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Influence of Milling Parameters on Head Rice Recovery: A Review

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A B S T R A C T

Among the major cereals of world, rice tops both in production and consumption. The production has increased manifolds but the losses during the post-harvest needs to be checked. The quality of rice is judged from the head rice yield (HRY). This paper reviews the various studies conducted affecting the head rice yield during the last 6 decades. It gives a detailed outline of various post-harvest processes, milling treatments, factors and latest technologies used in improving quality and production of head rice.

Introduction

Rice is amongst the oldest domesticated grain in the world and its cultivation has been recorded in ancient civilisations. The total rice production sums to 472.25 million tons, China leads in the production of rice (144 million metric tons) followed by India with a total production of 106 million metric tons (FAO, 2014). It is estimated that by 2025, 10 billion people will depend on rice as a main food and demand will reach about 880 Million tons.

Rice is consumed as whole grain, rice flour, rice flakes, puffed rice etc. but amongst them whole rice holds the major share in consumption pattern (IRC, 2002). Among cereals, rice is mainly consumed in the whole form after appropriate processing.

It is estimated that the post-harvest losses range from 15 to 16 percent of the rice crop out of which about 9 per cent of paddy is lost primarily due to use of old and outdated methods of drying and milling, improper and unscientific methods of storage, transport and handling (FAO, 2004).

Out of the total estimated losses in the rice crop (15-16%) are primary due to practice of unscientific old and traditional methods of drying, milling, handling, transportation etc. Whereas two to three per cent losses are reported at the producer level (FAO, 2004).

It has been estimated that total post-harvest losses of paddy at producers' level are about 2.71 per cent of total production.

Milling is defined as removal of husk from the paddy and converting it to edible form. The milled rice without polishing are called brown rice. Once the outer layer (bran) is removed by polishing it is converted to polished rice. The efficiency of polishing is dependent on moisture content, during the harvesting, milling, the milling conditions, type of mill employed etc.

Finally during the milling of paddy, rice is obtained along with number of rice fractions and by products *viz.* rough rice, milled rice, germ, rice brokens, a mixture of bran and husk. Rice quality is a combination of physical and chemical characteristics, which can be divided into four broad interrelated categories:

Processing or milling quality;
Cooking and eating quality;
Appearance quality;
Nutritive quality.

Each category is described by a specific set of criteria that collectively determine the suitability of rice for a specific market or consumer. The head rice yield / whole grain is the most important factor or rice milling and processing industry (Marchezan, 1991). As the cooking quality of broken rice is very poor, the market price with broken grains is much less than that for whole grains (Li *et al.*, 1999). The ultimate goal of the rice industry is to achieve maximum head rice yield (HRY) from the milling process.

The definitions of few terminologies which will be used in the review are given for quick reference (RKMP, 2014):

Rough rice or paddy: Defined as rice in the husk after harvesting.

Husked rice/brown rice: Rice from which only the husk has been removed retaining the bran layers and most of the germ together. Such rice is sometimes reflected to as bran rice even though there are variations having red or white bran coats.

Milled rice: Rice from which husk, germ and bran layers have been removed mechanically.

White Rice/polished rice: When the outer layers of bran are completely removed.

Parboiled rice: Rice, processed by steaming or soaking in hot water, (heating usually by steam) and drying. Parboiled paddy can be milled to various degrees or home produced in the same way as ordinary paddy. It is called as parboiled milled or parboiled hand pounded.

Broken rice: Husked, milled or hand pounded milled rice with grain size between $3/4^{th}$ to $1/4^{th}$ size of whole grain.

Head rice yield: Head rice yield is the weight percentage of rough rice that remains as whole rice (three-fourths kernel or greater) after complete milling.

Milling yield/Total yield: Milling yield is the weight percentage of rough rice that remains as milled rice; i.e., the sum of head rice and "brokens"

Effect of parboiling

Parboiling consists of soaking, steaming or hot water boiling followed by drying of the paddy. It increases milling yields, nutritional value and resistance to spoilage by insects and mould. Comparing the nutritional properties of milled and parboiled rice the latter resulted in better retention of nutrients and water soluble minerals due to its solubility and migration of nutrients to the centre. The quality of parboiled rice is assessed by its browning index and head rice (Juliano, 1985;

Pederson *et al.,* 1989; Heinemann *et al.,* 2005).

