① **Running title**

Study of Rice Physicothermal Properties

② **Title**

Effect of the Drying Process on the Physical Properties and Cooking Quality of Japonica Aromatic Rice

③ **Author**

Jafar HASHEMI[1], Naoto SHIMIZU[1*], Toshinori KIMURA[2]

④ **Affiliations**

[1]Graduate School of Life and Environmental Sciences, University of Tsukuba, Ibaraki 305-8572, Japan

[2]Graduate School of Agriculture, Hokkaido University Kita-9, Nishi-9, Kita-ku, Sapporo, 060-8589, Japan

⑤ [*] **Telephone and fax number of correspondence author**

Tel & Fax: +81-(0)29-853-7239

E-mail: shimizu@sakura.cc.tsukuba.ac.jp

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Abstract. Rice is a major economic crop in Iran, where it is usually dried using a batch-type dryer until the final moisture content (FMC) reaches below 9%. The influence of low FMC (about 9%) produced by four drying temperatures (30, 40, 50, and 60º C) on the physical properties, milling, and cooking qualities of short grain aromatic rice were investigated. The obtained data were also compared with standard FMC (about12%) treatments which were dried in a batch type dryer. The experimental result showed that for low FMC samples, head rice yield (HRY) was increased by 4% at drying temperatures of 30ºC and 40ºC but was reduced by about 20% at 60°C in comparison with control samples (25°C, 60% RH). The water uptake ratio (WUR) and volume expansion ratio (VER) were decreased significantly as the drying temperatures were increased. We can conclude that low FMC (9%) could produce higher HRY, if the drying temperature is 40°C or less. In addition, high drying temperatures (50°C and 60°C) caused increases in the number of fissured kernels, energy consumption and decreases in HRY, WUR, and VER. Maintaining the HRY and keeping a cooking quality at maximum level are the main task for the optimization of drying process. It was occurred at drying temperature less than 40°C with a low FMC for aromatic rice. Therefore, a drying temperature of more than 40°C would result in deterioration of quality of *japonica* type aromatic rice, followed by low FMC.

Key words: Aromatic rice, Cooking, Drying, Head rice

1. Introduction

Paddy drying is a complex process, which involves simultaneous heat, mass, and momentum transfer through porous media. It is a continuous process in which the temperature of the air and grain, the moisture content (MC) of the grain, and the humidity of the air all change simultaneously [1]. Integrating the effects of moisture and temperature on changes in the properties of rice kernels is important for understanding quality deterioration during the drying process. Some researchers have showed that the physical and thermal properties of long and medium-grain rice are linear functions of MC [2, 3]. Rice kernel MC and temperature during drying will also determine the mechanical properties of the kernels. Temperature and MC gradients within a kernel may generate regions with different mechanical properties for example expansion coefficients or specific volumes, which may create stresses sufficient to fissure the kernel [4], and fissured kernels may break during the milling process and thus reduce the head rice yield (HRY). Arora et al. [5] suggested that in order to increase HRY, the drying air temperature should be held below 53°C, and showed that there is an increase in the number of fissured rice kernels above this transition temperature.

Cooking is a process of heat treatment given the foodstuffs to make them edible and suitable for consumption. It is determined on the basis of the variety and its physicochemical properties. Variations in the behavior of rice during cooking are mainly due to its total amylose content, the degree of milling, the cooking time, the drying temperature, and its final moisture content (FMC) [6-9]. It is a fact that color and cooking characteristics of the milled rice are the important factors deciding the quality that influence the consumer preference and marketability of the rice. At FMC about 12%, the color of rice was transparent, whereas at low FMC, it was opaque (10, 11) which has been preferred by Iranian consumers. The severity of the heat treatment during the drying process greatly affects on the white rice color and cooking quality [8].

In Iran, average rice post-harvest losses are more than 28%, and major losses occur during the drying stages due to the use of inappropriate method and equipments, which regularly involve use of the batch-type dryer [10]. Non-uniformity in MC and over-drying of grains, as often occurs in batch dryers, may affect the physical and thermal properties of rice, increasing the losses and therefore the costs of processing [12]. To overcome the non-uniformity in MC, millers have typically increased the drying temperature and time in order to minimize the differences in MC between layers, which subsequently cause a low grain FMC: about 9% [13]. There are also questions related to whether the low FMCs produced by different drying temperatures has any effect on the physical properties, as well as the milling and cooking quality of rice. Very little information is available about the HRY and cooking quality when the FMC is reduced to less than the standard level for safe storage (at about 12%), because this is not a common practice in countries other than Iran. Changing the color of rice at low FMC might be affected on the cooking quality.

Given this situation, it is worthwhile to investigate the effect of low FMC (at about 9%), drying temperature, and the combination of the two on the physical properties, milling and cooking qualities

of rice and to compare these with those of rice with a standard FMC level (at about 12%). The specific objectives of the present study were to examine the effects of low FMC, produced by different drying temperatures on the: 1) physical properties; in particular temperature distribution, Fissure formation, milling quality, and HRY, 2) cooking quality; such as water uptake ratio (WUR), volume expansion ratio (VER), and solid content (Sc), 3) and compare those results with standard FMC treatments.

2. Materials and Methods

2.1 Materials

Rice of the variety Kaori (aromatic, short-grain), with an average MC of about 26% (all MC values are expressed on a wet basis, unless stated otherwise), was harvested in October 2005 at a plot at the Agriculture Research Farm of the University of Tsukuba in Japan. Immediately after harvest, rice samples were cleaned with a dockage tester (Carter-Day Co., Minneapolis, MN), sealed in polyethylene bags, and then stored at 4°C until required. Before the experiment began, the rough rice was taken from the refrigerator and placed in the laboratory overnight. This was done to allow the grain warm up to the ambient air temperature. Deep-layer drying was performed using the batch-type dryer in the same drying chamber as described by Hashemi et al. [14]. Figure 1 is a schematic diagram showing the batch dryer, a deep bed dryer, and its components as used in this study. Three thermocouple sensors were used at the bottom, middle, and the top, respectively, of the rough rice. Changes in the material temperature during drying were recorded using a data logger. The values reported are the averages of the material temperatures measured during drying in the three layers. In the dryer used, the temperature of the heated air can be controlled to $\pm 1^{o}$C by a sensor controller. Three principal size parameters (length, width and grain thickness) of brown rice were measured manually by using a micrometer with 0.001-mm precision. The average for 20 well-distributed randomly drawn grains was calculated. The measurement was carried out in triplicate and averages were used in calculations. The reference dimensions of brown rice samples of short-bold grain Kaori were a slenderness ratio (length/width) of 1.7 and a grain thickness of 2.12 mm.

