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Effects of fluidized bed drying temperature and tempering time on quality of waxy rice

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Translucent kernel

ABSTRACT

Waxy rice, which is soft and sticky in nature, can be used as a raw material to produce many food products. After being harvested, high-moisture waxy paddy must be dried to appropriate moisture content to prolong its storage life and to achieve higher head rice yield. Fluidized bed dryer could be used to dry waxy rice at high-temperature. However, due to the high heat and mass transfer rates during drying, stresses are generated in a rice kernel, leading to crack and low head rice yield. Tempering is thus recommended to reduce the moisture-induced stresses in the kernel after rapid drying. In this study, the effects of fluidized bed drying temperature (90, 110, 130 °C) and tempering time (30–120 min) on the quality of waxy rice, i.e., head rice yield, thermal properties, pasting properties, color, translucent kernel and microstructure, were investigated. The results showed that head rice yield of waxy rice after drying was significantly lower than that of the reference sample even when tempering was performed. Higher drying temperatures led to higher head rice yield while the tempering time did not have any effect on the head rice yield except when the drying temperature of 90 °C was used. Drying at higher temperatures also affected the starch granule morphology and the pasting properties. Waxy rice changed its appearance from opaque white to translucent when being dried at 130 °C.

1. Introduction

Waxy rice (*Oryza sativa*) is a rice variety that contains a large amount of amylopectin, which is responsible for its stickiness. Because of its soft and sticky nature, waxy rice is used as a raw material for producing various kinds of food products, e.g., rice cake, rice cracker and puffed rice (Keeratipibul et al., 2008).

Waxy rice is normally harvested at a moisture content in the range of 28–30% dry basis (d.b.) and dried to a moisture content of around 16% (d.b.). While the rice is being dried, moisture gradient exists in a grain kernel. This naturally leads to development of crack in the kernel. Fissured kernel cannot generally withstand abrasive force during milling; subsequent head rice yield is thus poor (Cnossen et al., 2003; Tirawanichakul et al., 2004). To achieve higher head rice yield, suitable drying technique and condition must be employed. Although there are a number of dryers that could possibly be used to dry waxy rice such as cross-flow dryer, concurrent-flow dryer, mixed-flow dryer and rotary dryer (Brooker et al., 1992), fluidized bed dryer may be the most appropriate one since it can provide good mixing, high heat and mass transfer rates and has proved suitable for drying many types of grain products (Goksu et al., 2005; Soponronnarit and Prachayawarakorn, 1994; Soponronnarit et al., 1997; Mujumdar and Devahastin, 2003). However, high drying rate may lead to poor head rice quality due to excessive crack as mentioned earlier (Karbassi and Mehdizadeh, 2008). To reduce crack in a kernel, tempering between drying passes is recommended in order to reduce moisture-induced stress (Poomsa-ad et al., 2005; Tuyen et al., 2009).

In addition to the head rice quality, other qualities, e.g., pasting properties and color, are also important because these properties directly affect the overall quality of waxy rice. Several studies have indeed been reported on the effect of thermal treatment on the morphological structure and the pasting viscosity of waxy rice flour (Anderson and Guraya, 2006; Sung et al., 2008). Microwave drying slightly affected the morphological structure of waxy rice starch, but caused a significant change in the pasting viscosity (Anderson and Guraya, 2006). A treatment with gamma radiation using the dose ranging from 0.5 to 2 kGy could decrease the pasting viscosity of waxy rice (Sung et al., 2008).

Despite the above-mentioned previous works, information on drying, especially on fluidized bed drying, of waxy rice is very limited. Therefore, the main objective of this study was to investigate the effects of fluidized bed drying temperature and tempering time on the quality of waxy rice. The waxy rice quality was considered

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in terms of the head rice yield, thermal properties, pasting properties, color, translucent kernel and microstructure.

2. Materials and methods

2.1. Experimental set-up

A schematic diagram of a hot air fluidized bed dryer and its accessories is shown in Fig. 1. The system consists of three major components: a cylindrical drying chamber with an inner diameter of 20 cm and a height of 140 cm; 12 kW electrical heaters with a temperature controller; and a backward-curved-blade centrifugal fan, which was driven by a 1.5 kW motor. Exhaust air could be recycled, if needed, by means of two butterfly valves.

2.2. Materials

Dried long grain rough waxy rice (RD6) was provided by the Rice Research Institute, Ubon Ratchathani province, Thailand. The rice was re-moistened, homogenized and kept in a cold storage at 4–6 °C for 7 days prior to an experiment. The initial moisture content of the re-moistened waxy rice was 28.8% (d.b.). Moisture content of rough waxy rice was determined by drying 50 g of rough waxy rice sample at temperature of 103 °C for 72 h in a hot air oven (Memmert, model no. ULE500, Schwabach, Germany). The waxy rice (RD6) has an amylose content in the range of 4–6% (Noomhorm et al., 1997; Varavinit et al., 2003). Before starting each experiment, the waxy rice was placed in ambient environment until its temperature was close to ambient temperature ($T \sim 30$ °C).

2.3. Drying of waxy rice

A batch of 1.9 kg of re-moistened sample was dried in the fluidized bed dryer. The experiments were carried out at temperatures of 90, 110 and 130 °C at a superficial air velocity of 2.5 m/s, which is around $1.5U_{mf}$ (Soponronnarit and Prachayawarakorn, 1994). The desired moisture content after fluidized bed drying was 22–24% (d.b.). The semi-dried waxy rice was then tempered for 30 up to 120 min in order to reduce moisture stresses created during drying. In the tempering step, the sample was kept in a closed jar to avoid moisture loss. After the tempering step, the sample was ventilated with ambient air (temperature and relative humidity of 30 °C and 55–60%, respectively) in a thin-bed ventilator with a static bed depth of around 3.5 cm at a superficial air velocity of 0.15 m/s until the moisture content of the sample reached 16% (d.b.) (ventilation time was around 30–40 min) (Soponronnarit, 1987). Moisture content of rough waxy rice was determined by drying 50 g of rough waxy rice sample at temperature of 103 °C for 72 h in a hot air oven (Memmert, model no. ULE500, Schwabach, Germany). After that the sample was kept in a sealed plastic bag at 4–6 °C for 2 weeks before quality analysis. In order to compare the quality of waxy rice obtained from the above processing conditions, the quality of a reference sample, obtained by shade drying with the final moisture content of around 16% (d.b.), was also determined. The quality of dried waxy rice was evaluated in terms of the head rice yield, thermal properties, pasting properties, color, translucent kernel and microstructure.

2.4. Head rice yield evaluation

Waxy rice (250 g) from each treatment was dehulled with a bench-top dehusker (Satake, model no. THU-35, Hiroshima, Japan), then polished by a Satake rice polisher (Satake, model no. TM05, Hiroshima, Japan). The sample was subsequently separated by an indent cylinder (Satake, model no. TRG-05A, Hiroshima, Japan) to determine the head rice yield; in this case the head rice yield is defined as milled rice having kernel length of at least 75% of its original length. Head rice yield was calculated by dividing the head rice mass by an initial rough rice mass. All experiments were performed in duplicate and the average values were reported.

2.5. Thermal properties evaluation

Waxy rice flour was prepared by grinding waxy rice with an ultra centrifugal mill (Retsch, model no. ZM 100, Hann, Germany)

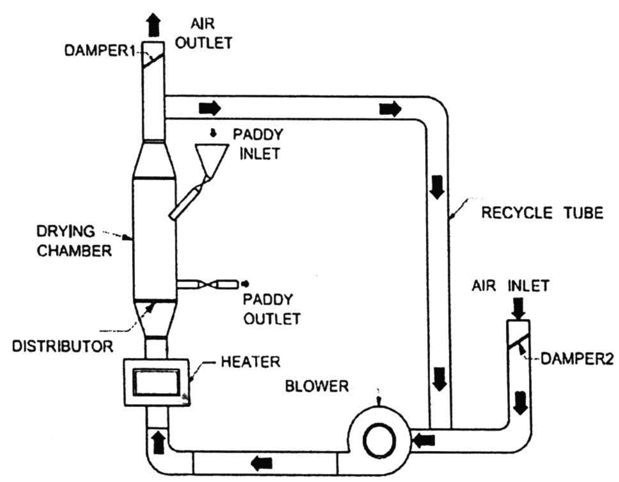

Fig. 1. A schematic diagram of a batch hot air fluidized bed dryer.

through a 0.25-mm screen (the moisture content of flour was 16% (d.b.)). Thermal analysis of flour was performed using a differential scanning calorimeter (Perkin Elmer, model no. DSC-7, Norwalk, CT). The waxy rice flour (3 mg) was accurately weighed into an aluminium DSC pan; 10 μL of distilled water was added and the pan was hermetically sealed. The sample was left to stand for 1 h at room temperature (25 °C) before DSC scanning. Indium was used for a calibration of the DSC and an empty pan was used as a reference. All samples were heated from 40 to 100 °C at a scanning rate of 10 °C/min. The major parameters of each DSC profile were described as onset temperature, peak temperature and conclusion temperature. From the DSC profile, the transition enthalpy was determined and the degree of gelatinization of waxy rice flour was then calculated by the following equation:

$$SG\,(\%) = \left(1 - \left[\frac{\Delta H}{\Delta H_c}\right]\right) \times 100 \qquad (1)$$

where SG is the degree of gelatinization, ΔH is the transition enthalpy of treated waxy rice (J/g (dry matter)) and ΔH_c is the transition enthalpy of raw waxy rice (J/g (dry matter)). All experiments were performed in duplicate and the average values were reported.

2.6. Pasting properties evaluation

Pasting properties of waxy rice flour (with an average particle size of 125 μm) were determined using a Rapid Visco Analyzer, RVA (Newport Scientific, model no. RVA-4, Warriewood, Australia) following the standard method 61-02 (AACC, 1995). Waxy rice flour (3 g on dry basis) was poured into distilled water (25 mL) in a canister and mixed thoroughly. The mixture was stirred at 960 rpm for the first 10 s and then changed to 160 rpm for the rest of the analysis. The temperature of the slurry was first maintained at 50 °C for 1.5 min and then raised to 95 °C at a rate of 12 °C/min. After that the temperature was maintained at 95 °C for 2.5 min, followed by a cooling to 50 °C at 12 °C/min; the temperature was then maintained at 50 °C for 2.1 min. The total time of an experiment was 12.5 min. A plot of the pasting viscosity in an arbitrary RVA unit (RVU) versus time was then made. The peak viscosity, which was obtained from the pasting curve, indicates the water-binding capacity of the mixture and is often correlated with the final product quality; it also provides an indication of the viscous load likely to be encountered by cooking. Setback viscosity was also obtained from the curve and is used as an indicator of gelling or retrogradation tendency of waxy rice. All experiments were performed in triplicate and the average values were reported.