The quality of parboiled rice is measured as head rice yield and browning index (BI). The effect of air temperature on BI showed that the temperature of 70°C or below yielded parboiled rice of tolerable light yellow color (Elbert *et al.,* 2001). During parboiling the head rice yield varies from 68-74 per cent and yield decreases with the increase in temperature and increases with the increase in tempering time. Tempering period is the stage in which paddy is kept in a closed bin without airflow. After a sufficiently long period of tempering, the moisture profile throughout the paddy becomes uniform. It helps to maintain a uniform moisture profile in the grain, reducing the tensile strength during the first stage of drying. It also reduces the drying time, increases energy efficiency and the head rice yield. The energy efficiency is mainly dependent upon the steaming time and temperature (Li *et al.,* 1999; Steffe, 1979; Zhang and Litchfield, 1991; Soponronnarit *et al.,* 1999). In addition, tempering also reduces the drying time in the final stage, resulting in more effective energy utilisation.

Parboiling temperature and duration had significant influence on the hardness. Parboiling of dehusked paddy by soaking at 70°C for 1.5 h and steaming for 12 min (Abrol, 1983), soaking at 75°C followed by natural cooling (Pillaiyar and Mohandass,1981) soaking at 70–100°C and cooling at room temperature for 2 h followed by open steaming for 20 min (Kar *et al.,* 1999) have been documented. The last method reduced cooking time by 30% and saved 40 % energy. They further reported an increase in hardness of ‘parboiled dehusked rice' samples with the increase in steaming time. A cooking time of 11.6 min was employed which resulted in less sticky rice than raw rice and less hard than traditional parboiled rice (Bello *et al.,* 2004). Steaming of parboiled rice increases the hardness thus increasing the yield of head rice (Islam *et al.,* 2004). Study on reducing the cost of parboiling equipment by precluding the need for large boilers and steaming tanks with elaborate steam distribution systems, in addition to improvements in the quality of the parboiled rice was done by Adhikaritanayaka and Noomhorm (1998).

Recommended soaking temperature for rough rice should be 5°C less than the gelatinization temperature of that particular variety which is 73-86°C for long grain rice (Kimura *et al.,* 1993; Fan *et al.,* 1999). It is followed by steaming for which soaked rice should have about 30–35% moisture content (w.b.) (Bhattacharya, 1985). The activation energies for chroma and total colour difference were 22.1 and 11.1 kJ mol^{-1}, respectively. The colour development due to parboiling was least at low steaming pressure and short times (Somchart *et al.,* 2005).

Effect of Milling

Factors affecting head rice yield

India enjoys a wide range of agro climatic conditions. The climatic conditions with high humidity and temperature have detrimental effect on the milling yield of grains. The increase in temperature during the milling causes the thermal stress due to fluctuation in temperature from 30°C (grain temperature) to 45°C (after milling). This effect is increased manifolds when the ambient temperature varies from 40-50°C in summers. The changes in temperature of the grains have been correlated negatively with HRY.

The efficiency of milling is decided by its HRY and whiteness other than deciding its transaction price which is also dependent on shape, size and cleanliness of the rice

(Conway, 1991). Head rice is capable of fetching two to three times more price than that of broken kernels. A number of studies have been focused on improving milling quality through plant breeding programs, improved cultural practices, optimization of harvesting and drying conditions (Abud *et al.,* 2000; A-Bond *et al.,* 2007; Dong *et al.,* 2003; Gravois, 1998). Delay in harvest has been shown to reduce HRY due to low kernel moisture contents (Sajawan *et al.,* 1990), optimum moisture content for seven US varieties to harvest varied from 16% to 21.5 % (d.b.) to achieve maximum HRY (Jodari and Linscombe, 1996). To reduce the occurrence of fissures and improve the milling characteristics research has been pursued on post-harvest management of rice along with optimising the conditions for harvesting and drying. Increase in the bulk surface temperature of the grain during milling due to abrasion/friction induces thermal stress, leading to crack generation and ultimately results in reduction in head rice yield (Debabandya and Satish, 2004).

The determination of milled rice quality parameters by image processing techniques will enable regular monitoring of milling operation in an objective manner, and thus allowing the operator to quickly react within a few minutes to changes in material properties. Digital image analysis was used to determine the head rice yield (HRY), three-dimensional features (length, projected area perimeter) were recorded from the milled samples. Characteristic Dimension Ratio (CDR) was computed which is defined as the ratio of the sum of a particular dimensional feature of all head rice kernels to that of all kernels comprising head and broken rice in the sample (Yadav and Jindal, 2001). The results showed that two-dimensional imaging of milled rice kernels could be used for making quantitative assessment of HRY and degree of milling for on-line monitoring and better control of the rice milling operation. Quality parameters like whiteness and HRY should be estimated from two dimensional image while the correlation mean gray level have been reported with the lipid concentration on the surface of rice kernels (Fant *et al.,* 1994). It was hypothesized that the overall whiteness of milled rice could be estimated simply from the mean value of the gray level distribution obtained from the digitized image of the bulk sample. Digital image analysis has been used to estimate the area of the bran layer on the surface of rice kernels and correlated with the surface lipids concentration determined by chemical analysis (Liu *et al.,* 1998).