2.2 Drying

Arora et al. [5] suggested that the drying air temperature should be held below 53°C to minimize the effect of thermal expansion on rice fissuring while maintaining quality. We considered that a drying temperature of 50°C was optimum (common knowledge) and used other drying temperatures that were lower and higher than this approved level for the present study. The drying time is a function of the FMC of paddy. Trial experiment was done to estimate the drying time to acquire the desired moisture level at every drying temperature. The rough rice sample were weighed every 30 min during the drying process. The experiment was considered finished when the FMC was reached to approximately 12% (a standard FMC for milling and safe storage [15]) and 9% (representing the

low FMC widely used in Iran [13]). Experiments were carried out at four drying temperatures, 30, 40, 50, and 60°C, with different drying times to achieve the standard FMC and the low FMC. Thus there were eight different drying conditions resulting from the combination of four different drying temperatures and two different drying times for each temperature, corresponding to standard and low FMC. For comparison with experimental data, a reference sample was dried in a chamber with controlled temperature (25%) and humidity (60%) (Humidity Cabinet, LHL-113; TABAI Espec Corp., Japan) to achieve a rice equilibrium MC (EMC) of approximately 12.5% [5, 16].

Drying using each set of experimental conditions was replicated, and the mean values are reported here. The initial and final MCs of the rice samples were determined by drying duplicate samples for 72 h in an air-oven set at 105°C [15]. The average drying rate (*dR*, %/h) is calculated based on the initial MC (*Mi*, %), final MC (*Mf*, %), and drying time (*t*, min) as follows;

$$dR = \frac{(M_i - M_f) \times 60}{t} \qquad (1)$$

The number of fissured kernels (F) was assessed before and after the drying treatment. One hundred rice kernels randomly picked from each sample were manually dehulled to avoid mechanical damage to the kernel, and then each kernel was inspected using a grain scope (TX-200; Kett Electric Laboratory, Tokyo, Japan). To determine the breaking force for individual kernels (R), a rigidity test was conducted on each of 20 randomly selected kernels without fissures using a texture analyzer (Texture Analyzer TA-XT2i; Stable Micro Systems, Surrey, UK). The total energy consumption during the drying process was measured with a power meter (Model W-787Y, Namikoshi Elec., Hyogo-ken, Japan). The energy consumption per kg moisture removed (E_m) can be calculated based on the total energy consumption and moisture load of the sample, which has been described previously by Hashemi et al. [14].

2.3 Measuring the milling quality

The milling test was conducted 1 hour after drying ceased, when the sample temperature had dropped. Three hundred grams of dried paddy was weighed and hulled in a rubber roll husker (L-THU-35A; Satake Engineering, Japan) to produce brown rice. The huller was set so that no more than 5% of the sample remained unhulled. Brown rice samples were subsequently weighed and milled with a vertical friction-type milling machine (VP-31T; Yamamoto, Tendu, Japan), for which the pressure and flow rate levers were set to 3 and 4 respectively. Subsequently, milled rice samples were weighed and separated into head rice and broken rice by using an indent cylinder-type rice grader (TRG type; Satake, Japan) for 6 min to remove the broken kernels from the whole grains. The milling quality of the dried rice was evaluated in terms of the HRY, which was defined as the percentage of head rice mass remaining from the original 300-g rough rice sample [17]. The whiteness (W) of the white rice samples was assessed using an automated color meter (CR-20; Konica Minolta Holdings, Tokyo, Japan). The color intensity of the sample was correlated to

chromaticity coordinates, and determined using the same equation used by Kimura [18].

2.4 Cooking quality test

The cooking procedure was divided into the soaking and cooking periods. In the soaking period, 10 g of head rice was placed in a small wire-mesh cylinder (78 mm × 38 mm), which was then placed in a 300-ml beaker with 100 ml distilled water (at room temperature) for 60 min. The optimum soaking and cooking conditions were determined for milled rice by Shimizu et al. [19]. Subsequently, the soaked rice with the remaining water was transferred to a rice cooker (Model SR-03F, 0.3 dm3, 100 V, 200W; National Electric, Osaka, Japan), where the rice simmered in hot water for about 20 min to gelatinize the core of the grains [20]. The cooked rice was drained by gravity and then was transferred to an airtight desiccator for 1 h after cooking until the sample had cooled down. At that time, the moisture of grains near the surface was unrepresentatively low, so these grains were not used for sampling and blotted out.

The cooked rice MC was measured by drying 2 g of cooked rice in an air-oven at 135°C for 2 h [19]. The WUR [21], VER [19], and Sc [22] were measured using the formulae described by Hashemi et al. [14]. The cooking quality measurements were carried out in triplicate per sub-sample and the average values were taken.

2.5 Statistical Analysis

Statistical analysis was performed for a two-factor experiment with a completely randomized design (2f-CRD). The experimental variables included R, E_m, F, HRY, W, WUR, VER, and Sc. The two factors were drying temperature and FMC, with four and two levels, respectively. Differences between the treated samples were determined using the Fisher multiple range test (least significant difference analysis; LSD) at the 5% and 1% probability levels (Table 1). Relationships between different properties were determined using Pearson correlation and are shown in Table 2.

3. Results and Discussion

3.1 Changes in the physical properties

To study the influence of FMC on rice quality, the effect of low and standard FMC on the physical parameters corresponding to drying conditions are discuss in following section.

3.1.1 Moisture desorption and drying rate

A figure 2 shows the relationship between moisture losses and drying time at four different drying temperatures for standard and low FMC. As the drying proceeded, the moisture loss in the rice decreased as heat energy was absorbed, and decreased the drying rate. The FMC and drying temperature had a statistically significant (P<0.01) effect on the drying rate (Table 2). It is assumed

that the high drying rate will be result from high drying temperature and consequently faster transfer of MC from the kernel. With an increase in drying temperature from 30°C to 40°C, 50°C, and 60°C, the percentage reduction in drying time was 47%, 67%, and 72% for the standard FMC (Fig. 2a), and 44%, 67%, and 79% for the low FMC (Fig. 2b) treatments, respectively. It was shown that if the drying temperature increases by 10°C, this would give a 20% reduction in the drying time. At the beginning of the drying process, depending on the drying temperature, the drying rate profiles were at a maximum level. After evaporation of the surface water, the drying rate decreased. The trends in reduction were similar at identical temperatures for the two different FMC. The drying rates of samples dried at the four different temperatures converged.

Comparisons on reduction time between the low and standard FMC treatments have shown that the drying time increased by about 85%, 98%, 65%, and 37% for samples dried to 9% FMC relative to those dried to 12% FMC at the same drying temperatures (30, 40, 50, and 60°C, respectively) (Fig. 2a, 2b). The difference in moisture between the initial and final measurements was 14 and 17 percentage points for the standard and low FMCs, respectively. By lowering the FMC by about 3 percentage points (from about 12% to 9%), the drying time significantly increased. It shows that further reduction MC of samples beyond 12%, at lower MC increases the drying time significantly due to the restricted movement of moisture from the core to the surface of kernel. Irrespective of drying air temperature, the drying time was found to increase significantly with decrease in FMC. Similar trends have been reported by Das et al. [23], who studied the drying characteristics of three varieties of high moisture paddy dried in a batch type dryer.