2.7. Color evaluation

The color of polished waxy rice was measured by HunterLab ColorFlex (Reston, VA) using a D65 light source, large viewing area and the observer angle of 10°. Before each color measurement, the spectrophotometer was calibrated with a standard white plate ($X = 78.50$, $Y = 83.40$, $Z = 87.63$). The color values were expressed as L (lightness/darkness), a (redness/greenness) and b (yellowness/blueness). The whiteness index (WI) was then calculated by the following equation (Chen et al., 1999):

$$WI = 100 - [(100 - L)^2 + a^2 + b^2]^{0.5} \qquad (2)$$

All experiments were performed in triplicate and the average values were reported.

2.8. Translucent kernel evaluation

A kernel which had a translucent area of larger than 50% of its total area was defined as a translucent kernel. The translucency was evaluated manually by visual observation. Thousand kernels were randomly chosen from the dried milled waxy rice. The result was reported as the percentage of translucent kernels, which was calculated from the mass of the translucent kernels divided by the total mass of the sample. All experiments were performed in triplicate and the average values were reported.

2.9. Microstructure evaluation

The microstructure of each sample was observed by a scanning electron microscope (SEM) (JSM-5600, model no. JSM-5600LV, Tokyo, Japan). The waxy rice kernel was cut along its cross-sectional axis, attached to an SEM stub, coated with gold by a sputter-coater. The coated sample was then photographed at an accelerating voltage of 15 kV. The inspected location of the kernel was between the kernel surface and the endosperm centre.

2.10. Statistical analysis

All data were subjected to the analysis of variance (ANOVA) using SPSS® software and presented as mean values with standard deviations. Differences between mean values were established using Duncan's multiple range tests at a confidence level of 95% ($p \leq 0.05$).

3. Results and discussion

3.1. Drying kinetics

The drying curves of waxy rice undergoing fluidized bed drying at various temperatures are shown in Fig. 2. As expected, the moisture removal rate was enhanced at higher drying temperatures. The required drying time to reach the desired moisture content of 22–24% (d.b.) was about 2–4 min. This moisture content was not safe for storage. However, a further decrease in the moisture content at this stage would cause a rapid drop of the head rice yield, as will be discussed in the following section.

3.2. Effects of moisture content and drying temperature on head rice yield

Fig. 3 shows the effects of drying temperature and moisture content after the first-stage fluidized bed drying on the head rice yield. The head rice yield of the reference sample, obtained by drying waxy rice in shade, was approximately 48.5%. It can be seen in this figure that higher drying temperatures caused only a small

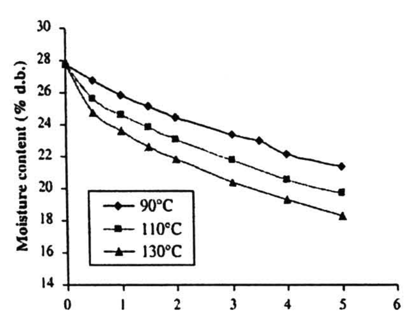

Fig. 2. Drying curves of waxy rice at temperatures of 90, 110 and 130 °C.

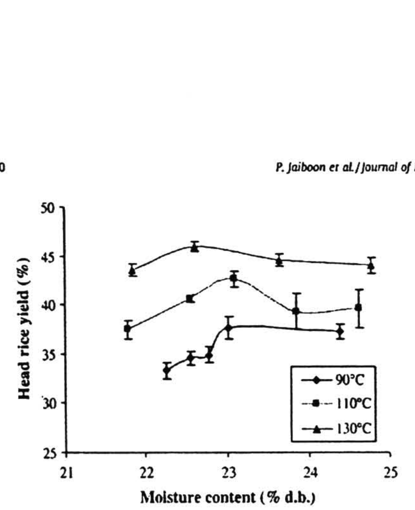

Fig. 3. Effects of drying temperature and moisture content after fluidized bed drying on head rice yield (no tempering). (reference waxy rice, M_{in} = 28.8% (d.b.), head rice yield = 48.5%).

drop in the head rice yield as compared to that of the reference sample. These results are opposite to those reported in the case of low-temperature drying (Cnossen et al., 2003). In the case of low-temperature drying (<60 °C), a larger fraction of broken kernels was noted as the drying temperature increased. This phenomenon was proposed to be due to higher moisture gradients, hence larger stresses, at higher drying temperatures. In the case of high-temperature drying, however, the opposite phenomenon might be due to modification of starch granules, which could enhance the molecular binding forces amongst the granules; paddy could thus withstand more abrasive force during milling. A smaller fraction of broken kernels was thus observed. To confirm this hypothesis, the dried samples were taken to analyze for their thermal properties, pasting properties and morphology; the results will be presented in later sections.

As shown in Fig. 3, waxy rice should not be dried to moisture content lower than 22–23% (d.b.); otherwise, the head rice yield would drop significantly, particularly when waxy rice was dried at 90 °C. The limitation of moisture content after the first-stage drying noted in this study is similar to that reported in the literature (Srzednicki and Driscoll, 1995; Soponronnarit and Prachayawarakorn, 1994; Prachayawarakorn et al., 2005) although the rice compositions were different; in the previous works, the amylose content in rice was much higher than that of waxy rice in this study.

It is interesting to note that when comparing the present results with those reported in the literature (e.g., Tirawanichakul et al., 2004), the results are not similar although the drying conditions were almost the same (>100 °C). In the study of Tirawanichakul et al. (2004), after drying, the head rice yield of rice, which contains higher amylose content of 15%, was relatively higher than that of the reference rice. However, when high-temperature fluidized bed drying was applied to waxy rice, which has an amylose content of 4–6%, the head rice yield was lower than that of the reference rice. Based on this difference, it might be possible to conclude that the amylose content plays an important role on the head rice quality, in addition to the drying condition. During gelatinization, which takes place during high-temperature drying, amylose, which has a linear chain structure, would leach out from the inside of starch granules and form a network amongst itself (Li et al., 2008). This formation would enhance the binding forces. The head rice yield of gelatinized high-amylose rice is therefore higher. On the other hand, for waxy rice, which mainly consists of amylopectin, the network formation during gelatinization is more difficult since the starch molecules are more difficult to get closer since the branching structure of amylopectin limits its mobility (Li et al., 2008). The head rice yield of dried waxy rice was thus lower than that of the reference sample.

3.3. Moisture content during tempering

To release the stresses developed during high-temperature drying, the dried waxy rice sample, with the moisture content of around 23% (d.b.), was tempered in a closed jar. The tempering temperature was set at the kernel temperature after the fluidized bed drying stage and the tempering time was in the range of 30–120 min.

Table 1 shows the moisture content and kernel temperature of waxy rice after drying at different temperatures. The kernel temperature ranged between 65 and 69 °C. During the tempering step, there was no moisture loss from the sample; the moisture content of rice was equal to that after fluidized bed drying.

3.4. Effect of tempering time on head rice yield

The influence of the tempering time on the change of head rice yield of waxy rice is shown in Fig. 4. It is seen that tempering insignificantly improved the head rice yields of the samples dried at 110 and 130 °C while it could significantly improve the head rice yield

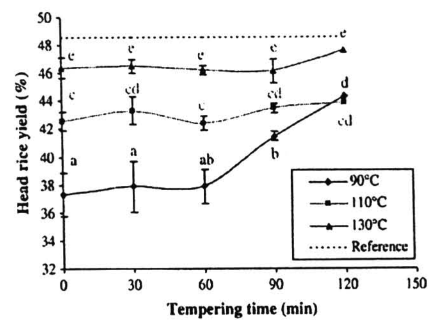

Fig. 4. Percentage of head rice yield of waxy rice after drying and tempering. Different letters above experimental points mean that the values are significantly different ($p < 0.05$).

Table 1
Moisture content and grain temperature at different drying conditions.

T_D (°C)	MC after FBD (% d.b.)	DT (min)	T_C (°C)	Moisture content at different tempering periods (% d.b.)			
				30	60	90	120
90	23.0	3.5	64.9	23.0	23.0	23.0	23.0
110	23.1	2.0	65.9	23.1	23.1	23.1	23.1
130	22.6	1.5	69.1	22.6	22.6	22.6	22.6

T_D = drying temperature, MC = moisture content, FBD = fluidized bed drying, DT = drying time required for fluidized bed drying, T_C = grain temperature after drying.

of the sample dried at 90 °C. As shown in Fig. 4, the head rice yield increased from 37.5% at 60 min to 44.0% at 120 min tempering time when drying was performed at 90 °C. The improved head rice yield could be attributed to the starch gelatinization, which occurred during tempering as can be seen in Table 2; the degrees of gelatinization were 3.8% for the sample with no tempering and 10.4% for the sample after tempering for 120 min, respectively. In addition to the gelatinization effect, the damage of starch granules after drying at 90 °C might not be severe and thus allowed the gelatinization to take a more obvious effect. However, even though tempering could help improve the head rice quality; the amount of head rice yield was still lower than that of the reference waxy rice.

3.5. Thermal properties

Table 2 lists the thermal properties of waxy rice after drying and tempering. The gelatinization temperature of waxy rice before drying was in the range of 61 and 77 °C. After drying and tempering, the gelatinization temperature increased. The enthalpy required for melting starch after drying decreased with an increase in the drying temperature and tempering time. The degree of starch gelatinization varied widely depending on the drying temperature and tempering time, the first factor being more important. This result agrees with the previously reported results (Tuyen et al., 2009). The degree of gelatinization noted in this study ranged between 25 and 30% at a drying temperature of 130 °C and decreased to only 4–10% at 90 °C. The DSC results corresponded to the results of head rice yield in that higher degree of gelatinization resulted in a smaller fraction of broken rice kernels.

3.6. Pasting properties

The changes of the pasting properties of waxy rice flour obtained from various processing conditions are presented in Table 3. The values of the peak viscosity were significantly lower for the flour of waxy rice dried at 110 and 130 °C and tempered for 0, 30 and 120 min as compared with that of the reference waxy rice. These results agree with the DSC results, showing that the

Table 2
Effects of drying temperature and tempering time on gelatinization properties of waxy rice flour.