Milling experiments were conducted by certain modifications in vertical mill plant where the optimal conditions were 15% moisture content, shaft speed of 900 min^{-1}, emery stones of mesh size no. 50, zero outlet resistance and milling rate of 2·3 t h^{-1} (Yan *et al.,* 2005). The optimisation was based on the embryo adherence ratio, broken rice ratio, and whiteness of milled rice. White embryo rice is white rice with embryo, having valuable nutrients and fibre. The factors affecting the adherence of rice embryo include mill characteristics (Koh, 1993; Hosokawa *et al.,* 1995).

Effect of degree of milling (DOM) on rice quality

The DOM of rice was cultivar dependent (Siebenmorgen *et al.,* 2006). Most of the physical properties significantly affected DOM. Researchers have co-related the length and aspect ratio positively with DOM while the width, thickness and sphericity and bulk density showed negative co-relation with DOM (Sun and Siebenmorgen, 1993; Prom-u-Thai *et al.,* 2007b). Surface area and true density had non-significant effect on the DOM at all milling stages (0-100s) (Liang *et al.,* 2008). DOM affected the nutritional quality of milled rice grains. Previous studies have reported loss of selenium (Kunlun *et al.*, 2009), loss of protein (28.6%), total minerals (84.7%) (Lamberts *et al.*, 2007), iron (24-84%) (Prom-u-Thai *et al.*, 2007a) with DOM.

Effect of drying and tempering on milling of rice

High yield of brokens is the major problems of the rice industry. The breakage of kernels during milling is caused due to stress cracks (fissures). Major factors responsible for fissuring are rice variety, management of post-harvest operations and drying conditions which include drying methodology and operating conditions (Ban, 1971; Bautista *et al.*, 2000; Kunze, 1979; Kunze and Choudhury, 1972; Nguyen and Kunze, 1984; Sharma and Kunze, 1982; Cnossen and Siebenmorgen, 2000). The proportion of fissured kernels increases with the temperature and the evaporating capacity of the air (Bonazzi *et al.*, 1997).

It is important to understand the changes caused during post-harvest handling of grains leading to formation of fissures to control and optimize drying conditions for maximizing milling quality. Fissures are caused due to rapid adsorption and desorption moisture during post handling operations (Kunze and Choudhury, 1972; Cnossen *et al.*, 2003). During drying, the moisture evaporates from the surface of the grain which is followed by the diffusion of the moisture from the centre of the grain to the surface (Li *et al.*, 1999).This causes compressive force in the outer layer and tensile force in the inner portion. When the compressive stresses at the grain surface exceed the tensile strength of its interior, the kernel will be fissured. A grain with a fissure is likely to break when the kernel is milled (Sharma and Kunze, 1982).

The quality of rough rice can be damaged if air with high evaporative capacity is used for drying, function of temperature and RH (Bonazzi *et al.*, 1997). High drying temperatures, up to 80 °C, can be used without affecting the processing quality of the rice provided that the RH of the air is high (Abud *et al.*, 2000).

Post-drying tempering at high temperature (60°C) resulted in greater moisture removals and drying time reductions up to 38% can be achieved. Percentage of fissured kernels was drastically reduced when drying was performed in two or three steps compared to drying in one step. Tempering at high temperature reduced the percentage of fissured kernels and enhanced HRY (Head Rice Yield). For attaining a moisture removal of six points without affecting the rough rice quality, drying in two stages with the post drying tempering period of 60°C gave the best results along with energy saving (Aquerreta *et al.*, 2007).

A number of drying methods were applied to study the effects of drying conditions on par-boiled rice viz. hot air drying, sun drying, super-heated steam, fluidised bed drying and vacuum drying. The drying temperature has a negative effect while the tempering time has a positive effect on HRY (Elbert *et al.*, 2001). The browning index was mainly affected by the temperature of the air used for drying. It was recorded that pre-steaming time increased the HRY, degree of gelatinisation and pasting properties and decreased the white belly of partially par-boiled rice (Thanit *et al.*, 2009).