3.1.2 Rigidity

As shown in Table 3, rigidity was higher for samples dried to the low FMC than those dried to the standard FMC. The average rigidity was approximately 56 N and 84 N for the standard and low FMC treatments, respectively. Much work has been published on kernel rigidity as a factor in such diverse areas as drying and handling [24], kernel appearance and translucency, processing and grain breakage during milling [25, 26], and cooking quality [9, 19]. It can be stated that low FMC samples would have a greater HRY after milling due to their higher rigidity. In the present study, the FMC had a significant (P<0.01) effect on the rigidity of rough rice (Table 1). Nagato et al. [24] found that the hardness at any specified point within the endosperm increases or decreases linearly in accordance with a decrease or increase in its MC, which is consistent with the present results.

3.1.3 Fissured kernels

The trends of progressive increases in the number of fissured kernels with increasing drying temperature for two FMC treatments are illustrated in Fig. 3. The percentage of fissured kernels increased with increases in drying temperature for both FMC treatments: from 4% (30°C) to 22% (60°C) for the standard FMC and from 2% (30°C) to 30% (60°C) the low FMC. The highest

percentage of fissured kernels was found with the low FMC treatment and the highest temperature. The initial percentage of fissured kernels was 2%. Many factors might affect the formation of fissures in the kernels, including drying air temperature, initial MC, final MC, kernel thickness, and tempering conditions. Kunze and Choudhury [25] reported that improper drying conditions can be a major cause of fissuring. Theories explaining fissure creation are based on the reaction of rice when subjected to tensile and comprehensive stresses due to the existence of a moisture gradient within the kernel [25, 27, 5]. A high drying temperature caused increases in the moisture gradients within kernels, and subsequently caused shrinking within the rice kernel, which can result in increases in the grain stresses and then an increase in the percentage of fissured kernels. Kunz [28] found that fissure formation is caused by a moisture gradient created during fast drying. As described above, it should be pointed out that the maximum fissure rate occurred at the 60°C drying temperature, followed by the 50°C, 40°C, and then the 30°C drying temperatures for both FMCs. This result was consistent with those of previous studies [25, 29]. As is evident from Fig. 3, the amount of fissured kernels in the 30°C, low FMC treatment was lower than that at the same temperature for the standard FMC treatment. This might be due to the longer drying time, which eliminated kernel stress induced by moisture gradients. This state is similar to that which occurs during the tempering process, which is effective in preserving HRY.

Drying temperature had a major effect (P<0.01) on fissure formation, and FMC also had an effect, albeit smaller. The amounts of fissured kernels found in the present study were higher than those reported by other researchers [29-31]. Fan et al. [31] reported that the HRY reduction for Bengal, medium-grain rice, was greater under the same drying conditions than the HRY reduction for cypress, long-grain rice that is more slender than Bengal. In the present study, the average thickness of the Kaori grains was 2.12 mm, which was about 35% more than the variety thickness used by Siebmorgen et al. [29]. This thickness would have allowed a high moisture gradient to develop, and would have made the grain more susceptible to fissuring, especially at high drying temperatures. This finding emphasizes the fact that the thickness of kernels should be considered during the drying and post-drying processes, especially under severe drying conditions.

3.1.4 Energy consumption

The details of energy consumption per unit of moisture removed for all treatments are shown in Table 3. The E_m for the low FMC was higher than that of standard FMC. With an increase in drying temperature from 30°C to 60°C, the E_m increased from 15.8 to 18.3 kWh/kg-water for standard FMC and decreased from 32 to 23 kWh/kg-water for low FMC treatments. The long drying time required for a low FMC may have caused this reduction as compared with the standard FMC. Obviously, as found in previous studies, reduction of MC to the standard FMC is quicker than to the low FMC [12]. Drying temperature and FMC level had a significant (P<0.05 and 0.01) effect on the E_m (Table 1), but the interaction of temperature and FMC was significant only at low FMC. This signifies that

when the final MC is reduced by 12%, the E_m could not differ at indicated temperature. Increasing the drying temperature has considerable effect on the reduction of energy and depreciation of the equipments. But the effect of heating duration in particular at high temperature on the rice quality deterioration should be considered. Heating duration is one of the major parameter which has been affected on the rice properties during the drying process. Heating duration was closely related with diffusion of heat and moisture in the grain [17]. At low temperature, the longer heating duration not only has not negative effect on the quality of rice but also gradually decrease the moisture gradient. Therefore, low FMC samples, which was dried at 40°C or less drying temperature has longer heating duration with minimum effect on the physical properties. It is because of elimination of stress-strain which produced by moisture gradient. As shows in Figs. 2, the heating duration were decreased with increase of drying temperature at identical FMC. It might be resulted in higher fissured kernels which subsequently deteriorate the physicochemical quality of rice.

3.2 Milling quality

Milling quality is based on the HRY, because this is the product of greatest economic value, being twice as valuable as broken kernels. Fig. 4 shows the HRYs for samples dried at different drying temperatures and for the control sample, when FMC was set at standard and low levels, respectively. The amount of reduction in HRY varied with FMC and drying temperature. It can be seen that the HRY decreased with increases in drying temperature. Compared with the control sample, the reduction in HRY was 3.8, 5.4, 11, and 18% at 30°C, 40°C, 50°C, and 60°C drying temperatures, respectively, for the standard FMC treatments. The HRY for the low FMC treatments increased by about 4% at the 30°C and 40°C drying temperatures, and then was reduced by about 0.5% and 19% at the 50°C and 60°C drying temperatures, respectively. The maximum and minimum values corresponded to the low FMC treatments. The HRYs for the low FMC samples that were dried at 30°C and 40°C were a little higher than the corresponding samples for the standard FMC treatments. This indicates that the HRY significantly depends on drying temperature at a low FMC. The reduction of HRY is related to rigidity, thickness, and viscoelasticity of the rice kernels which are discussed as follows. As shown in Table 3, rigidity has a negative relationship with FMC. The HRY should be increased for those samples with low FMC that dried at low drying temperatures, because the rigidity of the sample was significantly increased. HRY decreases at high temperatures due to increases in the number of fissured kernels. It should be noted that the stronger rigidity may not always improve HRY. This can be noticed easily in the case of paddy dried to low FMC at 60°C.

Kernel thickness is a significant factor affecting kernel fissuring and HRY reduction, with thicker kernels being more susceptible to fissuring than thin kernels. Jindal and Siebenmorgen [30] noted that a greater HRY reduction can be attributed to a greater thickness of kernels. Short-grain rice is generally known for its high strength and stable milling qualities compared with long-grain rice, but in severe drying conditions, reduction in HRY is correlated with the thickness of the grain.

