1982). The magnitude of MC gradients during drying determines the fissuring potential of rice grains after drying. The more moisture is removed from the surface, the higher the MC gradients inside the kernels, and the higher the percentage of fissured rice grains formed after

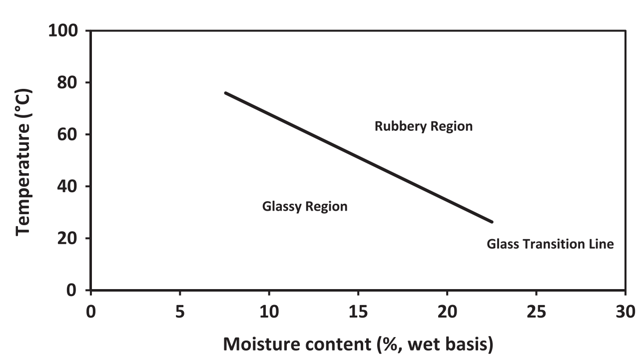

Fig. 2. Temperature-moisture content glass transition relationship for Bengal and Drew brown rice [Adapted from Siebenmorgen et al. (2004)].

drying. The *T* and RH of the drying air have a clear effect on the percentages of fissured kernels and subsequent kernel breakage during dehulling and milling. Evidently, the amount of moisture removed during drying, which is determined by the initial and final grain MC, is also a critical parameter determining the formation of fissures in the rice grain after drying (Abud-Archila et al., 2000; Aguerre et al., 1986; Bonazzi et al., 1997; Chen et al., 1997; Fan et al., 2000; Iguaz et al., 2006; Jia et al., 2002; Kunze, 1979; Li et al., 1999; Mossman, 1986; Nguyen and Kunze, 1984; Sarker et al., 1996; Schluterman and Siebenmorgen, 2007; Sharma and Kunze, 1982; Siebenmorgen et al., 2005; Yang et al., 2003).

In commercial operations, rice drying is often conducted in multiple steps, whereby each drying step is followed by a tempering period that minimizes the MC gradients inside the rice kernel, and, thus, fissuring and subsequent rice breakage (Kunze and Calderwood, 1994). The presence of these MC gradients and fissures has been nicely visualized using magnetic resonance imaging techniques (Hwang et al., 2009). Higher ratios of tempering time over drying time in one cycle, and lower drying times in one cycle result in lower levels of fissured rice kernels. In addition, tempering rice immediately after drying at the *T* of the drying air prevents fissuring during subsequent cooling by allowing the MC gradients to subside (Aquerreta et al., 2007; Cnossen et al., 2003; Cnossen and Siebenmorgen, 1999; Dong et al., 2009; Iguaz et al., 2006; Li et al., 1999; Nguyen and Kunze, 1984; Ondier et al., 2012a; Schluterman and Siebenmorgen, 2007; Sharma and Kunze, 1982; Steffe et al., 1979; Yang et al., 2003).

The impact of MC gradients on fissuring in rice grains during moisture desorption can be explained based on the glass transitions of the rice kernel. Given a specified MC, the glass transition temperature (T_g) is defined as the *T* at which the kernel passes from a glassy to a rubbery state, or *vice versa*. The T_g of rice depends on its MC. At a *T* below T_g, the amorphous material in the rice kernel exists in the glassy state, while at a *T* above T_g, it exists in the rubbery state. Rice kernels in the glassy state have lower expansion coefficients, specific volumes, and diffusivities than rice kernels in the rubbery state (Cnossen et al., 2000, 2002; Cnossen and Siebenmorgen, 2000; Perdon et al., 2000; Siebenmorgen et al., 2004). Fig. 2 shows the relationship between T_g and MC for brown rice of the cultivar Bengal and Drew [Adapted from Siebenmorgen et al. (2004)].

At harvest (25 °C, 16–22% MC), rice grains are in the glassy state, since their T_g is *ca.* 37 °C. During drying, the kernel *T* increases rapidly to the *T* of the drying air. Depending on the air *T*, the entire kernel or regions within the kernel are either glassy or rubbery (Cnossen et al., 2000; Perdon et al., 2000; Siebenmorgen et al., 2004). Drying either above or below T_g significantly affects the drying rate. Moisture diffusivity is much higher in the rubbery region, and, as a result, the rice grains dry at a higher rate (Cnossen et al., 2002). When drying above T_g, the entire rice kernel initially transitions from the glassy to rubbery state. However, during drying the surface of the rice kernel, because of its lower MC, may transition back into the glassy state, while the center, because of its higher MC, remains in the rubbery state (Cnossen and Siebenmorgen, 2000; Cnossen et al., 2002; Yang and Jia, 2004). The different material properties of both states induce differential stresses within the kernels, which can cause the kernel to fissure. During cooling, entire kernels or regions within the kernels which were rubbery become glassy (Cnossen and Siebenmorgen, 2000; Perdon et al., 2000). It seems logical that MC gradients in the rice kernels at the end of drying can result in some kernel sections being above their T_g, while others are below it. In this view, the outer rice layers are in a glassy state, whereas the inner portion is still in a rubbery state, which can cause kernel fissuring. However, conditioning rice grains at a *T* above T_g, thereby allowing the MC gradients to subside before the rice is cooled to *T* below T_g, results in the different regions of the rice grain transitioning to the glassy state at the same time. As a consequence, no differential stresses are created within the rice grains and fissuring is limited (Cnossen and Siebenmorgen, 2000; Schluterman and Siebenmorgen, 2007; Yang et al., 2003; Zhang et al., 2003).

3.1.4. Moisture adsorption/desorption induced fissures during storage

Additional fissuring can occur in the dried rice grains during storage, depending on RH and *T* of the surrounding air and the rice grain MC (Kunze and Calderwood, 2004; Lloyd and Siebenmorgen, 1999; Siebenmorgen and Meullenet, 2004; Siebenmorgen et al., 1998a, 2009; Stermer, 1968).

3.2. Chalkiness

Rice chalkiness appears as a white opaque area, which can make up part of or the entire rice grain. The starch granules in the chalky rice endosperm are loosely packed, and the resulting air spaces impact refraction of light through the grain (Ashida et al., 2009; Tashiro and Wardlaw, 1991a). These airspaces are visualized using X-ray microtomography (Zhu et al., 2012). According to different authors, chalky kernels break more easily during dehulling and milling than translucent rice kernels, and, thus, decrease HRY (Bautista et al., 2009b; Juliano et al., 1993; Patindol and Wang, 2002; Perez et al., 1996; Swamy and Bhattacharya, 1982b). The lower resistance of chalky rice kernels to grain breakage can be attributed to their low hardness (Ashida et al., 2009; Singh et al., 2003; Tamaki et al., 2006), which makes them less resistant to mechanical stresses. In addition, the numerous air spaces in the endosperm of chalky rice kernels may increase the susceptibility to fissure formation (Swamy and Bhattacharya, 1982b), and, hence, to kernel breakage during dehulling and milling. Differences in breakage susceptibility between non-chalky rice grains may find their origin in differences in endosperm compactness and micro-porosity.

The presence and degree of chalkiness are influenced both by environmental and genetic factors. In general, heat during grain-filling is considered to be the most important environmental factor influencing chalkiness. High *T* during specific stages of grain development tends to increase the portion of rice kernels that have a chalky area, while low *T* tends to decrease or eliminate it (Ambardekar et al., 2011; Cooper et al., 2008; Fitzgerald and Resurreccion, 2009; Lanning et al., 2011; Lisle et al., 2000; Patindol and Wang, 2002; Tashiro and Wardlaw, 1991b; Yoshida and Hara, 1977). However, some cultivars are almost free from chalkiness, even when exposed to high *T* during cultivation, while others consistently produce chalky grains. This clearly is evidence for a genetic component in chalkiness as is the presence of several quantitative trait loci that associate with it (Ambardekar et al., 2011; Bautista et al., 2009b; Fitzgerald and Resurreccion, 2009; Lanning et al., 2011; Wan et al., 2005; Yamakawa et al., 2008, 2007).

The HRY of chalky rice cultivars is positively affected by use of nitrogen fertilizer. Nitrogen fertilization increases the number of protein bodies inside the endosperm. As a consequence, the voids between the loosely packed, irregular shaped starch granules in chalky rice are filled. Hence, the weakness of the chalky kernels de-

Table 1
Length–width ratios used to determine grain type (Taylor and Duodu, 2009).