Sutherland and Ghaly (1992), applied hot-air fluidization technique on paddy which comprised of soaking (80°C for 5 h), pre-steaming (102°C for 70 s), drying using fluidization technique with hot-air (140 °C for 2 min), tempering (30 min) followed by ventilating at ambient air temperature until the final moisture content reached approximately 14–16% d.b. While studying the feasibility of paddy drying using hot-air fluidized bed it was found that the head rice yield was related to the final moisture content. An increase in the initial moisture content leads to increase in the head rice yield. The development of stresses inside the kernel due to rapid drop of moisture content in fluidized bed drying causes the reduction of head rice yield affecting the rice quality and low commercial value (Soponronnarit and Prachayawarakorn, 1994). To maximize the full kernel yield, the tempering stage was recommended after the first stage of drying for reducing moistures stresses (Steffe, 1979; Soponronnarit *et al.,* 1999; Cnossen *et al.,* 2003). Partial gelatinization was caused in pre-steamed rice which increases the strength of the grain thereby increasing its hardness as compared to that of the reference rice (Kato *et al.,* 1983).

Superheated-steam drying has many plus points such as high drying rate and deodorization of products (Iyota *et al.,* 2002). The moisture content after first-stage drying and tempering have a dominant effect on head-rice yield and operating time in reducing high-moisture contents to a safe level. It was suggested that steaming at 150°C for the first stage and the moisture content after first-stage drying should be not lower than 22.5% dry basis, with subsequent tempering for at least 25 minutes (Somchart *et al.,* 2005).

A higher intermittent ratio or lower unit drying time caused lower percentage of fissured rice (Li *et al.,* 1999). The kernels did not fissure immediately after drying so method could be developed to prevent h the formation of fissures (Bautista *et al.,* 2000). Tempering at temperature 45°C reduced the fissured kernel by 25 % in comparison to storage at low temperatures (Nguyen and Kunze, 1984), tempering at 50°C reduced fissuring incidence by 32 to 50% compared to tempering at 20°C (Renjie *et al.,* 2009), tempering at even higher temperature (60°C) permitted faster drying time without affecting the rice quality (Cnossen and Siebenmorgen, 2000; Cnossen *et al.,* 2003). Rate of open crack formation increased with decreasing the soaking temperature. Water diffusion into rice grains should be accelerated to prevent the formation of open cracks (Takuma *et al.,* 2011). The effect of far-infrared (FIR) irradiation on drying and milling quality of paddy revealed that critical moisture content after the fluidized bed drying was around 23% d.b. whereas incorporating with the FIR irradiation could continuously reduce the moisture content to 21% d.b. without affecting paddy head rice yield and whiteness (Naret *et al.,* 2004).

Rice fissuring problem is more prevalent in drying with heated air at 60°C (Kunze, 1979; Sharma and Kunze, 1982). Fissuring in the kernels is caused due to the stresses developed due to moisture and temperature gradients developed during drying. After drying the causative factors are drying rate and storage relative humidity, where the percentage of fissured kernels increased with the increase in drying temperatures (Siebenmorgen *et al.,* 2006; Kunze, 1979; Nguyen and Kunze, 1984; Sharma and Kunze, 1982; Yang *et al.,* 2002). Tempering allows moisture diffusion from the interior to the external surface of the grain kernels to decrease the moisture gradients and then reduces the rice fissuring (Iguaz *et al.,* 2006; Schluterman and Siebenmorgen, 2007).

Proper tempering with high temperatures can reduce the kernel fissuring in severe drying conditions and enhance the HRY independently of the number of drying steps involved (Aquerreta *et al.,* 2007; Perdon *et al.,* 2007). The number of fissured kernels reduced by about 25% for rice (variety Brazos) dried and stored at 60°C and 45°C respectively compared to that stored at 10°C (Nguyen and Kunze, 1984).

Aqueretta *et al.,* 2007 reported that the percentage of fissured kernels was reduced and HRY enhanced on tempering at higher temperature irrespective of the number of drying steps. A hypothesis was developed by Sharma and Kunz, 1982 to explain rice kernel fissuring during drying and tempering by incorporating the glass transition temperature concept. It is considered that the state transition of starch occurred in the temperature range typically used in rice drying and tempering processes plays an important role in rice kernel fissuring (Perdon *et al.*, 2000; Siebenmorgan *et al.*, 2004). The differences in amylose and protein contents affected the thermal properties due to their influence on the degree of crystallinity (Perdon *et al.*, 2000).