Condition	Transition temperature (°C)			ΔH (J/g)	Degree of gelatinization (%)
	T_{onset}	T_{peak}	$T_{conclude}$		
Reference, M_{in} = 28.8% d.b.	61.1	68.5	76.8	6.8	0
T = 90 °C, M_{in} = 28.8% d.b., without tempering	61.5	69.2	77.9	6.6	3.8
T = 90 °C, M_{in} = 28.8% d.b., tempering time of 30 min	62.0	70.0	78.4	6.5	4.8
T = 90 °C, M_{in} = 28.8% d.b., tempering time of 120 min	62.8	70.6	78.4	6.1	10.4
T = 110 °C, M_{in} = 28.8% d.b., without tempering	61.7	69.4	78.1	5.9	14.0
T = 110 °C, M_{in} = 28.8% d.b., tempering time of 30 min	62.3	69.7	78.2	5.4	20.8
T = 110 °C, M_{in} = 28.8% d.b., tempering time of 120 min	62.2	69.7	78.3	5.2	24.4
T = 130 °C, M_{in} = 28.8% d.b., without tempering	61.8	69.5	78.2	5.1	24.6
T = 130 °C, M_{in} = 28.8% d.b., tempering time of 30 min	61.9	69.5	78.4	5.0	26.4
T = 130 °C, M_{in} = 28.8% d.b., tempering time of 120 min	62.7	70.4	78.6	4.8	29.6

Table 3
Pasting properties of waxy rice after processing at different conditions.

Condition	Peak viscosity (RVU)	Final viscosity (RVU)	Setback (RVU)	Pasting temperature (°C)
Reference, M_{in} = 28.8% d.b.	248.0 ± 0.3^{g}	131.4 ± 0.5^{a}	-116.6 ± 0.6^{a}	65.2 ± 0.5^{a}
T = 90 °C, M_{in} = 28.8% d.b., without tempering	246.9 ± 1.5^{g}	137.5 ± 6.3^{bc}	-109.5 ± 7.8^{b}	65.6 ± 0.7^{a}
T = 90 °C, M_{in} = 28.8% d.b., tempering time of 30 min	245.7 ± 1.0^{fg}	142.9 ± 1.2^{d}	-102.8 ± 2.0^{c}	65.3 ± 0.4^{a}
T = 90 °C, M_{in} = 28.8% d.b., tempering time of 120 min	242.5 ± 4.5^{ef}	143.8 ± 1.3^{d}	-98.7 ± 3.3^{c}	65.3 ± 0.6^{a}
T = 110 °C, M_{in} = 28.8% d.b., without tempering	244.0 ± 1.6^{efg}	143.2 ± 0.9^{d}	-100.8 ± 2.6^{c}	66.7 ± 0.2^{bc}
T = 110 °C, M_{in} = 28.8% d.b., tempering time of 30 min	241.2 ± 1.2^{de}	140.2 ± 1.3^{cd}	-101.0 ± 2.5^{c}	66.6 ± 0.4^{b}
T = 110 °C, M_{in} = 28.8% d.b., tempering time of 120 min	235.4 ± 1.7^{bc}	135.5 ± 0.8^{ab}	-99.9 ± 0.8^{c}	67.6 ± 0.6^{d}
T = 130 °C, M_{in} = 28.8% d.b., without tempering	237.4 ± 1.1^{cd}	140.4 ± 3.3^{cd}	-97.0 ± 2.2^{c}	66.8 ± 0.2^{bc}
T = 130 °C, M_{in} = 28.8% d.b., tempering time of 30 min	233.0 ± 2.8^{ab}	135.6 ± 1.6^{ab}	-97.4 ± 1.5^{c}	67.5 ± 0.4^{cd}
T = 130 °C, M_{in} = 28.8% d.b., tempering time of 120 min	230.2 ± 4.3^{a}	140.5 ± 2.2^{cd}	-89.8 ± 2.1^{d}	68.1 ± 0.2^{d}

Different superscripts in the same column mean that the values are significantly different ($p \leqslant 0.05$).

Table 4
Color of waxy rice at various drying temperatures and tempering time.

Condition	L	a	b	WI
Reference, M_{in} = 28.8% d.b.	83.3 ± 0.8^{ab}	-0.1 ± 0.0^{abc}	12.2 ± 0.2^{a}	79.4 ± 0.7^{abcd}
T = 90 °C, M_{in} = 28.8% d.b., without tempering	84.6 ± 0.4^{cdef}	-0.1 ± 0.0^{abc}	12.1 ± 0.2^{a}	80.4 ± 0.4^{ef}
T = 90 °C, M_{in} = 28.8% d.b., tempering time of 30 min	85.0 ± 0.5^{ef}	-0.1 ± 0.0^{abc}	12.4 ± 0.2^{ab}	80.4 ± 0.3^{ef}
T = 90 °C, M_{in} = 28.8% d.b., tempering time of 120 min	84.7 ± 0.2^{cdef}	-0.0 ± 0.0^{cde}	13.3 ± 0.1^{gh}	80.6 ± 0.4^{ef}
T = 110 °C, M_{in} = 28.8% d.b., without tempering	84.6 ± 0.3^{cdef}	-0.1 ± 0.0^{abc}	12.1 ± 0.2^{a}	79.8 ± 0.4^{cde}
T = 110 °C, M_{in} = 28.8% d.b., tempering time of 30 min	84.3 ± 0.6^{cde}	-0.1 ± 0.0^{abc}	12.5 ± 0.1^{abcd}	79.7 ± 0.1^{bcde}
T = 110 °C, M_{in} = 28.8% d.b., tempering time of 120 min	84.7 ± 0.3^{cdef}	-0.2 ± 0.1^{a}	12.4 ± 0.2^{abc}	80.2 ± 0.1^{ef}
T = 130 °C, M_{in} = 28.8% d.b., without tempering	83.4 ± 0.3^{ab}	-0.0 ± 0.0^{cd}	12.9 ± 0.0^{def}	80.3 ± 0.4^{ef}
T = 130 °C, M_{in} = 28.8% d.b., tempering time of 30 min	83.1 ± 0.5^{a}	0.1 ± 0.1^{de}	13.1 ± 0.4^{efgh}	78.6 ± 0.6^{a}
T = 130 °C, M_{in} = 28.8% d.b., tempering time of 120 min	83.9 ± 0.8^{abc}	0.0 ± 0.1^{bcd}	13.4 ± 0.3^{h}	79.0 ± 0.8^{abc}

Different superscripts in the same column mean that the values are significantly different ($p \leqslant 0.05$).

Table 5
Percentage of translucent kernels at various drying temperatures and tempering time.

Condition	Translucent kernel (%)
Reference, M_{in} = 28.8% d.b.	0
T = 90 °C, M_{in} = 28.8% d.b., without tempering	0
T = 90 °C, M_{in} = 28.8% d.b., tempering time of 30 min	0
T = 90 °C, M_{in} = 28.8% d.b., tempering time of 120 min	0
T = 110 °C, M_{in} = 28.8% d.b., without tempering	0
T = 110 °C, M_{in} = 28.8% d.b., tempering time of 30 min	0
T = 110 °C, M_{in} = 28.8% d.b., tempering time of 120 min	0
T = 130 °C, M_{in} = 28.8% d.b., without tempering	2.9 ± 0.2
T = 130 °C, M_{in} = 28.8% d.b., tempering time of 30 min	7.8 ± 0.0
T = 130 °C, M_{in} = 28.8% d.b., tempering time of 120 min	10.4 ± 0.3

degrees of starch gelatinization at such temperatures were indeed in the range of 14–30%. However, no significant differences between the treated samples and the reference sample were noted when the rice was dried at 90 °C and tempered for 0 and 30 min; an exception was noted when the tempering time of 120 min was used. The effect of gelatinization on the peak viscosity was also reported by Taechapairoj et al. (2004) and Jaisut et al. (2008). The decrease in the peak viscosity was closely related to the degree of gelatinization.

For the setback viscosity, the thermally treated waxy rice flour exhibited lower setback viscosity than the reference waxy rice. The tempering time and drying temperature changed the setback viscosity in such a way that an increase in the drying temperature and tempering time decreased the setback viscosity. The lowering of the setback viscosity represents firmer texture of waxy rice after drying and tempering. This result is similar to the finding of Anderson and Guraya (2006) who reported that thermal deterioration of amylopectin and amylose in starch granules during heating could cause lower peak viscosity.

3.7. Color

The WI is normally used to characterize the color of white rice and this value can be calculated by Eq. (2). The values of WI, along with the L-, a-, b-values, of waxy rice processed at different conditions are listed in Table 4. Waxy rice dried at 90 °C had higher WI than the reference sample. The higher whiteness resulted from the higher L-value of waxy rice after processing (84.6–85.0), as com-

(a) Rewetted waxy rice (opaque white kernel)

(b) Waxy rice dried at 90 °C with no tempering (opaque white kernel)

(c) Waxy rice dried at 90 °C and tempered for 120 min (opaque white kernel)

(d) Waxy rice dried at 110 °C and tempered for 120 min (opaque white kernel)

(e) Waxy rice dried at 130 °C and tempered for 120 min (opaque white kernel)

(f) Waxy rice dried at 130 °C and tempered for 120 min (translucent kernel)

Fig. 5. Scanning electron micrographs of waxy rice at various drying temperatures and tempering time.

pared to that of the reference sample. The higher *L*-value might be attributed to the shorter drying time and the gelatinization of starch. During gelatinization, starch granules collapsed and produced transparent layer, leading to a more glossy product (Iyota et al., 2001; Jamradloedluk et al., 2007). The tempering time did not affect the WI and *L*- and *a*-values when drying was performed at 90 °C; the *b*-value was affected at the tempering time of 120 min, however.

At elevated drying temperatures, however, dried waxy rice became darker relative to the sample dried at 90 °C as indicated by the lower *L*-values. The lower *L*-values at higher drying temperatures might be attributed to the yellowish pigments formation. These pigments were formed by the non-enzymatic browning reactions, hence the change of the rice color. Both the *a*- and *b*-values also increased with the drying temperature and tempering time. Due to the changes of these color parameters, the WI dropped from 80.4 at 90 °C to 79 at 130 °C, the value close to that of the reference sample.

Since there is currently no standard or guideline to evaluate the color of waxy rice, a private rice mill with several years of experience with waxy rice was consulted. Based on the practical experience of the mill, the color of all dried samples was still acceptable; dried waxy rice would not be acceptable if it has an *L*-value of lower than 84.4 ± 0.5, *a*-value of higher than 0.54 ± 0.1 and the *b*-value of higher than 15.1 ± 0.1. Based on these limiting values, the calculated WI is 78.3 ± 0.4, which is very close to the values of WI listed in Table 4. These results indicated that using WI to characterize the color of waxy rice is inappropriate since the *a*- and *b*-values are less influential to the value of WI than the *L*-value.

