

## Effects of Some Physicochemical Properties of Paddy Rice Varieties on Puffing Qualities by Microwave “ORIGINAL”

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### ABSTRACT

Ten paddy rice varieties, both waxy and non-waxy paddy rice, which are cultivated in the northern and northeastern region of Thailand, were selected to study the effects of some physicochemical properties on the qualities of puffing rice (puffed yield, expansion volume, expansion ratio and bulk density) using microwaves at a frequency of 2450MHz and power at 800 watts. It was found that the amylose content (range 5.58-21.24%) was strongly negatively correlated with all qualities of puffed rice: puffed yield ( $r=-0.95^{**}$ ), expansion volume ( $r=-0.82^{**}$ ), expansion ratio ( $r=-0.79^{**}$ ) and bulk density ( $r=-0.78^{**}$ ). The starting time of puffing negatively correlated with puffed yield ( $r=-0.67^{*}$ ), while tightness of husk (lemma-palea) interlocking, thickness of ventral region layer, husk content, width and length of brown rice were unrelated to puffed rice quality. Amylose content could explain the puffing qualities of puffing rice. The coefficient of determination ( $R^2$ ), for the linear correlation with amylose content with regard to the quality of rice puffing for puffed yield, expansion volume, expansion ratio and bulk density was 0.91, 0.67, 0.62 and 0.61, respectively. Paddy rice with suitable physicochemical properties for puffing by microwave heating has low amylose, a thin ventral region and a puffing time that starts quickly and continues, as exhibited in rice varieties RD 6, RD 10 and NSPT.

**Key words:** puffing, puffed rice, microwave, physicochemical

### INTRODUCTION

Puffed rice (known in Thailand as “kow tok” or “kow pong”) is a wholegrain puffed product from paddy rice or milled rice. It is commonly used in snacks, cereal drinks, ready-to-eat breakfast cereal and infant food. Not only is puffed rice a staple in the diet for carbohydrate and protein, it also contributes beneficial nutrients including dietary fiber, vitamins, minerals and phytochemicals which have been linked to reduced disease risk (FDA, 2006; Seal *et al.*, 2006). Generally, rice is puffed with hot air, hot sand and gun puffing. In Thailand, roasting in a hot pan and

frying in hot oil are generally used. Roasting has the risk of burning and producing defects, while the oil from frying can be absorbed and easily turns rancid. Thus, a new method has been developed.

At the present, there is an increasing trend to use microwaves for food processing due to the fact that microwave heating is more efficient than the traditional heating processes with benefits that include: quicker start-up time, faster heating, energy efficiency, space saving, selective heating and final products with improved nutritive quality (Sumnu, 2001). It is possible to use microwave energy for baking, puffing or popping. One of the most popular applications of microwave heating

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is the popping of popcorn. However, the quality of popcorn measured by popcorn expansion is affected by various factors such as: variety, popping procedure, pericarp thickness and kernel size (Lin and Anantheswaran, 1988; Dofing *et al.*, 1990; Pordesimo *et al.*, 1991; Zhang and Hoseney, 1998). Previous studies have found that the quality of puffed rice measured by puffing expansion and puffed yield was affected by the maturity and variety of rice, puffing procedure, chemical and physical properties (Srinivas and Desikachar, 1973; Murugesan and Bhattacharya, 1986, 1991). Murugesan and Bhattacharya (1991) reported that paddy rice had a high degree of husk interlocking that was highly positively correlated with puffing expansion. Srinivas and Desikachar (1973) found that good puffing paddy rice varieties showed a weak point with a thin aleurone layer. Simsrisakul (1991) reported that puffing waxy paddy rice in hot air provided higher expansion and puffed yield than with high amylose paddy rice. Contrarily, Murugesan and Bhattacharya (1991) found that amylose and protein had no relationship to puffing expansion. The optimum temperature for maximum volume and kernel puffed percent was different for the hot sand puffing method (about 200°C) and the hot air puffing method (225°C) (Murugesan and Bhattacharya, 1986). Moraru and Kokini (2003) explained that microwave expansion involves both nucleation and cell growth. Nucleation depends on process parameters and the volume of the polymer and cell growth is governed by the rheological properties of the bubble walls. This was consistent with Mariotti *et al.* (2006), who reported that the quality of puffed cereals by gun puffing, such as puffed rice was strongly affected by the morphology of the starch granules.

Although puffed rice has been produced for a long time in Thailand, there is a very little scientific information, especially on puffing paddy rice using microwaves. This study was instigated because of the lack of research that explains the

effects of microwaving on the physical and chemical properties of puffed rice and its effect on puffing quality.