Fissured kernels are found both in artificial as well as natural drying in the field after harvest (Kunze and Calderwood, 1985). Moisture gradients developed in the rice kernels during drying cause differential stress inside the kernel and are a reason for later fissuring (Kunze, 1979). The number of fissured kernels can be reduced by doing intermittent drying, with tempering periods inserted between drying cycles as tempering shortens the total in-dryer time and helps prevent rice fissuring and breakage, giving a decrease of 20% in fissures compared to continuous drying by equalising the moisture concentration trends and decreasing the size of moisture gradients (Li *et al.*, 1999; Iguaz *et al.*, 2006).

Modulus of elasticity, bending strength, and fracture energy of the sound brown rice kernels increased with longer drying. Mechanical properties measured on the sound kernels at different drying durations would not be affected by the loss of the sound kernels to fissured or broken kernels (Zhang *et al.*, 2005). The finite element simulation studies of internal stresses of rice by Jia *et al.*, 2002 revealed that tensile stresses showed a sharp increase in the beginning of drying, peaked shortly after drying, and then dropped gradually thereafter. For understanding the fissuring problem it is pertinent to know the mechanical properties of rice kernels which include the tensile strength (Kunze and Choudhury, 1976; Arora *et al.*, 1973), compressive strength (Prasad and Gupta, 1973) and bending strength (Nguyen and Kunze, 1984; Bamrungwong *et al.*, 1987; Chattopadhyay *et al.*, 1979; Lu and Siebenmorgen, 1995). Fissures might develop in rice kernels during or after the drying process if the tempering is omitted after drying when the rice kernels go from rubbery to glassy transition state. Tempering has been shown to be an effective way to preserve HRY that would otherwise be reduced for an extended drying duration (Cnossen and Siebenmorgen, 2000; Steffe and Singh, 1980). Fissures could be initiated and/or propagated during the drying (desorptive) process.

An increase in the temperature and evaporating capacity of air augmented the percentage of fissured kernels whereas intermediate and final tempering improved final rice quality by decreasing the number of fissured kernels and thereby increasing head rice yield (Iguaz *et al*., 2006).

Glass transition temperature of a rice kernel is a function of moisture content. As the kernel temperature passed through its glass transition temperature (T_g) there is a change in expansion coefficient, specific volume and diffusivity of the rice kernel (Perdon, 1999). If tempering after drying is performed under T_g, then a different expansion coefficient is created in the two parts of the kernel, the outer layer is in the glassy state while the centre is still in the rubbery state which cause kernel fissuring Cnossen *et al.,* 2003.

Tempering temperatures of 60°C followed high temperatures up to 80°C for drying can save time without diminishing rice quality

(Cnossen *et al.,* 2003; Iguaz *et al.,* 2006). A decrease in the drying temperature and increase in tempering time was found to increase the HRY between 68% and 74% depending on the operating conditions. German *et al.,* 2002 inferred that having a tempering time at 16 % moisture content between a two-steps drying gives satisfactory rice yield with acceptable browning index for drying temperatures of 70°C or below (German *et al.,* 2000).

The removal of large amount of moisture from parboiled rice requires multiple-stage drying interspersed with as it promotes moisture equilibration in rice and considerably reduces breakage during milling (Bhattacharya and Swamy, 1967). The moisture content of the grain influences its mechanical properties (Yang *et al.,* 2003; Zoerb, 1958) whereas the grain temperature variation affects the coefficient of thermal expansion and other physical properties (Ekstrom *et al.,* 1966). The greatest MC gradient existed in a direction perpendicular to the long axis of rice kernels and in the middle section of the longitudinal span of a kernel (Chen *et al.,* 1999; Sarker *et al.,* 1996; Yang *et al.,* 2000).

Artificial drying immediately after harvesting is one of the main causes of kernel fissures. Virtually invisible fissures lead to high breakage ratios during milling. Head rice yield is not affected by high drying temperatures if evaporating capacity remains low (Abud *et al.,* 2000). Drying paddy by superheated steam increased the HRY as it promoted starch gelatinization than that which is dried by hot air but the higher degree of Maillard's reaction especially during the first few minutes of drying resulted in lower values of whiteness of paddy. But little difference was noted difference between the percentage of white belly of paddy dried by superheated steam and hot air (Wathanyoo *et al.,* 2004). Higher drying air temperature results in a higher grain temperature and longer tempering time leads to partial gelatinization of starch granules inside paddy affecting the grain qualities in a similar way to parboiled rice (Inprasit and Noomhorm, 2001). Fluidized bed drying parameters affecting the various properties of paddy are moisture content, drying air temperature and bed thickness (Sutherland and Ghaly, 1992).

