รายงานวิจัยฉบับสมบูรณ์

โครงการ: **อิทธิพลของการเตรียมวัตถุดิบและการอบแห้งไมโครเวฟสุญญากาศต่อคุณลักษณะผลิตภัณฑ์อาหารว่างจากผักและผลไม้**

โดย รองศาสตราจารย์นันทวัน เทอดไทย
และ Professor Weibiao Zhou (mentor)

มิถุนายน 2555

สัญญาเลขที่ MRG5380047

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สนับสนุนโดยสำนักงานคณะกรรมการการอุดมศึกษา สำนักงานกองทุนสนับสนุนการวิจัย และ มหาวิทยาลัยเกษตรศาสตร์

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Nantawan Therdthai

12 June 2012

Abstract

Project Code: MRG5380047

Project Title: Effect of pretreatment and microwave vacuum drying on characteristics of dried snack products from fruits and vegetables

Investigators:

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Project Period: 2 years

This project aimed to investigate effect of pretreatment (including osmotic dehydration, blanching and freezing) and microwave vacuum drying on characteristics of dried snack. Mandarin was subjected to osmotic dehydration prior to microwave vacuum drying. Osmotic solutions were varied using different ratios of sucrose to glycerol (9:1, 7:3 and 5:5 w/w). With osmotic dehydration, dielectric properties of mandarin were changed significantly ($P \leq 0.05$). During drying, page model was the best to describe moisture change of osmotically dehydrated mandarin. An increase in microwave power from 4.8 W/g to 6.4 W/g increased drying rate without significant effect on hardness of dried samples. Nonetheless, the hardness was significantly ($P \leq 0.05$) reduced by an increase in the glycerol ratio in the osmotic solution. The increase in microwave power and glycerol ratio significantly ($P \leq 0.05$) decreased β-carotene content and thereby affected colour of the dried mandarin. In addition to mandarin, papaya strips were subjected to blanching and freezing prior to microwave vacuum drying. Blanching increased dielectric properties of papaya particularly blanching in salt solution ($P \leq 0.05$). The blanching in salt, sucrose and mixed solutions increased internal resistance to mass transfer during the microwave vacuum drying. Therefore Biot number of mass transfer was increased while mass diffusivity was reduced. Freezing decreased dielectric constant and loss factor, but increased pore size of the dried and un-blanched sample. Blanching increased pore size and rehydration ability, regardless of freezing.

Keywords: drying, microwave, freezing, blanching, osmotic dehydration

บทคัดย่อ

รหัสโครงการ: MRG5380047

ชื่อโครงการ: อิทธิพลของการเตรียมวัตถุดิบและการอบแห้งไมโครเวฟสุญญากาศต่อคุณลักษณะผลิตภัณฑ์อาหารว่างจากผักและผลไม้

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ระยะเวลาโครงการ: 2 ปี

โครงการนี้มีเป้าหมายในการศึกษาอิทธิพลของการเตรียม (ได้แก่ การออสโมติกดีไฮเดรชัน การลวก และการแช่แข็ง) และการอบแห้งแบบไมโครเวฟสุญญากาศต่อลักษณะของอาหารว่างอบแห้ง โดยนำส้มสายน้ำผึ้งมาผ่านการออสโมติกดีไฮเดรชั่นในสารละลายออสโมติกที่มีสัดส่วนของซูโครสและกลีเซอรอลต่างๆกัน (9:1, 7:3 และ 5:5 w/w) ก่อนการอบแห้งแบบไมโครเวฟสุญญากาศ การออสโมติกดีไฮเดรชั่นทำให้สมบัติไดอิเลคทริกของส้มสายน้ำผึ้งเปลี่ยนแปลง ($P \leq 0.05$) ระหว่างการอบแห้งส้มสายน้ำผึ้ง สามารถใช้แบบจำลองเพจอธิบายการเปลี่ยนแปลงความชื้นได้ โดยการเพิ่มระดับกำลังไมโครเวฟจาก 4.8 W/g เป็น 6.4 W/g สามารถเพิ่มอัตราการอบแห้งโดยไม่ส่งผลต่อความแข็งของส้มสายน้ำผึ้งอบแห้ง อย่างไรก็ตามความแข็งของส้มสายน้ำผึ้งอบแห้งลดลงได้ โดยการเพิ่มสัดส่วนของกลีเซอรอลระหว่างการออสโมติกดีไฮเดรชัน การเพิ่มกำลังไมโครเวฟและสัดส่วนของกลีเซอรอลทำให้ปริมาณเบต้าแคโรทีนลดลงและมีผลต่อสีของส้มสายน้ำผึ้งอบแห้ง นอกจากส้มสายน้ำผึ้งแล้ว การศึกษานี้ได้นำมะละกอเส้นมาผ่านการลวกและการแช่แข็งก่อนการอบแห้งแบบไมโครเวฟสุญญากาศ พบว่า การลวกทำให้ค่าสมบัติไดอิเลคทริกของมะละกอสูงขึ้น ($P \leq 0.05$) โดยเฉพาะการลวกในสารละลายเกลือ แต่การลวกในสารละลายเกลือ ซูโครส และสารละลายผสม ส่งผลให้ค่าแรงต้านภายในต่อการถ่ายเทมวลระหว่างการอบแห้งเพิ่มขึ้น ค่า Biot number สูงขึ้น และ mass diffusivity ลดลง ขณะที่การแช่แข็งทำให้ค่า dielectric constant และ loss factor ลดลง แต่สามารถเพิ่มความเป็นรูพรุนในโครงสร้างของมะละกออบแห้งที่ไม่ผ่านการลวกได้ อย่างไรก็ตามการลวกทั้งที่ร่วมและไม่ร่วมกับการแช่แข็ง สามารถเพิ่มขนาดรูพรุนและความสามารถในการคืนตัวของมะละกออบแห้ง

คำหลัก : การอบแห้ง ไมโครเวฟ การแช่แข็ง การลวก ออสโมติกดีไฮเดรชัน

Contents

Executive summary

Project Code: MRG5380047

Project Title: Effect of pretreatment and microwave vacuum drying on characteristics of dried snack products from fruits and vegetables

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Background

In the Asia Pacific region, market value of snack in Thailand was the biggest, approximately $260 million per year. In addition, the snack market has been growing consistently with increased competition. Consumer preference of snack became increasingly sophisticated. It required research and development to produce new variety of snack. Major factors influencing decision making of consumer were taste, flavor, price and health issues (Nicely, 2004). Snack from fruit and vegetable could be preferable, when health issues were concerned. However, taste and flavor also needed improvement. In the category of dried fruit and vegetable snack, microwave vacuum drying should be used to reduce drying time. From the previous study (Therdthai and Zhou, 2009), the microwave vacuum drying was also good at development of porous structure and thereby improved rehydration. However, to develop the microwave vacuum dried products as snack, pretreatment methods ie. osmotic dehydration, chilling, freezing, and blanching of materials should be undertaken prior to the drying, in order to improve textural, structural, appearance, taste and flavor characteristics of vegetable and fruit snack. Therefore, this project was proposed to investigate the effect of pretreatment and microwave vacuum drying process parameters on characterizations of vegetable and fruit snack.

Objectives

To determine effect of pretreatment and drying process on characteristics of microwave vacuum dried products

Research methodology

Materials: Mandarins (mandarin *cv. (Sai-Namphaung)*), papaya (*Carica papaya* L.) at green stage, glycerol (Hong Huat Co., Ltd, Bangkok, Thailand) and sucrose (Mitr Phol Sugar Corp., Supanburi, Thailand).

Methods

1. Determination of effect of osmotic dehydration and microwave vacuum drying on quality of dried mandarin

1.1 Osmotic dehydration of mandarin

Peeled mandarin segments were soaked in osmotic solution containing a mixture of sucrose solution (60 g/ 100 g (w/w)) to glycerol solution (60 g/ 100 g (w/w)) in a ratio of 9:1, 7:3 and 5:5 w/w, respectively. The ratio between the sample and osmotic solution was 1:5. The osmotic solution was agitated at 4.2 rad/s using an automatic rotating paddle. During osmotic dehydration, moisture content of all samples was analyzed using a vacuum oven (Binder VD53, Germany) at 70 ^{0}C (AOAC, 2000). Dielectric properties of the osmotically dehydrated mandarin using an open-ended coaxial probe and a network analyzer (Dielectric measurement kit V.2.1.0.; Püschner, Schwanewede, Germany).

1.2 Microwave vacuum drying of osmotically dehydrated mandarin

After osmotic dehydration, the mandarin samples (200 g per batch) were dried in a microwave vacuum dryer (MarchCool, Bangkok, Thailand) at 2.45 GHz and 13.33 kPa. Based on the IMPI 2-Liter test (Buffler, 1993), the microwave powers were operated at 960 W and 1280 W. Drying kinetics of osmotically dehydrated mandarin was determined and simulated using thin layer models.

1.3 Quality measurement of microwave vacuum dried mandarin

Colour (CIE L*, C* and h^{0}) of the microwave vacuum dried mandarin was analyzed using a spectrophotometer (CM-3500d; Konica Minolta Holdings Inc., Tokyo, Japan. β-carotene (vitamin A) content was determined using AOAC (1997). Hardness of the dried mandarin samples was determined using Lloyd texture analyzer (TA500; Lloyd Instruments Ltd., Hampshire, UK).

2. Determination of effect of blanching and freezing prior to microwave vacuum drying on quality of dried papaya strips.

2.1 Pretreatment of papaya strips prior to microwave vacuum drying

Papaya strips was pretreated by various conditions including:

Condition 1: Control

Condition 2: Blanching in water

Condition 3: Blanching in 5% w/w NaCl solution

Condition 4: Blanching in 10% w/w NaCl solution

Condition 5: Blanching in 15% w/w NaCl solution

Condition 6 Blanching in 15% w/w sucrose solution

Condition 7: Blanching in 5% w/w NaCl solution + 15% w/w sucrose solution

Condition 8: Blanching in 10% w/w NaCl solution + 15% w/w sucrose solution

Condition 9: Blanching in 15% w/w NaCl solution + 15% w/w sucrose solution

After blanching, samples were directly dried in the microwave vacuum dryer or frozen at -38^{0}C using air blast freezer (Cold Line Professional Equipment, Italy). Dielectric properties of control and pretreated materials were measured using an open-ended coaxial probe and a network analyzer (Dielectric measurement kit V.2.1.0.; Püschner, Schwanewede, Germany).

2.2 Microwave vacuum drying of papaya strips

The pretreated papaya strips (300 g per batch) were dried in a microwave vacuum dryer (MarchCool, Bangkok, Thailand), operated at 2.45 GHz, 1920 W and 13.33 kPa. Moisture content of all samples was analyzed using an oven method (AOAC, 2000). Moisture transfer parameters during microwave vacuum drying were estimated using Biot Number – lag factor correlation (Dincer and Hussain, 2004).

2.3 Quality measurement of microwave vacuum dried papaya strips

Structure of dried papaya was investigated using a scanning electron microscope (PHILIPS, XL series, Holland). *Rehydration ability was determined, according to method proposed by* Lewicki (1998).

3. Statistical analysis

All experiments were conducted with 2 replications. Difference between the means of all treatments was analyzed using a one-way ANOVA (SPSS® version 12.0). Duncan's Multiple Range was used to identify a difference at 95% significant level.

Project Plan

Project is planned to be carried out within 24 months as follows:

Schedule	**First year**		**Second year**	
	1-6 Months	**7-12 Months**	**1-6 Months**	**7-12 Months**
1. Determination of effect of osmotic dehydration on dielectric properties and microwave vacuum drying kinetics of raw material				
2. Determination of effect of osmotic dehydration and microwave vacuum drying on quality of dried snack				
3. Determination of effect of blanching and freezing on dielectric properties of raw material and mass transfer parameters during microwave vacuum drying				
4. Determination of effect of blanching and freezing prior to microwave vacuum drying on structure and rehydration ability of dried material				
5. Report writing				

Output

Therdthai, N., Zhou, W. and Pattanapa, K. (2011). Microwave vacuum drying of osmotically dehydrated mandarin cv. *(Sai-Namphaung). International Journal of Food Science and Technology*, **46**, 2401 – 2407. (Impact factor = 1.223)

Introduction

Microwave vacuum drying could be claimed as a rapid dehydration process. It could reduce drying time significantly, compared with conventional hot air drying. Too rapid mass transfer could damage the texture in some cases. Moreover non-uniformity of electromagnetic field could create hot spots during microwave heating. To improve characteristics of microwave vacuum dried products, pretreatment such as osmotic dehydration, freezing, chilling and blanching should be used to develop variety of appearance and texture.