## MATERIALS AND METHODS

### Materials

Ten varieties of paddy rice were used, consisting of two non-waxy paddy rice varieties (Suphan-Buri1 and Khao Dawk Mali105) and eight waxy paddy rice varieties. Each variety was purchased from the Rice Research Center in each province of Thailand, and had been harvested during September 2005 to May 2006. The ten varieties were: Suphan-Buri1 (SPBR1), Pathumthani province; Niaw-Phrae1 (NPH1), Phrae province; Niaw-San-Pah-Tawng (NSPT), Gam-Pai15 (GP15) and Sew-Mae-Jan (SMJ), Chiang Mai province; RD6, RD10 and Khao Dawk Mali105 (KDML105), Ubon Ratchathani province; Hahng-Yi71 (HY71), Nong Khai province; and Sakon-Nakhon (SKK), Sakon Nakhon province. All paddy rice samples were cleaned and stored at 12-15°C until used.

### Chemical analysis

The paddy rice samples were dehulled and ground using a Retsch Ultra centrifugal mill with a 0.12 mm mesh sieve screen. Moisture and protein content were determined according to AOAC (1990). Amylose content was determined using the method of Juliano (1971).

### Paddy rice physicochemical properties analysis

The physical properties of the samples were inspected by modifying the method of Murugesan and Bhattacharya (1991).

**The degree of husk interlocking** or region of overlapping of the lemma and palea was measured as follows. Each paddy rice grain was cut transversely at the center with a sharp razor blade, fixed on a stub with double-sided adhesive tape and sputter-coated with gold. The samples

were viewed with a scanning electron microscope (JEOL, JSM-5800LV) under high vacuum conditions at an accelerating voltage of 15 kV. The degree of husk interlocking was scored by the following scores.

(A) Hooking:	Score
in both lemma and palea;	3
only in lemma;	2
nil.	1
(B) Length of the overlap of lemma and palea at hooking points:	
high;	2
low.	1
(C) Closeness of the overlapping portions of lemma and palea to each other:	
Touching throughout;	4
Partially touching;	3
Not touching but close;	2
Well separated.	1

The average of the score on the two lateral sides was used. The final score was calculated as husk interlocking score = score A \* score B \* score C and the mean score was calculated. The maximum score was 24 and the minimum score was 1 (Figure 1).

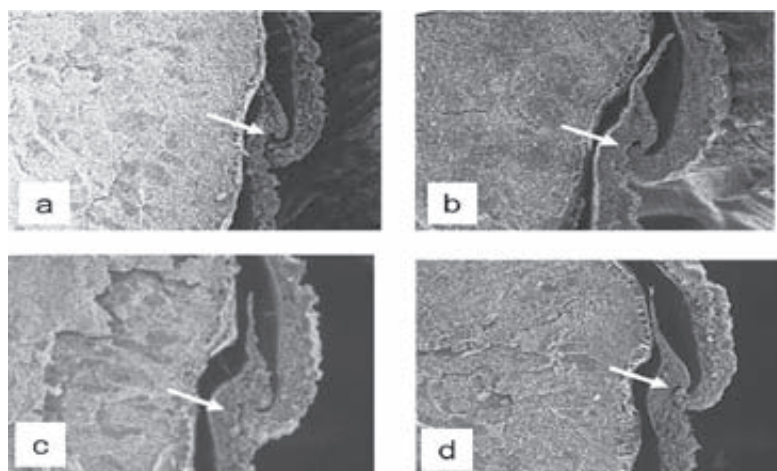
**The shellability of paddy** (percent by number of paddy rice shelled) was estimated using a Satake dehusker, with the clearance between the two rubber rolls fixed at 0.8 mm. One hundred grains were shelled in triplicate.

**The husk content** was estimated by shelling 30 g of paddy in a Satake dehusker, in triplicate and calculating the mean weight of the husk.

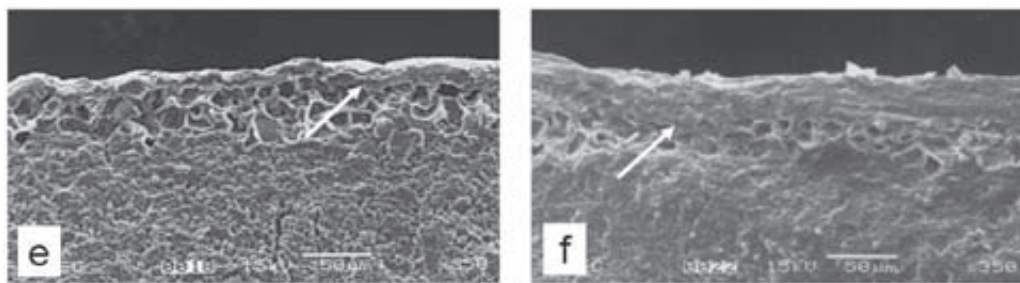
**The length and width** of 20 brown rice grains were measured using a vernier caliper. The means were reported.