The observed increases in the HRY at a low drying temperature could be also interpreted in terms of the viscoelasticity of rice kernels in conjunction with glass transition effects. The HRY will decrease due to the development of strains induced by the internal stresses that develop during the drying process. Strains have two components related to the viscoelasticity of kernels: the elastic (rubbery) component, which subsides as soon as the MC gradient declines, and the viscous (sticky) component, which is effectively eliminated with drying for an appropriate length of time at the appropriate tempering temperature [29]. As the drying process proceeds, if the surface moisture evaporates faster, the moisture gradient is increased afterwards. Low FMC achieved by a low drying temperature would allow adequate time to eliminate the majority of MC gradients and accordingly the elastic component of strains in rice kernels, because the creation of internal stresses is related to glass transition effects inside the kernel when the MC gradient increases [17]. Therefore, for samples dried at a low drying temperature with a low FMC, the percentage of fissured kernels was less, and thus a higher HRY was obtained. The thermo-physical properties of rice kernels will be different in the glassy versus rubbery states, corresponding to the states at below or above the transition temperature line. At low temperatures, kernels would not completely transition into the rubbery state, and thus little fissuring would be expected.

The others research results was used to compare with the obtained data in this study. Zhang et al. [32] in studying on the preservation of HRY for a long-grain variety noted that the HRY of a sample at low FMC was relatively high, even with a high drying temperature, given proper drying and post-drying conditions. The HRY values found in the present study appear similar to those found in other studies, except for the lower FMC with low drying temperatures (30°C and 40°C), which the values measured by other researchers [29, 30] were slightly lower. This might be due to the structure and physicochemical properties of *japonica* aromatic rice.

Statistical analysis confirmed that temperature and FMC had a significant effect on the HRY, and the LSD test revealed that there was no significant difference in HRY response for the 30°C and 40°C drying air temperatures. This indicates that a low drying temperature does not significantly affect the HRY, and that the HRYs are greatly improved at drying temperatures of 30°C and 40°C for the low FMC. Maintaining the HRY at maximum level is the key principle for the optimization of drying process. Therefore, the drying temperature below 40°C should be considered as the optimum for performing low FMC treatments. Higher drying temperatures (50°C and 60°C) produced significant (P<0.01) reductions in HRY for both FMC. This result was consistent with those of previous studies [28, 29, 32].

The average whiteness values for the control, standard FMC, and low FMC treatments were 69.1, 68.5, and 66.4, respectively (Table 3). The whiteness of milled rice was generally low when obtained from paddy dried to a low FMC level. The milled rice sample was more opaque when dried to the low FMC compared with the standard FMC. A similar whiteness trend was observed by Hashemi et al. [14], when they surveyed actual milling conditions in Iran.

3.3 Correlating HRY to physical properties of aromatic rice

Table 3 shows the correlation between HRY and fissured kernels. As indicated in Table 3, a strong negative correlation at a $P<0.01$ level was found between HRY and both drying rate (-0.91) and percentage fissured kernels (-0.85) for aromatic rice. The HRY reduction could be related to the drying rate and heating duration. This means that drying rate could be largely responsible for producing fissured kernels by increasing the moisture gradient, and subsequently affecting the HRY. When the moisture gradient declines, moisture from the central portion of the grain diffuses to the surface, causing it to expand, while the internal portion contracts due to moisture loss. The result is compression at the surface and tension in the central portions of the grain. Because of these partial expansion and partial contraction effects, stress concentration may occur in the interface between the regions of expansion and contraction. Based on the above discussion, the zones inside a rice kernel that had a high potential of stress concentration and were thus prone to fissure initiation during drying [25, 28]. Fissures caused by rapid moisture desorption occur primarily during the drying stage, and a grain with a fissure is likely to break when the kernel is milled [33]. Siebenmorgen et al. [29] found strong linear correlations between HRY and the percentage of fissured kernels, confirming the present results.

3.4 Cooking quality

The relationships between final moisture and WUR, VER, and Sc ratio as cooking quality indices at four drying temperature are presented in Fig. 5. Some factors are known to affect the cooking quality of rice, such as kernel thickness, cooking time, drying temperature, and final moisture [6, 7, 9]. Drying temperature significantly ($P<0.01$) influenced the WUR. The WUR was found to decrease with an increase in drying air temperature from 30°C to 50°C (Fig. 5a). The reason for this might be the negative influence of temperature on the ability of the starch structure to absorb and retain water, because starch from kernels also has an effect on the quality of rice. It has a high capacity to hydrogen bond to absorb more water and expand in volume without collapsing [9]. The WUR of samples with low FMC was higher than those samples dried up to standard FMC. In additional, with increase of drying temperature, the percentage reduction of WUR for the low FMC samples were higher than those in standard FMC, particularly at high temperatures. This confirms the finding of Batcher et al. [6] that differences in the WUR of cooked rice due to different drying temperatures are not significant at standard FMC levels.

We found a negative relationship between the VER and drying air temperature in both standard and low FMC (Fig. 5b). The VER was found to vary from 2.48 to 2.28. It decreased with increases in the drying air temperature. The Kaori variety (*japonica* short-grain) in general contains a low percentage of amylose and has a higher WUR, which causes a higher VER in comparison with the *indica* variety [34]. This might be due to the thickness of the grain, which is the major difference

between the grains of the two varieties. Mohapatra and Bal [9] found that grain thickness has a major effect on the VER of cooked rice, and that amylose content also has an effect. Jianrong et al. [35] stated that because *indica* and *japonica* are different subspecies of rice, there might exist some differences in their genetic mechanisms for controlling the performance of cooking quality traits. In the present study, we found a strong correlation (0.83) at a $P<0.01$ level between WUR and VER. This indicates that an increase in VER can largely be attributed to an increase in the WUR, which supports the previous finding that rice with a higher WUR can be ascribed to a higher VER, due to more water being absorbed [9].

Fig. 5c shows that the Sc varied between 7 and 8.7 for the standard FMC and 7.5 and 9.2 for the low FMC at different drying temperatures in the present study. With an increase in drying temperature, the Sc also increased. This result was consistent with previous study [6]. As expected, the average Sc of samples dried under control conditions was 6.5, which was the lowest of all treatments used. The amount of solid material (small part of the starch) in the residual liquid for this experiment was a little higher than amounts previously measured for a long-grain variety [6]. This might be due to the different physical properties of the Kaori short-grain variety. There was a strong positive correlation (0.89) at the $P<0.01$ level between the Sc and the percentage of fissured kernels. A higher drying temperature resulted in an increase in the number of fissured kernels and subsequently the particular size of starch was separated easily from the kernels. Higher solid residual for samples dried at the low FMC implies that using an MC lower than the standard could increase solid losses during the cooking process. For the optimization of drying process, the final moisture at standard level and the drying temperature below 40°C should be considered as the optimum for keeping the cooking quality of Kaori aromatic rice variety.