For process efficiency, pretreatment by freezing, blanching and osmotic dehydration possibly affected drying characteristics. Arévalo-Pinedo and Murr (2007) reported faster drying rate of vacuum drying when freezing was used as pretreatment of carrot and pumpkin. Blanching in various solutions could also influence drying curve of carrot (Górnicki and Kaleta, 2007). Comparing to the freezing, blanching presented less effect on drying kinetic rate, in the case of vacuum drying of carrot (Arévalo-Pinedo and Murr, 2006). For osmotic dehydration, Al-Harahsheh *et al.* (2009) found that concentration of sodium chloride (up to 0.1 N) in osmotic solution significantly increased microwave drying kinetic rate constant of tomato pomace. However, increasing sodium chloride to above 0.1 N reduced the drying kinetic rate constant. As solids gain and water losses during the osmotic dehydration, dielectric properties of materials were changed. Changrue *et al*. (2008) observed the significantly decreased dielectric constant in osmotically dehydrated carrot and strawberry. In addition, osmotic solution containing a mixture of sucrose and salt caused higher loss factor of carrot than the one containing only sucrose solution. Torringa *et al.* (2001) found that osmotic dehydration in salt solution prior to microwave-hot air drying increased loss factor and reduce penetration depth. As a result, heating profiles of concave-shaped mushroom (*Agaricus bisporus*) with 40 mm diameter at surface and centre were not much different. Therefore, the central overheating was reduced. In contrast, the decrease in dielectric constant and loss factor resulted in little microwave energy absorption ability and the reduced effectiveness of microwave drying (Wang and Chen, 2005).

For appearance, shrinkage characteristic was decreased by osmotic dehydration. Aktas *et al.* (2007) found reduced shrinkage in dried vegetables when either trehalose solution or powder was used together with blanching. Sodium chloride solution was also found to decrease the shrinkage of microwave assisted hot air dried mushroom (Torringa *et al*., 2001). In addition, natural color of material could be maintained. By using sucrose in the osmotic solution prior to hot air drying or vacuum drying, binding force of lycopene in the food matrix was strengthen, as a result, lycopene loss was reduced and red color was maintained (Shi *et al.,* 1999). However, selection of osmotic solution was also important. Osorio *et al.* (2007) found higher L* and a* values of Andes berries which immerged into 70% sucrose solution without glycerol than those immerged into the mixed solution between 70% sucrose and 65% glycerol (1:1 v/v).

Regarding textural and structural properties, drying with microwave heating could produce harder and firmer texture of dried fruit than the one without microwave heating (Contreras *et al*., 2008). Stepien (2008) found significant improvement of texture of dried carrot when osmotic dehydration was undertaken prior to microwave vacuum drying. Drying without osmotic dehydration yielded the dried carrot that had 3 times compression strength of the one with osmotic dehydration. However, blanching before drying increased compression strength, compared with the one without pretreatment. Erle and Schubert (2001) explained that the improvement of texture of microwave vacuum dried fruits with osmotic dehydration was because of gel formation between pectin and sucrose. In addition, Chenlo *et al*. (2004) reported the potential of the use of glycerol as solute in the osmotic solution to improve textural characteristics. Similarly, Aktas *et al*. (2007) observed the improvement of cell reconstruction properties of dried vegetables that used trehalose as pretreatment. To increase open-pore porosity, osmotic dehydration with sodium chloride solution should be used (Torringa *et al*., 2001). Kingcam *et al*. (2008) found obvious effect of pretreatment prior to low-pressure superheated steam drying on degree of retrogradation and thereby hardness, toughness and crystallinity. Pimpaporn *et al*. (2007) recommended the use of combined blanching and freezing prior to the low-pressure superheated steam drying to improve textural characteristic of potato chip.

For flavor and taste, osmotic dehydration undertaken before drying could modify flavor and taste of dried product, due to solid gain during osmotic dehydration. For tomato, microwave assisted air drying with osmotic dehydration with ternary solutions including 27.5% sucrose, 10% salt and water (w/w) and 2% of calcium lactate could produce better taste and flavor of dried tomato than that without osmotic dehydration (Heredia *et al.*, 2007). Likewise, Aktas *et al*. (2007) observed an improvement of flavor with the use of trehalose as pretreatment.

As above mentioned, pretreatment has been successfully taken prior to various drying methods. For microwave vacuum drying, few researches has studied on influence of osmotic dehydration and blanching on quality of dried carrot, apple and strawberry. However, interaction between pretreatment and drying process parameters has not been reported. In this study, various pretreatments will be taken prior to microwave-vacuum drying. Their effect combined with drying process parameters on characteristics of dried local fruit and vegetable snacks will be investigated.

Objective

To determine effect of pretreatment and drying process on characteristics of microwave vacuum dried products

Methodology

Materials

Mandarins (mandarin *cv. (Sai-Namphaung*)) were purchased from a local market, with an average diameter of 65±3 mm. They were peeled and fibre on the segment surface was removed. Papaya (*Carica papaya* L.) at green stage was bought locally. It was peeled and sliced to be a strip (approximately 2 mm x 3 mm x 50 mm). Glycerol (Hong Huat Co., Ltd, Bangkok, Thailand) and sucrose (Mitr Phol Sugar Corp., Supanburi, Thailand) were used as osmotic solutions.

Methods

1. Determination of effect of osmotic dehydration and microwave vacuum drying on quality of dried mandarin

1.1 Osmotic dehydration of mandarin

Peeled mandarin segments were soaked in osmotic solution containing a mixture of sucrose solution (60 g/ 100 g (w/w)) to glycerol solution (60 g/ 100 g (w/w)) in a ratio of 9:1, 7:3 and 5:5 w/w, respectively. The ratio between the sample and osmotic solution was 1:5. The osmotic solution was agitated at 4.2 rad/s using an automatic rotating paddle. During osmotic dehydration, mandarin was taken to measure its dielectric properties using dielectric measurement kit V.2.1.0.; Püschner, Schwanewede, Germany. Moisture content of all samples was analyzed using a vacuum oven (Binder VD53, Germany) at 70 ^{0}C (AOAC, 2000).

1.2 Measurement of dielectric properties of osmotically dehydrated mandarin

Dielectric constant (ε') represents the ability of materials to store electrical energy from an external electric field. The loss factor (ε'') represents the ability of materials to convert electric energy into thermal energy (Al-Harahsheh *et al*., 2009). To measure the dielectric constant and the loss factor at 2.45 GHz, the osmotically dehydrated mandarin segments were blended and used to fill a 40-mm diameter cylinder. An open-ended coaxial probe was placed into the cylinder. The signal was analyzed by a network analyzer (Dielectric measurement kit V.2.1.0.; Püschner, Schwanewede, Germany). All measurements were conducted in duplicate. For each duplication, there were 5 replications per treatment.

The dissipation factor or loss tangent (tan δ) is defined as a ratio of loss factor to dielectric constant (eqn 1).

$$\tan\delta = \frac{\varepsilon''}{\varepsilon'} \qquad (1)$$

The penetration depth, D_p, (the distance where the microwave power dropped to 1/*e* (e = 2.718) or 36.8% of the transmitted value of its surface value), was considered an important parameter in characterizing microwave heating (Sosa-Morales *et al.,* 2010) and can be calculated using eqn 2 (Singh & Heldman, 2001).

$$D_p = \frac{\lambda_0}{2\pi\sqrt{2\varepsilon'}}\left[(1+\tan^2\delta)^{1/2}-1\right]^{-1/2} \quad (2)$$

where: λ_0 = the free space microwave wavelength (for 2.45 GHz. λ_0=12.245 cm.)

1.3 Microwave vacuum drying of osmotically dehydrated mandarin

After osmotic dehydration, the mandarin samples (200 g per batch) were dried in a microwave vacuum dryer (MarchCool, Bangkok, Thailand) consisting of six magnetrons with a 360^0-rotating plate. The dryer was operated at 2.45 GHz frequency and 13.33 kPa pressure. The power level was investigated using the IMPI 2-Liter test (Buffler, 1993). A load of two 1-L beakers (Pyrex 1000) of water at an initial water temperature of 20±2 ^{0}C was placed in the centre of the dryer and the dryer was then turned on. After 2 min and 2 s, the beakers were removed from the dryer. The temperature of water in both beakers was measured and recorded. The power was calculated from eqn 3 (Buffler, 1991):

$$P(W) = 70 \times \frac{(\Delta T_1 + \Delta T_2)}{2} \quad (3)$$

where: P(W) = microwave power, ΔT_1 and ΔT_2 = temperature rise of the water in the first and second beakers, respectively, calculated by subtracting the initial water temperature from the final temperature.

In the current study, average final temperatures of the first and second beakers from the first operating condition were 34.0 and 33.4 ^{0}C, respectively. The average final temperatures of the first and second beakers from the second operating condition were 38.5 and 38.0 ^{0}C, respectively. Therefore, the microwave vacuum dryer was operated at two levels of microwave power, being 960 W (MV4.8) and 1280 W (MV6.4).

1.3.1 *Drying kinetics of osmotically dehydrated mandarin*

The change in moisture in the samples of osmotically dehydrated mandarin during further drying was expressed by the moisture ratio (eqn 4).

$$MR = \frac{X_t - X_e}{X_0 - X_e} \quad (4)$$

where: MR = moisture ratio, X_0 = initial moisture content dry basis (kg water kg^{-1} d.m.), X_e is equilibrium moisture content (kg water kg^{-1} d.m.) and X_t is moisture content dry basis (kg water kg^{-1} d.m.)

The kinetics of the moisture ratio during microwave vacuum drying was simulated using thin layer models are follows:

Lewis model (Lewis, 1921):	MR = exp (-kt)	(5)
Page model (Page, 1949):	MR = exp (-kt^{n})	(6)
Henderson and Pabis (Henderson & Pabis, 1961):	MR = a exp (-kt)	(7)
Logarithmic (Yaldiz *et al*., 2001):	MR = a exp (-kt) + c	(8)
Two-Term model (Sharaf-Eldeen *et al*., 1980):	MR = a exp (-kt) + c exp (-gt)	(9)
Wang & Singh (Wang & Singh, 1978):	MR = 1 + at + bt^{2}	(10)

where: k, n, a, b, c, and g = the model constants, t = the drying time (min).

Correlation coefficient (r) and root mean square error (eqn 11) between the modelled moisture ratio and the experimental data were used to determine each model's performance. In addition, residual plots were also provided to present pattern of error throughout the range of prediction.

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(MR_{pi} - MR_i)^2} \qquad (11)$$

where MR_{pi} and MR_i are predicted moisture ratio and experimental moisture ratio, respectively and n is a number of data points.

1.3.2 Colour measurement of osmotically dehydrated mandarin

The colour of the microwave vacuum dried mandarin was analyzed using a spectrophotometer (CM-3500d; Konica Minolta Holdings Inc., Tokyo, Japan) for 5 replications. Colour was determined using the CIE system with values of L*, C* and h^0 representing darkness-lightness, chroma and hue, respectively.

1.3.3 *β-carotene analysis of osmotically dehydrated mandarin*

To explain the colour change, β-carotene (vitamin A) content of the dried mandarin samples was determined using AOAC (1997) method with 3 replications. Samples (10$\pm$5 g) were extracted with petroleum ether (15 mL) for three times. After vortex for 2 min and centrifuging for 15 min, clear solution was brought to a filter (0.45

µm). The obtained clear solution was taken to measure the absorbance using a spectrophotometer (at 450 nm wave length). Thus, the concentration of β-carotene could be read from the standard curve.

1.3.4 Texture measurement of osmotically dehydrated mandarin

In general, hardness of dried food indicates sensory quality of the food and it is tested by compression. Too high a hardness is not preferred. After microwave vacuum drying until moisture content of mandarin was less than 0.1 kg water kg^{-1} d.m., the hardness of the dried mandarin samples was determined using a Lloyd texture analyzer (TA500; Lloyd Instruments Ltd., Hampshire, UK) with 5 N load cell. A 0.5 mm diameter ball probe was set at a speed of 0.8 $mm \cdot min^{-1}$ to test the compression force on the sample (15 mm x 30 mm). The peak of the compression force represented the single hardness of the dried mandarin samples. The measurement was conducted with 15 replications.

1.4 Statistical analysis

All experiments were conducted with 2 duplications. Difference between the means of all treatments was analyzed using a one-way ANOVA (SPSS® version 12.0). Duncan's Multiple Range was used to identify a difference at 95% significant level.

2. Determination of effect of blanching and freezing prior to microwave vacuum drying on quality of dried papaya strips.

2.1 Pretreatment of papaya strips prior to microwave vacuum drying

Papaya strips was pretreated by various conditions including:

Condition 1: Control

Condition 2: Blanching in water

Condition 3: Blanching in 5% w/w NaCl solution

Condition 4: Blanching in 10% w/w NaCl solution

Condition 5: Blanching in 15% w/w NaCl solution

Condition 6 Blanching in 15% w/w sucrose solution

Condition 7: Blanching in 5% w/w NaCl solution + 15% w/w sucrose solution

Condition 8: Blanching in 10% w/w NaCl solution + 15% w/w sucrose solution

Condition 9: Blanching in 15% w/w NaCl solution + 15% w/w sucrose solution

After blanching, samples were directly dried in the microwave vacuum dryer or frozen at $-38^{0}C$ using air blast freezer (Cold Line Professional Equipment, Italy) and then dried in the microwave vacuum dryer.