**The ventral region thickness** measured at the ventral sides. The brown rice grains were cut longitudinally, fixed on a stub with double-sided adhesive tape and sputter-coated with gold. The samples were viewed and measured with a scanning electron microscope (JEOL, JSM-5800LV) under high vacuum conditions at an accelerating voltage of 15 kV (Figure 2) by modifying the method of Srinivas and Desikachar (1973).

**White belly** grain is the term given to the opaque chalky portions on the ventral side (germ side). It was determined from a random selection of 100 brown rice kernels, cut



**Figure 1** SEM micrograph images of some different types of lemma-palea interlocking. The husk interlocking scores of the samples are: (a) 1×1×1, SMJ; (b) 3×2×3, NSPT; (c) 3×2×4, HY71; and (d) 2×1×2, RD6.



**Figure 2** Characteristics of ventral region layer thickness; (e) NSPT and; (f) SMJ.

transversely at the center with a sharp razor blade and viewed in a microbiological colony counter.

**Morphology of the starch granule** of brown rice was determined by cutting grains transversely at the center with a sharp razor blade. Samples were fixed on a stub with double-sided adhesive tape and sputter-coated with gold. The samples were viewed with a scanning electron microscope (JEOL, JSM 6301F) under high vacuum conditions at an accelerating voltage of 15 kV by modifying the method of Mariotti *et al.* (2006).

### Microwave puffing operation

After the initial moisture content of raw materials had been determined, the moisture content of the paddy was adjusted to  $14 \pm 0.3\%$  (wet basis). Paddy rice in a glass bottle was sprayed with distilled water and kept for 3-4 days until it reached equilibrium at room temperature (Srinivas and Desikachar, 1973). A microwave oven (Model M1712N SAMSUNG) was used at 2450 MHz 800 watts to puff the paddy rice. A sample of 30 g of paddy rice was put into a paper bag (size 16×30 cm) and placed at the center of the microwave oven and puffed for 120 s. The time that the grains took to start puffing was recorded and the temperature of the puffed rice was measured with an infrared thermometer (Chino, Japan). The data were averaged from triplicate observations. Husk and unpuffed paddy rice were separated by hand picking and weighed. The total volume of the

puffed samples was measured in a 100 and 500 mL graduated cylinder. The puffed yield, expansion volume, expansion ratio and bulk density (Simsrisakul, 1991) were calculated using Equations 1 to 4, respectively:

$$\text{Puffed yield (\%)} = \frac{\text{wt. of puffed rice (g)} * 100}{\text{wt. of paddy rice (g)}} \quad (1)$$

$$\text{Expansion volume} = \frac{\text{vol. of puffed rice (mL)}}{\text{wt. of paddy rice (g)}} \quad (2)$$

$$\text{Expansion ratio} = \frac{\text{vol. of puffed rice (mL)}}{\text{vol. of paddy rice (mL)}} \quad (3)$$

$$\text{Bulk density (g/mL)} = \frac{\text{wt. of puffed rice (g)}}{\text{vol. of paddy rice (mL)}} \quad (4)$$

### Statistical analysis

Analysis of variance (ANOVA) was performed on all test data. Duncan's multiple range test was used to compare the means among the paddy rice varieties. Pearson's correlation coefficient was used to compare the physicochemical parameters and the quality of the puffed rice samples. A simple linear regression was developed using the SPSS software version 11 for Windows to predict puffing qualities.

## RESULTS AND DISCUSSION

### Chemical properties of paddy rice varieties

The chemical compositions of paddy rice varieties are shown in Table 1. The moisture and protein content of paddy rice were in the range 10.52-12.26% and 6.32-8.34%, respectively. The protein content of NPH1 was the lowest (6.32%), whereas the highest was 8.34% for HY71. The protein content in the paddy rice depending on the varieties ( $p<0.05$ ). However, Juliano and Hicks (1996) indicated that 2% difference in rice protein content did not affect the quality of cooked rice. In this study, the paddy rice varieties showed less than 2% difference in protein content, thus the qualities of rice puffing may not have been affected by protein.

Amylose content of the paddy rice varieties was significantly different ( $p<0.05$ ) and could be classified into three groups: waxy rice; low-amylose content; and intermediate amylose content with values of 5.96-7.46, 15.98 and 21.24%, respectively. According to Mercier and Feillet (1975), starch is composed of linear amylose and branched amylopectin, which impact on expansion differently. High amylopectin content leads to light, elastic and homogeneously

expanded textures, while high amylose content leads to hard, less expanded textures. The linear amylose chains align themselves in the shear field and thus are difficult to pull apart during expansion (Moraru and Kokini, 2003).