4. Conclusions

The purpose of this study was to investigate the influence of low FMC, produced by different drying temperatures on the physical properties, milling and cooking quality of aromatic rice and compare those results with standard FMC treatments. For samples dried at 30°C and 40°C to the low FMC, rigidity was increased, which had been positive effect on the HRY, but energy consumption per unit of moisture removed was increased. Many fissures appeared in the low FMC treatments when the sample was dried at more than 50°C, whereas few fissures appeared at drying temperatures of 30°C and 40°C. Low FMC samples which were dried at low temperature can decrease the stresses in the rice kernel. As a result, the fissuring percentage lessens and it was able to maintain the HRY.

WUR and VER values decreased significantly ($P<0.05$) with an increase of drying air temperature from 30°C to 50°C, and then increased with a drying temperature higher than 50°C. A higher drying temperature is associated with reductions in the ability of the starch to absorb and retain water, and subsequently a reduction in volume expansion.

HRY and cooking qualities was the sole response for the optimization of drying process. Therefore, the drying temperature below 40°C should be considered as the optimum for performing low FMC treatments without diminishing final rice quality. Clearly, a drying temperature of more than 40°C has a major influence on deterioration in the quality of *japonica* type aromatic rice. Low FMC also has an effect. Other than temperature and FMC, some variety-specific factors, such as thickness and initial MC, might cause differences in the physical properties and cooking quality of rice, and should also be considered.

NOMENCLTURE

df : degree of freedom, -

dR : drying rate, %.hr^{-1}

E_m : energy consumption per kg removal moisture, kWh.kg^{-1}

FMC : final moisture content, %

F : fissure ratio, %

HRY : head rice yield, %

LSD : least significant difference analysis, -

MC : moisture content, w.b., %

M_i : initial moisture content, w.b., %

M_f : final MC, w.b., %

MR : milling ratio, -

R : rigidity, kg

RH : relative humidity, %

Sc : solid content, -

t : drying time, min

VER : volume expansion ratio, -

W : whiteness, -

WUR : water uptake ratio, -

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References

1) T. L. Thompson, R. M. Peart, G. H. Foster; Mathematical simulation of corn- a new model. Transactions of the ASAE, 11, 582–586 (1968) .

2) F. T. Wratten, W. D. Poole, J. L. Chesness, S. Bal, V. Ramarao; Physical and thermal properties of rough rice. Transactions of the ASAE, 12, 801- 803 (1969) .

3) K. Muthukumarappan, V. K. Jindal, S. Gunasekaran; Volumetric changes in rice kernels during desorption and adsorption. Transactions of the ASAE, 35, 235–241 (1992) .

4) A. A. Perdon, T. J. Siebenmorgen, A. Mauromoustakos; Glassy state transition and rice drying: development of a brown rice state diagram. Cereal Chem., 77, 708-713 (2000) .

5) V. K. Arora, S. M. Henderson, T. H. Burkhardt; Rice drying cracking versus thermal and mechanical properties. Transactions of the ASAE, 16, 320-327 (1973) .

6) O. M. Batcher, R. R. Little, E. H. Dawson, J. T. Hogan; Cooking quality of white rice milled from rough rice dried at different temperatures. Cereal Chemistry, 35, 428–434 (1958) .

7) K. R. Bhattacharya, C. M. Sowbhagya; Water uptake by rice during cooking. Cereal Science Today, 16, 420–424 (1971) .

8) E. T. Champagne, K. L. Bett-Garber, B. T. Vinyard, A. M. McChung, F. E. Barton II and K.A. Moldenhauer et al.; Correlation between cooked rice texture and rapid visco analyzer measurements. Cereal Chemistry, 76, 764–771 (1999) .

9) D. Mohapatra, S. Bal; Cooking quality and instrumental textural attributes of cooked rice for different milling fractions. Journal of Food Engineering, 73, 253-259 (2005) .

10) Experts team of JICA and ministry of agriculture of Iran; "The feasibility study on the irrigation and drainage development project in the Haraz River basin: Main report" Publisher: Japan International Cooperation Agency, Tokyo, AFN-JR-93-39, 1993, p. 4-27 .

11) J. Hashemi, A. Borghei, N. Shimizu, T. Kimura; Optimization of final moisture content of paddy in flat bed dryer with consideration of minimum losses and marketability. Journal of Agricultural Sciences and Natural Resources of Khazar, 3, 72-82 (2005) .

12) B. K. Bala; "Drying and storage of cereal grains" Oxford & IBH publishing Co. PVT. LTD., New Dehli, India, 1997, p. 125.

13) J. Hashemi, N. Shimizu, T. Kimura; Assessment of extreme reduction of paddy moisture. Proceedings the 40th Annual Report of Kanto Branch, the Japanese Society of Agricultural Machinery, Nagano, Japan, July 1-2 (2004) .

14) J. Hashemi, N. Shimizu, T. Kimura; Physical and cooking properties of aromatic rice during drying process by batch type dryer. Paper No. 066199. In proc. annual international meeting of the ASAE, Oregon, USA, July 9-12 (2006) .

15) ASAE; Moisture measurement-grain & seeds. ASAE Standard (29th Edn.), S352·1, St. Joseph, MI, USA (1982) .

16) P. Roy, N. Shimizu, S. Furuichi, T. Kimura; Improvement of traditional parboiling process. J. Japanese Soc. Agricultural Machinery, 65, 159-166 (2003) .

17) W. Yang, C. Jia, T. J. Siebenmorgen, A. G. Cnossen; Intra kernel moisture gradients and glass transition temperature in relation to head rice yield variation during heated air drying of rough rice. Paper No. 069. In proc. 12th international drying symposium. Netherlands (2000) .

18) T. Kimura; Improvement of rice parboiling with batch type. Agricultural engineering. Balkema, Rotterdam, 4, 2445-2453 (1989) .

19) N. Shimizu, T. Kimura, K. Ohtsubo, H. Toyoshima; Development of rice quality evaluating technique based on the physical properties of cooked rice. Journal of the Japanese Society of Agricultural Machinery, 59, 75-82 (1997) .

20) K. R. Bhattacharya, R. P. Subba; Effect of processing conditions on quality of parboiled rice. J. Agric. Food Chem., 14, 476–479 (1966) .

21) P. Pillaiyar, R. Mohandoss; Cooking qualities of parboiled rices produced at low and high temperatures. Journal of the Science of Food and Agriculture, 32, 475–480 (1981b) .

22) B. O. Juliano; Production and utilization of rice. Rice chemistry and technology (2nd ed.), American Association of Cereal Chemists, St. Paul, Minnesota, 1–16 (1985) .

23) I. Das, S. K. Das, S. Bal; Drying performance of a batch type vibration aided infrared dryer. Journal of Food Process Engineering, 64**,** 129-131 (2003) .

24) K. Nagato, M. Ebata, M. Ishikawa; On the formation of cracks in rice kernels during wetting and drying of paddies. Nippon Sakumotsu Gakkai Kiji, 33, 82-89 (1964) .

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

26) Y. Tirawanichakul, S. Prachayawarakorn, W. Varanyanond, S. Soponronnarit; Simulation and grain quality for in-store drying of paddy rice. Journal of Food Engineering, 64, 405–415 (2004) .