Rice form	Length–width ratio of		
	Long-grain	Medium-grain	Short-grain
Rough	⩾3.4	2.3–3.3	⩽2.2
Brown	⩾3.1	2.1–3.0	⩽2.0
Milled	⩾3.0	2.0–2.9	⩽1.9

creases. This decreases rice breakage in dehulling and milling (Fagade and Ojo, 1977; Leesawatwong et al., 2005; Nangju and Dedatta, 1970).

3.3. Immaturity

Rice grains in the field that have a MC exceeding 22% are generally considered to be immature (Bautista et al., 2000a, 2000b; Siebenmorgen et al., 1992). However, once the rice grains are harvested and dried to a MC to be safely stored, it is not clear how immaturity is defined. In some studies, immature rice kernels are defined as thin kernels, often green in color, with various levels (10 to 100%) of chalkiness (Bhattacharya, 1969; Swamy and Bhattacharya, 1982a). Others consider the presence of green bran as the only criterion for immaturity (Chen and Bergman, 2005; Matthews et al., 1981b; Siebenmorgen et al., 2006).

According to different workers, immature rice kernels lack strength, and, as a consequence, break relatively easy during dehulling and milling (Bautista et al., 2000b; Bhattacharya, 1969; Nangju and Dedatta, 1970; Siebenmorgen et al., 2006; ten Have, 1967). Bhattacharya (1969) reported an increased level of breakage (67.9% versus 14.8%) after dehulling of a rice sample enriched with immature rice kernels (65.4% versus 15.4%).

3.4. Kernel dimensions

Based on their length–width ratio (i.e. grain shape), rice grains of a given cultivar are classified into three different grain type categories: long-, medium- and short-grain rice (Table 1) (Taylor and Duodu, 2009). Within one rice cultivar, kernel dimensions can vary widely, mainly due to variations in kernel maturity (del Rosario et al., 1968; Jongkaewwattana and Geng, 2002; Jongkaewwattana et al., 1993b; Wadsworth et al., 1979). Some studies indicate that kernel dimensions impact HRY (Fan et al., 2000; Goodman and Rao, 1985; Jongkaewwattana and Geng, 2002; Kunze and Calderwood, 2004; Matthews et al., 1970, 1981b; Matthews and Spadaro, 1976; Sun and Siebenmorgen, 1993; Wadsworth et al., 1982), although others explain differences in HRY based on the content of fissured, chalky and immature rice grains (Swamy and Bhattacharya, 1979).

In medium- and short-grain rice, the distance between the surface and center of the rice grain is larger than in long-grain rice. As a consequence, a higher MC gradient is present in the former kernels, resulting in a higher susceptibility to fissure formation (Dong et al., 2010; Fan et al., 2000; Kunze et al., 2004; Nguyen and Kunze, 1984). Furthermore, slender grains seem to poorly resist mechanical stress, as Goodman and Rao (1985) and Jongkaewwattana and Geng (2002) observed a higher HRY in medium-grain rice than in long-grain rice. Furthermore, Matthews et al. (1970) found that the level of breakage as a result of milling exceeds the level of fissured rice kernels in long-grain rice, while in medium-grain rice both levels are similar.

The thickness distribution of a rice kernel population affects HRY (Jindal and Siebenmorgen, 1994; Matthews and Spadaro, 1976; Matthews et al., 1981a; Sun and Siebenmorgen, 1993; Wadsworth et al., 1982, 1979). Matthews and Spadaro (1976) showed that milling of thin long-grain rice fractions (kernel thickness 1.62–1.78 mm) results in high levels of broken kernels. Wadsworth et al. (1982) noted that HRYs are highest for long-grain rice kernels with intermediate thickness (1.78–1.98 mm). These findings were confirmed by Sun and Siebenmorgen (1993). They reported higher levels of broken grains in both thinnest (<1.83 mm) and thickest rice fractions (>2.03 mm). High kernel breakage in the thinnest fraction is attributed both to its high level of chalky and immature rice kernels, both of which are breakage susceptible (Matthews and Spadaro, 1976; Siebenmorgen et al., 2006; Wadsworth et al., 1982, 1979), and to the fact that thin kernels can break easily because their dimensions make them less resistant to mechanical stresses (Bautista et al., 2007; Lu and Siebenmorgen, 1995; Matthews et al., 1981b; Siebenmorgen et al., 2006; Siebenmorgen and Qin, 2005; Sun and Siebenmorgen, 1993). Some authors suggest that the high level of breakage in the thickest fraction is related to its increased amount of fissures. As thicker kernels most likely are more mature and drier, they become more susceptible to rapid moisture adsorption induced fissures (see Section 3.1) (del Rosario et al., 1968; Jindal and Siebenmorgen, 1994; Matthews et al., 1981b). However, Siebenmorgen et al. (2005) observed no apparent differences in kernel thickness distributions of fissured and non-fissured rice kernels.

It follows from the above that it is not always possible to relate HRY to one specific rice kernel characteristic. For example, that increased night T during cultivation decreases HRY (Ambardekar et al., 2011; Cooper et al., 2008, 2006; Counce et al., 2005; Lanning et al., 2011; Peng et al., 2004) may be explained by the impact of environmental T on rice grain dimensions (Cooper et al., 2008; Counce et al., 2005) and chalkiness (see Section 3.2). However, environmental T also affects the composition of rice. Elevated (nighttime) air Ts during critical grain-filling stages reduce the starch content and affect its chemical make-up (i.e. decreased amylose contents and changed ratios of long- to short chain amylopectin) (Aboubacar et al., 2006; Asaoka et al., 1985; Lanning et al., 2012; Suzuki et al., 2003). Likewise, elevated (nighttime) air Ts increase (Tashiro and Wardlaw, 1991b) or decrease (Lanning et al., 2012) the protein content, and decrease the accumulation of prolamins and globulins in the grains (Lin et al., 2010). As a consequence, differences in HRY may also find their origin in differences in composition of the rice grains. Further work in this area would seem appropriate.

4. Impact of parboiling on rice kernel breakage

About 20% of the rice produced worldwide is parboiled, i.e. "partially boiled". This three step hydrothermal treatment involves soaking, heating and drying of rice and is performed either on rough or on brown rice. Parboiling has a considerable impact on the texture and nutritional characteristics of cooked rice. In particular, cooked parboiled rice is firmer, less sticky and more nutritious than its cooked raw counterpart. It is also generally assumed that parboiling increases HRY. Parboiled rice has a darker color than raw rice and a slightly different flavor (Bhattacharya, 2004; Delcour and Hoseney, 2010a).

4.1. The parboiling process

Fig. 3 illustrates the different steps of parboiling (Delcour and Hoseney, 2010a). Traditionally, rough rice is used as feedstock for the process. Modern industrial parboiling starts from brown rice. We here focus on parboiling of rough rice. In the first step of conventional parboiling, rough rice is soaked in excess water at T below the starch gelatinization T. Soaking under these conditions yields rough rice with an average MC of ca. 30–32%. Following drainage, soaked rough rice is heated to gelatinize the starch by applying steam at T ranging from 100 to 120 °C during 5–30 min. Alternatively, microwave energy can be used. The heated rice has a MC of about 35%. For safe storage, the rice has to be dried, with or without tempering, to a MC below 14%. This drying step mostly occurs by means of heated air (Bhattacharya, 2004; Delcour and Hoseney, 2010a).

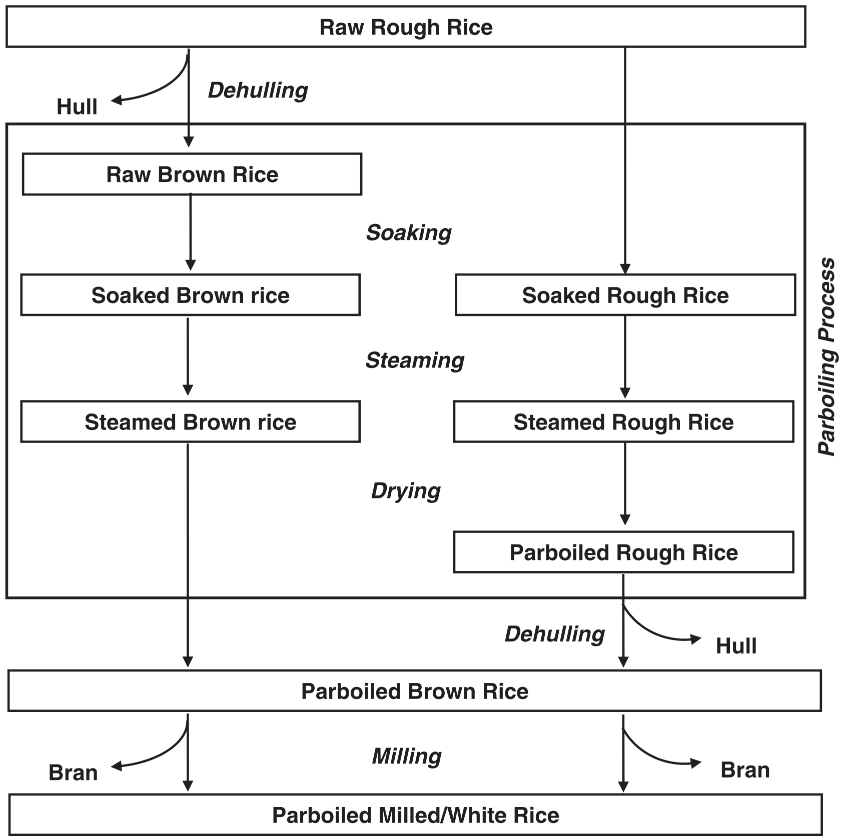

Fig. 3. Steps in the conversion of rough rice to milled parboiled rice (Delcour and Hoseney, 2010a).