### Physical properties of paddy rice varieties

The score for the degree of husk interlocking or the overlapping of the lemma and palea highlighted the different characteristics of paddy rice. In this study, scores for the paddy rice varieties ranged from 1-24, with the highest score for HY71 and the lowest score for SMJ (Table 2 and Figure 1a-d). In contrast, SMJ had a high shellability value (94.33%), but HY71 had a rather low value (81.33%). The much tighter paddy rice husk seemed to be more difficult to dehusk. HY71 had the lowest expansion volume and expansion ratio when compared with the group of waxy paddy rice. This was probably due to the fact that the overlapping of the lemma and palea was quite tight, which made the husk harder to explode and resulted in low expansion. The SMJ husks were loose and so could not keep the vapor pressure high enough to produce suitable exploding conditions, resulting in rather low values for the expansion volume and expansion ratio. The husk

**Table 1** The chemical properties of paddy rice varieties.

Variety	Moisture content (%)	Amylose content (%)	Protein content (%)
GP15	11.59±0.12 <sup>de</sup>	6.81±0.14 <sup>e</sup>	6.62±0.18 <sup>b</sup>
HY71	10.52±0.08 <sup>a</sup>	6.59±0.02 <sup>de</sup>	8.34±0.04 <sup>g</sup>
KDML105	11.81±0.14 <sup>c</sup>	15.98±0.05 <sup>g</sup>	7.37±0.16 <sup>ef</sup>
NPH1	10.72±0.14 <sup>ab</sup>	6.21±0.05 <sup>bc</sup>	6.32±0.03 <sup>a</sup>
NSPT	11.25±0.06 <sup>c</sup>	6.39±0.16 <sup>cd</sup>	6.81±0.03 <sup>bc</sup>
RD 10	11.66±0.12 <sup>c</sup>	6.04±0.14 <sup>b</sup>	7.03±0.05 <sup>cd</sup>
RD 6	11.73±0.20 <sup>e</sup>	6.36±0.02 <sup>cd</sup>	6.35±0.04 <sup>a</sup>
SKK	11.36±0.13 <sup>cd</sup>	7.06±0.07 <sup>f</sup>	7.58±0.01 <sup>f</sup>
SMJ	12.26±0.18 <sup>f</sup>	5.58±0.09 <sup>a</sup>	7.48±0.18 <sup>f</sup>
SPBR1	10.79±0.14 <sup>b</sup>	21.24±0.19 <sup>h</sup>	7.17±0.05 <sup>de</sup>

Note: 1 The data in this table were averaged from triplicate observations.

2 <sup>a,b</sup> in the same column with different letters are significantly different ( $p<0.05$ ).

3 GP15= Gam-Pai15, HY71= Hahng-Yi71, KDML105= Khao Dawk Mali 105, NPH1= Niaw-Phrae1, NSPT= Niaw-San-Pah-Tawng, SKK= Sakon-Nakhon, SMJ= Sew-Mae-Jan, and SPBR1= Suphan-Buri1.

content was lowest for SPBR1 (17.12%) and highest for GP15 (24.55%). The width and length of brown rice varied from 2.00-2.7 and 7.14-7.68mm, respectively, with the longest for SKK, while GP15 was the widest. White belly was the least for KMDL105 (2.00%) and the highest for GP15 (52%), which differed significantly ( $p<0.05$ ) to other waxy paddy rice varieties. The ventral region thickness was lowest for NSPT (13.54  $\mu$ g) and highest for SMJ (28.47  $\mu$ g) (Figure 2e and f). Morphological studies of the starch granules of various brown rice varieties showed that part of

the endosperm contained polygonal, compact starch granules with a size range of 3.44–5.50  $\mu$ m. SMJ had the smallest sized granules (3.44  $\mu$ m), whereas RD10 starch granules were the largest (5.50  $\mu$ m). GP15 starch granules tended to be spherical and had much more inter-granular space, which may be a characteristic of white belly kernels, whereas the SMJ starch granule was rather compact. RD10, RD6, SKK and NSPT starches granules had more uniform size and distribution than starch granules in other paddy rice varieties (Figure 3g-j).