2.2 Measurement of dielectric properties of pretreated papaya strips

To measure the dielectric constant and the loss factor at 2.45 GHz, the pretreated materials were packed into a 40-mm diameter cylinder. An open-ended coaxial probe was placed into the cylinder. The signal of the dielectric property was analyzed by a network analyzer (Dielectric measurement kit V.2.1.0.; Püschner, Schwanewede, Germany). All measurements were conducted in duplicate. The dissipation factor or loss tangent is defined as a ratio of loss factor to dielectric constant (eqn 1).

2.3 Microwave vacuum drying of papaya strips

The pretreated papaya strips (300 g per batch) were dried in a microwave vacuum dryer (MarchCool, Bangkok, Thailand) consisting of six magnetrons with a 360^{0}-rotating plate. The dryer was operated at 2.45 GHz frequency, 1920 W and 13.33 kPa. Moisture content of all samples was analyzed using an oven method (AOAC, 2000). The change in moisture of pretreated papaya strips during drying was expressed by the moisture ratio (eqn 4).

2.3.1 Determination of mass transfer parameters during microwave vacuum drying of papaya strips

Moisture transfer parameters during microwave vacuum drying were estimated using Biot Number – lag factor correlation (Dincer and Hussain, 2004) as follows:

$$MR = G \cdot \exp(-St) \tag{12}$$

where: G = lag factor, S = drying coefficient (s^{-1}), t = the drying time (s).

The Biot number for moisture transfer (Bi) was defined as equation 13.

$$Bi = 0.0576 \cdot G^{26.7} \tag{13}$$

Based on the relation developed by Dincer and Dost (1996), the moisture diffusivity (D: $m^2 \cdot s^{-1}$) was calculated by equation 14.

$$D = (SY^2)/(u^2) \tag{14}$$

Where: Y = half thickness for sample (m), $u = -419.24G^4 + 2013.8G^3 - 3615.8G^2 + 2880.3G - 858.94$

The goodness of the correlation coefficient (r) and root mean square error (RMSE) between the modeled moisture ratio and the experimental data were used to verify applicability of the Biot Number – lag factor correlation in the microwave vacuum drying of papaya strips.

2.3.2 Determination of structural characteristics of dried papaya strips

The structure of dried papaya was investigated using a scanning electron microscope (PHILIPS, XL series, Holland) with an accelerating voltage of 13.0 kV. Magnification was adjusted to 300x.

2.3.3 Determination of rehydration ability of dried papaya strips

Dried papaya strip (5 g) was rehydrated in water at ambient temperature for 5 min. According to Lewicki (1998), water absorption capacity (WAC) of dried food was estimated as:

$$WAC = \frac{w_r(100 - s_r) - w_d(100 - s_d)}{w_0(100 - s_0) - w_d(100 - s_d)} \tag{15}$$

where w_0, w_d and w_r = weight (g) of sample before drying, before rehydration and after rehydration, respectively. s_0, s_d and s_r = dried solid (%) of sample before drying, before rehydration and after rehydration, respectively.

Drying matter holding capacity (DHC), an indicative of dried material permeability to soluble could be calculated as:

$$DHC = \frac{w_r \cdot s_r}{w_d \cdot s_d} \tag{16}$$

Thus rehydration ability (RA) was estimated as:

$$RA = WAC \cdot DHC \tag{17}$$

Index of rehydration ability should be in the range of 0 - 1. The small index presented the highly damaged tissue during drying.

2.4 Statistical analysis

All experiments were conducted with 2 duplications. Difference between the means of all treatments was analyzed using a one-way ANOVA (SPSS® version 12.0). Duncan's Multiple Range was used to identify a difference at 95% significant level.

Results and Discussion

1. Effect of osmotic dehydration and microwave vacuum drying on quality of dried mandarin.

1.1 Effect of osmotic dehydration on dielectric properties of mandarin

The ratio of water loss and solid gain during osmotic dehydration could affect the dielectric properties of mandarin. In osmotic dehydration of mandarin, the previous study (Pattanapa *et al*., 2010) reported much higher increasing rate of water loss than that of solid gain. With the decreased water content, the dielectric constant decreased throughout the osmotic dehydration process (Fig. 1). Likewise, Changrue *et al*. (2008) also observed a decrease in the dielectric constant of osmotically dehydrated carrots and strawberries, compared with fresh materials. In the current study, the change in the dielectric constant was enhanced by an increase in the glycerol ratio in the osmotic solution (Table 1).

In addition to the dielectric constant, the loss factor also increased; as well as, the penetration depth was decreased throughout osmotic dehydration. This may cause a large absorption of microwave energy in a very shallow layer below the surface of mandarin, during drying. In general, the loss factor could be influenced by the amount of water and the ionic conductivity. In the current study, an increase in the glycerol ratio in the mixture used for osmotic dehydration could increase the loss factor significantly ($P \leq 0.05$).

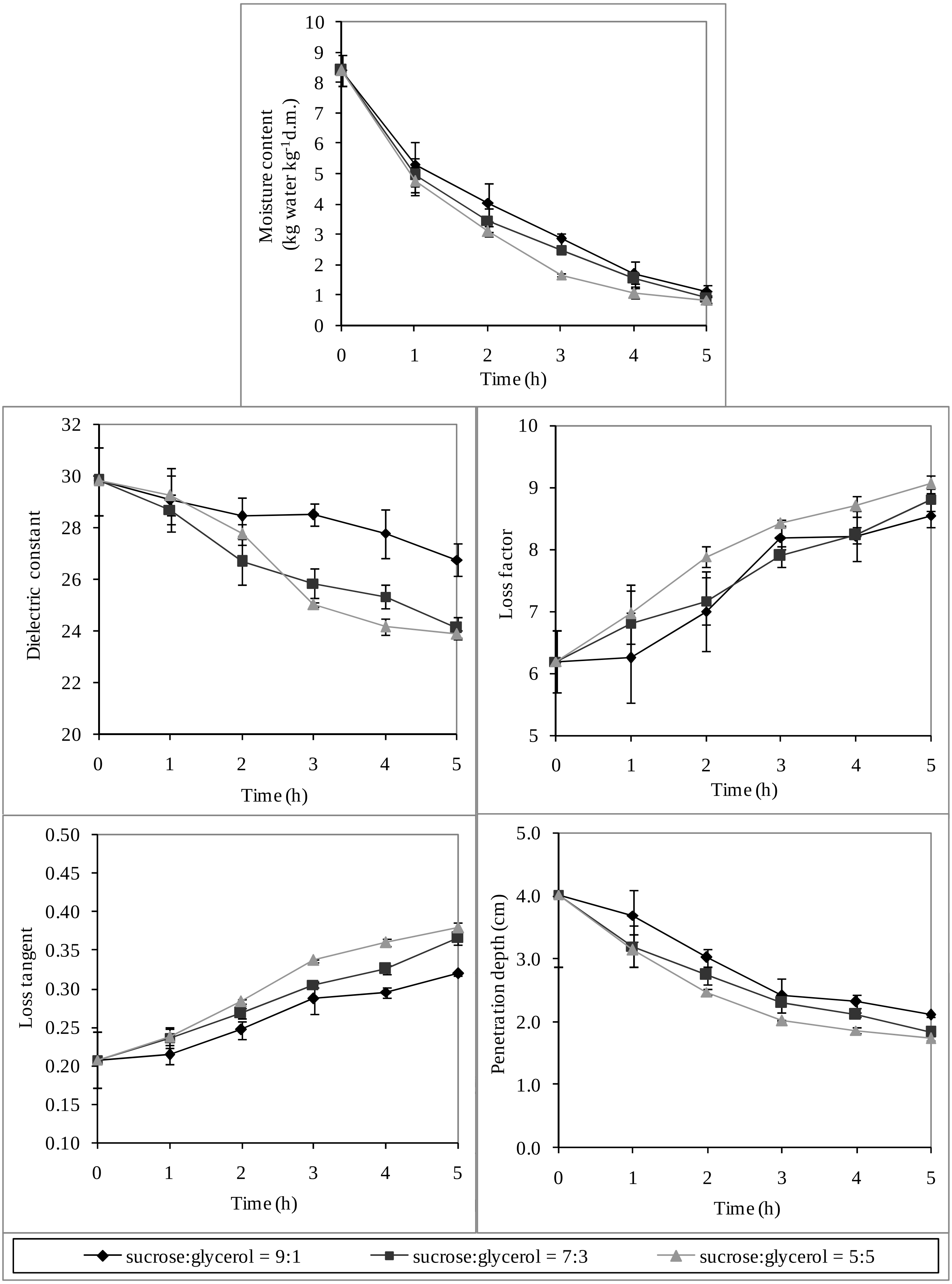

Figure 1 Changes during osmotic dehydration of mandarin: (a) moisture content, (b) dielectric constant, (c) loss factor, (d) loss tangent, and (e) penetration depth

Table 1 Dielectric properties of mandarin samples before and after osmotic dehydration.

Dielectric properties	Fresh mandarin	Ratio of sucrose to glycerol in osmotic solution mixture		
		9:1	7:3	5:5
Dielectric constant	29.80[a]	26.77[b]	24.11[c]	23.89[c]
Loss factor	6.19[c]	8.55[b]	8.81[ab]	9.06[a]
Loss tangent	0.21[c]	0.32[b]	0.36[a]	0.38[a]
Penetration depth (cm)	4.02[a]	2.11[b]	1.83[c]	1.74[c]

[a-c] Means within the same row with different letters are significantly different ($P \le 0.05$).

1.2 Effect of osmotic dehydration and microwave power on drying kinetics of mandarin

The comparison was firstly made on comparing the microwave vacuum drying to the previously studied hot air drying (Pattanapa *et al.*, 2010), after the osmotic dehydration. By using osmotic dehydration as a pre-treatment step for water removal, the moisture content of the mandarin samples at the beginning of drying was reduced from 8.41 to 0.84 - 1.13 kg water kg^{-1} d.m.. In the previous study, hot air drying at 70 ^0C was used to dry osmotically dehydrated mandarin for 360 min. In the current study with microwave vacuum drying at 4.8 - 6.4 W g^{-1}, the drying time was reduced to 5-7 min to obtain the moisture content less than 0.1 kg water kg^{-1} d.m. (Fig. 2). Applying microwave vacuum drying could speed up mass transfer, due to an increased pressure gradient between the inner and outer layers of the material. Increasing the microwave power intensity from 4.8 W g^{-1} to 6.4 W g^{-1} increased the drying rate. As a result, the drying time was decreased by 2 min. The results were consistent with those of Therdthai and Northongkom (2011), who reported a decrease in the drying time of fingerroot when the microwave power was increased. Comparing to the early drying period, the drying rate of the final period of microwave vacuum drying was decreased, because the water molecules were tightly bound, so that mobility of the water molecules or charged ions may become difficult. The loss factor might be decreased. This reduced the effectiveness of microwave heating.

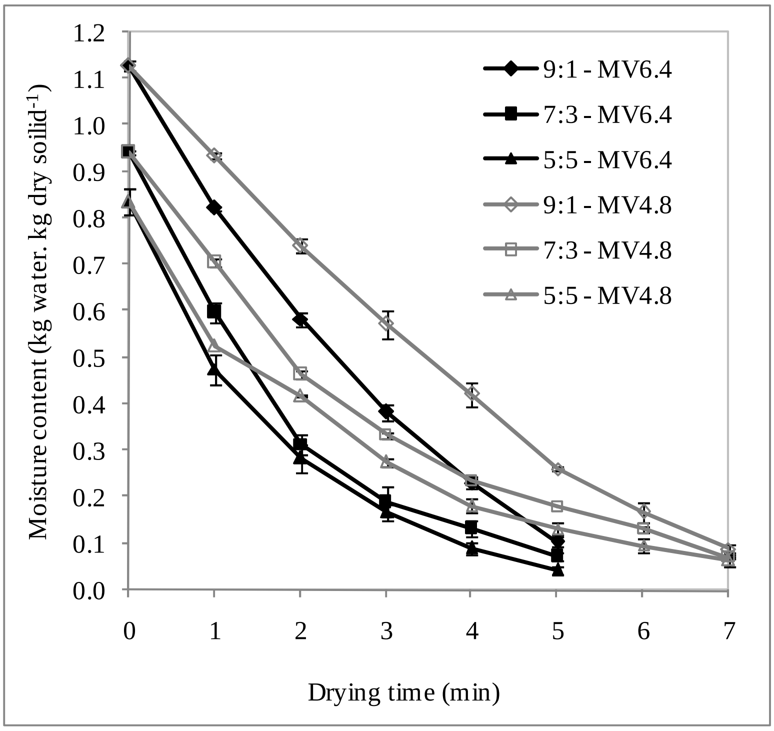

Figure 2 Moisture content of osmotically dehydrated mandarin samples during microwave drying. Vertical bars represent ± standard error from the mean value.