4.2. Effect of parboiling on rice breakage

While one of the main advantages of parboiling is the reduced level of breakage during dehulling and milling (Bhattacharya, 1969; Bhattacharya, 2004; Bhattacharya and Subba Rao, 1966a, 1966b; Delcour and Hoseney, 2010a; Mecham et al., 1961), this is only the case when the process is carried out properly. Indeed, the HRY of parboiled rice depends on the parboiling conditions and the resulting changes in physicochemical and mechanical properties. In particular, starch gelatinization and kernel fissuring impact the hardness of parboiled rice. The more homogeneous and compact ultrastructure obtained as a result of starch gelatinization increases the hardness of the rice grains (Bhattacharya, 2004; Biswas and Juliano, 1988; Islam et al., 2002a,b, 2004, 2001; Jagtap et al., 2008; Kimura, 1991; Pillaiyar and Mohandoss, 1981; Raghavendra Rao and Juliano, 1970), while the presence of fissures has the opposite effect (see Section 3.1). In addition, changes such as protein polymerization, amylose–lipid complex formation and amylopectin retrogradation may impact the breakage susceptibility. Furthermore, the response of each rice cultivar to a particular set of processing conditions varies, and, hence also the breakage susceptibility of the resultant parboiled rice. The phenomena of starch gelatinization and fissuring during parboiling and their impact on rice breakage are discussed in detail below.

4.2.1. Starch gelatinization

Both soaking and heating conditions impact the extent of swelling of the starch granules and degree of starch gelatinization. During soaking, the rice grains absorb water, and the starch granules inside the rice grain swell. When the swollen starch granules are heated at or above the starch gelatinization T, their structural order is irreversibly destroyed. The irreversible changes during gelatinization include loss of birefringence and crystallite melting. When only limited water is available, the gelatinization *T* shifts to higher values (Atwell et al., 1988; Delcour and Hoseney, 2010b; Derycke et al., 2005). As the rice grain MC and the severity of heating increase, the degree of starch gelatinization increases up to 100% (Biliaderis et al., 1993; Himmelsbach et al., 2008; Manful et al., 2008; Marshall et al., 1993; Miah et al., 2002a,b; Patindol et al., 2008; Priestley, 1976). However, during soaking, MC gradients exist inside the rice grain. Without equilibration, the MC at the center may be too low for the starch in the center of the rice kernel to gelatinize at the process T. As a result, parboiled rice grains with translucent outer layers and an opaque or white center can be obtained, i.e. the so called “white bellies” (Bhattacharya and Swamy, 1967; Marshall et al., 1993; Mecham et al., 1961; Ong and Blanshard, 1995; Tsang Mui Chung et al., 1990; Velupillai and Verma, 1982). According to some researchers, these “white bellies” are more breakage susceptible (Bhattacharya and Swamy, 1967; Mecham et al., 1961).

Thus, starch granule swelling and the degree of starch gelatinization determine whether air spaces and fissures, present before parboiling or induced during soaking (see Section 4.2.2), remain present in the parboiled rice grain or are sealed upon parboiling. As a consequence, parboiling conditions result in either increased or decreased HRYs (Bhattacharya, 1969; Marshall et al., 1993; Mecham et al., 1961; Miah et al., 2002a,b; Patindol et al., 2008; Priestley, 1976). The degree of starch gelatinization needed to increase HRY is, however, not clearly established. Using differential scanning calorimetry, a degree of starch gelatinization of *ca.* 40% is needed to obtain maximal HRY (Marshall et al., 1993; Miah et al., 2002a,b), whereas, based on amylose/iodine blue values after dispersion in alkali, Priestly (1976) claimed that complete gelatinization is required to improve milling breakage.

4.2.2. Fissuring

Kernel fissuring can impact the hardness of parboiled rice. During soaking and drying, fissures develop as a result of moisture absorption and desorption, respectively. There is no evidence in literature on the formation of fissures during the heating step.

4.2.2.1. Moisture absorption induced fissures during soaking. As mentioned before, moisture absorption during soaking results in MC gradients inside the rice grains. These MC gradients cause stresses in the grain which may result in fissuring (Desikachar and Subrahmanyan, 1961; Genkawa et al., 2011; Juliano et al., 1993; Perez et al., 2011, 2012; Srinivas et al., 1978; Swamy and Bhattacharya, 2009). The water migration and distribution inside rice kernels has been monitored by magnetic resonance imaging (Hong et al., 2009; Horigane et al., 2006). When the induced fissures do not disappear upon heating, the HRY of parboiled rice may be lower than that of its raw counterpart. According to Swamy and Bhattacharya (2009), fissures induced during soaking also seal after prolonged (more than 24 h) soaking due to the swelling of the starch granules.

Srinivas et al. (1978) observed no clear relationship between soaking *T* and the level of fissured rice grains. However, the initial rice grain MC was inversely proportional to the level of fissured rice grains. Genkawa et al. (2011) and Perez et al. (2011, 2012) suggested that, for milled rice, fissuring incidence decreases with increasing soaking *T* (from 15 to 55 °C), which they attributed to the faster decline in MC gradient as a result of the higher hydration rate. The relevance of this work for understanding fissuring of rough rice kernels may be limited because both hull and bran act as an initial barrier to water penetration (Bello et al., 2007; Thakur and Gupta, 2006).

4.2.2.2. Moisture desorption induced fissures during drying. MC gradients during drying of hydrothermally treated rough rice may result in fissure formation during drying. The level of broken rice grains depends on the drying rate (Bhattacharya and Swamy, 1967; Craufurd, 1963; Elbert et al., 2001; Rajkumar et al., 2004; Rao et al., 2007). Drying of hydrothermally treated rough rice differs from that of raw rough rice. Indeed, the MC of the former rice grain at the beginning of drying is higher and its starch granules are partially or completely gelatinized, such that it has less mobile water than raw rough rice. As a result, moisture removal may be easy at the beginning, but becomes more difficult towards the end of drying. In addition, fissures only develop after drying, when the hydrothermally treated rice grains are dried to a MC below the CMC, which ranges between 15% and 20%. It has therefore been suggested to introduce a tempering step to decrease the MC gradients inside the rice kernels before reaching the CMC. In such drying procedure, hydrothermally treated rice grains are dried rapidly to the CMC, as long as they are sufficiently tempered, and thereafter slowly dried to the final MC (Bhattacharya and Swamy, 1967; Elbert et al., 2001; Igathinathane et al., 2008). Tempering of rice immediately after drying can also prevent fissuring during subsequent cooling (Bhattacharya and Swamy, 1967; Velupillai and Verma, 1986).

5. Conclusions

In rice dehulling and milling, the level of broken kernels is largely determined by the intensity of processing and the intrinsic rice grain properties. However, as different methods are used to determine HRY and HRY is influenced by the DOM, it is difficult to correlate literature data. One of the main reasons for rice kernel breakage is the presence of fissures. These develop as a result of MC gradients created during rice grain handling, i.e. cultivation, harvest, drying and storage. Both moisture adsorption and desorption can induce kernel fissuring. However, it is not clear why some rice grains or cultivars are more resistant to fissuring than others even when exposed to the same environmental conditions. Besides fissures, chalkiness, immaturity and kernel dimensions impact HRY.

If parboiling is carried out properly, it can increase HRY of any rice given feedstock. Critical parameters seem to be the extent of starch gelatinization and kernel fissuring. There is, however, still much to be learned on how both phenomena impact HRY.