**Table 2** The Physical properties of paddy rice varieties.

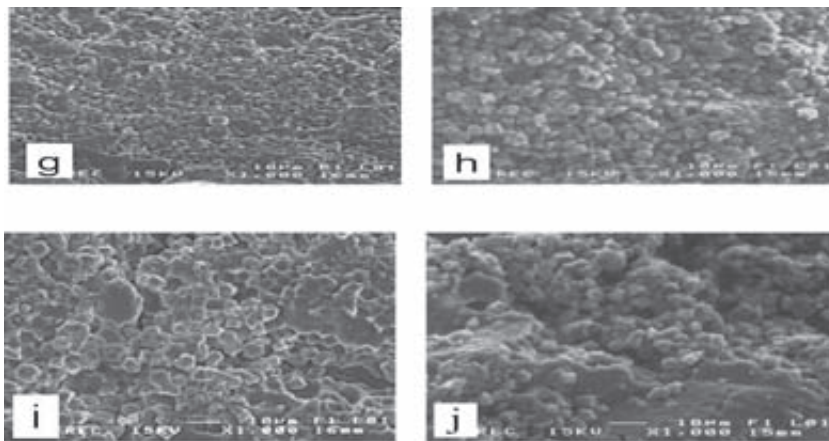
Variety	HL (score)	SH (%)	HC (%)	W (mm)	L (mm)	WB (%)	VT ( $\mu$ m)	STG( $\mu$ m)
GP15	14.00 $\pm$ 2.31 <sup>d</sup>	82.00 $\pm$ 3.61 <sup>abc</sup>	22.55 $\pm$ 2.79 <sup>d</sup>	2.70 $\pm$ 0.10 <sup>d</sup>	7.15 $\pm$ 0.05 <sup>a</sup>	52.00 $\pm$ 0.67 <sup>d</sup>	18.06 $\pm$ 0.57 <sup>cd</sup>	5.11 $\pm$ 0.25 <sup>de</sup>
HY71	24.00 $\pm$ 0.00 <sup>f</sup>	80.67 $\pm$ 3.06 <sup>a</sup>	21.52 $\pm$ 0.95 <sup>bcd</sup>	2.06 $\pm$ 0.08 <sup>ab</sup>	7.14 $\pm$ 0.12 <sup>a</sup>	24.31 $\pm$ 1.50 <sup>b</sup>	27.78 $\pm$ 0.67 <sup>f</sup>	4.44 $\pm$ 0.10 <sup>c</sup>
KDML105	5.00 $\pm$ 1.37 <sup>bc</sup>	90.67 $\pm$ 2.52 <sup>ef</sup>	20.78 $\pm$ 1.69 <sup>bc</sup>	2.00 $\pm$ 0.14 <sup>a</sup>	7.27 $\pm$ 0.23 <sup>a</sup>	1.67 $\pm$ 0.58 <sup>a</sup>	19.79 $\pm$ 1.04 <sup>de</sup>	3.89 $\pm$ 0.25 <sup>b</sup>
NPH1	16.00 $\pm$ 3.46 <sup>d</sup>	81.33 $\pm$ 3.21 <sup>ab</sup>	18.39 $\pm$ 0.71 <sup>a</sup>	2.31 $\pm$ 0.10 <sup>c</sup>	7.36 $\pm$ 0.14 <sup>ab</sup>	40.00 $\pm$ 3.00 <sup>c</sup>	17.71 $\pm$ 1.04 <sup>c</sup>	4.61 $\pm$ 0.10 <sup>c</sup>
NSPT	20.00 $\pm$ 3.46 <sup>c</sup>	82.00 $\pm$ 2.67 <sup>abc</sup>	22.05 $\pm$ 0.78 <sup>cd</sup>	2.16 $\pm$ 0.13 <sup>abc</sup>	7.24 $\pm$ 0.12 <sup>a</sup>	3.00 $\pm$ 0.50 <sup>a</sup>	13.54 $\pm$ 1.04 <sup>a</sup>	4.39 $\pm$ 0.25 <sup>c</sup>
RD 10	8.00 $\pm$ 0.00 <sup>c</sup>	83.67 $\pm$ 2.52 <sup>abc</sup>	18.33 $\pm$ 2.55 <sup>a</sup>	2.29 $\pm$ 0.14 <sup>c</sup>	7.58 $\pm$ 0.05 <sup>bc</sup>	3.00 $\pm$ 1.00 <sup>a</sup>	15.28 $\pm$ 1.30 <sup>ab</sup>	5.50 $\pm$ 0.17 <sup>e</sup>
RD 6	6.67 $\pm$ 2.31 <sup>bc</sup>	85.67 $\pm$ 2.52 <sup>bcd</sup>	18.47 $\pm$ 0.81 <sup>a</sup>	2.18 $\pm$ 0.07 <sup>abc</sup>	7.20 $\pm$ 0.13 <sup>a</sup>	4.00 $\pm$ 1.00 <sup>a</sup>	14.93 $\pm$ 1.59 <sup>ab</sup>	4.78 $\pm$ 0.35 <sup>cd</sup>
SKK	3.33 $\pm$ 1.15 <sup>ab</sup>	86.33 $\pm$ 1.53 <sup>cde</sup>	20.44 $\pm$ 1.71 <sup>b</sup>	2.13 $\pm$ 0.12 <sup>abc</sup>	7.68 $\pm$ 0.04 <sup>c</sup>	1.67 $\pm$ 0.58 <sup>a</sup>	16.67 $\pm$ 1.04 <sup>bc</sup>	4.83 $\pm$ 0.17 <sup>c</sup>
SMJ	1.00 $\pm$ 0.00 <sup>a</sup>	94.33 $\pm$ 2.08 <sup>f</sup>	21.93 $\pm$ 1.71 <sup>cd</sup>	2.21 $\pm$ 0.04 <sup>bc</sup>	7.29 $\pm$ 0.08 <sup>a</sup>	21.67 $\pm$ 3.79 <sup>b</sup>	28.47 $\pm$ 0.69 <sup>f</sup>	3.44 $\pm$ 0.35 <sup>a</sup>
SPBR1	4.67 $\pm$ 1.15 <sup>abc</sup>	89.33 $\pm$ 1.53 <sup>de</sup>	17.12 $\pm$ 3.56 <sup>a</sup>	2.12 $\pm$ 0.11 <sup>abc</sup>	7.20 $\pm$ 0.24 <sup>a</sup>	2.33 $\pm$ 1.53 <sup>a</sup>	20.49 $\pm$ 0.65 <sup>c</sup>	4.44 $\pm$ 0.19 <sup>c</sup>