3.8. Translucent kernels

Normally, waxy rice has an inherent characteristic of opaque white kernel. The translucent kernel is considered abnormal or defective for waxy rice (Patindol and Wang, 2003). For a rice mill, this defect is important and causes the waxy rice quality to drop from the premium grade. Table 5 lists the percentage of translucent kernels of waxy rice processed at different conditions. The kernel translucency started to be observed at a drying temperature of 130 °C. At this temperature, the percentage of translucent kernels was approximately 3% before tempering and increased to 10% at 120 min tempering time. The occurrence of translucent kernels might possibly be due to the disruption of all starch granules as indicated in Fig. 5f. This provided a homogeneous phase in the waxy rice kernel, implying a higher degree of starch gelatinization in the translucent kernels than in the opaque ones. To confirm this hypothesis, the waxy rice starch from the translucent kernels was taken to determine the degree of starch gelatinization; the result showed a complete gelatinization (data not shown).

3.9. Microstructure

The microstructure of waxy rice samples was examined by scanning electron microscopy (SEM). The micrographs of waxy rice processed at different drying temperatures and tempering time are shown in Fig. 5a–e for opaque white kernels. The starch granules of the reference waxy rice showed characteristically irregular polygons with diameters in the range of 2–9 μm (see Fig. 5a). When waxy rice was dried at 90 °C, the morphology of most starch granules, as shown in Fig. 5b and c, was rather similar to that of the reference waxy rice although there was some starch gelatinization (3.8–10.4%). The irreversible loss of the shape was, however, evident when using drying temperatures of 110 and 130 °C (see Fig. 5d and e) and some starch granules were fused together. Such starch granule modifications enabled the kernel to withstand abrasive force during milling. Fig. 5f shows the microstructure of translucent kernel obtained under the same drying condition as that in Fig. 5e; the polygonal shape of starch granules disappeared in the translucent kernel.

4. Conclusion

Fluidized bed drying technique can be applied to dry waxy rice. Drying waxy rice at higher temperatures led to only a small drop in the head rice yield as compared to that of the reference waxy rice. The superior head rice quality was due to modification of starch granules as depicted by the scanning electron microscopy and differential scanning calorimetry. The modification of starch granules also changed the pasting properties, i.e., peak viscosity and set back viscosity. The waxy rice color after high-temperature drying was slightly darker and had a pale yellow as compared to that of the reference waxy rice. The translucent kernels occurred when drying at 130 °C and the percentage of translucent kernels increased as the sample was tempered. From the above quality point of view, it is recommended that the drying temperature must be lower than 130 °C in order to prevent the formation of translucent kernels.

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Effect of high-temperature fluidized-bed drying on cooking, textural and digestive properties of waxy rice

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ABSTRACT

In this work, changes of the cooking and pasting properties as well as starch digestibility of waxy rice (RD6) during hot air fluidized bed drying were investigated. Re-moistened waxy rice at an initial moisture content of 28% dry basis (d.b.) was dried at 90–150 °C. Semi-dried waxy rice was tempered and dried again by ambient air until the moisture content reached 16% (d.b.). It was found that the degree of gelatinization increased with an increase in the drying temperature. At 130 and 150 °C the appearance of some waxy rice kernels changed from opaque to translucent, indicating complete gelatinization. Thermal degradation of amylopectin granules during high-temperature drying caused the starch to be more rapidly digested; this led to lower peak viscosity and setback viscosity. In addition, waxy rice processed at higher drying temperatures (90–150 °C) could adsorb more water and exhibited larger loss of solids during soaking. Such effects subsequently led to samples with lower hardness and higher stickiness. Based on the sensory analysis results, however, waxy rice dried at the above temperatures, when cooked, did not significantly differ in overall acceptability from the reference waxy rice.

1. Introduction

Waxy rice (*Oryza sativa*), which is sometimes called glutinous or sweet rice, is characterized by the opaque appearance and very low amylose content. Waxy rice is used as a raw material for producing a wide variety of products such as sweet rice cake and rice pudding. It is also consumed in the form of steamed rice in some South East Asian countries including Thailand, where it is mainly consumed in the northern and northeastern parts (Keeratipibul et al., 2008). Waxy rice after harvesting is typically sun dried on a concrete pad or by an LSU dryer. Such drying methods may nevertheless take long time. To enhance the drying rate, high-temperature drying is frequently used (Tirawanichakul et al., 2004; Prachayawarakorn et al., 2005; Jaiboon et al., 2009). However, high-temperature drying via an LSU dryer may not be appropriate for rice since a contact between grains and drying medium is generally poor.

Fluidized bed drying technique, on the other hand, may be an alternative method because this drying technique provides good mixing and excellent heat and mass transfer between grains and drying medium. Fluidized bed drying not only gives higher drying rate but has also proved to, in some cases, yield dried rice with higher quality. For example, it was shown that rough rice dried at higher temperatures in a fluidized bed dryer (>100 °C) had higher head rice yield than rice dried in shade (Tirawanichakul et al., 2004; Prachayawarakorn et al., 2005). In addition, the textural properties of rice after cooking were found to be similar to those of aged rice, i.e., firmer texture and less sticky (Soponronnarit et al., 2008). Such changes in the cooking properties are, however, the characteristics of rice containing high amylose, which can form a gel network during gelatinization. On the other hand, in the case of waxy rice, which mostly contains amylopectin, formation of a gel network is more difficult. Information on the cooking properties of waxy rice dried at high temperature is also still extremely limited.

In addition to the cooking properties, starch digestibility is also important as this information can be used to quantitatively describe the effect of starch-rich food consumption on postprandial glucose in the blood (Shu et al., 2009). Waxy rice is known to have high glycemic response as compared with other high-amylose rice varieties (Frei et al., 2003; Hu et al., 2004). When moist waxy rice starch granules are dried, inter- and intra-molecular hydrogen bonds between starch chains are disrupted, leading to swelling and disintegration of the granules. The accessibility of the digestive enzymes to the starch chains thus increases as gelatinization progresses (Chung et al., 2006). This in turn leads to more rapid starch digestion and subsequent higher glycemic index of the waxy rice.

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During high-temperature drying, however, starch may not be fully gelatinized due to limited water content in rice; thus a proportion of starch granules remain. It would be interesting to know the postprandial response of partially gelatinized starch.

The aim of this investigation was to study the effect of high-temperature fluidized bed drying on the cooking properties, kernel morphology, rice flour pasting properties and starch digestibility of waxy rice. The cooking quality was considered in terms of water uptake and solid loss, while the textural properties were assessed in terms of the hardness and stickiness. In addition, chain length distributions of amylopectin within waxy rice and consumer acceptability were also evaluated.

2. Materials and methods

2.1. Hot air fluidized bed dryer

Fig. 1 shows a schematic diagram of a hot air fluidized bed dryer and its accessories. The system consists of three major components: a cylindrical drying chamber with an inner diameter of 20 cm and a height of 140 cm; 12 kW electrical heaters with a temperature controller; and a backward-curved-blade centrifugal fan, which is driven by a 1.5 kW motor. Exhaust air can be recycled, if needed, by means of two butterfly valves.

2.2. Materials

Dry long grain rough waxy rice (RD6) was provided by the Rice Research Institute, Ubon Ratchathani province, Thailand. The rice was re-moistened, mixed and kept in cold storage at 4–6 °C for 7 days prior to an experiment. The initial moisture content of the re-moistened waxy rice was 28.8% dry basis (d.b.). The RD6 has amylose content in the range of 4–6% (Noomhorm et al., 1997; Varavinit et al., 2003). Before starting each experiment, the waxy rice samples were brought into thermal equilibrium with ambient temperature ($T \sim 30$ °C).

2.3. Drying of waxy rice

A batch of 1.9 kg of re-moistened sample was dried in the fluidized bed dryer. The experiments were carried out at temperatures of 90, 110, 130 and 150 °C at a superficial air velocity of 2.5 m/s, as recommended by Soponronnarit and Prachayawarakorn (1994). The desired moisture content after fluidized bed drying was 22–24% (d.b.). Semi-dried waxy rice was then tempered for either 30 or 120 min in order to reduce moisture stresses created during drying. In the tempering step, the sample was kept in a closed jar to avoid moisture loss. After the tempering step, the sample was ventilated with ambient air (temperature and relative humidity of 30 °C and 55–60%, respectively) in a thin-bed ventilator with a static bed depth of around 3.5 cm until the moisture content of the sample reached 16% (d.b.) (ventilation time was around 30–40 min). After that the sample was kept in a sealed plastic bag at 4–6 °C for 2 weeks before quality analysis. The quality of waxy rice obtained from the above processing conditions was also compared with that of a reference sample, obtained by shade drying.

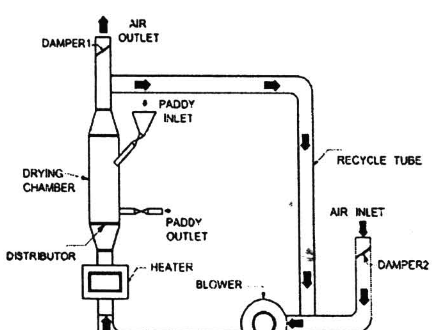

Fig. 1. A schematic diagram of a batch hot air fluidized bed dryer.

2.4. Moisture content evaluation

Moisture content of rough waxy rice was determined by drying 50 g of rough waxy rice sample at 103 °C for 72 h in a hot air oven (Memmert, ULE500, Schwabach, Germany).

2.5. Microstructure evaluation

The microstructure of each sample was observed with help of scanning electron microscopy (SEM). A waxy rice kernel was cut along its cross-sectional axis, attached to an SEM stub and coated with gold by a sputter-coater. The coated sample was then photographed using a scanning electron microscope (JSM, JSM-5600LV, Tokyo, Japan) at an accelerating voltage of 15 kV. The inspected location of the kernel was between the kernel surface and the endosperm centre.

2.6. Thermal property evaluation

Waxy rice flour was prepared by grinding waxy rice with an ultra centrifugal mill (Retsch, ZM 100, Haan, Germany) and passing through a 0.25-mm screen (the moisture content of flour was 16% (d.b.)). Thermal analysis of the flour was performed using a differential scanning calorimeter (Perkin Elmer, DSC-7, Norwalk, CT). The waxy rice flour (3 mg) was accurately weighed into an aluminium DSC pan; 10 μL of distilled water was added and the pan was hermetically sealed. The sample was left to stand for 1 h at room temperature (25 °C) before DSC scanning. Indium was used to calibrate the DSC and an empty pan was used as a reference. All samples were heated from 40 to 100 °C at a scanning rate of 10 °C/min. The major parameters of each DSC profile were described as onset temperature, peak temperature and conclusion temperature. From the DSC profile, the transition enthalpy was determined and the degree of gelatinization of waxy rice flour was then calculated by the following equation:

$$DG(\%) = \left(1 - \left[\frac{\Delta H}{\Delta H_c}\right]\right) \times 100 \qquad (1)$$

where DG is the degree of gelatinization, ΔH is the transition enthalpy of processed waxy rice flour (J/g (dry matter)) and ΔH_c is the transition enthalpy of raw waxy rice flour (J/g (dry matter)). All experiments were performed in duplicate and the average values are reported.