Secondly, variation of osmotic dehydration conditions could also affect the microwave vacuum drying rate. Due to change of loss and dissipation factors during osmotic dehydration using various mixtures of sucrose and glycerol solutions, the drying rate tended to increase, as the ratio of sucrose to glycerol in the osmotic solution was changed from 9:1 to 5:5 w/w. This coincided with the results of Wang and Chen (2005), who reported that the effectiveness of microwave drying could be improved by increasing the loss factor. In addition, Al-Harahsheh *et al*. (2009) found the increased drying rate constant of tomato pomace when the loss tangent was increased up to approximately 0.3.

Finally, to simulate the change of moisture content throughout the microwave vacuum drying, several thin layer models (eqn 5 - 10) were determined. Parameters of thin layer models were estimated as presented in Table 2. Due to the lowest RMSE (0.0039 - 0.0371) and the highest r (0.9929 - 0.9999), the Page model was found to be the best to describe the drying of osmotically dehydrated mandarin (Table 2). In addition, residual plot of the Page model was very close to the x-axis and not systematic (Fig. 3).

Table 2 Model parameters and performance of the thin layer models of osmotically dehydrated mandarin. (r = correlation coefficient and RMSE = root mean square error)

Condition	Model	Parameter	RMSE	r
MV4.8	Lewis	k = 0.2169	0.0663	0.9858
9:1	Page	k= 0.0961, n =1.4860	0.0066	0.9998
	Henderson & Pabis	k = 0.2463, a= 1.1583	0.0640	0.9812
	Logarithmic	k= 0.0696, a = 2.2414, c= -1.2122	0.0227	0.9968
	Two-Term model	k= 0.4022, a= 6.8507, c= -5.8513, g= 0.4663	0.0039	0.9999
	Wang & Singh	a= -0.1395, b= 0.0029	0.0254	0.9966
MV4.8	Lewis	k= 0.2456	0.0771	0.9822
7:3	Page	k= 0.0930, n= 1.5886	0.0238	0.9971
	Henderson & Pabis	k = 0.2777, a= 1.1742	0.0719	0.9775
	Logarithmic	k= 0.1093, a= 1.7195, c= -0.6736	0.0389	0.9918
	Two-Term model	k= 0.4595, a= 6.6610, c= -5.6591, g= 0.5422	0.0156	0.9987
	Wang & Singh	a= -0.1609, b= 0.0052	0.0423	0.9918
MV4.8	Lewis	k = 0.2958	0.0815	0.9816
5:5	Page	k= 0.1171, n= 1.5667	0.0275	0.9965
	Henderson & Pabis	k = 0.3304, a= 1.1889	0.0779	0.9768
	Logarithmic	k= 0.1620, a= 1.4360, c= -0.3853	0.0448	0.9903
	Two-Term model	k= 0.1120, a= 5.0688, c= -4.0176, g= 0.0837	0.0441	0.9906
	Wang & Singh	a= -0.1966, b= 0.0094	0.0462	0.9915
MV6.4	Lewis	k = 0.3750	0.0640	0.9872
9:1	Page	k = 0.2211, n= 1.3776	0.0039	0.9999
	Henderson & Pabis	k = 0.4162, a= 1.1629	0.0745	0.9828
	Logarithmic	k= 0.1595, a= 1.6425, c= -0.6253	0.0166	0.9986
	Two-Term model	k= 0.1015, a= 7.1103, c= -6.0962, g= 0.0791	0.0161	0.9986
	Wang & Singh	a= -0.2448, b= 0.0135	0.0155	0.9989
MV6.4	Lewis	k= 0.3531	0.0522	0.9886
7:3	Page	k= 0.2246, n= 1.3597	0.0371	0.9929
	Henderson & Pabis	k = 0.3662, a= 1.0493	0.0473	0.9881
	Logarithmic	k= 0.2847, a= 1.1637, c= -0.1312	0.0437	0.9898
	Two-Term model	k= 0.1998, a= 9.0243, c= -7.9922, g= 0.1847	0.0430	0.9901
	Wang & Singh	a= -0.2875, b= 0.0241	0.0397	0.9927
MV6.4	Lewis	k = 0.4693	0.0872	0.9793
5:5	Page	k= 0.2227, n= 1.5491	0.0162	0.9989
	Henderson & Pabis	k = 0.5271, a= 1.2363	0.1054	0.9725
	Logarithmic	k= 0.2210, a= 1.4666, c= -0.4364	0.0374	0.9939
	Two-Term model	k= 0.1653, a= 3.1760, c= -2.1454, g= 0.0944	0.0367	0.9941
	Wang & Singh	a= -0.2884, b= 0.0199	0.0361	0.9950

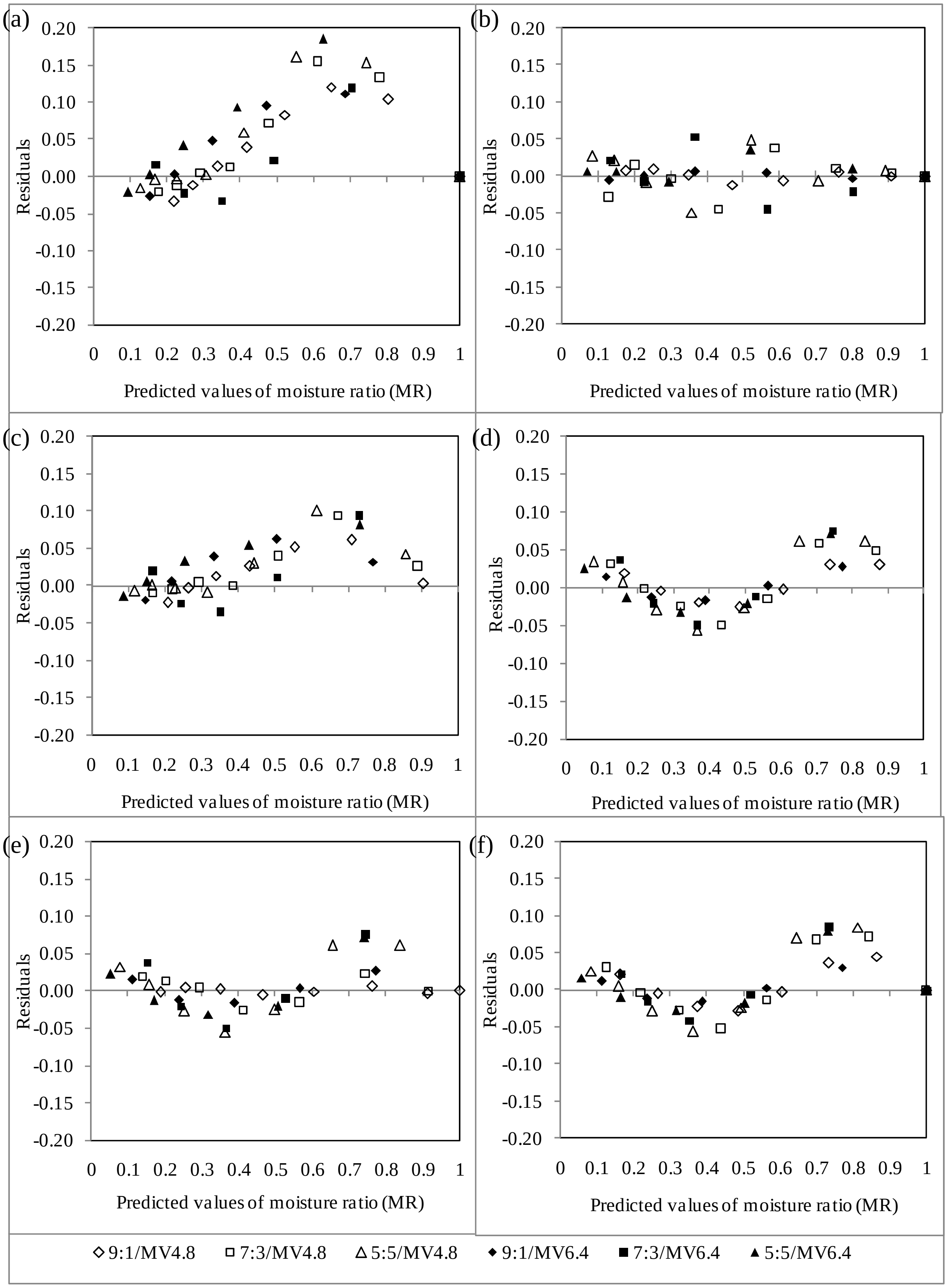

Figure 3 Residual plots of thin layer models: (a) Lewis, (b) Page, (c) Henderson&Pabis, (d) Logarithmic, (e) Two-term model and (f) Wang&Singh

1.3 Effect of osmotic dehydration and microwave power on quality of dried mandarin

1.3.1 Colour and β-carotene retention of dried mandarin

Before drying, the lightness (L*-value), chroma (C*-value) and hue angle (h^0) of the osmotically dehydrated mandarin samples were 46.43, 14.12 and 73.58, respectively. After drying, the intensity of colour increased due to water loss. From the hue angle, the sample colour changed from yellow to yellow-red after drying. Increasing the microwave power from 4.8 $W{\cdot}g^{-1}$ to 6.4 $W{\cdot}g^{-1}$ tended to reduce the lightness (Table 3). Similarly, a decrease in the ratio of sucrose in the mixture of the osmotic solution significantly ($P \leq 0.05$) reduced the lightness of the dried mandarin samples. Compared to hot-air drying (Pattanapa *et al*., 2010), the microwave vacuum drying produced lighter colour dried mandarin samples. This was possibly due to the applied vacuum condition and short drying time in the microwave vacuum drying that could decrease β-carotene loss.

Table 3 Colour, hardness and β-carotene content (mean ± standard error) of osmotically dehydrated mandarin samples after microwave vacuum drying.

Drying condition	Sucrose :glycerol ratio	L*	C*	h^0	β-carotene (μg/100g)	Hardness (N)
MV4.8	9:1	$55.34^{a} \pm 1.63$	$50.66^{a} \pm 2.33$	$62.07^{ab} \pm 0.56$	$1104.15^{a} \pm 15.75$	$0.52^{a} \pm 0.13$
	7:3	$50.78^{c} \pm 1.68$	$48.97^{bc} \pm 1.34$	$61.94^{abc} \pm 0.85$	$444.48^{c} \pm 45.44$	$0.35^{b} \pm 0.08$
	5:5	$49.87^{d} \pm 1.77$	$46.31^{d} \pm 1.65$	$61.19^{cd} \pm 1.77$	$55.77^{e} \pm 0.68$	$0.22^{c} \pm 0.05$
MV6.4	9:1	$53.96^{b} \pm 2.12$	$49.57^{ab} \pm 3.00$	$62.67^{a} \pm 1.65$	$760.16^{b} \pm 8.83$	$0.49^{a} \pm 0.11$
	7:3	$50.35^{cd} \pm 1.47$	$49.26^{bc} \pm 1.48$	$61.67^{bc} \pm 0.82$	$332.14^{d} \pm 0.48$	$0.31^{b} \pm 0.06$
	5:5	$48.34^{e} \pm 0.97$	$48.06^{c} \pm 1.02$	$60.67^{d} \pm 1.04$	$64.25^{e} \pm 2.50$	$0.25^{c} \pm 0.04$

[a-e] Means within the same column with different letters are significantly different ($P \leq 0.05$).

Increasing the microwave power from 4.8 $W{\cdot}g^{-1}$ to 6.4 $W{\cdot}g^{-1}$ did not significantly affect the hue ($P > 0.05$). However, by using a 5:5 ratio of sucrose to glycerol in the mixture of the osmotic dehydration, chroma was significantly increased as the microwave power was increased. With a constant concentration of osmotic solution (60 g/ 100 g (w/w)), reducing the sucrose ratio (by increasing the glycerol ratio) in the osmotic solution also decreased the hue angle and chroma of the osmotically dehydrated mandarin samples after microwave vacuum drying. This was possibly due to an increase in the β-carotene loss. Ruiz *et al.* (2005) found a linear relationship between the colour and carotene content of fresh apricots. Carotenoid was one of the components contributing to the colour of mandarins. Pre-treatment with sucrose during the osmotic dehydration possibly slowed down the loss of carotene, compared with osmotic dehydration without sucrose. Therefore, the colour intensity of the dried mandarin samples could be preserved. Increasing the sucrose ratio (that is, decreasing the glycerol ratio) in the osmotic solution could better maintain the β-carotene content of the dried mandarin samples.

Generally, the solubility of carotene was increased when the process temperature was increased during drying (Karabulut *et al.,* 2007). For microwave vacuum drying, increasing the microwave power caused an increased loss of β-carotene. However, there was no clear impact observed of microwave power in the studied range (4.8 - 6.4 $W{\cdot}g^{-1}$) on the chroma and hue angle of the dried mandarin samples. This was possibly because the vacuum conditions could help maintain the β-carotene content and thereby product colour.