Note: 1 The data in this table were averaged from triplicate observations.

2 <sup>a,b</sup> Means in the same column with different letters are significantly different ( $p<0.05$ ).

3 GP15= Gam-Pai15, HY71= Hahng-Yi71, KDML105= Khao Dawk Mali 105, NPH1= Niaw-Phrae1, NSPT= Niaw-San-Pah-Tawng, SKK= Sakon-Nakhon, SMJ= Sew-Mae-Jan, and SPBR1= Suphan-Buri1.

HL= Husk interlocking score, SH= Shellability, HC=Husk content, VT= Ventral region thickness, W= Width of brown rice, L= Length of brown rice, WB = White belly and STG = Starch granules size.



**Figure 3** Characteristics of starch granules: (g) SMJ; (h) GP15; (i) RD10; and (j) RD6.

### Puffing qualities of paddy rice

The data in Table 3 presents both quantity and quality characteristics of puffed rice for the paddy rice varieties. Differences were apparent in all qualities of rice puffing, including puffed yield, expansion volume, expansion ratio and bulk density, with a range of: 29.79-57.38%, 5.16-10.39 mL/g 2.72-5.97 mL/mL and 0.21-0.33 g/mL, respectively. Puffed rice from non-waxy paddy rice (SPBR1 and KDML105) was lower in value for all quality characteristics than puffed rice from all the waxy paddy rice varieties. The main reason may have been due to higher amylose content (Table 1). There were no quality relationships among the waxy paddy rice varieties cultivated in different areas, but the paddy rice in the northeastern area (NPH1, NSPT, GP15 and SMJ) seemed to have greater puffed yield than paddy rice in the north (RD6, RD10, SKK and HY71 Figure 4). The three paddy rice varieties with the highest values for puffed yield, expansion volume, expansion ratio and bulk density were RD 6, NSPT and RD10, respectively.

### Correlations between the paddy rice properties and the puffing qualities of puffed rice

Table 4 presents the correlations between the paddy rice properties and the puffing qualities of puffed rice for: puffed yield, expansion volume, expansion ratio and bulk density. The results show that none of the physical properties of paddy rice were related to the qualities of rice puffing, which was a similar result to Srinivas and Desikachar (1973). Husk interlocking score, husk content, width, length, white belly and starch granule size showed positive trends, whereas shellability and ventral region thickness layer had negative correlation trends. While chemical composition measured as the amylose content was highly negatively correlated with puffed yield ( $-0.95^{**}$ ), expansion volume ( $-0.82^{**}$ ), expansion ratio ( $-0.79^{**}$ ) and bulk density ( $-0.78^{**}$ ), these results were contrary to Murugesan and Bhattacharya (1991). The starting time of puffing was negatively correlated with puffed yield ( $-0.67^{*}$ ) and from observation it was found that rice started puffing when it was heated by microwave after 39-48 s and finished puffing within 120 s at 168-191°C. Paddy rice that produced a high puffed yield and high expansion volume had an earlier puffing start time and continued puffing longer.