Although much research has been performed on MC gradients and their significance for rice kernel fissuring, hypotheses are often based on computational predictions and should be further validated. In addition, elaborating on the glass transition concept may contribute to explaining moisture desorption induced fissuring during drying and subsequent cooling of hydrothermally treated rice. Visualisation techniques such as magnetic resonance imaging and X-ray microtomography may be useful for monitoring MC gradients and fissures during the different steps of the parboiling process and to relate this to breakage susceptibility.

From an industrial point of view, maximising the quantity of head rice obtained after milling is a priority. A better understanding of the relationships between chemical composition and physicochemical properties of rice kernels on the one hand, and HRY on the other hand would help plant breeders to develop breeding lines with a decreased susceptibility to breakage. Furthermore, better understanding of the parameters impacting kernel breakage during parboiling, can allow more optimized processing conditions that increase HRY after milling, without compromising the cooking quality of the end product.

Acknowledgements

We thank the Agentschap voor Innovatie door Wetenschap en Technologie in Vlaanderen (IWT, Brussels, Belgium) for financial support. W. De Man (Mars NV, Olen, Belgium) and L. Lamberts are thanked for helpful discussions. K. Brijs acknowledge the Industrial Research Fund (IOF, KU Leuven, Leuven, Belgium), for a position as Industrial Research Manager. This research is also part of the Methusalem program Food for the Future (2007–2014) at the KU Leuven (Leuven, Belgium). J.A. Delcour is W.K. Kellogg Chair in Cereal Science and Nutrition at the KU Leuven.

References

Aboubacar, A., Moldenhauer, K.A.K., McClung, A.M., Beighley, D.H., Hamaker, B.R., 2006. Effect of growth location in the United States on amylose content, amylopectin fine structure, and thermal properties of starches of long grain rice cultivars. Cereal Chemistry 83 (1), 93–98.

Abud-Archila, M., Courtois, F., Bonazzi, C., Bimbenet, J.J., 2000. Processing quality of rough rice during drying - modelling of head rice yield versus moisture gradients and kernel temperature. Journal of Food Engineering 45 (3), 161–169.

Aguerre, R., Suarez, C., Viollaz, P.E., 1986. Effect of drying on the quality of milled rice. Journal of Food Technology 21 (1), 75–80.

Ambardekar, A.A., Siebenmorgen, T.J., Counce, P.A., Lanning, S.B., Mauromoustakos, A., 2011. Impact of field-scale nighttime air temperatures during kernel development on rice milling quality. Field Crops Research 122 (3), 179–185.

Andrews, S.B., Siebenmorgen, T.J., Mauromoustakos, A., 1992. Evaluation of the McGill 2 rice miller. Cereal Chemistry 69 (1), 35–43.

Aquerreta, J., Iguaz, A., Arroqui, C., Virseda, P., 2007. Effect of high temperature intermittent drying and tempering on rough rice quality. Journal of Food Engineering 80 (2), 611–618.

Archer, T.R., Siebenmorgen, T.J., 1995. Milling quality as affected by brown rice temperature. Cereal Chemistry 72 (3), 304–307.

Asaoka, M., Okuno, K., Fuwa, H., 1985. Effect of envirmonmental-temperature at the milky stage on amylose content and fine-structure of amylopectin of waxy and nonwaxy endosperm starches of rice (*Oryza sativa* L.). Agricultural and Biological Chemistry 49 (2), 373–379.

Ashida, K., Iida, S., Yasui, T., 2009. Morphological, physical, and chemical properties of grain and flour from chalky rice mutants. Cereal Chemistry 86 (2), 225–231.

Atwell, W.A., Hood, L.F., Lineback, D.R., Varrianomarston, E., Zobel, H.F., 1988. The terminology and methodology associated with basic starch phenomena. Cereal Foods World 33 (3), 306–311.

Banaszek, M.M., Siebenmorgen, T.J., Sharp, R.N., 1989. Effects of moisture content at milling on head rice yield and degree of milling. Arkansas Farm Research 38 (2), 15.

Bautista, R.C., Siebenmorgan, T.J., Mauromoustakos, A., 2009a. The role of rice individual kernel moisture content distributions at harvest on milling quality. Transactions of the Asabe 52 (5), 1611–1620.

Bautista, R.C., Siebenmorgen, T.J., 2004. Milling quality trends with harvest moisture content and the relationship to individual kernel moisture content distribution. In: Norman, R.J., Meullenet, J.F., Moldenhauer, K.A.K. (Eds.), B.R. Wells Rice Research Studies 2004: Research Series 529, pp. 364–370.

Bautista, R.C., Siebenmorgen, T.J., Cnossen, A.G., 2000a. Characteristics of rice individual kernel moisture content and size distribution at harvest and during drying. In: Proceedings of the 12th International Drying Symposium (IDS2000), Noorderwijkhout, the Netherlands.

Bautista, R.C., Siebenmorgen, T.J., Counce, P.A., 2007. Rice kernel dimensional variability trends. Applied Engineering in Agriculture 23 (2), 207–217.

Bautista, R.C., Siebenmorgen, T.J., Courtin, P.A., 2009b. Rice kernel chalkiness and milling quality relationships of selected cultivars. B.R. Wells Rice Research Studies 2009: Research Series 581, pp. 220–229.

Bautista, R.C., Siebenmorgen, T.J., Nagamine, A., 2000b. Rice kernel properties affecting milling quality at harvest. In: Norman, R.J., Meullenet, J.F., Moldenhauer, K.A.K. (Eds.), B.R. Wells Rice Research Studies 2000: Research Series 485, pp. 238–241.

Bello, M.O., Tolaba, M.P., Suarez, C., 2007. Water absorption and starch gelatinization in whole rice grain during soaking. Lwt-Food Science and Technology 40 (2), 313–318.

Bennett, K.E., Siebenmorgen, T.J., Mauromoustakos, A., 1993. Effects of McGill No. 2 miller settings on surface fat concentration of head rice. Cereal Chemistry 70 (6), 734–739.

Bergman, C.J., Bhattacharya, K.R., Ohtsubo, K., 2004. Rice end-use quality analysis. In: Champagne, E.T. (Ed.), Rice: Chemistry and Technology. third ed. American Association of Cereal Chemists, St. Paul, MN, USA, pp. 415–472.

Bhashyam, M.K., Raju, G.N., Srinivas, T., Naidu, B.S., 1984. Physicochemical studies in relation to cracking properties in rice using isogenic lines. Journal of Food Science and Technology-Mysore 21 (5), 272–277.

Bhashyam, M.K., Srinivas, T., 1984. Varietal difference in the topography of rice grain and its influence on milling quality. Journal of Food Science 49 (2), 393–401.

Bhattacharya, K.R., 1969. Breakage of rice during milling, and effect of parboiling. Cereal Chemistry 46, 478–485.

Bhattacharya, K.R., 2004. Parboiling of rice. In: Champagne, E.T. (Ed.), Rice: Chemistry and Technology, third ed. American Association of Cereal Chemists, St. Paul, MN, USA, pp. 289–348.

Bhattacharya, K.R., Subba Rao, P.V., 1966a. Effect of processing conditions on quality of parboiled rice. Journal of Agricultural and Food Chemistry 14 (5), 476–479.

Bhattacharya, K.R., Subba Rao, P.V., 1966b. Processing conditions and milling yield in parboiling of rice. Journal of Agricultural and Food Chemistry 14 (5), 473–475.

Bhattacharya, K.R., Swamy, I.Y.M., 1967. Conditions of drying parboiled paddy for optimum milling quality. Cereal Chemistry 44, 592–600.

Biliaderis, C.G., Tonogai, J.R., Perez, C.M., Juliano, B.O., 1993. Thermophysical properties of milled rice starch as influenced by variety and parboiling method. Cereal Chemistry 70 (5), 512–516.

Biswas, S.K., Juliano, B.O., 1988. Laboratory parboiling procedures and properties of parboiled rice from varieties differing in starch properties. Cereal Chemistry 65 (5), 417–423.

Bonazzi, C., duPeuty, M.A., Themelin, A., 1997. Influence of drying conditions on the processing quality of rough rice. Drying technology 15 (3–4), 1141–1157.

Bond, N., 2004. Rice milling. In: Champagne, E.T. (Ed.), Rice: Chemistry and Technology, third ed. American Association of Cereal Chemists, St. Paul, MN, USA, pp. 283–300.

Champagne, E.T., Bett-Garber, K.L., Thompson, J., Mutters, R., Grimm, C.C., McClung, A.M., 2005. Effects of drain and harvest dates on rice sensory and physicochemical properties. Cereal Chemistry 82 (4), 369–374.

Champagne, E.T., Wood, D.F., Juliano, B.O., Bechtel, D.B., 2004. The rice grains and its gross composition. In: Champagne, E.T. (Ed.), Rice: Chemistry and Technology, third ed. American Association of Cereal Chemists, St. Paul, MN, USA, pp. 77–107.