1.3.2 Textural characteristics of dried mandarin

When water was removed from the cell, compared with fresh material, the cell membrane could be separated from the cell wall, resulting in cell wall deformation and increased mechanical stress on the middle lamellae (Castello *et al.,* 2009). In the current study, increasing the glycerol ratio (that is, reducing the sucrose ratio) in the osmotic solution significantly ($P \leq 0.05$) reduced the hardness of the dried samples (Table 3). Further microwave vacuum drying could develop a puffing structure in the dried mandarin samples. Similarly, an increase in puffing characteristics and crispness of fish slices was observed when microwave drying was operated at low pressure (Zhang *et al.,* 2007). In fact, the puffing characteristics were explained by two mechanisms: firstly, the difference between the air pressure in the product and the pressure in the chamber; and secondly vaporization due to an increased product temperature (Ressing *et al*., 2007). However, increasing the microwave power intensity from 4.8 to 6.4 $W{\cdot}g^{-1}$ did not have a significant effect on the hardness of the dried mandarin samples ($P > 0.05$).

2. Effect of blanching and freezing on microwave vacuum drying of papaya strips.

2.1 Effect of blanching and freezing on dielectric properties of papaya strips.

Table 4 presents variation of dielectric properties of papaya strips after pretreatment. Blanching in water could significantly ($P \leq 0.05$) increase dielectric constant, loss factor and loss tangent of papaya strips. However, freezing after blanching in water caused non-significant improvement of dielectric properties ($P > 0.05$) due to ice crystallization. By using sodium chloride solution for blanching, loss factor and loss tangent were significantly improved ($P \leq 0.05$). The increase in loss factor and loss tangent was enhanced by the increased concentration of salt solution. Blanching in 15% w/w sucrose solution did not change loss factor and loss tangent of papaya significantly, compared with those blanching in water ($P > 0.05$). Therefore, blanching in the mixture of 15% w/w sucrose solution and salt solution did not significantly improve the dielectric properties of papaya, compared with those blanched in only salt solution. This was possibly due to low molecule weight of sodium chloride (compared with sucrose). For the same blanching time, it is possible that more amount of salt was transferred into papaya than sucrose. Addition of salt in the blanching solution might increase amount of ionic substance and thereby loss factor. Therefore, it may increase efficiency of microwave heating during drying.

Table 4 Dielectric properties of papaya strips

Condition	Without freezing			Freezing		
	Dielectric constant	Loss factor	Loss tangent	Dielectric constant	Loss factor	Loss tangent
1	19.59 ± 5.31^{c}	3.26 ± 0.96^{f}	0.17 ± 0.01^{h}	8.19 ± 2.00^{f}	1.49 ± 0.32^{d}	0.19 ± 0.01^{f}
2	36.06 ± 1.42^{ab}	8.19 ± 1.02^{e}	0.23 ± 0.03^{g}	10.19 ± 1.20^{ef}	1.42 ± 0.23^{d}	0.14 ± 0.01^{f}
3	39.18 ± 1.22^{a}	11.83 ± 0.32^{d}	0.30 ± 0.01^{f}	11.61 ± 2.03^{de}	2.99 ± 0.70^{d}	0.25 ± 0.03^{e}
4	35.43 ± 2.59^{b}	13.60 ± 0.92^{c}	0.38 ± 0.01^{d}	18.55 ± 4.09^{ab}	6.23 ± 1.66^{c}	0.34 ± 0.07^{d}
5	36.92 ± 1.40^{ab}	18.90 ± 1.00^{a}	0.52 ± 0.02^{b}	14.69 ± 3.81^{bc}	10.10 ± 2.70^{b}	0.69 ± 0.03^{a}
6	36.75 ± 4.72^{ab}	8.79 ± 1.76^{e}	0.24 ± 0.02^{g}	13.88 ± 2.41^{bc}	2.18 ± 0.51^{d}	0.16 ± 0.02^{f}
7	35.36 ± 2.54^{b}	11.93 ± 0.48^{d}	0.34 ± 0.02^{e}	14.05 ± 2.97^{bc}	6.03 ± 0.41^{c}	0.44 ± 0.07^{c}
8	36.05 ± 1.10^{ab}	15.38 ± 0.58^{b}	0.43 ± 0.01^{c}	17.36 ± 1.48^{bc}	8.64 ± 1.01^{b}	0.50 ± 0.02^{b}
9	34.99 ± 1.63^{b}	19.31 ± 0.56^{a}	0.55 ± 0.03^{a}	20.93 ± 1.07^{a}	13.85 ± 0.57^{a}	0.66 ± 0.04^{a}

$^{a\text{-}f}$ Means within the same column with different letters are significantly different ($P \leq 0.05$)

2.2 Effect of microwave vacuum drying on mass transfer parameters during of papaya

Based on the Biot Number – lag factor correlation (Bi-G), mass transfer parameters were estimated as shown in Tables 5 and 6. Due to reasonable RMSE (0.0039 - 0.0371) and high r (0.9602 - 0.9943), the Biot Number – lag factor correlation should reasonably describe the mass transfer during the microwave vacuum drying of papaya strips.

Table 5 Mass transfer parameters during microwave vacuum drying of unfrozen papaya strips.

		Pretreatment condition								
		1	2	3	4	5	6	7	8	9
Mass Transfer parameter	G	1.2324	1.2399	1.2486	1.2918	1.3485	1.2918	1.3021	1.3126	1.3553
	S (s^{-1})	0.0040	0.0030	0.0040	0.0040	0.0040	0.0030	0.0050	0.0040	0.0040
	D x 10^9 ($m^2 \cdot s^{-1}$)	1.9864	1.4109	1.7653	1.3131	1.0067	0.9848	1.5422	1.1646	0.9907
	Bi	15.27	17.93	21.61	53.57	168.86	53.57	66.33	82.12	192.98
Performance	r	0.9772	0.9914	0.9775	0.9775	0.9723	0.9783	0.9602	0.9752	0.9674
	RMSE	0.0852	0.0560	0.0790	0.0853	0.0955	0.0755	0.1123	0.0928	0.1140

Table 6 Mass transfer parameters during microwave vacuum drying of frozen papaya strips.

		Pretreatment condition								
		1	2	3	4	5	6	7	8	9
Mass Transfer parameter	G	1.2386	1.1400	1.2969	1.2982	1.3126	1.3008	1.3100	1.3139	1.3192
	S (s^{-1})	0.0040	0.0030	0.0040	0.0040	0.0040	0.0040	0.0030	0.0040	0.0040
	D x 10^9 ($m^2 \cdot s^{-1}$)	1.8984	2.8310	1.2721	1.2623	1.1646	1.2431	0.8857	1.1567	1.1265
	Bi	17.45	1.90	59.61	61.22	82.12	64.58	77.85	84.34	93.85
Performance	r	0.9943	0.9799	0.9832	0.9862	0.9775	0.9787	0.9747	0.9771	0.9798
	RMSE	0.0610	0.0903	0.0839	0.0738	0.0941	0.1016	0.0935	0.0876	0.0795

Due to a narrow range of drying coefficients (0.003 – 0.005 s^{-1}), pretreatment did not cause noticeable variation in drying capability of papaya strips. By blanching in salt, sucrose and mixture solutions, lag factor was increased. That meant internal resistance in the pretreated papaya strips to moisture transfer was increased. This might be due to the solid gain (salt and sugar) during blanching. As Biot numbers of almost all samples were in the range of 0.1-100, internal and external resistances to moisture transfer were finite. However, an increase in Biot number indicated the increased significance of internal resistance to moisture transfer. McMinn (2004) stated that the internal resistance became significant when Biot number was over 100. In contrast, external resistance became significant when Biot number was less than 0.1. In this study, the external resistance was not significant. It is possible that the microwave provided rapid heating; as well as, the reduced pressure provided pressure gradient and enhanced moisture transfer. In addition, mass diffusivity tended to decrease when papaya strips was blanched in salt, sucrose or mixed solution. This was consistent with the increased lag factor. Freezing prior to drying also caused a slight decrease in mass diffusivity possibly due to structural change and state of water.

2.3 Structural characteristics of microwave vacuum dried papaya strips

Figure 4 presented structures of the untreated and dried papaya strips, the blanched and dried papaya strips and the blanched, frozen and dried papaya strips. The structure of the untreated and dried papaya strips was shrink and packed (Figure 4 [A1]). However, the structure of frozen and dried samples was more opened (Figure 4 [B1]). Porosity was clearly observed. Damage tissue could be observed in all blanched samples, regardless of blanching solution mixtures (Figure 4 [A2 – A9]). From SEM of the blanched and frozen samples (Figures 4 [B2 - B9]), freezing seemed to yield more damaged structure than the blanched samples without freezing. This was possibly due to ice crystallization during freezing. In particular, structure of the dried sample was clearly damaged when freezing was applied after blanching in water. However, the degree of damage was decreased when blanching in salt, sugar and mixed solution before freezing. It is possible that the increased soluble solid in papaya during blanching might reduce the free water content and thereby reduce ice formation.

2.4 Rehydration ability of microwave vacuum dried papaya strips

After rehydration in water for 5 min, sample weight was recorded. Thus rehydration ability of dried papaya strips was estimated as shown in Table 7. Water absorption capacity of the blanched samples was not significantly higher than that of control samples (P > 0.05). Blanching in the mixed solution between salt and sugar could improve water absorption capacity significantly (P $\leq$ 0.05). However, an increase in salt concentration in the mixture tended to slightly decrease drying matter holding capacity. Nonetheless, blanching in either only salt solution or the mixed solution of salt and sugar increased rehydration ability. Similar trend was also observed in the frozen samples. By freezing, water absorption capacity and dry matter holding capacity of un-blanched samples were increased, compared with those of un-frozen and un-blanched samples. Freezing caused an increase in water absorption, but a reduction of dry matter holding capacity. Therefore, rehydration ability of the frozen samples was not clearly improved, compared with the unfrozen samples.

Table 7 Rehydration performance of microwave vacuum dried papaya strips

Condition	Without freezing			Freezing		
	WAC	DHC	RA	WAC	DHC	RA
1	0.1912±0.0046 d	0.6003±0.0035 cd	0.1148±0.0021 d	0.2261±0.0202 c	0.6302±0.0087 abc	0.1426±0.0147 bc
2	0.2205±0.1106 cd	0.5873±0.0340 cd	0.1276±0.0574 cd	0.2216±0.0223 c	0.6492±0.2024 abc	0.1493±0.0973 bc
3	0.2686±0.0106 cd	0.6602±0.0264 ab	0.1772±0.0001 bc	0.2469±0.0049 c	0.7226±0.0284 a	0.1785±0.0106 b
4	0.2539±0.0105 cd	0.6749±0.0331 a	0.1712±0.0013 bc	0.2932±0.0117 b	0.6818±0.0077 ab	0.1999±0.0057 a
5	0.2689±0.0164 cd	0.5991±0.0320 cd	0.1614±0.0184 bcd	0.2431±0.0018 c	0.4824±0.0155 c	0.1172±0.0029 c
6	0.2927±0.0266 bc	0.5536±0.0014 de	0.1621±0.0151 bcd	0.3217±0.0076 b	0.6113±0.0150 abc	0.1966±0.0002 a
7	0.3785±0.0052 ab	0.6190±0.0062 bc	0.2343±0.0056 a	0.3058±0.0134 b	0.4680±0.0576 c	0.1435±0.0239 bc
8	0.4327±0.0185 a	0.5533±0.0186 de	0.2392±0.0022 a	0.3582±0.0081 a	0.4888±0.0019 c	0.1751±0.0033 b
9	0.3811±0.0094 ab	0.5080±0.0097 e	0.1936±0.0085 ab	0.3803±0.0245 a	0.5142±0.0221 bc	0.1958±0.0210 a

$^{a\text{-}e}$ Means within the same column with different letters are significantly different (P $\leq$ 0.05).