**Table 3** Puffing qualities of puffed rice.

Variety	Puffed yield (%)	Expansion volume (mL/g)	Expansion ratio (mL/mL)	Bulk density (g/mL)
GP15	56.24±0.95 <sup>e</sup>	9.42±0.70 <sup>cde</sup>	4.58±0.33 <sup>cd</sup>	0.28±0.00 <sup>cd</sup>
HY71	49.58±1.45 <sup>c</sup>	7.00±0.32 <sup>b</sup>	3.71±0.15 <sup>b</sup>	0.27±0.01 <sup>bc</sup>
KDML105	40.86±3.00 <sup>b</sup>	6.66±0.70 <sup>b</sup>	3.48±0.32 <sup>b</sup>	0.21±0.01 <sup>a</sup>
NSPT	57.09±0.52 <sup>e</sup>	10.27±0.11 <sup>e</sup>	4.95±0.00 <sup>cd</sup>	0.27±0.00 <sup>bc</sup>
NPH1	54.66±2.40 <sup>de</sup>	8.61±0.29 <sup>c</sup>	4.49±0.17 <sup>c</sup>	0.29±0.01 <sup>de</sup>
RD 10	56.97±1.58 <sup>e</sup>	9.84±0.25 <sup>de</sup>	5.14±0.07 <sup>d</sup>	0.30±0.00 <sup>e</sup>
RD 6	57.38±0.86 <sup>e</sup>	10.39±0.76 <sup>e</sup>	5.97±0.51 <sup>e</sup>	0.33±0.01 <sup>f</sup>
SKK	54.00±1.12 <sup>de</sup>	9.99±0.62 <sup>e</sup>	4.74±0.33 <sup>cd</sup>	0.26±0.01 <sup>b</sup>
SMJ	51.54±0.90 <sup>cd</sup>	8.77±0.30 <sup>cd</sup>	4.50±0.11 <sup>c</sup>	0.27±0.01 <sup>bc</sup>
SPBR 1	29.79±1.27 <sup>a</sup>	5.16±0.22 <sup>a</sup>	2.72±0.14 <sup>a</sup>	0.21±0.00 <sup>a</sup>

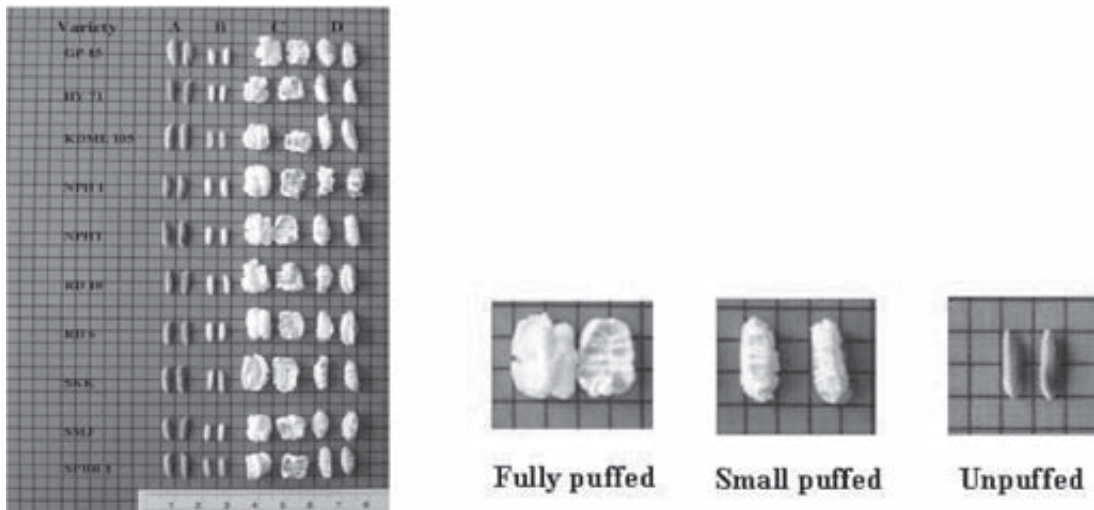
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The experiment produced some interesting results regarding the amylose content and the puffing qualities of the paddy rice varieties SMJ and HY1. These two varieties had low amylose content, but had low puffed yield and expansion volume. When considering physical

properties, such as the husk interlocking, SMJ had the lowest score (1) (Figure 1a), while HY1 had the highest score (24) (Figure 1c). The Pearson correlation coefficients show that husk interlocking was strongly negative correlated with shellability ( $r = -0.84^{**}$ ). Therefore, the



**Figure 4** Puffed rice from paddy rice varieties: (A) paddy rice; (B) brown rice; (C) fully puffed rice; and (D) small puffed rice.

**Table 4** Pearson's correlation coefficients ( $r$ ) for the physicochemical properties of paddy rice varieties with the puffing qualities of puffed rice.

	Puffing qualities ( $n=13$ )			
	Puffed yield	Expansion vol.	Expansion ratio	Bulk density
Chemical compositions				
Moisture content	0.26	0.41	0.42	0.18
Protein content	-0.33	-0.44	-0.50	-0.47
Amylose content	-0.95**	-0.82**	-0.79**	-0.78**
Physical properties				
Husk interlocking	0.30	0.05	0.01	0.18
Husk content	0.35	0.25	0.10	-0.10
Shell ability	-0.24	-0.02	-0.01	-0.09
Width of brown rice	0.44	0.43	0.25	0.15
Length of brown rice	0.01	0.24	-0.22	0.04
Ventral thickness	-0.35	-0.54	-0.51	-0.39
White belly	0.29	0.04	-0.01	0.15
Starch granule size	0.40	0.41	0.40	0.52
Starting time to puffing	-0.67*	-0.56	-0.61	-0.58
Puffing temperature	0.35	0.29	0.26	0.32