Chau, N.N., Kunze, O.R., 1982. Moisture content variations among harvested rice grains. Transactions of the Asae, 1037–1040.

Chen, H., Siebenmorgen, T.J., Marks, B.P., 1997. Relating drying rate constant to head rice yield reduction of long-grain rice. Transactions of the Asae 40 (4), 1133–1139.

Chen, M.H., Bergman, C.J., 2005. Influence of kernel maturity, milling degree, and milling quality on rice bran phytochemical concentrations. Cereal Chemistry 82 (1), 4–8.

Choi, B.M., Lanning, S.B., Siebenmorgen, T.J., 2010. A review of hygroscopic equilibrium studies applied to rice. Transactions of the Asabe 53 (6), 1859–1872.

Cnossen, A.G., Jimenez, M.J., Siebenmorgen, T.J., 2003. Rice fissuring response to high drying and tempering temperatures. Journal of Food Engineering 59 (1), 61–69.

Cnossen, A.G., Siebenmorgan, T.J., Yang, W., Bautista, R.C., 2000. An application of glass transition temperature to explain rice kernel fissure occurrence during the drying process. In: 12th International Drying Symposium (IDS2000), Noordwijkerhout, the Netherlands.

Cnossen, A.G., Siebenmorgen, T.J., 1999. Determining minimum tempering durations while maintaining head rice yield. In: Norman, R.J., Meullenet, J.-F., Moldenhauer, K.A.K. (Eds.), B.R. Wells Rice Research Studies 1999: Research Series 476, pp. 331–339.

Cnossen, A.G., Siebenmorgen, T.J., 2000. The glass transition temperature concept in rice drying and tempering: effect on milling quality. Transactions of the Asae 43 (6), 1661–1667.

Cnossen, A.G., Siebenmorgen, T.J., Yang, W., 2002. The glass transition temperature concept in rice drying and tempering: effect on drying rate. Transactions of the Asae 45 (3), 759–766.

Cooper, N.T.W., Siebenmorgen, T.J., 2007. Correcting head rice yield for surface lipid content (degree of milling) variation. Cereal Chemistry 84 (1), 88–91.

Cooper, N.T.W., Siebenmorgen, T.J., Counce, P.A., 2008. Effects of nighttime temperature during kernel development on rice physicochemical properties. Cereal Chemistry 85 (3), 276–282.

Cooper, N.T.W., Siebenmorgen, T.J., Counce, P.A., Meullenet, J.F., 2006. Explaining rice milling quality variation using historical weather data analysis. Cereal Chemistry 83 (4), 447–450.

Counce, P.A., Bryant, R.J., Bergman, C.J., Bautista, R.C., Wang, Y.J., Siebenmorgen, T.J., Moldenhauer, K.A.K., Meullenet, J.F.C., 2005. Rice milling quality, grain dimensions, and starch branching as affected by high night temperatures. Cereal Chemistry 82 (6), 645–648.

Counce, P.A., Keisling, T.C., Mitchell, A.J., 2000. A uniform, objective, and adaptive system for expressing rice development. Crop Science 40 (2), 436–443.

Counce, P.A., Siebenmorgen, T.J., Vories, E.D., Pitts, D.J., 1990. Time of draining and harvest effects on rice grain yield and quality. Journal of Production Agriculture 3 (4), 436–445.

Craufurd, R.Q., 1963. Sorption and desorption in raw and parboiled paddy. Journal of the Science of Food and Agriculture 14 (10), 744–750.

Deepa, C., Singh, V., 2010. Shelling, milling, nutritional and functional properties of selected rice varieties. Oryza 47 (2), 110–117.

del Rosario, A.R., Briones, V.P., Vidal, A.J., Juliano, B.O., 1968. Composition and endosperm structure of developing and mature rice kernel. Cereal Chemistry 45 (3), 225–235.

Delcour, J.A., Hoseney, R.C., 2010a. Rice and oat processing. Principles of Cereal Science and Technology, third ed. AACC International, St. Paul, MN, USA, pp. 149–160.

Delcour, J.A., Hoseney, R.C., 2010b. Starch. Principles of Cereal Science and Technology, third ed. AACC International, St. Paul, MN, USA, pp. 23–51.

Delcour, J.A., Hoseney, R.C., 2010c. Structure of cereals. Principles of Cereal Science and Technology, third ed. AACC International, St. Paul, MN, USA, pp. 1–22.

Derycke, V., Vandeputte, G.E., Vermeylen, R., De Man, W., Goderis, B., Koch, M.H.J., Delcour, J.A., 2005. Starch gelatinization and amylose-lipid interactions during rice parboiling investigated by temperature resolved wide angle X-ray scattering and differential scanning calorimetry. Journal of Cereal Science 42 (3), 334–343.

Desikachar, H.S.R., Subrahmanyan, V., 1961. The formation of cracks in rice during wetting and its effect on the cooking characteristics of the cereal. Cereal Chemistry 38, 356–364.

Dong, R., Lu, Z., Liu, Z.H., Koide, S., Cao, W., 2010. Effect of drying and tempering on rice fissuring analysed by integrating intra-kernel moisture distribution. Journal of Food Engineering 97, 164–167.

Dong, R.J., Lu, Z.H., Liu, Z.Q., Nishiyama, Y., Cao, W., 2009. Moisture distribution in a rice kernel during tempering drying. Journal of Food Engineering 91 (1), 126–132.

Ece, M.C., Cihan, A., 1993. A liquid diffusion model for drying rough rice. Transactions of the Asae 36 (3), 837–840.

Elbert, G., Tolaba, M.P., Suarez, C., 2001. Effects of drying conditions on head rice yield and browning index of parboiled rice. Journal of Food Engineering 47 (1), 37–41.

Fagade, S.O., Ojo, A.A., 1977. Influence of plant density and nitrogen on yield and milling quality of lowland rice in Nigeria. Experimental Agriculture 13 (1), 17–24.

Fan, J., Siebenmorgen, T.J., Yang, W., 2000. A study of head rice yield reduction of long- and medium-grain rice varieties in relation to various harvest and drying conditions. Transactions of the Asae 43 (6), 1709–1714.

FAO, 2010. Rice market monitor. <http://www.fao.org/docrep/013/am016e/am016e00.pdf> (06.08.12).

Fitzgerald, M.A., Resurreccion, A.P., 2009. Maintaining the yield of edible rice in a warming world. Functional Plant Biology 36 (12), 1037–1045.

Genkawa, T., Tanaka, F., Hamanaka, D., Uchino, T., 2011. Incidence of open crack formation in short-grain polished rice during soaking in water at different temperatures. Journal of Food Engineering 103 (4), 457–463.

Goodman, D.E., Rao, R.M., 1985. Effect of grain type and milled rice kernel hardness on the head rice yields. Journal of Food Science 50 (3), 840–842.

Graves, A.M., Siebenmorgen, T.J., Saleh, M.I., 2009. A comparative study between the McGill #2 laboratory mill and commercial milling systems. Cereal Chemistry 86 (4), 470–476.

Himmelsbach, D.S., Manful, J.T., Coker, R.D., 2008. Changes in rice with variable temperature parboiling: thermal and spectroscopic assessment. Cereal Chemistry 85 (3), 384–390.

Hogan, J.T., Karon, M.L., 1955. Moisture in grain – hygroscopic equilibria of rough rice at elevated tempartures. Journal of Agricultural and Food Chemistry 3 (10), 855–860.

Hong, Y.S., Hong, K.S., Lee, E.S., Cho, J.H., Lee, C., Cheong, C., Lee, C.H., 2009. MR imaging and diffusion studies of soaked rice. Food Research International 42 (2), 237–245.

Horigane, A.K., Takahashi, H., Maruyama, S., Ohtsubo, K., Yoshida, M., 2006. Water penetration into rice grains during soaking observed by gradient echo magnetic resonance imaging. Journal of Cereal Science 44 (3), 307–316.

Hwang, S.-S., Cheng, Y.-C., Chang, C., Lur, H.-S., Lin, T.-T., 2009. Magnetic resonance imaging and analyses of tempering processes in rice kernels. Journal of Cereal Science 50 (1), 36–42.

Igathinathane, C., Chattopadhyay, P.K., Pordesimo, L.O., 2008. Moisture diffusion modeling of parboiled paddy accelerated tempering process with extended application to multi-pass drying simulation. Journal of Food Engineering 88 (2), 239–253.