2.7. Amylopectin chain length distributions evaluation

Amylopectin was de-branched by isoamylase enzyme (Hayashibara Biochemical Laboratories, Okayama, Japan) according to the method of Jane and Chen (1992). The amylopectin branch chain length distributions were analyzed using a high-performance anion-exchange chromatography system equipped with a pulsed amperometric detector (HPAEC-PAD) (Dionex, DX-120, Sunnyvale, CA). HPAEC-PAD consists of a GS50 gradient pump, AS50 automated sampler, ED50 electrochemical detector, CarboPac PA-1 analytical column (2 × 250 mm) and CarboPac PA-1 guard column (2 × 50 mm). The electrochemical detector, with a gold working electrode versus a $Ag/AgCl_{(sat)}$ reference electrode, was operated at the following waveform: $E_1 = 0.05$ V ($t_1 = 0$ s), $E_2 = 0.05$ V ($t_2 = 0.2$ s), $E_3 = 0.05$ V ($t_3 = 0.4$ s), $E_4 = 0.75$ V ($t_4 = 0.41$ s), $E_5 = 0.75$ V ($t_5 = 0.6$ s), $E_6 = -0.15$ V ($t_6 = 0.61$ s) and $E_7 = -0.15$ V ($t_7 = 1.0$ s). The injection volume was 20 µL and elution of the components in the hydrolysate was carried out with 150 mM sodium hydroxide as eluent A and 150 mM sodium hydroxide in 500 mM sodium acetate solution as eluent B. The eluents were prepared with 18 MΩ cm deionized water and filtered through a 0.45 µm membrane filter (Simona, PVDF, Kirn, Germany). The gradient profiles of eluent A:B were 75:25% at 0 min, 60:40% at 7 min, 10:90% at 67 min, 0:100% at 67.1 min and 0:100% at 85 min. The eluent gradients were operated at ambient temperature at a flow rate of 0.3 mL/min. The chain length distributions were represented as a percentage of the total peak area and the detector response when the degree of polymerization was disregarded. All experiments were performed in triplicate and the average values are reported.

2.8. Water uptake evaluation

Twenty g of milled waxy rice was soaked in 100 mL of distilled water for 16 h at room temperature. The soaked waxy rice was then drained to remove excess water and weighed. An increase in the mass was calculated and is reported as the percentage water uptake (Bean et al., 1984). All experiments were performed in triplicate and the average values are reported.

2.9. Solid loss evaluation

The drained water from the waxy rice soaking process was collected in a pre-weighed Erlenmeyer flask and evaporated at 105 °C for 24 h. The sample was cooled in a desiccator for 45 min and then weighed again. An increase in the mass of the Erlenmeyer flask divided by the mass of the waxy rice sample (20 g) was then defined as the solids loss:

$$\text{Solid loss}(\%) = \frac{\text{Increased mass of Erlenmeryer flask}}{\text{Mass of waxy rice sample}} \times 100 \quad (2)$$

All experiments were performed in triplicate and the average values are reported.

2.10. Cooking method

Before cooking waxy rice was washed and soaked for 16 h in water at room temperature and then drained. Soaked milled waxy rice was steamed over boiling water in a perforated steamer for 30 min and then allowed to stand at ambient condition for 10 min prior to further analysis (Juliano, 1985).

2.11. Textural properties evaluation

Hardness and stickiness of cooked waxy rice were determined by a texture analyzer (Stable Micro System, TA XT Plus, Surrey, UK). Six kernels of each cooked waxy rice sample were placed on aluminium plate. A cylindrical probe with a diameter of 50 mm was used to compress the kernels to 90% deformation at the test speed and posttest speed of the probe of 0.5 and 1 mm/s, respectively. The hardness of the cooked waxy rice defined as the maximum force on the first compression while the stickiness was recorded as the negative force of the first cycle (during the pulling out of the cylindrical probe). All experiments were performed in triplicate and the average values are reported.

2.12. Pasting property evaluation

Pasting properties of waxy rice flour (with an average particle size of 125 µm) were determined using a Rapid Visco Analyzer (RVA) (Newport Scientific, RVA-4, Warriewood, Australia) following the standard method AACC 61-02 (AACC, 1995). Waxy rice flour (3 g on dry basis) was poured into distilled water (25 mL) in a canister and mixed thoroughly. The mixture was stirred at 960 rpm during the first 10 s and then changed to 160 rpm for the rest of the analysis. The temperature of the slurry was first maintained at 50 °C for 1.5 min and then raised to 95 °C at a rate of 12 °C/min. After that the temperature was maintained at 95 °C for 2.5 min, followed by a cooling to 50 °C at 12 °C/min; the temperature was then maintained at 50 °C for 2.1 min. The total time of an experiment was 12.5 min. A plot of the pasting viscosity in an arbitrary RVA unit (RVU) versus time was then made. The peak viscosity, which was obtained from the pasting curve, indicates the water-binding capacity of the mixture and is often correlated with the final product quality; it also provides an indication of the viscous load likely to be encountered by cooking. Setback viscosity (final viscosity – peak viscosity) is used as an indicator of gelling or retrogradation tendency of the waxy rice. All experiments were performed in triplicate and the average values are reported.

2.13. Digestibility evaluation

Waxy rice starch digestibility was analyzed according to the method proposed by Goni et al. (1997). A sample of 50 mg of waxy rice was prepared in 30-mL Erlenmeyer flask with 4 mL of distilled water. The sample was then cooked for 30 min. Subsequently, 10 mL of KCl–HCl buffer at pH 1.5 was added; the sample was homogenized for 2 min using an Ultra Turrax homogenizer (IKA Labortechnik, T25, Staufen, Germany). After that 0.2 mL of a solution containing 1 mg of pepsin from porcine stomach mucosa (Sigma, P-7000, St. Louis, MO) in 10 mL of KCl–HCl buffer at pH 1.5 was added into the sample. The sample was placed in a shaking water bath (Heto-Holten A/S, SBD50, Allerød, Denmark) at 40 °C for 60 min. The volume of the sample was then adjusted to 25 mL by adding 15 mL of tris-maleate buffer (pH 6.9). Before starting the starch hydrolysis 5 mL of tris-maleate buffer containing 2.6 IU of α-amylase from *Bacillus* species (Sigma, A-6814, St. Louis, MO) were added to the sample. The flask was placed in a shaking water bath at 37 °C. Aliquot (0.1 mL) was taken out from the flask at every 30 min interval for a total time of 180 min. The sample was then placed in boiling water for 5 min to inactivate α-amylase. One mL of 0.4 M sodium-acetate buffer at pH 4.75 and 30 µL of amyloglucosidase from *Aspergillus niger* (Sigma, A9913-10 mL, St. Louis, MO) were added to hydrolyze the soluble starch and the sample was incubated at 60 °C for 45 min. Finally, the glucose concentration was measured using the glucose oxidase-peroxidase kit (Sigma Chemical Co., G3660-1CAP, St. Louis, MO). The rate of starch digestion was defined as the percentage of the total starch hydrolyzed at different times (30, 60, 90, 120, 150 and 180 min). All experiments were performed in duplicate and the average values are reported. The following equation, established by Goni et al. (1997), was used to describe the kinetics of the starch hydrolysis:

$$C = C_\infty(1 - e^{-kt}) \quad (3)$$

where C, C_∞ and k are the percentage of starch hydrolyzed at time t, percentage of starch hydrolyzed at 180 min and kinetic constant, respectively. The area under the hydrolysis curve (AUC) was calculated by following equation:

$$\text{AUC} = C_\infty(t_f - t_0) - \left(\frac{C_\infty}{k}\right)(1 - \exp(-k(t_f - t_0))) \quad (4)$$

where t_0 and t_f are the initial time (0 min) and the final time (180 min), respectively. A hydrolysis index (HI) was obtained by dividing the area under the hydrolysis curve of the sample by that of fresh white bread (Goni et al., 1997). The glycemic index of a sample was then estimated according to Goni et al. (1997) as:

$$GI = 39.71 + 0.549HI \quad (5)$$

2.14. X-ray diffraction analysis

X-ray diffraction (XRD) patterns of dried waxy rice flour were obtained using a Bruker AXS D8 DISCOVER XRD (Bruker AXS GmbH, Karlsruhe, Germany) under the following conditions: 40 kV and 40 mA with CuKα radiation at a wavelength of 0.1546 nm with a scanning rate of the diffraction angle 2θ of 2°/min. A sample of 0.5 g of dried waxy rice flour was placed in a holder. The relative intensity of the diffraction peak was recorded in the scattering range (2θ) of 4–40° and the crystallinity (X_c) of the sample was calculated by:

$$X_c = \frac{A_c}{A_c + A_a} \times 100\% \quad (6)$$

where A_c and A_a are the areas of crystalline and noncrystalline regions, respectively.

2.15. Sensory evaluation

For determination of the cooking quality, 300 g of waxy rice were washed and soaked for 16 h in distilled water at room temperature and then drained. Soaked milled waxy rice was steamed over boiling water in a perforated steamer for 30 min. The quality of cooked waxy rice was evaluated on the basis of its palatability. Eleven trained panelists from the Pathum Thani Rice Research Center, Pathum Thani province, Thailand, were invited to evaluate the odor, color, glossiness, stickiness, hardness and overall acceptability of the cooked waxy rice using a nine-point hedonic scale of 1–9 as described in Table 1.

2.16. Statistical analysis

All data were subjected to the analysis of variance (ANOVA) using SPSS® software and are presented as mean values with standard deviations. Differences between mean values were established using Duncan's multiple range tests at a confidence level of 95% ($p < 0.05$).

3. Results and discussion

3.1. Microstructure and thermal properties of dried waxy rice

Based on visual observation waxy rice samples appeared different when dried at different temperatures. The dried waxy rice had opaque white kernels when dried at 90 °C, a characteristic which is similar to the native waxy rice. When waxy rice was dried at higher temperatures, a small number of kernels appeared translucent. The percentage of translucent kernels, defined as the number of translucent kernels divided by the total number of kernels, was 7.8% and 14.9% when the drying temperature was 130 and 150 °C, respectively. The formation of translucent kernels might be caused by modification of starch granules during drying. Fig. 2 shows the morphologies of starch granules belonging to the samples dried at different temperatures. It is seen that the translucent kernel shown in Fig. 2d (drying temperature of 150 °C) did not have any starch granules left, whilst the opaque white kernel shown in Fig. 2c still contained some starch granules. These results indicated that starch granule disappearance led to homogenous phase or absence of air spaces inside a kernel, allowing some light to transmit through the kernel, which in turn resulted in the observed translucency.