\* means significant: \*  $p < 0.05$  and \*\*  $p < 0.01$ .

relationship of husk interlocking with puffing quality might be explained by the fact that the loosely hooked husk affects the capacity to maintain vapor pressure before the kernel explodes, which acts like the pericarp in maize. Hosene *et al.* (1983) indicated that the pericarp in maize serves as a pressure valve to hold internal steam pressure until the threshold level required to expand the grain was reached. In addition, Pordesimo *et al.* (1990) found that the thickness of the pericarp affected popcorn expansion, which corresponds to the experimental result for SMJ where the ventral region layer was thicker than in other varieties (Figure 2f). It is probable that the thicker ventral region layer results in the driving force not being enough for the ventral layer to explode. The simple linear regression showed that amylose content (AC) could explain 91% of the puffed yield, 67% of the expansion volume, 62% of the expansion ratio and 61% of the bulk density,

as shown in Equations 5-8:

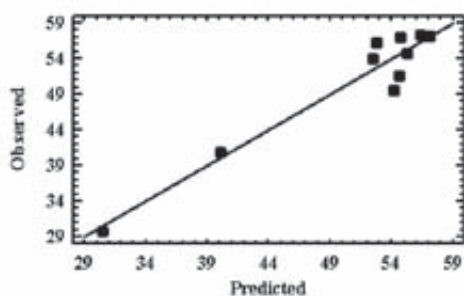
$$\text{Puffed yield} = 64.921 - 1.599AC \quad (R^2 = 0.92) \quad (5)$$

$$\text{Expansion volume} = 11.024 - 0.273AC \quad (R^2 = 0.67) \quad (6)$$

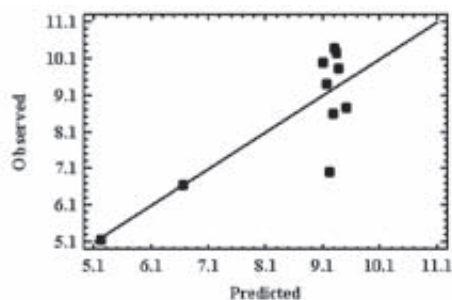
$$\text{Expansion ratio} = 5.630 - 0.136AC \quad (R^2 = 0.62) \quad (7)$$

$$\text{Bulk density} = 0.312 - 0.0053AC \quad (R^2 = 0.61) \quad (8)$$

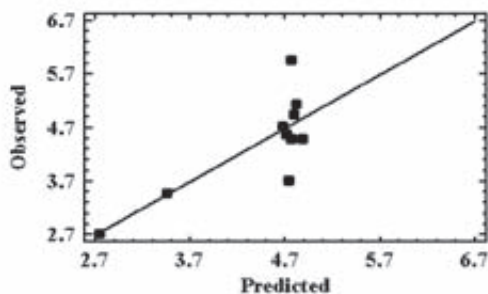
As shown in Figure 5, the models were in moderate agreement with the observed results of puffed yield in Figure 5A, with the predicted data generally clustered around the straight line, which showed the suitability of the established model in describing the puffed yield of rice puffing. The linear relationship of puffed yield (Equation 5) can be used to predict the puffing quality resulting from microwave heating. For the other puffing qualities, such as expansion volume, expansion ratio and bulk density, the linear relationship with amylose content of paddy rice is not clear, as is shown by the lower  $R^2$  values.



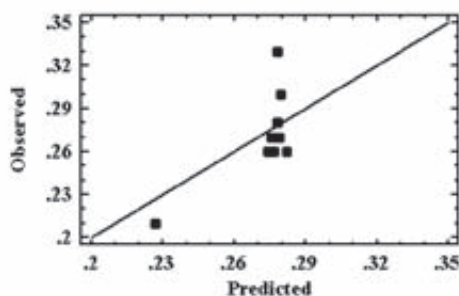
(A) Puffed yield



(B) Expansion volume



(C) Expansion ratio



(D) Bulk density

**Figure 5** The observed and predicted values of puffing qualities: (A) Puffed yield; (B) Expansion volume; (C) Expansion ratio; and (D) Bulk density.

## CONCLUSION

Paddy rice can be puffed by microwave heating, producing puffed rice that has expansion volume, expansion ratio and bulk density similar to the general standard for cereal grain that has been puffed. The highest puffed yield was 57.38%. A linear relationship between puffed yield and amylose content could predict puffed yield up to 90%. The physical properties were less correlated to the quality of rice puffing. The suitable paddy rice varieties for puffing were identified as RD6, RD10 and NSPT.

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