27) H. Kobayashi, Y. Miwa, M. Ishikowa;. On the mechanism of cracking in rice kernels during drying of paddies particularly moisture distribution and drying strain in one kernel. Research Bulletin of the Faculty of Agriculture of Gifu University, 33, 279-293 (1972) .

28) O. R. Kunze; Fissuring of the rice grain after heated air drying. Transactions of the ASAE, 22, 1197-1207 (1979) .

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

30) V. K. Jindal, T. J. Siebenmorgen; Simulation of low temperature rough rice drying and rewetting in shallow beds. Transactions of the ASAE, 37, 863–871 (1994) .

31) J. Fan, T. J. Siebenmorgen, W. Yang; 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, 1709-1714 (2000) .

32) Q. Zhang, W. Yang, C. Jia; Preservation of head rice yields under high temperature tempering as explained by the glass transition of rice kernels. American Ass0ciation of Cereal Chemistry, 80, 684-688 (2003) .

33) A. D. Sharma, O. R. Kunze; Post-drying fissure developments in rough rice. ASAE, 25, 465–468, 474 (1982) .

34) G. C. He, K. Kogure, H. Suzuki; Development of endosperm and synthesis of starch in rice grain. III. Starch property affected by temperature during grain development. Jpn. J. Crop Sci., 59, 340-345 (1990) .

35) L. Jianrong, C. Shi, M. Wu, J. Wu; Analysis of genetic effects for cooking quality traits of japonica rice across environments. Plant Science, 168, 1501–1506 (2005) .

Table 1 Analysis of variance for physical properties, milling, and cooking quality of Kaori aromatic rice.

Variables	***df***	**dR**	**R**	**E_M**	**F**	**HRY**	**W**	**WUR**	**VER**	**Sc**
		F_c	F_c	F_c	F_c	F_c	F_c	F_c	F_c	F_c
Drying temperature	3	212^{**}	1.4^{ns}	6.0^{*}	28.2^{**}	74^{**}	0.48^{ns}	5.1^{*}	8.8^{**}	5.03^{*}
FMC	1	70.7^{**}	120^{**}	258^{**}	1.3^{ns}	32^{**}	14.5^{**}	0.04^{ns}	1.3^{ns}	1.4^{ns}
Temperature and FMC	3	1.9^{ns}	0.1^{ns}	16.8^{**}	1.6^{ns}	90.3^{**}	0.3^{ns}	0.5^{ns}	1.1^{ns}	0.1^{ns}

^{ns} Not significant; * Significant at a level of 5%; **Significant at a level of 1%; F_c: Calculated F in F-test

Table 2 Pearson's correlation coefficients for the relationship between drying, milling, and cooking variables.

Variable	dR	R	F	Em	HRY	W	VER	WUR
Rigidity, R	-0.07							
Fissure, F	0.89**	0.22						
Energy per unit moisture removed MC, Em	0.17	0.76*	0.22					
Head rice yield, HRY	-0.91**	0.26	-0.85**	0.16				
Whiteness, W	-0.02	-0.88**	-0.31	-0.80	-0.15			
Volume expansion, VER	0.13	0.30	-0.03	0.79**	0.19	-0.41		
Water uptake, WUR	-0.13	0.27	-0.23	0.71*	0.32	-0.44	0.83**	
Solid content, Sc	0.83**	0.44	0.89**	0.56	-0.62	-0.47	0.34	0.03

*Significant at $P<0.05$ and **Significant at $P<0.01$

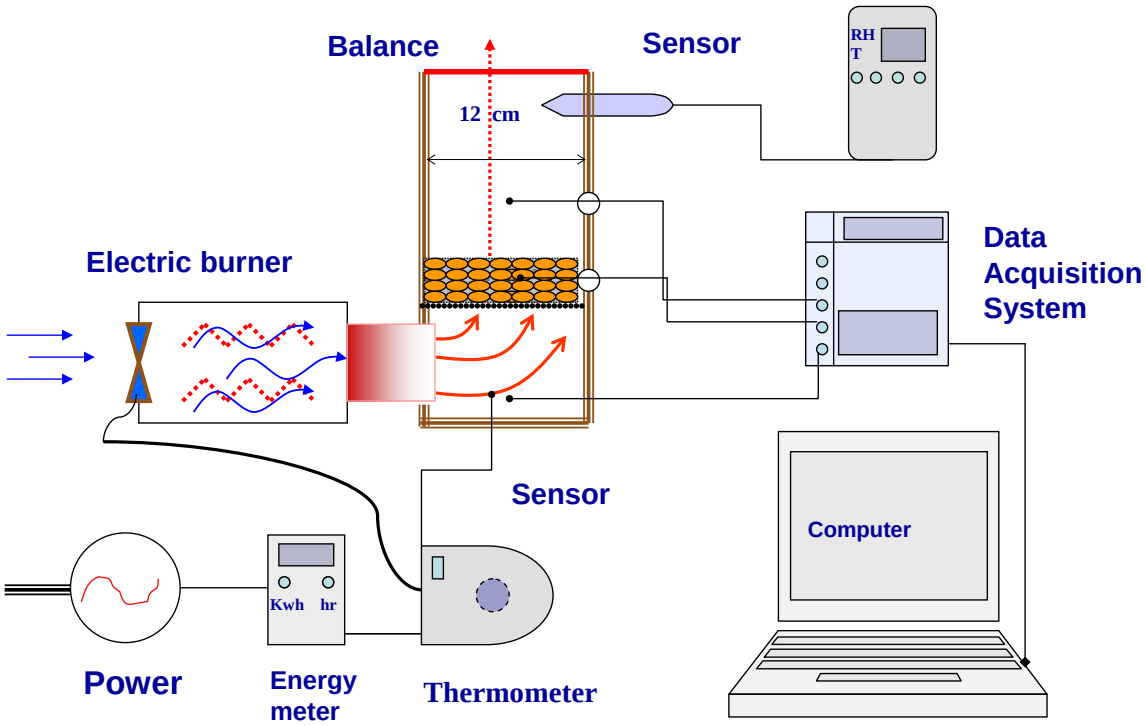
Table 3 Experimental data for the physical properties and milling quality of aromatic Kaori rice when subjected to different drying temperatures to attain a standard or low FMC.