When a drying temperature of 90 °C was used, the starch morphology of the opaque white kernel was insignificantly different from that of the native waxy rice kernel, exhibiting an irregular polygonal shape. At a drying temperature of 150 °C, however, the starch granule characteristics of the dried opaque waxy rice kernel were different from those of the reference kernel: the polygonal starch granule shape was less defined and some starch granules were disrupted. It was therefore expected that the amorphous region destabilized, adsorbed water, swelled and disrupted. Swelling imposed stress upon amylopectin crystallites; this caused amylopectin double helices within the crystallites to dissociate, leading to the breakdown of the integrity of the starch granules (Donald, 2004).

Table 2 shows the thermal properties results of the translucent and opaque waxy rice flour. The translucent waxy rice flour was obtained at a drying temperature of 150 °C. From a DSC thermogram, the characteristic temperatures of the translucent kernel, i.e., the onset, peak and conclusion temperatures were not found, indicating that the kernel translucency after drying was caused by complete gelatinization. This result agreed well with the SEM results shown in Fig. 2d.

For the opaque kernels obtained at different drying temperatures, it was noted that the characteristic temperatures of the dried waxy rice flour changed significantly from that of the native flour, implying the modification of waxy rice starch thermal properties after drying. The onset temperature, for example, increased for the dried waxy rice. Such a change in the thermogram was related to the corresponding enthalpy change. The enthalpies of the waxy rice dried at higher temperatures were lower and the corresponding higher degrees of starch gelatinization were observed.

As shown in Table 2, the tempering time affected starch gelatinization. The starch gelatinization of the sample dried at 90 °C was 4.8% at 30-min tempering time and increased to 10.4% when the tempering time increased to 120 min; this result could improve the head rice quality (Jaiboon et al., 2009). At other drying temperatures, the dried waxy rice samples obtained at 120-min tempering time were not taken to determine their thermal properties since the head rice of the samples dried at such conditions was the same as that of the sample tempered for 30 min as reported by Jaiboon et al. (2009). The waxy rice obtained by drying at 90 °C and tempering for 120 min was therefore chosen for subsequent quality tests.

Table 1
Meaning of hedonic scores (1–9) of each sensory parameter.

Score	Whiteness	Glossiness	Stickiness	Hardness	Overall
9	White	Very glossy	Very sticky	Very hard	Extremely like
7	Creamy white	Moderately glossy	Moderately sticky	Moderately hard	Moderately like
5	Slightly brown	Slightly glossy	No sticky-no separated	Not hard-not tender	Neither like nor dislike
3	Moderately brown	Moderately dull	Moderately separated	Moderately tender	Moderately dislike
1	Brown	Very dull	Well separated	Very tender	Extremely dislike

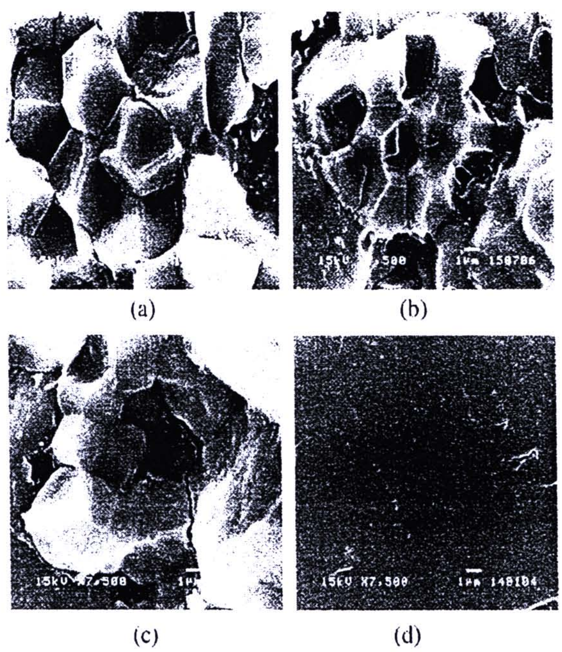

Fig. 2. Morphologies of reference waxy rice, opaque waxy rice and translucent waxy rice processed under different conditions: (a) Reference waxy rice (opaque white kernel). (b) Waxy rice dried at 90 °C and tempered for 30 min (opaque white kernel). (c) Waxy rice dried at 150 °C and tempered for 30 min (opaque). (d) Waxy rice dried at 150 °C and tempered for 30 min (translucent).

Table 2
Thermal property of waxy rice flour processed under different conditions.

Processing condition	Transition temperature (°C)			ΔH (J/g)	Degree of gelatinization (%)
	T_{onset}	T_{peak}	$T_{conclude}$		
Reference (opaque)	61.1 ± 0.0	68.5 ± 0.0	76.8 ± 0.05	6.8	0
T = 90 °C, t = 30 min (opaque)	62.0 ± 0.0	70.0 ± 0.05	78.4 ± 0.05	6.5	4.8
T = 90 °C, t = 120 min (opaque)	62.8 ± 0.05	70.6 ± 0.05	78.4 ± 0.0	6.1	10.4
T = 110 °C, t = 30 min (opaque)	62.3 ± 0.0	69.7 ± 0.0	78.2 ± 0.05	5.4	20.8
T = 130 °C, t = 30 min (opaque)	61.9 ± 0.05	69.5 ± 0.05	78.4 ± 0.0	5.0	26.4
T = 150 °C, t = 30 min (opaque)	62.9 ± 0.0	70.9 ± 0.0	79.2 ± 0.05	4.4	35.4
T = 150 °C, t = 30 min (translucent)	-	-	-	-	100

T = drying temperature (°C), t = tempering time (min).

3.2. Chain length distributions of amylopectin

Fig. 3 displays the chain length distributions of amylopectin within the reference and dried waxy rice samples. The amylopectin branch chains in waxy rice could be classified into short chains (DP6-12, DP13-24) and long chains (DP25-36, DP37-49) (Bertoft, 2004). The highest proportion of amylopectin branch chains in the present waxy rice samples was found at DP13-24, which was accounted for 53.5–53.9%, while the smallest proportion was found at DP37-49 (3.0–3.2%). Highest proportion of short chains (DP13-24) tended to lead to samples having soft texture after cooking (Ong and Blanshard, 1995; Nakamura et al., 2006). The chain length distributions of amylopectin in the samples after drying were not different from that of the reference sample, indicating that the gelatinization that occurred during drying did not change the amylopectin chains.

3.3. Water uptake and solid loss of waxy rice

Table 3 shows the values of the water uptake and solid loss of opaque and translucent waxy rice samples. The water uptake and solid loss of the reference waxy rice sample were 33.7% and 2.4%, respectively. The water uptake and solid loss of opaque kernel samples after drying increased significantly; higher drying temperatures resulted in larger values of both water uptake and solid loss. On the other hand, the tempering time did not significantly affect any of the cooking properties of the sample dried at 90 °C. This is due to the fact that the increase in the degree of gelatinization at

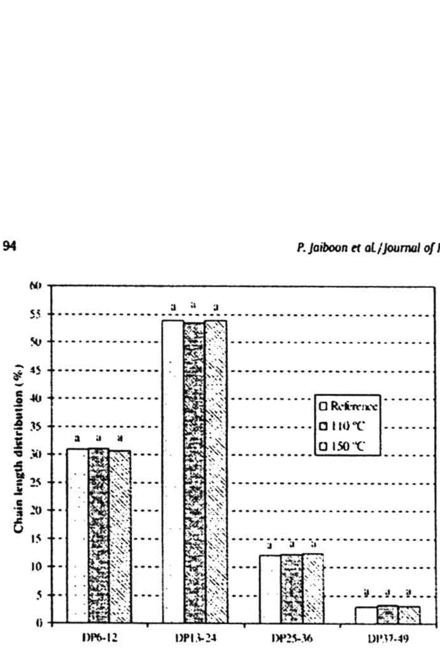

Fig. 3. Chain length distributions of amylopectin in waxy rice starch. Similar superscripts in the same group imply that the values are not significantly different ($p < 0.05$).

tempering time of both 30 and 120 min might be so small that it had no significant effect on any of the cooking properties of waxy rice dried at 90 °C. For the translucent waxy rice sample, it was not possible to determine the amount of water uptake because the kernel collapsed as a result of starch leaching into the soaking water; the collapse was due to disruption of the crystalline region along with the fact that the waxy rice mainly consists of short amylopectin chains (as can be seen in Fig. 3), resulting in waxy rice being easily hydrolyzed during soaking.

The water uptake and solid loss of waxy rice samples seemed to increase with an increase in the degree of starch gelatinization. During gelatinization starch granules disrupt but in the case of RD6 waxy rice gel network could not be easily formed since the amylopectin in the RD6 mainly consists of short chains (see also Fig. 3). Hence, when soaking, waxy rice starch could simply absorb water and be hydrolyzed, resulting in larger water uptake and subsequently higher solid loss. This implies that as the degree of starch gelatinization increased waxier starch gel was exposed to water, leading to more solid loss. The solid loss results of the waxy rice samples were not similar to those of rice with high amylose content, i.e., 15% or higher (Soponronnarit et al., 2008; Gujral and Kumar, 2003); the amount of solid loss decreased significantly when the high-amylose rice gelatinized partially or completely.

3.4. Textural properties of cooked waxy rice

The hardness and stickiness values of cooked waxy rice samples are shown in Table 3. The hardness and stickiness of the cooked reference sample were 52.1 and 0.9 N, respectively. The hardness of cooked waxy rice was noted to be significantly lower than that of the rice containing higher amylose content (Singh et al., 2005), implying the soft texture of cooked waxy rice. This is because RD6 has a large amount of short amylopectin chains as mentioned earlier. Drying temperature had a strong effect on the hardness and stickiness of the cooked samples; higher drying temperatures caused lower hardness and higher stickiness. This corresponded to the water uptake and solid loss result mentioned in Section 3.3. The textural information of the translucent cooked waxy rice was not available for the reason mentioned in the previous section.

3.5. Pasting properties of waxy rice flour

Four major pasting properties, i.e., peak, final and setback viscosities as well as the pasting temperature are reported in Table 4 for both translucent and opaque waxy rice samples. Peak viscosity and pasting temperature of waxy rice flour from a sample dried at 90 °C and tempered for 30 min insignificantly changed from the values of the reference sample, whilst the final and setback viscosities were noted to be sensitive at this drying temperature; the setback viscosity significantly decreased whereas the final viscosity significantly increased. At drying temperatures higher than 90 °C, the peak and setback viscosities significantly decreased from those of the reference sample. The decrease in the peak viscosity after drying indicated a reduced swelling capacity of starch granules due to the disruption of starch granules (Pukkahuta et al., 2008). As shown in Table 4, the translucent waxy rice flour from a sample dried at 150 °C did not seem to have any starch granules left and hence the lowest peak viscosity. On the other hand, the opaque waxy rice obtained at the same drying temperature as the translucent rice showed a significantly higher peak viscosity.