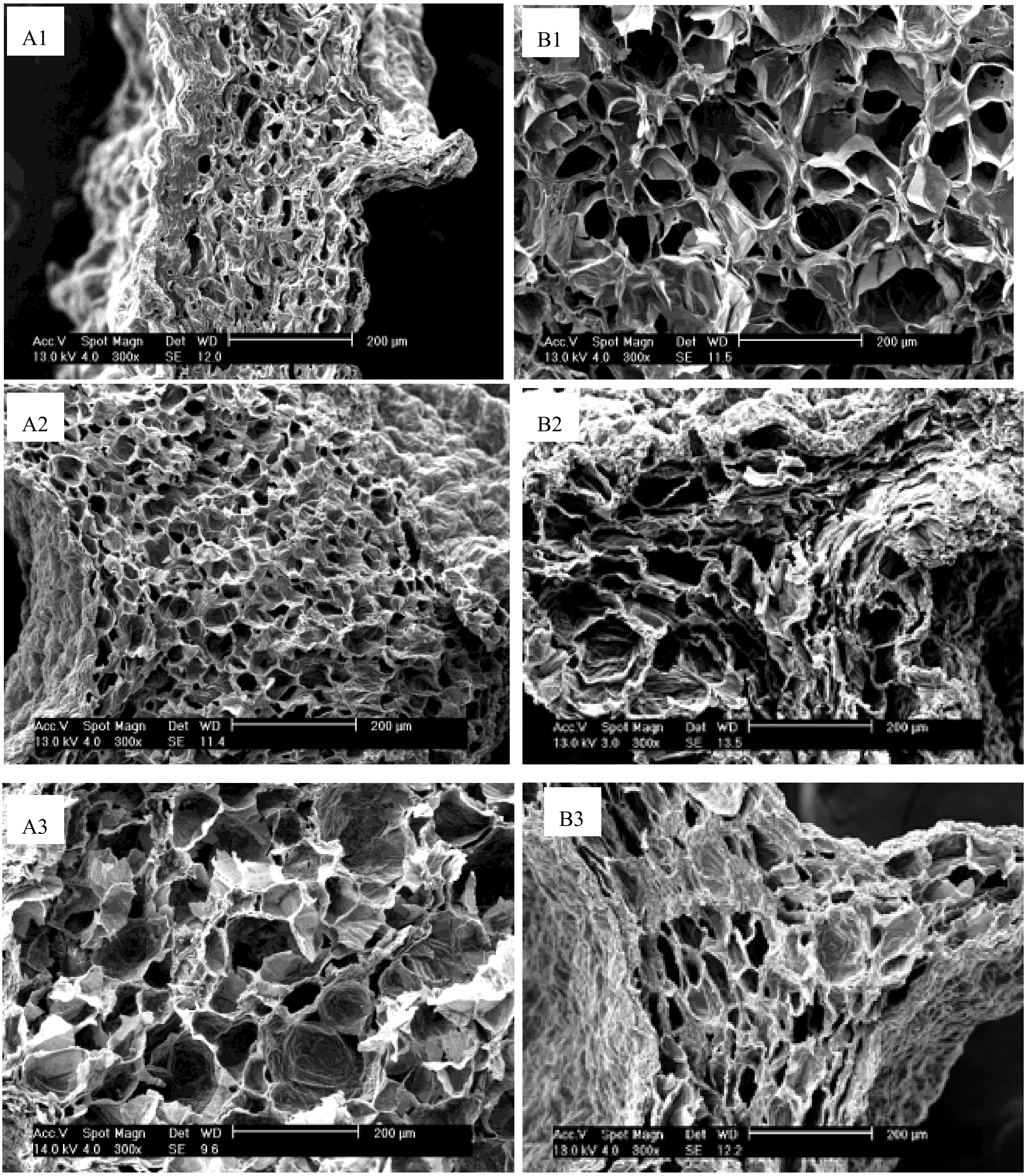

Figure 4 Scanning electron micrograph of microwave dried papaya strips (con.)

Condition 1 – 9 without freezing (A1 – A9) and condition 1 – 9 with freezing (B1 – B9).

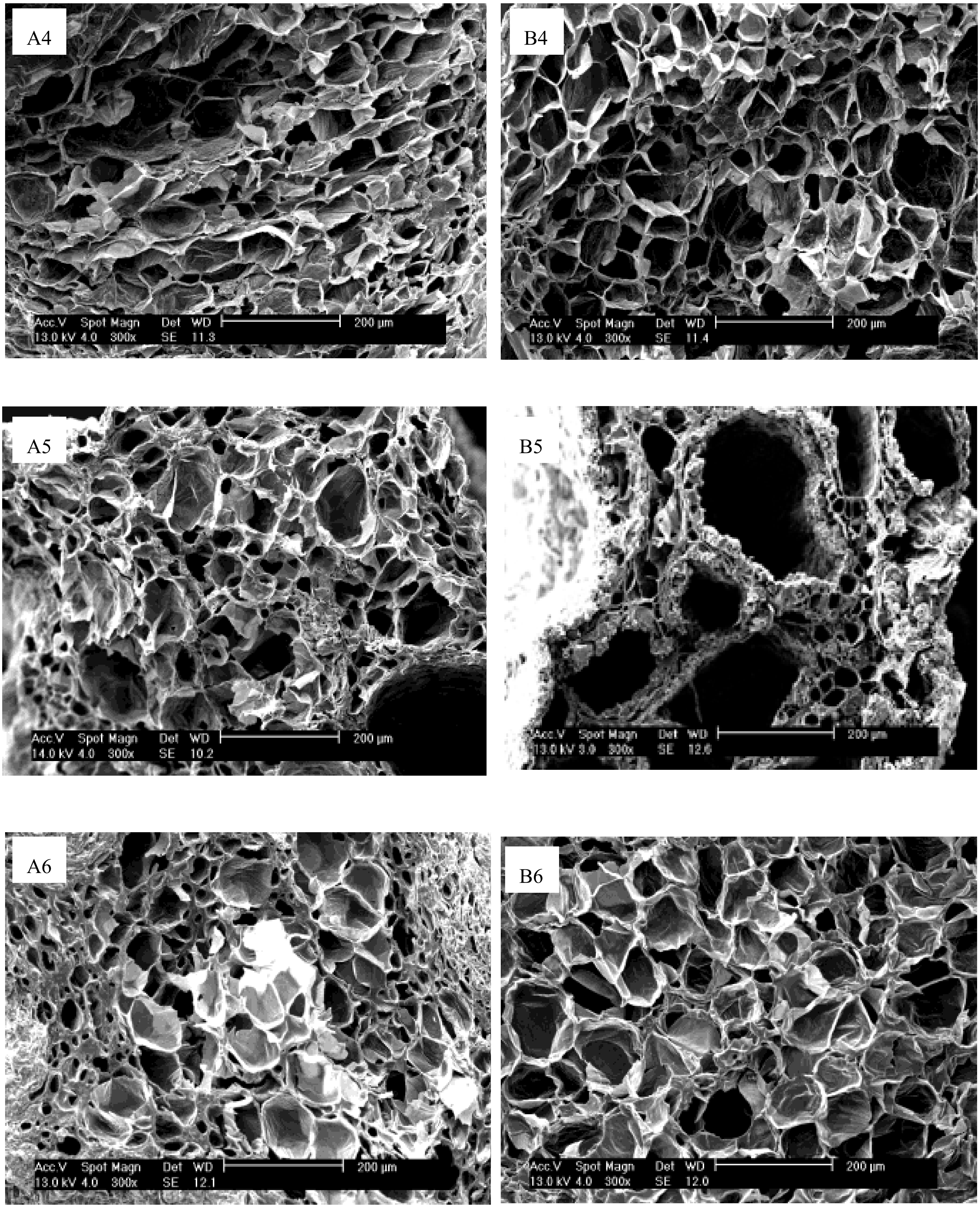

Figure 4 Scanning electron micrograph of microwave dried papaya strips (con.)

Condition 1 – 9 without freezing (A1 – A9) and condition 1 – 9 with freezing (B1 – B9).

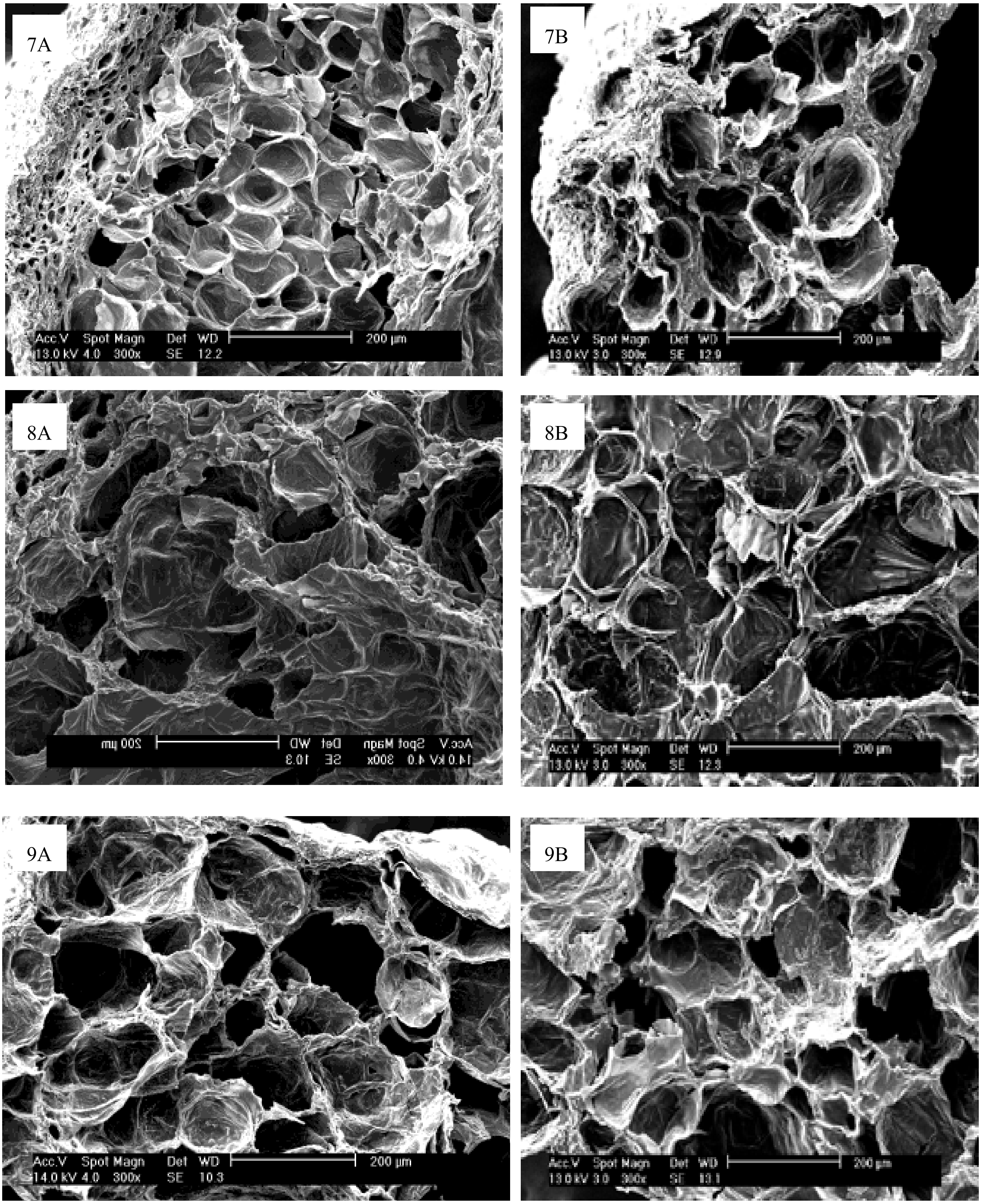

Figure 4 Scanning electron micrograph of microwave dried papaya strips (con.)

Condition 1 – 9 without freezing (A1 – A9) and condition 1 – 9 with freezing (B1 – B9).

Conclusion

Osmotic dehydration significantly affected dielectric properties of mandarin samples ($P \leq 0.05$). An increase in the glycerol ratio in the osmotic solution increased the loss factor and loss tangent of the mandarin samples, but decreased the dielectric constant and penetration depth. With modification of the dielectric properties of the mandarin samples, the drying rate during the microwave vacuum drying was improved. In addition, the drying rate was enhanced by an increase in microwave power. However, the increased microwave power significantly ($P \leq 0.05$) decreased the amount of β-carotene in dried mandarin. In addition, retention of β-carotene in the dried mandarin was decreased when the glycerol ratio in the osmotic solution increased ($P \leq 0.05$). Texture was affected by pre-water removal by osmotic dehydration using an increased ratio of glycerol reducing the hardness of the dried samples ($P \leq 0.05$). However, no significant effect of microwave power on the dried mandarin texture was observed in the study ($P \leq 0.05$). Therefore, osmotic dehydration was recommended as a pre-treatment of fruit prior to the microwave vacuum drying to improve texture, colour and retention of β-carotene in dried fruit snack.

Blanching prior to microwave vacuum drying increased dielectric constant, loss factor and loss tangent of papaya strips. With addition of salt in the blanching solution, the improvement of dielectric properties was significant ($P \leq 0.05$). The degree of improvement was enhanced by an increase in salt concentration. In contrast, addition of sucrose in the blanching solution did not affect dielectric properties clearly. However, blanching papaya strips in salt, sucrose and mixed solutions tended to increase internal resistance to mass transfer during microwave vacuum drying. Therefore Biot number of mass transfer was increased while mass diffusivity was reduced. Freezing after blanching in the solutions yielded lower dielectric constant and loss factor than only blanching. However, its effect on loss tangent was not clear. Due to ice formation, the dried papaya strips from frozen materials had an opened and damaged structure. The porosity of structure due to freezing was noticeable in the un-blanched sample. However, blanching with and without freezing before microwave vacuum drying increased pore size and rehydration ability.

Recommendation

Effect of pretreatment and microwave vacuum drying on sensorial quality of the dried products should be determined to estimate acceptability of products. In addition, effect of the microwave vacuum drying on functional quality of product should be investigated.