Final moisture	**Control**	**Standard FMC†**				**Low FMC††**			
Drying temperature		**30ºC**	**40ºC**	**50ºC**	**60ºC**	**30ºC**	**40ºC**	**50ºC**	**60ºC**
Drying time (min)	13920	698.0	366.0	255.0	197.5	1290.0	727.5	420.0	270.0
Drying rate (%/h)	0.06	1.26	2.34	3.41	4.43	0.79	1.33	2.44	3.80
Em* (kWh/kg-water)	--	15.8	16.6	17.9	18.3	32.1	31.2	25.5	23.1
Final MC (%)	12.8	12.4	12.4	12.3	11.8	9.9	9.7	9.6	9.7
Final rigidity (N)	56.9	54.4	57.4	60.0	52.8	82.2	85.0	88.9	80.5
Final density (kg/m^3)	559.5	562.5	551.5	559.7	557.6	551.1	543.5	543.8	546.8
Relative HRY (%)	1.0	0.96	0.95	0.89	0.83	1.04	1.05	0.95	0.82
Whiteness	68.3	68.1	68.5	69.0	68.2	66.8	65.7	66.8	66.1

* Energy consumption per unit of moisture removed

† The final moisture of about 12% , †† The final moisture of about 9%

1


Balance
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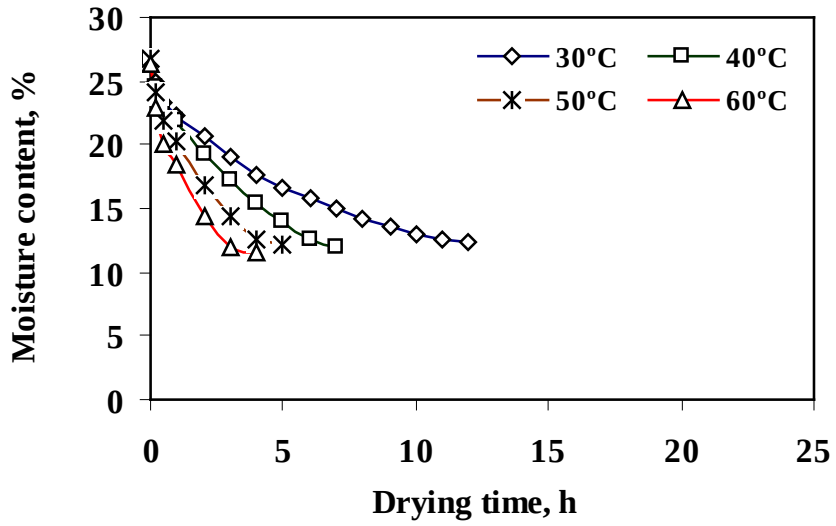
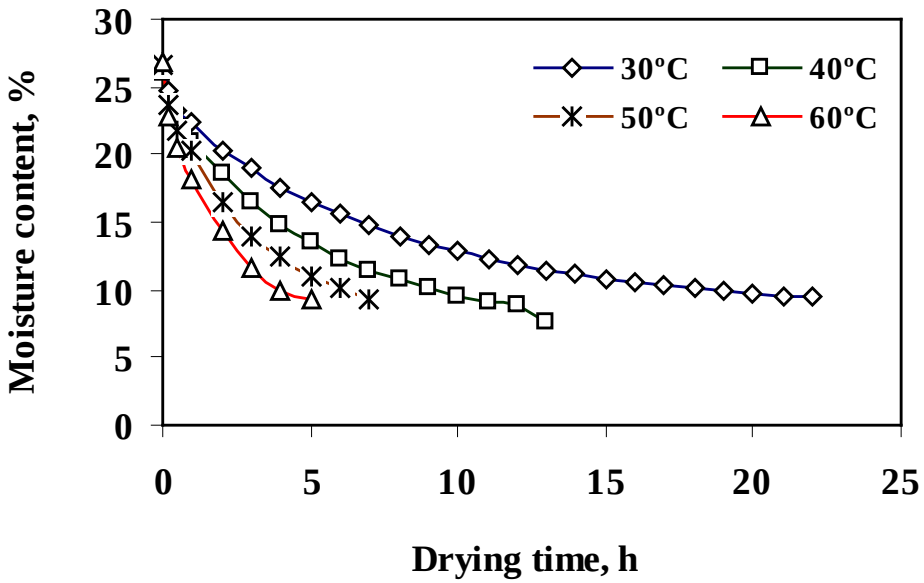
Computer
Kwh
hr
Power
Energy
meter
Thermometer

2

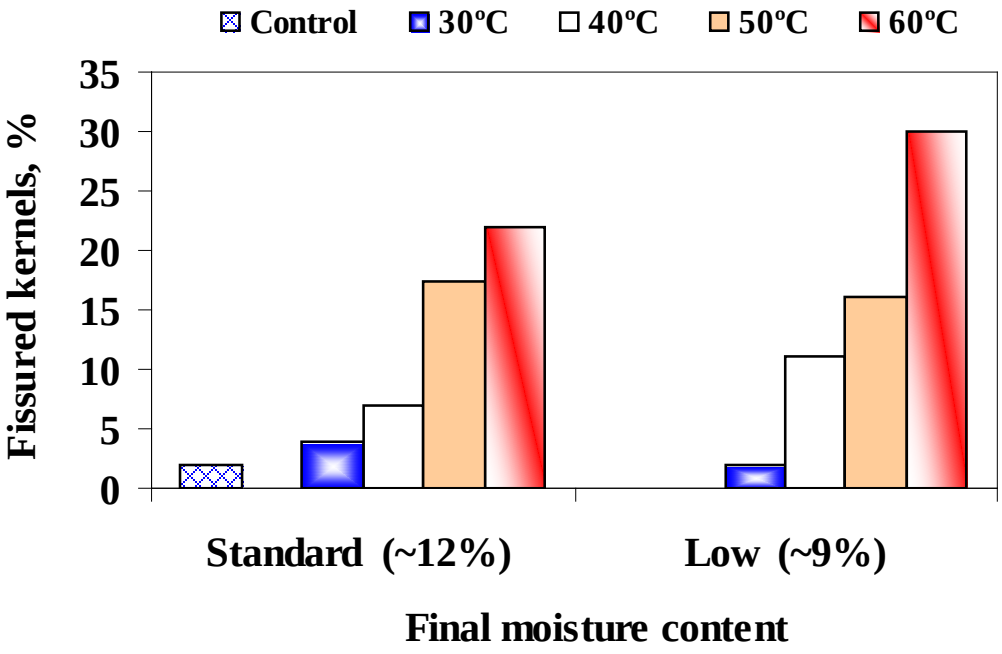

30
25
20
15
10
5
0
Moisture content, %
0
5
10
15
20
25
Drying time, h
30°C
40°C
50°C
60°C

(a)