Setback viscosity is commonly used to describe an increase in the viscosity that occurs upon cooling of a pasted starch (Anderson and Guraya, 2006). As shown in Table 4, drying at higher temperatures resulted in lower values of the setback viscosity, implying less re-association of amylopectin branch chains in the waxy rice. From these results, it is possible to conclude that the re-association of amylopectin branch chains was the lowest for the translucent waxy rice, with the lowest value of the setback viscosity of −26.9 ± 8.1 RVU.

3.6. Hydrolysis of waxy rice starch

The starch hydrolysis curves of various samples are shown in Fig. 4. It was found that the starch hydrolysis of all samples reached the maximum at the digestion time of around 30 min. A reference waxy rice sample showed the lowest total starch hydrolysis with the value of 70.2%. The starch hydrolysis was higher for the samples dried at higher drying temperatures. As shown in

Table 3
Cooking properties of milled waxy rice and textural properties of cooked waxy rice processed under different conditions.

Processing condition	Cooking properties of milled waxy rice		Textural properties of cooked waxy rice	
	Water uptake (%)	Solid loss (%)	Hardness (N)	Stickiness (N)
Reference (opaque)	33.7 ± 0.6^{a}	2.4 ± 0.0^{a}	52.1 ± 4.2^{a}	0.9 ± 0.6^{a}
T = 90 °C, t = 30 min (opaque)	37.8 ± 0.6^{b}	2.9 ± 0.2^{b}	49.4 ± 3.6^{ab}	1.1 ± 0.5^{a}
T = 90 °C, t = 120 min (opaque)	39.3 ± 0.2^{b}	3.1 ± 0.0^{b}	45.0 ± 6.2^{abc}	1.3 ± 0.5^{ab}
T = 110 °C, t = 30 min (opaque)	43.6 ± 1.4^{c}	3.6 ± 0.2^{c}	43.4 ± 1.2^{bc}	1.6 ± 0.6^{ab}
T = 130 °C, t = 30 min (opaque)	49.5 ± 1.5^{c}	5.4 ± 0.1^{d}	37.7 ± 2.3^{c}	2.0 ± 0.1^{b}
T = 150 °C, t = 30 min (opaque)	55.7 ± 1.9^{d}	6.6 ± 0.2^{e}	30.6 ± 3.2^{d}	2.0 ± 0.1^{b}
T = 150 °C, t = 30 min (translucent)	N/A	100	N/A	N/A

T = drying temperature (°C), t = tempering time (min), N/A = not available.
Different superscripts in the same column mean that the values are significantly different ($p < 0.05$).

Table 4
Pasting properties of waxy rice flour processed under different conditions.

Processing condition	Peak viscosity (RVU)	Final viscosity (RVU)	Setback viscosity (RVU)	Pasting temperature (°C)
Reference (opaque)	248.0 ± 0.3^{f}	131.4 ± 0.5^{a}	-116.6 ± 0.6^{a}	65.2 ± 0.5^{b}
$T = 90$ °C, $t = 30$ min (opaque)	245.7 ± 1.0^{ef}	142.9 ± 1.2^{d}	-102.8 ± 2.0^{b}	65.3 ± 0.4^{b}
$T = 90$ °C, $t = 120$ min (opaque)	242.5 ± 4.5^{de}	143.8 ± 1.3^{d}	-98.7 ± 3.3^{bc}	65.3 ± 0.6^{b}
$T = 110$ °C, $t = 30$ min (opaque)	241.2 ± 1.2^{d}	140.2 ± 1.3^{c}	-101.0 ± 2.5^{bc}	66.6 ± 0.4^{c}
$T = 130$ °C, $t = 30$ min (opaque)	233.0 ± 2.8^{c}	135.6 ± 1.6^{b}	-97.4 ± 1.5^{c}	67.5 ± 0.4^{d}
$T = 150$ °C, $t = 30$ min (opaque)	225.0 ± 0.2^{b}	136.1 ± 0.7^{b}	-88.9 ± 0.9^{d}	68.9 ± 0.3^{e}
$T = 150$ °C, $t = 30$ min (translucent)	213.4 ± 8.8^{a}	186.5 ± 1.0^{e}	-26.9 ± 8.1^{e}	62.4 ± 0.1^{a}

T = drying temperature (°C), t = tempering time (min).
Different superscripts in the same column mean that the values are significantly different ($p < 0.05$).

Fig. 4, the translucent waxy rice sample, with complete gelatinization, showed the highest starch hydrolysis.

Table 5 shows the values of the estimated parameters C_∞ and k the hydrolysis index (HI) and the glycemic index (GI) of the samples dried under different conditions. All hydrolysis parameters of the fluidized bed dried waxy rice samples were higher than those of the reference waxy rice. The GI of the reference waxy rice sample was 108, implying a more rapid starch digestion than white bread (GI = 100). This GI value of RD6 was similar to that reported for Karaya (GI = 109.2) and Yunuo No. 1 (GI = 106.3) waxy rice cultivars as reported by Frei et al. (2003) and Hu et al. (2004), respectively. The value of GI increased by 1% for the waxy rice dried at 90 °C and 8% at 150 °C. In the case of the translucent kernel, which occurred due to complete gelatinization, it was found that the GI value increased by up to 16%. The reason why the GI value of dried waxy rice was higher was the gelatinization of the starch (Chung et al., 2006). When the waxy rice starch granules were dried at higher temperature, more crystalline region disrupted, thus allowing more digestive enzyme to attack the substrate.

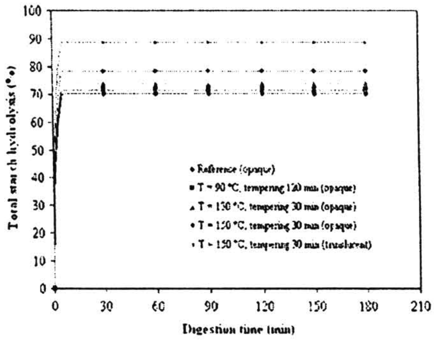

Fig. 4. *In vitro* starch hydrolysis of reference and waxy rice processed under different conditions.

3.7. X-ray diffraction patterns of waxy rice

Fig. 5 illustrates the X-ray diffraction patterns of waxy rice both before and after drying. The reference waxy rice flour exhibited an A-type pattern with diffraction peaks at 2θ = 17 and 18°, together with individual peaks at 2θ = 15 and 23°. This result was similar to those of non-waxy rice starch varieties as reported by Ong and Blanshard (1995). The degree of crystallinity was 17.7% for the reference waxy rice, while the value became smaller after drying. Drying at higher temperatures could destroy more crystalline structure, resulting in lower degrees of crystallinity. It is indeed seen in Fig. 5 that the degrees of crystallinity of opaque waxy rice were 16.8%, 15.9% and 15.2% when the drying temperatures of 90, 130 and 150 °C were used, respectively. The drying temperature in the range of 90–130 °C led to insignificantly different degree of crystallinity when comparing with the reference rice; on the other hand, drying at 150 °C led to a significantly different degree of crystallinity. For the translucent sample, the crystalline domains could not at all be detected.

3.8. Correlations between degree of gelatinization and GI and degree of crystallinity

The correlations between the degree of gelatinization and *in vitro* starch digestibility as well as degree of crystallinity are shown in Fig. 6. The values of GI and degree of crystallinity correlated well with the degree of gelatinization as indicated by the higher R^2-values of 0.98 and 0.93, respectively. From these results, it could be concluded that more disruption of the crystalline regions in the waxy rice starch led to higher enzymatic accessibility, resulting in the increase in the GI value; the GI value correlated positively with the degree of gelatinization, but negatively with the degree of crystallinity.

3.9. Sensory evaluation of cooked waxy rice

Table 6 shows the results of sensory evaluation of cooked waxy rice properties, i.e., whiteness, glossiness, stickiness, hardness and overall acceptability. Cooked waxy rice samples used for the sensory evaluation were specifically selected and only the opaque

Table 5
Model parameters, hydrolysis index (HI) and average glycemic index (GI) of waxy rice starch samples.

Processing condition	C_∞ (%)	k (min^{-1})	HI	GI
Reference (opaque)	70.2	0.83	125.5 ± 2.8^{a}	108.6 ± 1.6^{a}
$T = 90$ °C, $t = 120$ min (opaque)	71.8	0.83	127.5 ± 1.4^{ab}	109.7 ± 0.8^{ab}
$T = 130$ °C, $t = 30$ min (opaque)	73.8	0.92	132.1 ± 1.8^{b}	112.2 ± 1.0^{b}
$T = 150$ °C, $t = 30$ min (opaque)	78.4	0.95	140.3 ± 0.2^{c}	116.7 ± 0.1^{c}
$T = 150$ °C, $t = 30$ min (translucent)	88.6	0.98	158.6 ± 6.0^{d}	126.6 ± 3.3^{d}

T = drying temperature (°C), t = tempering time (min).
Different superscripts in the same column mean that the values are significantly different ($p < 0.05$).

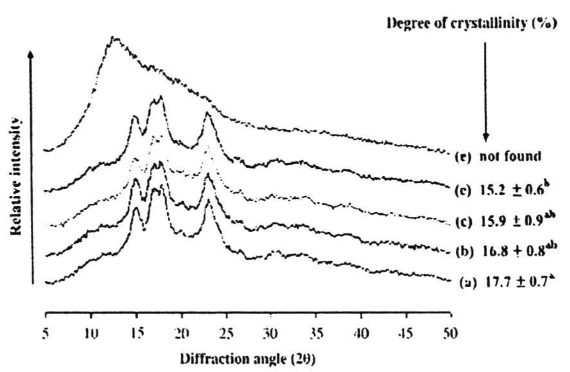

Fig. 5. X-ray diffraction patterns of waxy rice flour. (a) Reference (opaque); (b) T = 90 °C, t = 120 min (opaque); (c) T = 130 °C, t = 30 min (opaque); (d) T = 150 °C, t = 30 min (opaque); (e) T = 150 °C, t = 30 min (translucent) (T = drying temperature (°C), t = tempering time (min)).