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Original article

Microwave vacuum drying of osmotically dehydrated mandarin cv. (*Sai-Namphaung*)

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Summary Mandarin [mandarin cv. (*Sai-Namphaung*)] was subjected to osmotic dehydration prior to microwave vacuum drying. Osmotic solutions were varied using different ratios of sucrose to glycerol (9:1, 7:3 and 5:5 w/w). Because of the decreased moisture content and solid gain during osmotic dehydration, dielectric properties of mandarin were changed significantly ($P \leq 0.05$). The osmotically dehydrated mandarin was then dried further using microwave vacuum drying at 4.8 and 6.4 W g^{-1}. Among thin layer models, page model was the best to describe the drying of osmotically dehydrated mandarin. An increase in the microwave power could increase drying rate without significant effect on hardness of dried samples. Nonetheless, the hardness was significantly ($P \leq 0.05$) reduced by an increase in the glycerol ratio in the osmotic solution. The increase in microwave power and glycerol ratio significantly ($P \leq 0.05$) decreased β-carotene content and thereby affected colour of the dried mandarin.

Keywords Drying, glycerol, mandarin, microwave, osmotic dehydration.

Introduction

Conventional hot air drying is a slow process and causes poor quality of dried materials. Recently, several studies applied microwave energy to speed up the drying process of plant materials such as mint leaves (Therdthai & Zhou, 2009), bamboo shoot (Bal *et al*., 2010), finger root (Therdthai & Northongkom, 2011) and so on. Mandarins contain high moisture content (approximately 88%). By using osmotic dehydration prior to drying, some water can be partially removed from fruit, because of the increased osmotic pressure that produces the driving force for water diffusion from the fruit tissue to the osmotic solution (Rastogi *et al*., 2005). Therefore, osmotic dehydration helps to reduce the length of thermal drying.

Mass transportation in an osmotic system could affect moisture content and thereby the dielectric properties of some materials. In food products, dielectric properties were related to the volumetric water concentration and ionic conductivity. Vacuum impregnation in solutions of nanoscale calcium carbonate prior to drying could greatly increase the loss factor of sea cucumber. Therefore, drying time of the microwave freeze-drying of sea cucumber could be reduced from 12.5 to 10.0 h (Duan *et al*., 2010). In addition to the increased drying rate, the residue of solutes in the material from osmotic dehydration could affect dielectric properties and thereby the uniformity of microwave heating. Torringa *et al*. (2001) found that osmotic dehydration in salt solution prior to microwave–hot air drying increased loss factor and reduced penetration depth. As a result, heating profiles of concave-shaped mushroom (*Agaricus bisporus*) with 40 mm diameter at surface and centre were not much different. Therefore, the central overheating was reduced. In contrast, the decrease in dielectric constant and loss factor resulted in little microwave energy absorption ability and the reduced effectiveness of microwave drying (Wang & Chen, 2005).

In addition to dielectric properties, mechanisms of mass transportation in an osmotic system could affect the cellular structure, and thereby, the characteristics of osmotically dehydrated products (Azoubel *et al*., 2009). Erle & Schubert (2001) showed an improvement in the structure of dried fruits with osmotic dehydration, which might have been because of the gel formation between pectin and sucrose. Therefore, they found that the shrinkage of osmotically dehydrated apple and strawberry samples after two-stage microwave vacuum drying

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was less than that of the samples without osmotic treatment.

To improve the process efficiency and quality of dried mandarin, this study used osmotic dehydration to partially remove water prior to further microwave vacuum drying. Kinetics of the microwave vacuum drying of osmotically dehydrated mandarins was determined. In addition, the effects of the sucrose to glycerol ratio in the osmotic solution and of microwave drying conditions on the colour and texture of the dried samples were investigated.

Materials and methods

Materials

Mandarins [mandarin *cv.* (*Sai-Namphaung*)] were purchased from a local market, with an average diameter of 65 ± 3 mm. They were peeled and fibre on the segment surface was removed. Glycerol (Hong Huat Co. Ltd, Bangkok, Thailand) and sucrose (Mitr Phol Sugar Corp., Supanburi, Thailand) were used as osmotic solutions.

Osmotic dehydration

Peeled mandarin (270 days of maturity after full bloom) segments were soaked in osmotic solution containing a mixture of sucrose solution [60/100 g (w/w)] to glycerol solution [60/100 g (w/w)] in a ratio of 9:1, 7:3 and 5:5 w/w, respectively. The ratio between the sample and osmotic solution was 1:5. The osmotic solution was agitated at 4.2 rad s^{-1} using an automatic rotating paddle. After osmotic dehydration, moisture content of all samples was analysed using a vacuum oven (Binder VD53; WTB Binder, Tuttlinge, Germany) at 70 °C, 13.3 kPa (AOAC, 2000).

Measurement of dielectric properties of osmotically dehydrated mandarin

Dielectric constant (ϵ') represents the ability of materials to store electrical energy from an external electric field. The loss factor (ϵ'') represents the ability of materials to convert electrical energy into thermal energy (Al-Harahsheh *et al.*, 2009). To measure the dielectric constant and the loss factor at 2.45 GHz, the osmotically dehydrated mandarin segments were blended and used to fill a 40-mm diameter cylinder. An open-ended coaxial probe was placed into the cylinder. The signal was analysed by a network analyzer (Dielectric measurement kit V.2.1.0.; Püschner, Schwanewede, Germany). All measurements were conducted in duplicate. For each duplication, there were five replications per treatment.

The dissipation factor or loss tangent (tan δ) is defined as a ratio of loss factor to dielectric constant (eqn 1).

$$\tan\delta = \frac{\varepsilon''}{\varepsilon'} \qquad (1)$$

The penetration depth, D_p, (the distance where the microwave power dropped to 1/*e* (*e* = 2.718) or 36.8% of the transmitted value of its surface value), was considered an important parameter in characterising microwave heating (Sosa-Morales *et al.*, 2010) and can be calculated using eqn 2 (Singh & Heldman, 2001).

$$D_p = \frac{\lambda_0}{2\pi\sqrt{2\varepsilon'}}\left[\left(1+\tan^2\delta\right)^{1/2} - 1\right]^{-1/2} \qquad (2)$$

where λ_0 = the free space microwave wavelength (for 2.45 GHz; λ_0 = 12.245 cm).

Microwave vacuum drying

After osmotic dehydration, the mandarin samples (200 g per batch) were dried in a microwave vacuum dryer (MarchCool, Bangkok, Thailand) consisting of six magnetrons with a 360° rotating plate (similarly described in Therdthai & Northongkom (2011)). The dryer was operated at 2.45 GHz frequency and 13.33 kPa pressure. The power level was investigated using the IMPI 2-L test (Buffler, 1993). A load of two 1-L beakers (Pyrex 1000) with water at an initial water temperature of 20 ± 2 °C was placed in the centre of the dryer and the dryer was then turned on. After 2 min and 2 s, the beakers were removed from the dryer. The temperature of water in both beakers was measured and recorded. The power was calculated from eqn 3 (Buffler, 1991):

$$P(W) = 70 \times \frac{(\Delta T_1 + \Delta T_2)}{2} \qquad (3)$$

where $P(W)$ = microwave power, ΔT_1 and ΔT_2 = temperature rise of the water in the first and second beakers, respectively, calculated by subtracting the initial water temperature from the final temperature.

In this study, average final temperatures of the first and second beakers from the first operating condition were 34.0 and 33.4 °C, respectively. The average final temperatures of the first and second beakers from the second operating condition were 38.5 and 38.0 °C, respectively. Therefore, the microwave vacuum dryer was operated at two levels of microwave power, being 960 W (MV4.8) and 1280 W (MV6.4).

Drying kinetics

The change in moisture in the samples of osmotically dehydrated mandarin during further drying was expressed by the moisture ratio (eqn 4).

$$MR = \frac{X_t - X_e}{X_o - X_e} \quad (4)$$

where MR = moisture ratio, X_0 = initial moisture content dry basis (kg water kg^{-1} d.m.), X_e is equilibrium moisture content (kg water kg^{-1} d.m.) and X_t is moisture content dry basis (kg water kg^{-1} d.m.)

The kinetics of the moisture ratio during microwave vacuum drying was simulated using thin layer models as follows:

Lewis model (Lewis, 1921):

$$\mathrm{MR} = \exp(-\mathrm{kt}) \quad (5)$$

Page model (Page, 1949):

$$\mathrm{MR} = \exp(-\mathrm{kt^n}) \quad (6)$$

Henderson & Pabis (1961):

$$\mathrm{MR} = \mathrm{a}\exp(-\mathrm{kt}) \quad (7)$$

Logarithmic (Yaldiz *et al.*, 2001):

$$\mathrm{MR} = \mathrm{a}\exp(-\mathrm{kt}) + \mathrm{c} \quad (8)$$

Two-term model (Sharaf-Eldeen *et al.*, 1980):

$$\mathrm{MR} = \mathrm{a}\exp(-\mathrm{kt}) + \mathrm{c}\exp(-\mathrm{gt}) \quad (9)$$

Wang & Singh (1978):

$$\mathrm{MR} = 1 + \mathrm{at} + \mathrm{bt}^2 \quad (10)$$

where k, n, a, b, c and g = the model constants, t = the drying time (min).

Correlation coefficient (r) and root mean square error (eqn 11) between the modelled moisture ratio and the experimental data were used to determine each model's performance. In addition, residual plots were also provided to present pattern of error throughout the range of prediction.

$$\mathrm{RMSE} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(\mathrm{MR}_{pi} - \mathrm{MR}_i)^2} \quad (11)$$

where MR_{pi} and MR_i are predicted moisture ratio and experimental moisture ratio, respectively, and n is a number of data points.

Quality measurement of dried mandarin

Colour measurement

The colour of the microwave-vacuum dried mandarin was analysed using a spectrophotometer (CM-3500d; Konica Minolta Holdings Inc., Tokyo, Japan) for five replications. Colour was determined using the CIE system with values of L^*, C^* and $h°$ representing darkness–lightness, chroma and hue, respectively.

β-Carotene analysis

To explain the colour change, β-carotene (vitamin A) content of the dried mandarin samples was determined using AOAC (1997) method with three replications. Samples (10 ± 5 g) were extracted with petroleum ether (15 mL) for three times. After vortexing for 2 min and centrifuging for 15 min, clear solution was brought to a filter (0.45 μm). The obtained clear solution was taken to measure the absorbance using a spectrophotometer (at 450 nm wave length). Thus, the concentration of β-carotene could be read from the standard curve.

Texture measurement

In general, hardness of dried food indicates sensory quality of the food, and it is tested by compression. Too high a hardness is not preferred. After microwave vacuum drying, until the moisture content of mandarin was < 0.1 kg water kg^{-1} d.m., the hardness of the dried mandarin samples was determined using a Lloyd texture analyzer (TA500; Lloyd Instruments Ltd., Hampshire, UK) with 5 N load cell. A 0.5-mm diameter ball probe was set at a speed of 0.8 mm min^{-1} to test the compression force on the sample (15 mm × 30 mm). The peak of the compression force represented the single hardness of the dried mandarin samples. The measurement was conducted with 15 replications.

Statistical analysis

All experiments were conducted with two duplications. Difference between the means of all treatments was analysed using a one-way ANOVA (SPSS® version 12.0; SPSS Co., Ltd., Bangkok, Thailand). Duncan's multiple range was used to identify a difference at 95% significant level.

Results and discussion

Dielectric properties of osmotically dehydrated mandarin

The ratio of water loss and solid gain during osmotic dehydration could affect the dielectric properties of mandarin. In osmotic dehydration of mandarin, the previous study (Pattanapa *et al.*, 2010) reported much higher increasing rate of water loss than that of solid gain. With the decreased water content, the dielectric constant decreased throughout the osmotic dehydration process (Fig. S1). Likewise, Changrue *et al.* (2008) also observed a decrease in the dielectric constant of osmotically dehydrated carrots and strawberries, compared with fresh materials. In the current study, the change in the dielectric constant was enhanced by an increase in the glycerol ratio in the osmotic solution (Table 1).

Table 1 Dielectric properties of mandarin samples before and after osmotic dehydration

Dielectric properties	Fresh mandarin	Ratio of sucrose to glycerol in osmotic solution mixture		
		9:1	7:3	5:5
Dielectric constant	29.80[a]	26.77[b]	24.11[c]	23.89[c]
Loss factor	6.19[c]	8.55[b]	8.81[ab]	9.06[a]
Loss tangent	0.21[c]	0.32[b]	0.36[a]	0.38[a]
Penetration depth (cm)	4.02[a]	2.11[b]	1.83[c]	1.74[c]

Means within the same row with different letters are significantly different ($P \leq 0.05$).

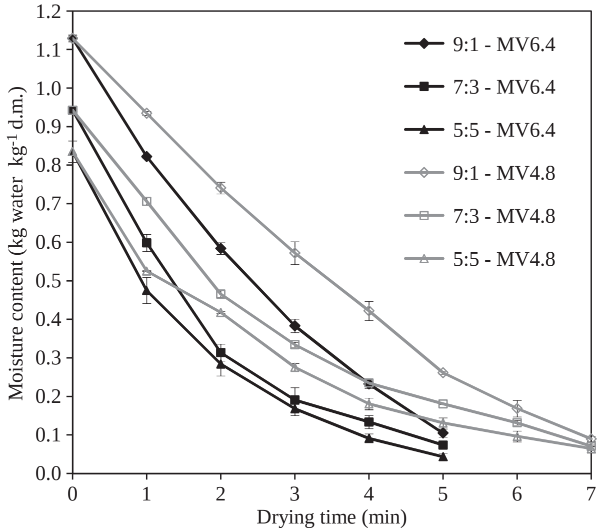

Figure 1 Moisture content of osmotically dehydrated mandarin samples during microwave drying. Vertical bars represent ± standard error from the mean value.