Iguaz, A., Rodriguez, M., Virseda, P., 2006. Influence of handling and processing of rough rice on fissures and head rice yields. Journal of Food Engineering 77 (4), 803–809.

Islam, M.R., Roy, P., Shimizu, N., Kimura, T., 2002a. Effect of processing conditions on physical properties of parboiled rice. Food Science and Technology Research 8 (2), 106–112.

Islam, M.R., Shimizu, N., Kimura, T., 2001. Quality evaluation of parboiled rice with physical properties. Food Science and Technology Research 7 (1), 57–63.

Islam, M.R., Shimizu, N., Kimura, T., 2002b. Effect of processing conditions on thermal properties of parboiled rice. Food Science and Technology Research 8 (2), 131–136.

Islam, M.R., Shimizu, N., Kimura, T., 2004. Energy requirement in parboiling and its relationship to some important quality indicators. Journal of Food Engineering 63 (4), 433–439.

Jagtap, P.S., Subramanian, R., Singh, V., 2008. Influence of soaking on crushing strength of raw and parboiled rice. International Journal of Food Properties 11 (1), 127–136.

Jia, C.-C., Yang, W., Siebenmorgen, T.J., Bautista, R.C., Cnossen, A.G., 2002. A study of rice fissuring by finite-element simulation of internal stresses combined with high-speed microscopy imaging of fissure appearance. Transactions of the Asae 45 (3), 741–749.

Jindal, V.K., Siebenmorgen, T.J., 1994. Effects of rice kernel thickness on head rice yield reduction due to moisture adsorption. Transactions of the Asae 37 (2), 487–490.

Jodari, F., Linscombe, S.D., 1996. Grain fissuring and milling yields of rice cultivars as influenced by environmental conditions. Crop Science 36 (6), 1496–1502.

Jongkaewwattana, S., Geng, S., 1991. Effect of nitrogen and water managment on panicle development and milling quality of California Rice (*Oryza sativa* L.). Journal of Agronomy and Crop Science 167 (1), 43–52.

Jongkaewwattana, S., Geng, S., 2002. Non-uniformity of grain characteristics and milling quality of california rice (*Oryza sativa* L.) of different maturities. Journal of Agronomy and Crop Science 188 (3), 161–167.

Jongkaewwattana, S., Geng, S., Brandon, D.M., Hill, J.E., 1993a. Effect of nitrogen and harvest grain moisture on head rice yield. Agronomy Journal 85 (6), 1143–1146.

Jongkaewwattana, S., Geng, S., Hill, J.E., Miller, B.C., 1993b. Within-panicle variability of grain filling in rice cultivars with different maturities. Journal of Agronomy and Crop Science 171 (4), 236–242.

Juliano, B.O., Perez, C.M., Cuevasperez, F., 1993. Screening for stable high head rice yields in rough rice. Cereal Chemistry 70 (6), 650–655.

Kachru, R.P., Matthes, R.K., 1976. The behaviour of rough rice in sorption. Journal of Agricultural Engineering Research 21 (4), 405–416.

Kimura, T., 1991. Effects of processing conditions on the hardening characteristics of parboiled grain. Journal of the Society of Agricultural Structures (Japan) 22 (2), 49–54.

Kohlwey, D.E., 1992. The quest for the whole grain in rice milling. Cereal Foods World 37 (8), 633–634.

Kunze, O.R., 1977. Moisture adsorption influences on rice. Journal of Food Process Engineering 1, 167–181.

Kunze, O.R., 1979. Fissuring of the rice grain after heated air drying. Transactions of the Asae 22 (5), 1197–1201.

Kunze, O.R., 2001. Effect of drying on grain quality – moisture readsorption causes fissured grains. Cereal Foods World 46 (1), 16–19.

Kunze, O.R., Calderwood, D.L., 1994. Rough rice drying. In: Juliano, B.O. (Ed.), Rice: Chemistry and Technology, second ed. American Association of Cereal Chemists, St. Paul, MN, USA, pp. 233–263.

Kunze, O.R., Calderwood, D.L., 2004. Rough rice drying – moisture adsorption and desorption. In: Champagne, E.T. (Ed.), Rice: Chemistry and Technology, third ed. American Association of Cereal Chemists, St. Paul, MN, USA, pp. 223–268.

Kunze, O.R., Choudhury, M.S.U., 1972. Moisture adsorption related to tensile-strength of rice. Cereal Chemistry 49 (6), 684–696.

Kunze, O.R., Lan, Y., Wratten, F.T., 2004. Physical and mechanical properties of rice. In: Champagne, E.T. (Ed.), Rice: Chemistry and Technology, third ed. American Association of Cereal Chemists, St. Paul, MN, USA, pp. 191–221.

Kunze, O.R., Peralta, E.K., Turner, F.T., 1988. Fissured rice related to grain moisture, weather and fertilization rates. International winter meeting of the American Society of Agricultural Engineers, Chicago, IL, USA.

Lanning, S.B., Siebenmorgen, T.J., Ambardekar, A.A., Counce, P.A., Bryant, R.J., 2012. Effects of nighttime air temperature during kernel development of field-grown rice on physicochemical and functional properties. Cereal Chemistry 89 (3), 168–175.

Lanning, S.B., Siebenmorgen, T.J., Counce, P.A., Ambardekar, A.A., Mauromoustakos, A., 2011. Extreme nighttime air temperatures in 2010 impact rice chalkiness and milling quality. Field Crops Research 124 (1), 132–136.

Leesawatwong, M., Jamjod, S., Kuo, J., Dell, B., Rerkasem, B., 2005. Nitrogen fertilizer increases seed protein and milling quality of rice. Cereal Chemistry 82 (5), 588–593.

Li, C.Y., Liu, J.T., Chen, L.N., 2003. The moisture distribution of high moisture content rough rice during harvesting, storage, and drying. Drying Technology 21 (6), 1115–1125.

Li, Y.B., Cao, C.W., Yu, Q.L., Zhong, Q.X., 1999. Study on rough rice fissuring during intermittent drying. Drying Technology 17 (9), 1779–1793.

Liang, H., Li, Z., Tsuji, K., Nakano, K., Nout, M.R., Hamer, R.J., 2008. Milling characteristics and distribution of phytic acid and zinc in long-, medium- and short-grain rice. Journal of Cereal Science 48 (1), 83–91.

Lin, C.J., Li, C.Y., Lin, S.K., Yang, F.H., Huang, J.J., Liu, Y.H., Lur, H.S., 2010. Influence of high temperature during grain filling on the accumulation of storage proteins and grain quality in rice (*Oryza sativa* L.). Journal of Agricultural and Food Chemistry 58 (19), 10545–10552.

Lisle, A.J., Martin, M., Fitzgerald, M.A., 2000. Chalky and translucent rice grains differ in starch composition and structure and cooking properties. Cereal Chemistry 77 (5), 627–632.

Lloyd, B.J., Siebenmorgen, T.J., 1999. Environmental conditions causing milled rice kernel breakage in medium-grain varieties. Cereal Chemistry 76 (3), 426–427.

Lu, R., Siebenmorgen, T.J., 1995. Correlation of head rice yield to selected physical and mechanical properties of rice kernels. Transactions of the Asae 38 (3), 889–894.

Manful, J.T., Grimm, C.C., Gayin, J., Coker, R.D., 2008. Effect of variable parboiling on crystallinity of rice samples. Cereal Chemistry 85 (1), 92–95.

Marshall, W.E., Wadsworth, J.I., Verma, L.R., Velupillai, L., 1993. Determining the degree of gelatinization in parboiled rice: comparison of a subjective and an objective method. Cereal Chemistry 70 (2), 226–230.

Matthews, J., Abadie, T.-J., Deobald, H.J., Freeman, C.C., 1970. Relation between head rice yields and defective kernels in rough rice. Rice Journal 73, 6–12.

Matthews, J., Spadaro, J.J., 1975. Rice breakage during combine harvesting. Rice Journal, 59–63.

Matthews, J., Spadaro, J.J., 1976. Breakage of long-grain rice in relation to kernel thickness. Cereal Chemistry 53 (1), 13–19.

Matthews, J., Wadsworth, J.I., Spadaro, J.J., 1981a. Chemical composition of starbonnet variety rice fractionated by rough-rice kernel thickness. Cereal Chemistry 58 (4), 331–334.

Matthews, J., Wadsworth, J.I., Spadaro, J.J., 1981b. Rough rice breakage in relation to kernel thickness for hand-harvested and combine harvested rice. Transactions of the Asae 24 (1), 255–258.

McCauley, G.N., Way, M.O., 2002. Drain and harvest timing affects on rice grain drying and whole-milled grain. Field Crops Research 74 (2–3), 163–172.