The rice drying industry employs heated air in different dryer designs. A temperature of 45-78°C is used in column and cross flow dryers whereas some multi stage dryers operate at temperatures as high as 80-200°C. These high temperatures are the main cause of kernel fissuring and breakage during milling (Inprasit and Noomhorm, 2001; Calderwood, 1975; Hogan and Karon, 1955). As high temperature drying establishes a MC gradient between the surface and the centre of the kernel due to evaporation from the outer layers of the kernel (Siebenmorgan *et al.,* 2004). Air with high evaporative capacity is shown to adversely affect the rough rice quality (Bonazzi *et al.,* 1997). Kunze and Calderwood, 1985 inferred that it is the drying rate rather than the drying air temperature which determines the quality of rice.

The MC gradient results in tensile and compressive stresses within the kernel, which if sufficiently large, provoke kernel fissuring and breakage. Tempering thus results in a more uniform moisture distribution within the kernel by facilitating moisture diffusion from the core to the surface (Cihan and Ece, 2001).

Cihen and Ece, 2001 found that a certain amount of moisture can be quickly removed at a higher temperature (60°C) in a rubbery state, or above the glass transition temperature, without significantly lowering the head rice yield. A high heating rate and energy efficiency are achieved by IR radiation heating where (Das *et al.,* 2004b) medium and far IR sources, with wavelengths of 2–100 μm, have been investigated for drying agricultural products (Arinze *et al.,* 1987; Nindo *et al.,* 1995) and maximum absorption of IR radiation by medium grain rough rice occurred at a wavelength of 2.9 μm as reported by Bekki, 1991. Mixing is recommended to achieve uniform heating of the rice in thick bed to overcome the limited penetration capability of IR (Nindo *et al.,* 1995). Rapid cooling using forced air is not conducive as it removes considerable amount of moisture creating significant moisture and temperature gradients causing fissures (Kunze and Choudhury, 1972). The differences in the thermo mechanical properties of the starch at different stages would generate stresses and fissures, resulting in breakage during milling and a lower rice milling quality (Perdon *et al.,* 2007; Siebenmorgan *et al.,* 2004). Therefore, controlled slow cooling will be very important for high temperature rice drying.

Parameters affecting milling quality of rice

Rice kernel breakage during the milling process is affected by different parameters such as paddy harvesting conditions, paddy drying, physical properties of paddy kernels, environmental conditions, and type and quality of milling system components. Increase in the removal of bran layer is directly correlated with the kernel whiteness (Champagne *et al.,* 1996; Park *et al.,* 2001). Rice breakage was mostly due to mechanical stresses rather than thermal stresses (Matthews *et al.,* 1970). The moisture of paddy has a significant effect on the milling system yield which showed an increase by 0.7-3% on 1% reduction of paddy moisture in the range of 10-14% (Pominski *et al.,* 1961). The least rice breakage was achieved on milling paddy at a moisture content of 12-14 % (w.b.) using three abrasive whiteners in series and one friction whitener as polisher (Afzalinia *et al.,* 2002). The method of harvesting also influenced the rice breakage during milling when the breakage was 5% more of sample harvested by combine rather than that which were manually harvested.

Paddy moisture content for milling process of 12 to 14% wet basis (w.b.) and using three abrasive whiteners in series and one friction whitener as a polisher had the least rice breakage (Afzalinia *et al.,* 2002). Paddy moisture content had significant effect on milling system yield so that for 1% reduction of paddy moisture in the range of 10 to 14%, performance of milling system increased by 0.7 to 3% (Pominski *et al.,* 1961).

On evaluated the effect of harvesting method on rice breakage during the milling process it was found that rice breakage of samples that had been harvested by combine was 5% more than that of the manually harvested samples (Matthews and Spadaro, 1975). Moreover, rice breakage during the milling process increased with the decreasing kernel diameter (Matthews and Spadaro, 1976) and also with the increasing paddy moisture content in the range of 12 to 16% (Dilday, 1987). To have a high quality milling process with reasonable rice breakage, paddy must be harvested at the optimum moisture content and at the suitable stage of maturity (Luh, 1991).

Long and tiny rice kernels were more susceptible to breakage during the milling process (Clement and Seguy, 1994). Paddy drying conditions affected the rice breakage during the milling process so that rice breakage rapidly increased with the decreasing moisture content of paddy drying air (Peuty *et al.,* 1994). The difference between paddy temperature and milling environment temperature decreased the performance of rice milling system; relative humidity of milling environment had significant effect on milling system yield (Autrey *et al.,* 1995).