In addition to the dielectric constant, the loss factor also increased; as well as, the penetration depth was decreased throughout osmotic dehydration. This may cause a large absorption of microwave energy in a very shallow layer below the surface of mandarin, during drying. In general, the loss factor could be influenced by the amount of water and the ionic conductivity. In the current study, an increase in the glycerol ratio in the mixture used for osmotic dehydration could increase the loss factor significantly ($P \leq 0.05$).

Drying kinetics of osmotically dehydrated mandarin

The comparison was firstly made on comparing the microwave vacuum drying with the previously studied hot air drying (Pattanapa *et al.*, 2010), after the osmotic dehydration. By using osmotic dehydration as a pre-treatment step for water removal, the moisture content of the mandarin samples at the beginning of drying was reduced from 8.41 to 0.84–1.13 kg water kg^{-1} d.m. In the previous study, hot air drying at 70 °C was used to dry osmotically dehydrated mandarin for 360 min. In the current study with microwave vacuum drying at 4.8–6.4 W g^{-1}, the drying time was reduced to 5–7 min to obtain the moisture content <0.1 kg water kg^{-1} d.m. (Fig. 1). Applying microwave vacuum drying could speed up the mass transfer, because of an increased pressure gradient between the inner and outer layers of the material. Increasing the microwave power intensity from 4.8 to 6.4 W g^{-1} increased the drying rate. As a result, the drying time was decreased by 2 min. The results were consistent with those of Therdthai & Northongkom (2011), who reported a decrease in the drying time of finger root when the microwave power was increased. Comparing to the early drying period, the drying rate of the final period of microwave vacuum drying was decreased, because the water molecules were tightly bound, so that mobility of the water molecules or charged ions may become difficult. The loss factor might be decreased. This reduced the effectiveness of microwave heating.

Secondly, variation in osmotic dehydration conditions could also affect the microwave vacuum drying rate. Because of change in loss and dissipation factors during osmotic dehydration using various mixtures of sucrose and glycerol solutions, the drying rate tended to increase, as the ratio of sucrose to glycerol in the osmotic solution was changed from 9:1 to 5:5 w/w. This coincided with the results of Wang & Chen (2005), who reported that the effectiveness of microwave drying could be improved by increasing the loss factor. In addition, Al-Harahsheh *et al.* (2009) found the increased drying rate constant of tomato pomace when the loss tangent was increased up to approximately 0.3.

Finally, to simulate the change in moisture content throughout the microwave vacuum drying, several thin layer models (eqns 5–10) were determined. Parameters of thin layer models were estimated as presented in Table 2. Because of the lowest root mean square error (RMSE) (0.0039–0.0371) and the highest r (0.9929–0.9999), the Page model was found to be the best to describe the drying of osmotically dehydrated mandarin (Table 2). In addition, residual plot of the Page model was very close to the x-axis and not systematic (Fig. S2).

Quality of dried mandarin

The quality attributes of the dried mandarin samples are shown in Table 3.

Table 2 Model parameters and performance of the thin layer models of osmotically dehydrated mandarin

Condition	Model	Parameter	RMSE	r
MV4.8	Lewis	k = 0.2169	0.0663	0.9858
9:1	Page	k = 0.0961, n = 1.4860	0.0066	0.9998
	Henderson & Pabis	k = 0.2463, a = 1.1583	0.0640	0.9812
	Logarithmic	k = 0.0696, a = 2.2414, c = −1.2122	0.0227	0.9968
	Two-term model	k = 0.4022, a = 6.8507, c = −5.8513, g = 0.4663	0.0039	0.9999
	Wang & Singh	a = −0.1395, b = 0.0029	0.0254	0.9966
MV4.8	Lewis	k = 0.2456	0.0771	0.9822
7:3	Page	k = 0.0930, n = 1.5886	0.0238	0.9971
	Henderson & Pabis	k = 0.2777, a = 1.1742	0.0719	0.9775
	Logarithmic	k = 0.1093, a = 1.7195, c = −0.6736	0.0389	0.9918
	Two-term model	k = 0.4595, a = 6.6610, c = −5.6591, g = 0.5422	0.0156	0.9987
	Wang & Singh	a = −0.1609, b = 0.0052	0.0423	0.9918
MV4.8	Lewis	k = 0.2958	0.0815	0.9816
5:5	Page	k = 0.1171, n = 1.5667	0.0275	0.9965
	Henderson & Pabis	k = 0.3304, a = 1.1889	0.0779	0.9768
	Logarithmic	k = 0.1620, a = 1.4360, c = −0.3853	0.0448	0.9903
	Two-term model	k = 0.1120, a = 5.0688, c = −4.0176, g = 0.0837	0.0441	0.9906
	Wang & Singh	a = −0.1966, b = 0.0094	0.0462	0.9915
MV6.4	Lewis	k = 0.3750	0.0640	0.9872
9:1	Page	k = 0.2211, n = 1.3776	0.0039	0.9999
	Henderson & Pabis	k = 0.4162, a = 1.1629	0.0745	0.9828
	Logarithmic	k = 0.1595, a = 1.6425, c = −0.6253	0.0166	0.9986
	Two-term model	k = 0.1015, a = 7.1103, c = −6.0962, g = 0.0791	0.0161	0.9986
	Wang & Singh	a = −0.2448, b = 0.0135	0.0155	0.9989
MV6.4	Lewis	k = 0.3531	0.0522	0.9886
7:3	Page	k = 0.2246, n = 1.3597	0.0371	0.9929
	Henderson & Pabis	k = 0.3662, a = 1.0493	0.0473	0.9881
	Logarithmic	k = 0.2847, a = 1.1637, c = −0.1312	0.0437	0.9898
	Two-term model	k = 0.1998, a = 9.0243, c = −7.9922, g = 0.1847	0.0430	0.9901
	Wang & Singh	a = −0.2875, b = 0.0241	0.0397	0.9927
MV6.4	Lewis	k = 0.4693	0.0872	0.9793
5:5	Page	k = 0.2227, n = 1.5491	0.0162	0.9989
	Henderson & Pabis	k = 0.5271, a = 1.2363	0.1054	0.9725
	Logarithmic	k = 0.2210, a = 1.4666, c = −0.4364	0.0374	0.9939
	Two-term model	k = 0.1653, a = 3.1760, c = −2.1454, g = 0.0944	0.0367	0.9941
	Wang & Singh	a = −0.2884, b = 0.0199	0.0361	0.9950

r, correlation coefficient; RMSE, root mean square error.

Table 3 Colour, hardness and β-carotene content (mean ± standard error) of osmotically dehydrated mandarin samples after microwave vacuum drying

Drying condition	Sucrose:glycerol ratio	L^*	C^*	$h°$	β-carotene (μg/100 g)	Hardness (N)
MV4.8	9:1	55.34^{a} ± 1.63	50.66^{a} ± 2.33	62.07^{ab} ± 0.56	1104.15^{a} ±15.75	0.52^{a} ± 0.13
	7:3	50.78^{c} ± 1.68	48.97^{bc} ± 1.34	61.94^{abc} ± 0.85	444.48^{c} ± 45.44	0.35^{b} ± 0.08
	5:5	49.87^{d} ± 1.77	46.31^{d} ± 1.65	61.19^{cd} ± 1.77	55.77^{e} ± 0.68	0.22^{c} ± 0.05
MV6.4	9:1	53.96^{b} ± 2.12	49.57^{ab} ± 3.00	62.67^{a} ± 1.65	760.16^{b} ± 8.83	0.49^{a} ± 0.11
	7:3	50.35^{cd} ± 1.47	49.26^{bc} ± 1.48	61.67^{bc} ± 0.82	332.14^{d} ± 0.48	0.31^{b} ± 0.06
	5:5	48.34^{e} ± 0.97	48.06^{c} ± 1.02	60.67^{d} ± 1.04	64.25^{e} ± 2.50	0.25^{c} ± 0.04

Means within the same column with different letters are significantly different ($P \leq 0.05$).

Colour and β-carotene retention of dried mandarin

Before drying, the lightness (L^*-value), chroma (C^*-value) and hue angle ($h°$) of the osmotically dehydrated mandarin samples were 46.43, 14.12 and 73.58, respectively. After drying, the intensity of colour increased because of water loss. From the hue angle, the sample colour changed from yellow to yellow-red after drying. Increasing the microwave power from 4.8

to 6.4 W g^{-1} tended to reduce the lightness. Similarly, a decrease in the ratio of sucrose in the mixture of the osmotic solution significantly ($P \leq 0.05$) reduced the lightness of the dried mandarin samples. Compared with hot air drying (Pattanapa *et al.*, 2010), the microwave vacuum drying produced lighter colour dried mandarin samples. This was possibly because of the applied vacuum condition and short drying time in the microwave vacuum drying that could decrease β-carotene loss.

Increasing the microwave power from 4.8 to 6.4 W g^{-1} did not significantly affect the hue ($P > 0.05$). However, by using a 5:5 ratio of sucrose to glycerol in the mixture of the osmotic dehydration, chroma was significantly increased as the microwave power was increased. With a constant concentration of osmotic solution [60 g/100 g (w/w)], reducing the sucrose ratio (by increasing the glycerol ratio) in the osmotic solution also decreased the hue angle and chroma of the osmotically dehydrated mandarin samples after microwave vacuum drying. This was possibly because of an increase in the β-carotene loss. Ruiz *et al.* (2005) found a linear relationship between the colour and carotene content of fresh apricots. Carotenoid was one of the components contributing to the colour of mandarins. Pre-treatment with sucrose during the osmotic dehydration possibly slowed down the loss of carotene, compared with osmotic dehydration without sucrose. Therefore, the colour intensity of the dried mandarin samples could be preserved. Increasing the sucrose ratio (that is, decreasing the glycerol ratio) in the osmotic solution could better maintain the β-carotene content of the dried mandarin samples.

Generally, the solubility of carotene was increased when the process temperature was increased during drying (Karabulut *et al.*, 2007). For microwave vacuum drying, increasing the microwave power caused an increased loss of β-carotene. However, there was no clear impact observed for microwave power in the studied range (4.8–6.4 W g^{-1}) on the chroma and hue angle of the dried mandarin samples. This was possibly because the vacuum conditions could help maintain the β-carotene content and thereby product colour.

Textural characteristics of dried mandarin

When water was removed from the cell, compared with fresh material, the cell membrane could be separated from the cell wall, resulting in cell wall deformation and increased mechanical stress on the middle lamellae (Castello *et al.,* 2009). In the current study, increasing the glycerol ratio (that is, reducing the sucrose ratio) in the osmotic solution significantly ($P \leq 0.05$) reduced the hardness of the dried samples (Table 3). Further, microwave vacuum drying could develop a puffing structure in the dried mandarin samples. Similarly, an increase in puffing characteristics and crispness of fish slices was observed when microwave drying was operated at low pressure (Zhang *et al.*, 2007). In fact, the puffing characteristics were explained by two mechanisms: firstly, the difference between the air pressure in the product and the pressure in the chamber and secondly, vaporisation because of an increased product temperature (Ressing *et al.*, 2007). However, increasing the microwave power intensity from 4.8 to 6.4 W g^{-1} did not have a significant effect on the hardness of the dried mandarin samples ($P > 0.05$).

Conclusion

To dry mandarin using microwave vacuum drying, osmotic dehydration with a mixture of sucrose and glycerol in osmotic solution should be applied, to modify dielectric properties of mandarin samples. An increase in the glycerol ratio in the osmotic solution increased the loss factor and loss tangent of the mandarin samples, but decreased the dielectric constant and penetration depth. With modification of the properties of the mandarin samples, the drying rate during the microwave vacuum drying was improved. In addition, the drying rate was enhanced by an increase in microwave power. However, the increased microwave power significantly ($P \leq 0.05$) decreased the amount of β-carotene. In addition, retention of β-carotene in the dried mandarin samples decreased when the glycerol ratio in the osmotic solution increased ($P \leq 0.05$). Texture was affected by pre-water removal by osmotic dehydration using an increased ratio of glycerol reducing the hardness of the dried samples ($P \leq 0.05$). However, no significant effect of microwave power on the dried mandarin texture was observed in the study ($P \leq 0.05$).

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Supporting Information

Additional Supporting Information may be found in the online version of this article:

Figure S1. Changes during osmotic dehydration of mandarin: (a) moisture content, (b) dielectric constant, (c) loss factor, (d) loss tangent and (e) penetration depth.

Figure S2. Residual plots of thin layer models: (a) Lewis, (b) Page, (c) Henderson & Pabis, (d) Logarithmic, (e) Two-term model and (f) Wang & Singh.

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