Mecham, D.K., Kester, E.B., Pence, J.W., 1961. Parboiling characteristics of California medium grain rice. Food Technology 15 (11), 475–479.

Miah, M.A.K., Haque, A., Douglass, M.P., Clarke, B., 2002a. Parboiling of rice. Part I: Effect of hot soaking time on quality of milled rice. International Journal of Food Science and Technology 37 (5), 527–537.

Miah, M.A.K., Haque, A., Douglass, M.P., Clarke, B., 2002b. Parboiling of rice. Part II: Effect of hot soaking time on the degree of starch gelatinization. International Journal of Food Science and Technology 37 (5), 539–545.

Mossman, A.P., 1986. A review of basic concepts in rice drying research. Critical Reviews in Food Science and Nutrition 25 (1), 49–105.

Nangju, D., Dedatta, S.K., 1970. Effect of time of harvest and nitrogen level on yield and grain breakage in transplanted rice. Agronomy Journal 62 (4), 468–474.

Nguyen, C.N., Kunze, O.R., 1984. Fissures related to post-drying treatments in rough rice. Cereal Chemistry 61 (1), 63–68.

Ondier, G.O., Siebenmorgen, T., Mauromoustakos, A., 2012a. Drying characteristics and milling quality of rough rice dried in a single pass incorporating glass transition principles. Drying Technology 30 (16), 1821–1830.

Ondier, G.O., Siebenmorgen, T.J., Mauromoustakos, A., 2010. Low-temperature, low-relative humidity drying of rough rice. Journal of Food Engineering 100 (3), 545–550.

Ondier, G.O., Siebenmorgen, T.J., Mauromoustakos, A., 2012b. Equilibrium moisture contens of pureline, hybrid, and parboiled rice kernel fractions. Applied Engineering in Agriculture 28 (2), 237–247.

Ong, M.H., Blanshard, J.M.V., 1995. The significance of starch polymorphism in commercially produced parboiled rice. Starch-Starke 47, 7–13.

Patindol, J., Newton, J., Wang, Y.J., 2008. Functional properties as affected by laboratory-scale parboiling of rough rice and brown rice. Journal of Food Science 73 (8), 370–377.

Patindol, J., Wang, Y.J., 2002. Fine structures of starches from long-grain rice cultivars with different functionality. Cereal Chemistry 79 (3), 465–469.

Peng, S.B., Huang, J.L., Sheehy, J.E., Laza, R.C., Visperas, R.M., Zhong, X.H., Centeno, G.S., Khush, G.S., Cassman, K.G., 2004. Rice yields decline with higher night temperature from global warming. Proceedings of the National Academy of Sciences of the United States of America 101 (27), 9971–9975.

Perdon, A., Siebenmorgen, T.J., Mauromoustakos, A., 2000. Glassy state transition and rice drying: development of a brown rice state diagram. Cereal Chemistry 77 (6), 708–713.

Perez, C.M., Juliano, B.O., Liboon, S.P., Alcantara, J.M., Cassman, K.G., 1996. Effects of late nitrogen fertilizer application on head rice yield, protein content, and grain quality of rice. Cereal Chemistry 73 (5), 556–560.

Perez, J.H., Tanaka, F., Uchino, T., 2011. Comparative 3D simulation on water absorption and hygroscopic swelling in japonica rice grains under various isothermal soaking conditions. Food Research International 44 (9), 2615–2623.

Perez, J.H., Tanaka, F., Uchino, T., 2012. Modeling of mass transfer and initiation of hygroscopically induced cracks in rice grains in a thermally controlled soaking condition: with dependency of diffusion coefficient to moisture content and temperature – a 3D finite element approach. Journal of Food Engineering 111 (3), 519–527.

Pillaiyar, P., Mohandoss, R., 1981. Hardness and colour of parboiled rices produced at low and high temperatures. Journal of Food Science and Technology 18, 7–9.

Pominski, J., Wasserman, T., Schultz Jr., E.F., Spadaro, J.J., 1961. Increasing laboratory head and total yields of rough rice by milling at low moisture levels. Rice Journal 64 (10), 11.

Priestley, R.J., 1976. Studies on parboiled rice – Part 2: Quantitative study of the effects of steaming on various properties of parboiled rice. Food Chemistry 1 (2), 139–148.

Proctor, A., Goodman, D.E., 1985. Physicochemical differences between milled whole kernel rice and milled broken rice. Journal of Food Science 50 (4), 922–925.

Qin, G., Siebenmorgen, T.J., 2005. Harvest location and moisture content effects on rice kernel-to-kernel breaking force distributions. Applied Engineering in Agriculture 21 (6), 1011–1016.

Raghavendra Rao, S.N., Juliano, B.O., 1970. Effect of parboiling on some physicochemical properties of rice. Journal of Agricultural and Food Chemistry 18 (2), 289–294.

Raghavendra Rao, S.N., Narayana, M.N., Desikachar, H.S.R., 1967. Studies on some comparative milling properties of raw and parboiled rice. Journal of Food Science Technology 4, 150–155.

Rajkumar, P., Varadharaju, N., Devadas, C.T., 2004. Effect of drying methods on increasing milling yield of parboiled paddy varieties using rubber roll sheller. Journal of Food Science and Technology-Mysore 41 (3), 303–305.

Rao, P.S., Bal, S., Goswami, T.K., 2007. Modelling and optimization of drying variables in thin layer drying of parboiled paddy. Journal of Food Engineering 78 (2), 480–487.

Reid, J.D., Siebenmorgen, T.J., Mauromoustakos, A., 1998. Factors affecting the slope of head rice yield vs. degree of milling. Cereal Chemistry 75 (5), 738–741.

Rhind, D., 1962. The breakage of rice in milling: a review. Tropical Agriculture (Trinidad) 39, 19–28.

Sarker, N.N., Kunze, O.R., Strouboulis, T., 1996. Transient moisture gradients in rough rice mapped with finite element model and related to fissures after heated air drying. Transactions of the Asae 39 (2), 625–631.

Schluterman, D.A., Siebenmorgen, T.J., 2007. Relating rough rice moisture content reduction and tempering duration to head rice yield reduction. Transactions of the Asabe 50 (1), 137–142.

Sharma, A.D., Kunze, O.R., 1982. Post-drying fissure developments in rough rice. Transactions of the Asae 25 (2), 465–468.

Siebenmorgen, T.J., 1994. Role of moisture content in affecting head rice yield. In: Marshall, W.E., Wadsworth, J.I. (Eds.), Rice Science and Technology. Marcel Dekker, New York, NY, USA, pp. 341–380.

Siebenmorgen, T.J., Banaszek, M.M., Kocher, M.F., 1990. Kernel moisture content variation in equilibrated rice samples. Transactions of the Asae 33 (6), 1979–1983.

Siebenmorgen, T.J., Bautista, R.C., Meullenet, J.F., 2006. Predicting rice physicochemical properties using thickness fraction properties. Cereal Chemistry 83 (3), 275–283.

Siebenmorgen, T.J., Counce, P.A., Lu, R., Kocher, M.F., 1992. Correlation of head rice yield with individual kernel moisture content distribution at harvest. Transactions of the Asae 35 (6), 1879–1884.

Siebenmorgen, T.J., Jindal, V.K., 1986. Effects of moisture adsorption on the head rice yields of long-grain rough rice. Transactions of the Asae 29 (6), 1767–1771.

Siebenmorgen, T.J., Meullenet, J.F., 2004. Impact of drying, storage and milling on rice quality and functionality. In: Champagne, E.T. (Ed.), Rice: Chemistry and technology, third ed. American Association of Cereal Chemists, St. Paul, Minnesota, USA, pp. 301–328.

Siebenmorgen, T.J., Nehus, Z.T., Archer, T.R., 1998a. Milled rice breakage due to environmental conditions. Cereal Chemistry 75 (1), 149–152.

Siebenmorgen, T.J., Perdon, A.A., Chen, X., Mauromoustakos, A., 1998b. Relating rice milling quality changes during adsorption to individual kernel moisture content distribution. Cereal Chemistry 75 (1), 129–136.

Siebenmorgen, T.J., Qin, G., 2005. Relating rice kernel breaking force distributions to milling quality. Transactions of the Asae 48 (1), 223–228.

Siebenmorgen, T.J., Qin, G., Jia, C., 2005. Influence of drying on rice fissure formation rates and mechanical strength distributions. Transactions of the Asae 48 (5), 1835–1841.

Siebenmorgen, T.J., Saleh, M.I., Bautista, R.C., 2009. Milled rice fissure formation kinetics. Transactions of the Asabe 52 (3), 893–900.