Quality as affected by rice grain properties

The inherent properties of rice and grain determine the quality of the milled rice. The amylose content in endosperm of non-waxy rice is reduced by an increase in the environment temperature (Asaoka *et al.,* 1985). Amylose content has positive correlation with textural properties and solid loss in gruel leading to hard texture and less cooking time (Singh *et al.,* 2005).

The knowledge of the physical and mechanical properties of the agricultural products is of fundamental importance for the correct storage procedure and for design, dimensioning, manufacturing and operating different equipment used in post harvesting main processing operations of these products (Silva and Corrêa, 2000).

All textural parameters showed a significant correlation with each other and had a positive correlation with amylose and negative correlation with cooking time. Amylose content was correlated positively with the solids loss in the gruel and all the textural parameters. The cultivars with high amylose content were observed to have a hard texture and less cooking time (Singh et. al. 2005). The higher environment temperature decreased amylose content in endosperm of non-waxy rice (Asaoka et. al 1985). A study revealed that no significant difference between the tensile strengths along the short and the long axes of the grain was observed, from which it follows that there is no significant anisotropy in the two measured directions (Kamst *et al.,* 1999). The Young's moduli from the diametral compression experiments and from the uniaxial compression measurements are not significantly different.

Thermal conductivity, specific heat and thermal diffusivity are three important thermal properties to the quantitative analysis of a drying process. At temperatures around 53^{o}C, the rice variety Calora incurred a rapid increase in the percentage of broken kernels, and it kernels exhibited a marked increase in the rate of thermal expansion. The thermal conductivity of rough rice increased with increasing moisture content. It was found that the thermal conductivity changed little below and increased considerably above the glass transition temperature (Yang *et al.,* 2003).

An investigation reported that the bulk density of all varieties increases with rice grain processing. This increasing could go up to 51% and the varieties differ statistically among them. In general the specific gravity of the rice grains is not influenced by the processing or by the varieties. The porosity of the bulk rice grains is affected by the processing, being the higher for rough rice and the lower for milled rice. The difference goes up to 26%. The external static and dynamic friction coefficients decrease with processing in all type of wall materials and varieties, the static friction coefficient being more affected by varieties than the dynamic friction coefficient. The higher friction coefficients are from wood surface and the lower ones from steel surface (Corrêa *et al.,* 2007).

Many studies shows that the moisture absorption by rice kernels as well as solid loss during cooking vary among different rice varieties usually characterized by their physicochemical properties such as amylose content, gel consistency, alkali spreading value or gelatinization temperature and protein content. For example, the water uptake rates were inversely related to the amylose content of three rice varieties under a study (Metcalf and Lund 1985). High protein rice required more water and longer time to cook (Husain 1981). High amylose rice has higher capacity to absorb moisture during cooking. The moisture absorption by cooked rice kernels with cooking duration could be best expressed by a modified exponential relationship for all rice varieties. The trends of moisture absorption during cooking were different among selected varieties manifested by their physicochemical properties, namely, amylase content (AC), alkali spreading value (AS), protein content (PC) and gel consistency (GC). Thus, the water uptake of milled rice during cooking in excess water can be predicted from its physicochemical properties (Yadav and Jindal 2007).

Modelling

A model is an intellectual tool which represents an abstract of a system or a process using mathematical concepts and languages. Modelling involves recording observations, its analyses (model fitting) and based on these results, predicting the behaviour of a particular process or parameter in the future. Different models to predict the drying behaviour, water absorption trend etc have been evaluated in rice processing.

A simple modelling framework was devised to study and analyse equilibrium moisture data in foods based on molecular thermodynamics, providing useful physical insight on the nature of the EMC in foods (Vasquez *et al.,* 2011). The favourable results suggested its application for further analysis of EMC in foods.

A useful mathematical model to develop a re-wetting method for brown rice by using film packaging technique, design was established. Packaging of rice with polymeric film mainly aimed at inhibiting change in moisture content of the rice was established. The proposed model was based on the water vapour balance in the film package containing brown rice. The predicted RH and rice moisture content inside a package were in close association with experimental readings of re-wetting experiments (Genkawa *et al.,* 2008).

Tanakaa *et al.,* 2010 developed a mathematical model to predict a moisture content profile during the thick layer re-wetting process of brown rice unpackaged and packaged with low density polyethylene (LDPE) and polybutylene terephthalate (PBT) films. It was concluded that the proposed re-wetting model could successfully describe the thick layer re-wetting of brown rice under the experimental conditions.