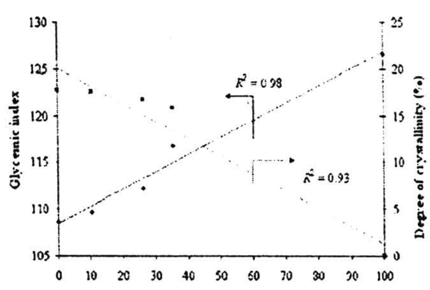

Fig. 6. Correlation between degree of gelatinization and GI as well as degree of crystallinity.

kernels were evaluated. The results indicated that the whiteness, glossiness and stickiness of the fluidized bed dried waxy rice were not significantly different from those of the reference sample. The fluidized bed dried waxy rice after cooking was creamy white, relatively glossy and rather sticky. In contrast, the drying temperature had a significant effect on the hardness of cooked waxy rice. The cooked waxy rice was tender when it was dried at temperatures above 110 °C. This result corresponded to those obtained instrumentally. Overall, the fluidized bed dried waxy rice, upon cooking, was acceptable and was noted to be not significantly different from the reference sample. The overall acceptability was in the range of 6.6–7.2, indicating that the panelists moderately liked the cooked waxy rice samples.

4. Conclusion

High-temperature fluidized-bed drying caused starch to gelatinize; higher degree of waxy rice starch gelatinization was observed at higher drying temperatures. Drying at temperatures of 130 and 150 °C changed the appearance of some waxy rice from opaque to translucent. The decrease in the crystallinity or the increase in the degree of starch gelatinization, in turn, affected the cooking properties, starch digestion and viscoelastic properties. The water uptake, solid loss and GI increased with an increase in the drying temperature, while the hardness of cooked waxy rice decreased. The overall acceptability of the waxy rice dried at different temperatures was not different from that of the reference waxy rice obtained by shade drying.

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Table 6
Sensory evaluation results of cooked waxy rice processed under different conditions.

Processing condition	Whiteness	Glossiness	Stickiness	Hardness	Overall acceptability
Reference	7.4 ± 0.5[a]	8.0 ± 0.9[a]	8.4 ± 0.7[a]	7.6 ± 0.7[a]	7.2 ± 0.6[a]
T = 90 °C, t = 30 min	7.4 ± 0.5[a]	8.0 ± 0.9[a]	8.4 ± 0.7[a]	7.6 ± 0.7[ab]	7.1 ± 0.7[a]
T = 90 °C, t = 120 min	7.3 ± 0.5[a]	7.9 ± 0.8[a]	8.4 ± 0.7[a]	7.0 ± 0.4[bc]	7.0 ± 0.8[a]
T = 110 °C, t = 30 min	7.3 ± 0.5[a]	8.2 ± 0.8[a]	8.6 ± 0.5[a]	7.3 ± 0.6[abc]	6.8 ± 0.6[a]
T = 130 °C, t = 30 min	7.3 ± 0.5[a]	8.2 ± 0.8[a]	8.6 ± 0.5[a]	7.0 ± 0.4[bc]	7.0 ± 0.9[a]
T = 150 °C, t = 30 min	7.3 ± 0.5[a]	8.1 ± 0.8[a]	8.6 ± 0.5[a]	6.7 ± 0.6[c]	6.6 ± 0.8[a]

T = drying temperature (°C), t = tempering time (min).
Different superscripts in the same column mean that the values are significantly different ($p < 0.05$).

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ประวัติการศึกษา	
ระดับปริญญาตรี	วิทยาศาสตรบัณฑิต (ฟิสิกส์ประยุกต์) มหาวิทยาลัยมหาสารคาม พ.ศ. 2542
ระดับปริญญาโท	วิทยาศาสตรมหาบัณฑิต (เทคโนโลยีพลังงาน) มหาวิทยาลัยเทคโนโลยีพระจอมเกล้าธนบุรี พ.ศ. 2549
ระดับปริญญาเอก	ปรัชญาดุษฎีบัณฑิต (เทคโนโลยีพลังงาน) มหาวิทยาลัยเทคโนโลยีพระจอมเกล้าธนบุรี พ.ศ. 2553
ทุนการศึกษา	ทุนการศึกษาระดับปริญญาเอก โครงการเครือข่ายเชิงกลยุทธ์เพื่อการผลิตและพัฒนาอาจารย์ในสถาบันอุดมศึกษา ครั้งที่ 1 จากสำนักงานคณะกรรมการการอุดมศึกษา (สกอ.) ประจำปี พ.ศ. 2549 ระยะเวลา 4 ปี (พ.ศ. 2550-2554)
ผลงานที่ได้รับการตีพิมพ์	1. Jaiboon, P., Prachayawarakorn, S., Devahastin, S. and Soponronnarit, S., 2009, "Effects of Fluidized Bed Drying Temperature and Tempering Time on Quality of Waxy Rice", **Journal of Food Engineering**, Vol. 95, pp. 517-524. 2. Jaiboon, P., Prachayawarakorn, S., Devahastin, S., Tungtrakul, P. and Soponronnarit, S., 2011, "Effect of High-Temperature Fluidized-Bed Drying on Cooking, Textural and Digestive Properties of Waxy Rice", **Journal of Food Engineering**, Vol. 105, pp. 89-97.

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7. เพชรรัตน์ ใจบุญ, สมเกียรติ ปรัชญาวรากร, สักกมน เทพหัสดิน ณ อยุธยา และ สมชาติ โสภณรณฤทธิ์, 2552, "ผลของฟลูอิไดเซชันอุณหภูมิสูงที่มีต่อคุณภาพของข้าวเหนียว", **วารสารวิทยาศาสตร์เกษตร**, ฉบับที่ 40 (พิเศษ), เล่มที่ 3, หน้า 281-284.

8. เพชรรัตน์ ใจบุญ, สมเกียรติ ปรัชญาวรากร, สักกมน เทพหัสดิน ณ อยุธยา และ สมชาติ โสภณรณฤทธิ์, 2553, “ผลของเจลาทิไนเซชันที่มีต่อสมบัติด้านเนื้อสัมผัสของข้าวเหนียวกล้อง”, **วารสารวิทยาศาสตร์เกษตร**, ฉบับที่. 41(พิเศษ), เล่มที่ 3/1, หน้า 393-396.

มหาวิทยาลัยเทคโนโลยีพระจอมเกล้าธนบุรี

ข้อตกลงว่าด้วยการโอนลิขสิทธิ์ในวิทยานิพนธ์

วันที่ 10 มีนาคม พ.ศ. 2551

ข้าพเจ้า นางสาวเพชรรัตน์ ใจบุญ รหัสประจำตัว 50500313

เป็นนักศึกษาของมหาวิทยาลัยเทคโนโลยีพระจอมเกล้าธนบุรี ระดับปริญญา ☐ โท ☐ เอก ☑ ปร.ด

หลักสูตร ปรัชญาดุษฎีบัณฑิต สาขาวิชาเทคโนโลยีพลังงาน คณะพลังงานสิ่งแวดล้อมและวัสดุ

อยู่บ้านเลขที่ ......๙๙ ม.1...... ตรอก/ซอย ......-...... ถนน ......-......

ตำบล/แขวง ......หนองเอี่ยน...... อำเภอ/เขต ......คำชะอี...... จังหวัด ......มุกดาหาร......

รหัสไปรษณีย์ ......49110...... ขอโอนลิขสิทธิ์ในวิทยานิพนธ์ให้ไว้กับมหาวิทยาลัยเทคโนโลยีพระจอมเกล้าธนบุรี โดยมี ดร.พัฒนะ รักความสุข ตำแหน่ง คณบดีคณะพลังงานสิ่งแวดล้อมและวัสดุ เป็นผู้รับโอนลิขสิทธิ์และมีข้อตกลง ดังนี้

1. ข้าพเจ้าได้จัดทำวิทยานิพนธ์ เรื่อง "การอบแห้งข้าวเหนียวด้วยเทคนิคฟลูอิไดเซชัน" ซึ่งอยู่ในความควบคุม ศ.ดร.สมชาติ โสภณรณฤทธิ์, รศ.ดร.สมเกียรติ ปรัชญาวรากร, รศ.ดร.สักกมน เทพหัสดินฯ ตามมาตรา 14 แห่ง พ.ร.บ. ลิขสิทธิ์ พ.ศ. 2537 และถือว่าเป็นส่วนหนึ่งของการศึกษาตามหลักสูตรของมหาวิทยาลัยเทคโนโลยีพระจอมเกล้าธนบุรี

2. ข้าพเจ้าตกลงโอนลิขสิทธิ์จากผลงานทั้งหมดที่เกิดขึ้นจากการสร้างสรรค์ของข้าพเจ้าในวิทยานิพนธ์ให้กับมหาวิทยาลัยเทคโนโลยีพระจอมเกล้าธนบุรี ตลอดอายุแห่งการคุ้มครองลิขสิทธิ์ตามมาตรา 23 แห่งพระราชบัญญัติลิขสิทธิ์ พ.ศ. 2537 ตั้งแต่วันที่ได้รับอนุมัติโครงร่างวิทยานิพนธ์จากมหาวิทยาลัย

3. ในกรณีที่ข้าพเจ้าประสงค์จะนำวิทยานิพนธ์ไปใช้ในการเผยแพร่ในสื่อใด ๆ ก็ตาม ข้าพเจ้าจะต้องระบุว่าวิทยานิพนธ์เป็นผลงานของมหาวิทยาลัยเทคโนโลยีพระจอมเกล้าธนบุรีทุก ๆ ครั้งที่มีการเผยแพร่

4. ในกรณีที่ข้าพเจ้าประสงค์จะนำวิทยานิพนธ์ไปเผยแพร่หรืออนุญาตให้ผู้อื่นทำซ้ำหรือดัดแปลงหรือเผยแพร่ต่อสาธารณชนหรือกระทำการอื่นใด ตามมาตรา 27, มาตรา 28 และมาตรา 29 และมาตรา 30 แห่งพระราชบัญญัติลิขสิทธิ์ พ.ศ. 2537 โดยมีค่าตอบแทนในเชิงธุรกิจ ข้าพเจ้าจะกระทำได้เมื่อได้รับความยินยอมเป็นลายลักษณ์อักษรจากมหาวิทยาลัยเทคโนโลยีพระจอมเกล้าธนบุรี

ลงชื่อ.......................................ผู้โอนลิขสิทธิ์

ได้ทุนจากวิจัย สำนักงานคณะกรรมการการอุดมศึกษา

(นางสาวเพชรรัตน์ ใจบุญ)

ลงชื่อ.......................................ผู้รับโอนลิขสิทธิ์

(ดร.พัฒนะ รักความสุข)

ลงชื่อ.......................................พยาน

(ศ.ดร.สมชาติ โสภณรณฤทธิ์)

ลงชื่อ.......................................พยาน

(รศ.ดร.สมเกียรติ ปรัชญาวรากร)