Siebenmorgen, T.J., Yang, W., Sun, Z., 2004. Glass transition temperature of rice kernels determined by dynamic mechanical thermal analysis. Transactions of the Asae 47 (3), 835–839.

Singh, N., Sodhi, N.S., Kaur, M., Saxena, S.K., 2003. Physico-chemical, morphological, thermal, cooking and textural properties of chalky and translucent rice kernels. Food Chemistry 82 (3), 433–439.

Smith, W.D., Mc Crea, W., 1951. Where breakage occurs in the milling of rice. Rice Journal 54 (2), 14–15.

Srinivas, T., Bhashyam, M.K., Mahadevappa, M., Desikachar, H.S.R., 1977. Varietal differences in crack formation due to weathering and wetting stress in rice. Indian Journal of Agricultural Sciences 47 (1), 27–31.

Srinivas, T., Bhashyam, M.K., Mune Gowda, M.K., Desikachar, H.S.R., 1978. Factors affecting crack formation in rice varieties during wetting and field stresses. Indian Journal of Agricultural Sciences 48 (7), 424–432.

Steffe, J.F., Singh, R.P., Bakshi, A.S., 1979. Influence of tempering time and cooling on rice milling yields and moisture removal. Transactions of the Asae 22 (5), 1214–1218.

Stermer, R.A., 1968. Environmental conditions and stress cracks in milled rice. Cereal Chemistry 45 (4), 365–373.

Sun, H., Siebenmorgen, T.J., 1993. Milling characteristics of various rough kernel thickness fractions. Cereal Chemistry 70 (6), 727–733.

Suzuki, Y., Sano, Y., Ishikawa, T., Sasaki, T., Matsukura, U., Hirano, H.Y., 2003. Starch characteristics of the rice mutant du2-2 Taichung 65 highly affected by environmental temperatures during seed development. Cereal Chemistry 80 (2), 184–187.

Swamy, Y.M.I., Bhattacharya, K.R., 1979. Breakage of rice during milling: effect of kernel defects and grain dimensions. Journal of Food Process Engineering 3, 29–42.

Swamy, Y.M.I., Bhattacharya, K.R., 1982a. Breakage of rice during milling. 1. Types of cracked and immature grains. Journal of Food Science and Technology-Mysore 19 (3), 106–110.

Swamy, Y.M.I., Bhattacharya, K.R., 1982b. Breakage of rice during milling. 4. Effect of kernel chalkiness. Journal of Food Science and Technology-Mysore 19 (3), 125–126.

Swamy, Y.M.I., Bhattacharya, K.R., 2009. Induction and healing of cracks in rice grain during water-soaking of paddy. Journal of Food Science and Technology-Mysore 46 (2), 136–138.

Takai, H., Barredo, I.R., 1981. Milling characteristics of a friction laboratory rice mill. Journal of Agricultural Engineering Research 26 (5), 441–448.

Tamaki, M., Kurita, S., Toyomaru, M., Itani, T., Tsuchiya, T., Aramaki, I., Okuda, M., 2006. Difference in the physical properties of white-core and non-white-core kernels of the rice varieties for sake brewing is unrelated to starch properties. Plant Production Science 9 (1), 78–82.

Tashiro, T., Wardlaw, I.F., 1991a. The effect of high temperature on kernel dimensions and the type and occurence of kernel damage in rice. Australian Journal of Agricultural Research 42 (3), 485–496.

Tashiro, T., Wardlaw, I.F., 1991b. The effect of high temperature on the accumulation of dry matter, carbon and nitrogen in the kernel of rice. Australian Journal of Plant Physiology 18 (3), 259–265.

Taylor, J.R.N., Duodu, K.G., 2009. Applications of non-wheat testing methods. In: Cauvain, S., Young, L. (Eds.), The ICC Handbook of Cereals, Flour, Dough & Product Testing: Methods and Applications. DEStech Publications, Lancester, PS, USA, pp. 197–235.

ten Have, H., 1967. Research and breeding for mechanical culture in surinam. Centre for Agricultural Publications and Documentation, Wageningen, the Netherlands.

Thakur, A.K., Gupta, A.K., 2006. Water absorption characteristics of paddy, brown rice and husk during soaking. Journal of Food Engineering 75 (2), 252–257.

Tsang Mui Chung, M., Velupillai, L., Verma, L.R., 1990. Soak temperature and equilibrium effect on parboiled rice quality. Applied Engineering in Agriculture 6 (3), 337–339.

USDA, 2005. United States Standards for Rice. Federal Grain Inspection service, Washington, DC, USA.

Velupillai, L., Pandey, J.P., 1990. The impact of fissured rice on mill yields. Cereal Chemistry 67 (2), 118–124.

Velupillai, L., Verma, L.R., 1982. Parboiled rice quality as affected by the level and distribution of moisture after the soaking process. Transactions of the Asae 25 (5), 1450–1456.

Velupillai, L., Verma, L.R., 1986. Drying and tempering effects on parboiled rice quality. Transactions of the Asae 29 (1), 312–319.

Wadsworth, J.I., 1994. Degree of milling. In: Marshall, W.E., Wadsworth, J.I. (Eds.), Rice Science and Technology. Marcel Dekker, New York, NY, USA, pp. 139–176.

Wadsworth, J.I., Matthews, J., Spadaro, J.J., 1979. Physical and physicochemical properties of Starbonnet variety rice fractionated by rough rice kernel thickness. Cereal Chemistry 56 (6), 499–505.

Wadsworth, J.I., Matthews, J., Spadaro, J.J., 1982. Milling performance and quality characteristics of Starbonnet variety rice fractionated by rough rice kernel thickness. Cereal Chemistry 59 (1), 50–54.

Wan, X.Y., Wan, J.M., Weng, J.F., Jiang, L., Bi, J.C., Wang, C.M., Zhai, H.Q., 2005. Stability of QTLs for rice grain dimension and endosperm chalkiness characteristics across eight environments. Theoretical and Applied Genetics 110 (7), 1334–1346.

Wang, Y.J., Wang, L.F., Shephard, D., Wang, F.D., Patindol, J., 2002. Properties and structures of flours and starches from whole, broken, and yellowed rice kernels in a model study. Cereal Chemistry 79 (3), 383–386.

Webb, B.D., Calderwood, D.L., 1977. Relationship of moisture content to degree of milling in rice. Cereal Foods World 22 (9), 484–487.

Yadav, B.K., Jindal, V.K., 2008. Changes in head rice yield and whiteness during milling of rough rice (*Oryza sativa* L.). Journal of Food Engineering 86 (1), 113–121.

Yamakawa, H., Ebitani, T., Terao, T., 2008. Comparison between locations of QTLs for grain chalkiness and genes responsive to high temperature during grain filling on the rice chromosome map. Breeding Science 58 (3), 337–343.

Yamakawa, H., Hirose, T., Kuroda, M., Yamaguchi, T., 2007. Comprehensive expression profiling of rice grain filling-related genes under high temperature using DNA microarray. Plant Physiology 144 (1), 258–277.

Yang, W., Jia, C., 2004. Glass transition mapping inside a rice kernel. Transactions of the Asae 47 (6), 2009–2015.

Yang, W., Jia, C.C., Siebenmorgen, T.J., Howell, T.A., Cnossen, A.G., 2002. Intra-kernel moisture responses of rice to drying and tempering treatments by finite element simulation. Transactions of the Asae 45 (4), 1037–1044.

Yang, W., Jia, C.C., Siebenmorgen, T.J., Pan, Z., Cnossen, A.G., 2003. Relationship of kernel moisture content gradients and glass transition temperatures to head rice yield. Biosystems Engineering 85 (4), 467–476.

Yoshida, S., Hara, T., 1977. Effects of air temperature and light on grain filling of an indica and a japonica rice (*Oryza sativa* L.) under controlled environmental conditions. Soil Science and Plant Nutrition 23 (1), 93–107.

Zhang, Q., Yang, W., Jia, C., 2003. Preservation of head rice yield under high-temperature tempering as explained by the glass transition of rice kernels. Cereal Chemistry 80 (6), 684–688.

Zhang, Q., Yang, W., Sun, Z., 2005. Mechanical properties of sound and fissured rice kernels and their implications for rice breakage. Journal of Food Engineering 68 (1), 65–72.

Zhu, L.J., Dogan, H., Gajula, H., Gu, M.H., Liu, Q.Q., Shi, Y.C., 2012. Study of kernel structure of high-amylose and wild-type rice by X-ray microtomography and SEM. Journal of Cereal Science 55 (1), 1–5.