Courtois *et al.,* 2001 concluded that the rice kernel is modelled as a two water compartment system and as a whole concerning heat and quality. The external transfers are governed by Fick and Fourier laws. The compartmental approach is mainly used to render the internal resistance in the most efficient way on the computer. Results have shown a robust behaviour for such a non-linear system. Soaking is a pre-treatment operation usually done before cooking of milled rice to provide desired softness and texture in the final cooked rice, which plays a vital role in deciding consumer's preference.

The prediction models developed for the drying rate constant using a power law model and an Arrhenius model had higher coefficient of determination 0.94 and 0.94 indicating both the models fit adequately. Drying time was dependent mostly on drying air temperature followed by grain depth and air velocity (Rao *et al.,* 2007).

With increase in air temperature the heat transfer coefficient during convective air drying increased. The milling quality improved with increase in air velocity and decrease in grain bed depth and air temperature. The head yield in convective air drying was mostly affected by grain bed depth followed by drying air temperature. Drying air velocity had little impact on the head yield (Rao *et al.,* 2007).

Cooling the grain until a safe temperature is reached, can inhibit insect and mould activity and minimise the use of chemical treatments. An aeration system can also prevent deterioration by reducing the temperature gradients throughout the grain bulk which may cause moisture migration and pockets of mouldy grain (Metzger *et al.,* 1983). As for the drying process, the proportion of fissured kernels increases with the temperature and the evaporating capacity of the air (Bonazzi *et al.,* 1997; Aguerre *et al.,* 1986). A mathematical model based on dynamic heat and mass balances was developed to stimulate the evolution of grain and air temperature and moisture content in a rough rice storage bin with forced cool air ventilation. The model and parameters used in the model are applicable for temperature prediction purposes. Using the model it is possible to predict the evolution of grain temperature and moisture and the time needed to cool the stored grain under different ventilation conditions (Iguaz *et al.,* 2004). HRY and whiteness could be successfully modelled during milling operation in relation to the physicochemical properties of rice. Reduction in HRY was a power function of the milling duration with R^2 of fitting ranging from 0.974 to 0.997 and root mean square error (RMSE) values of below 1% among the selected varieties (Husain *et al.,* 1987).

Modified GAB model was more appropriated to predict desorption equilibrium moisture content of rough rice for the range of temperatures and water activities studied. Modified Chung–Pfost model and modified Henderson model gave an acceptable fitting, while modified Halsey model and modified Oswin model did not seem appropriate for the description of the desorption moisture isotherms of rough rice at drying temperatures (Iguaz *et al.,* 2006).

In a simulation, the flow restrictions were found in the processes for separating brown rice and for sorting coloured rice and needed an increase in the hourly capacities of the brown rice separator and the rice colour sorter. As the automated rice mill plant was described by the developed model, it could be used for designing and improving rice mill plants. There were no flow restrictions in the processes of destoning, hulling, milling, polishing, but there was a severe flow restriction in the colour sorting process due to high sensitivity and low feed-rate of a colour sorter in the simulation (Chung and Lee, 2003).

To be able to minimize cracks and breakage, a predictive model of the stresses and deformations in the material during drying is necessary. As the fissures in rice kernels are due to a tension failure, the tensile strength must be known to be able to predict the cracking of the grains. It is known that the deformation rate has an influence on the mechanical properties (Chattopadyay and Hamann, 1994).

It is forecasted that the demand of rice is expected to increase to 880 million tons by 2025, and to meet this demand good agricultural and milling practices are needed to minimize the losses in post-harvest management. The post-harvest losses are attributed to a combination of factors during production and post-production operations. Several efforts are being done in order to maintain the grain quality of this crop in its different processing operations. Percentage of HRY is the most important parameter in the milling. The grain behavior is dependent on moisture content during the harvest, drying mechanism, moisture content present during milling, milling conditions i.e. type of mill used, speed, temperature gradient, degree of polishing, variety of paddy, pretreatments given before milling etc. The major problem in milling is of grain breakage thus reducing the HRY, caused due to development of compressive and tensile forces in the grain. These stresses are mainly caused due to the thermal gradient developed during milling. To minimize the temperature gradient, modification in the existing machinery is required. HRY is better in parboiled rice due to gelatinization of starch. Parboiled rice are able to bear the frictional forces to higher value thus yielding better head rice yield but the cost of the machinery affects the economics of operation. Thus, the rice post-harvest system requires improvement in the use of resources for research and development.

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