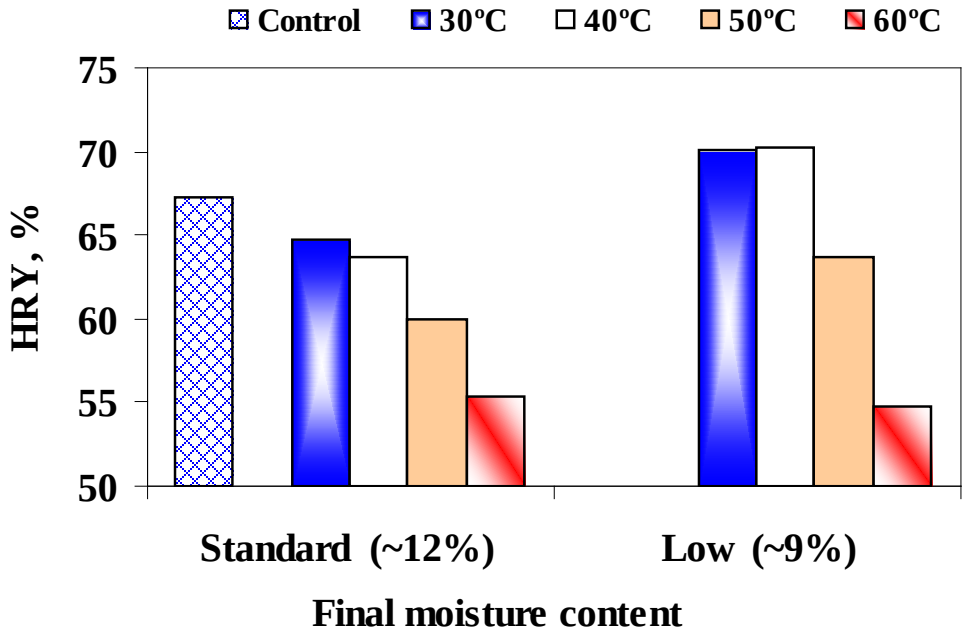

30
25
20
15
10
5
0
Moisture content, %
0
5
10
15
20
25
Drying time, h
30°C
40°C
50°C
60°C

(b)

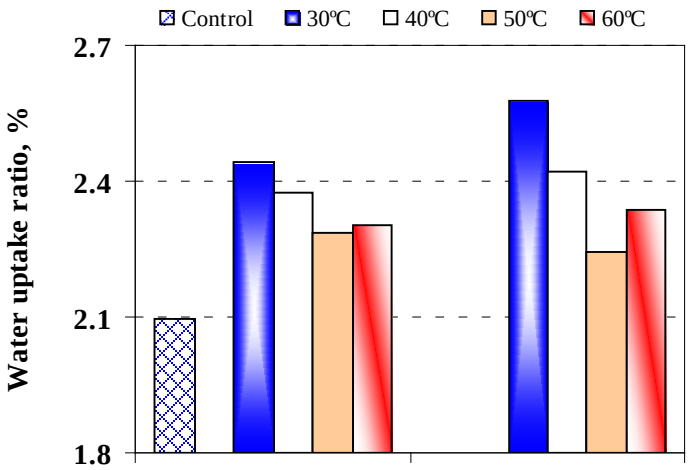
3


Control
30ºC
40ºC
50ºC
60ºC
Fissured kernels, %
35
30
25
20
15
10
5
0
Standard (~12%)
Low (~9%)
Final moisture content

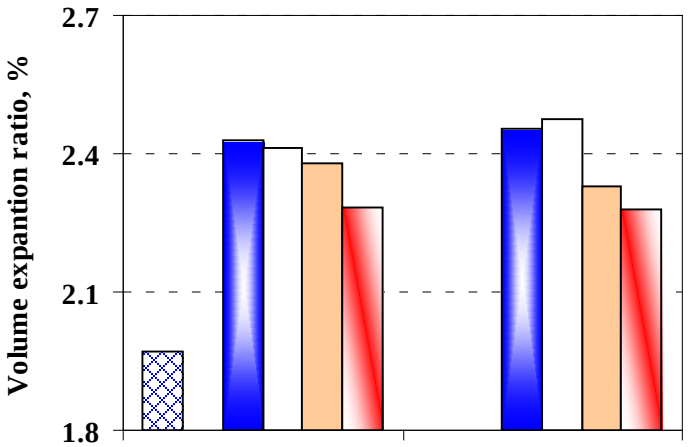
4


Control
30°C
40°C
50°C
60°C
75
70
65
60
55
50
HRY, %
Standard (~12%)
Low (~9%)
Final moisture content

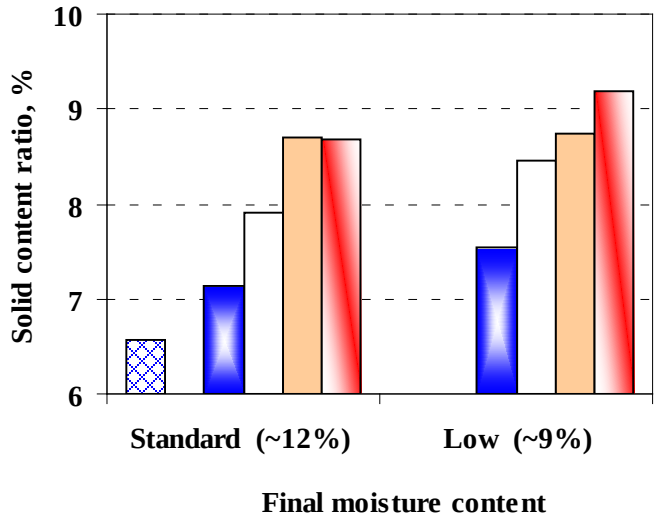
5


Control
30ºC
40ºC
50ºC
60ºC
2.7
2.4
2.1
1.8
Water uptake ratio, %

(a)


2.7
2.4
2.1
1.8
Volume expantion ratio, %

(b)


10
9
8
7
6
Solid content ratio, %
Standard (~12%)
Low (~9%)
Final moisture content

(c)

List of Figures

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香り米の物理的性質および炊飯特性に及ぼす乾燥工程の影響

イランではバッチ式の乾燥機により主要な穀物である籾水分を 9%まで乾燥する。香り米籾の最終水分が、約 12%（標準水分籾）と約 9%（低水分籾）になるように籾温度 30, 40, 50, 60°C の４つの処理区で試料籾を乾燥処理し，得られた籾，玄米，精米の物理的性質及び炊飯特性を調べた。低水分籾の歩留まりの結果として，対照処理区（乾燥処理条件：温度 25℃, 相対湿度 60%）の籾と比べて，60°C の乾燥処理区では歩留まりが 20％低く、30°C と 40°C の乾燥処理区では 4%高かった。炊飯特性試験における加熱吸水率と膨張容積比は、乾燥処理の温度が高くなると低下した。低水分籾では，温度が 40℃もしくはそれ以下の乾燥処理の場合，高い歩留まりを示すことが明らかにになった。加えて，温度（50~60℃）の乾燥処理は，胴割れ粒，乾燥エネルギーを増加させ，歩留まり，加熱吸水率及び膨張容積比を低下させる原因となる。高い歩留まりの維持と炊飯特性試験の指標が，乾燥プロセス最適化の目安となり，香り米を低水分まで 40℃以下の温度で乾燥処理する条件によってもたらされる。物理的性質と炊飯特性試験の結果から，40℃以上の高い温度での乾燥処理は，日本型香り米の品質劣化をもたらす。

キーワード: 香り米, 炊飯、乾燥, ヘッドライス