รายงานวิจัยฉบับสมบูรณ์

โครงการ: **การพัฒนากระบวนการอบแห้งผักและผลไม้โดยการใช้เทคโนโลยีร่วมกับไมโครเวฟ**

โดย ผู้ช่วยศาสตราจารย์นันทวัน เทอดไทย

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สัญญาเลขที่ MRG5080227

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Nantawan Therdthai

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Abstract

Project Code: MRG5080227

Project Title: Drying process development of fruit and vegetable using microwave assisted technology

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Project Period: 2 years

Mint (*Mentha cordifolia* Opiz ex Fresen) and mandarin (*Sai-Namphaung*) were subjected to microwave vacuum drying and hot air drying. For mint, three microwave intensities i.e. 8.0 $W.g^{-1}$, 9.6 $W.g^{-1}$ and 11.2 $W.g^{-1}$ were applied with pressure controlled at 13.33 kPa. Two drying temperatures of 60^0C and 70^0C were examined for hot air drying of mint. Lewis's, Page's and Fick's models were used to describe drying kinetics under various drying conditions. Effective moisture diffusivities were determined to be 4.6999×10^{-11}, 7.2620×10^{-11}, 9.7838×10^{-11}, 0.9648×10^{-11} and 1.1900×10^{-11} $m^2.s^{-1}$ for microwave vacuum drying at 8.0 $W.g^{-1}$, 9.6 $W.g^{-1}$ and 11.2 $W.g^{-1}$, hot air drying at 60^0C and 70^0C, respectively. For mandarin, osmotic dehydration was used for pre-water removal before drying. Osmotic solutions were varied in ratios of sucrose and glycerol (9:1, 7:3 and 5:5). Effective moisture diffusivities were determined to be 7.2620×10^{-12}, 7.0301×10^{-12} and 1.0738×10^{-11} for sucrose: glycerol ratio at 9:1, 7:3 and 5:5, respectively. The osmotically dehydrated mandarin was then dried in three drying conditions: hot air drying at 70^0C, microwave vacuum drying at 4.8 $W.g^{-1}$ and microwave vacuum drying at 6.4 $W.g^{-1}$. In this study, it was proved that the microwave vacuum drying could increase drying kinetic rate constant and thereby reduce drying time of mint leaves and osmotically dehydrated mandarin, compared with the hot air drying. In addition, color lightness of the microwave vacuum dried mint leaves and osmotically dehydrated mandarin was significantly higher than that of the hot air dried samples ($p\leq0.05$). However, increasing microwave power intensity significantly decreased vitamin A content and thereby reduced lightness of dried mandarin. For structure, microwave vacuum dried mandarin had puffing characteristic whereas hot air dried mandarin had soft and firm characteristics. From scanning electron micrographs, the microwave vacuum dried mint leaves had a more porous and uniform structure than the hot air dried ones. Therefore, rehydration rate constants of the dried mint leaves by the microwave vacuum drying at 9.6 $W.g^{-1}$ and 11.2 $W.g^{-1}$ microwave intensity were significantly higher than those by the hot air drying at 60^0C and 70^0C ($p\leq0.05$).

Keywords: drying, microwave, mint, mandarin, model

บทคัดย่อ

รหัสโครงการ: MRG5080227

ชื่อโครงการ: การพัฒนากระบวนการอบแห้งผักและผลไม้โดยการใช้เทคโนโลยีร่วมกับไมโครเวฟ

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ระยะเวลาโครงการ: 2 ปี

โครงการวิจัยนี้ได้ศึกษาการอบแห้งใบสะระแหน่ (*Mentha cordifolia* Opiz ex Fresen) และส้มสายน้ำผึ้ง (Mandarin cv (*Sai-Namphaung*)) โดยใช้ไมโครเวฟสุญญากาศเปรียบเทียบกับลมร้อน สำหรับใบสะระแหน่ได้ใช้ความเข้มของไมโครเวฟ 3 ระดับ ได้แก่ 8.0 $W.g^{-1}$, 9.6 $W.g^{-1}$ และ 11.2 $W.g^{-1}$ ภายใต้การควบคุมความดันที่ 13.33 kPa. และใช้การอบแห้งแบบลมร้อนที่อุณหภูมิ 60^{0}C และ 70^{0}C ระหว่างการอบแห้ง ได้นำแบบจำลอง Lewis, Page และ Fick มาอธิบายการเปลี่ยนแปลงความชื้น เมื่ออบแห้งภายใต้สภาวะต่างๆ พบว่า Effective moisture diffusivities ของการอบแห้งด้วยไมโครเวฟสุญญากาศที่ระดับความเข้มของไมโครเวฟ 8.0 $W.g^{-1}$, 9.6 $W.g^{-1}$ และ 11.2 $W.g^{-1}$ และ การอบแห้งด้วยลมร้อนที่อุณหภูมิ 60^{0}C และ 70^{0}C มีค่า 4.6999×10^{-11}, 7.2620×10^{-11}, 9.7838×10^{-11}, 0.9648×10^{-11} และ 1.1900×10^{-11} $m^2.s^{-1}$ ตามลำดับ สำหรับส้มสายน้ำผึ้ง ได้นำการออสโมติกดีไฮเดรชั่นมาใช้ในการลดปริมาณน้ำก่อนการอบแห้ง โดยสารสะสายออสโมติกที่ใช้มีสัดส่วนซูโครสต่อกลีเซอรอลต่างๆกัน เมื่อใช้สัดส่วนซูโครสต่อกลีเซอรอล 9:1, 7:3 และ 5:5 ค่า Effective moisture diffusivities เท่ากับ 7.2620×10^{-12}, 7.0301×10^{-12} และ 1.0738×10^{-11} ตามลำดับ หลังจากนั้นจึงนำส้มไปทำการอบแห้งภายใต้สภาวะต่างๆ ได้แก่ การอบแห้งด้วยลมร้อนที่อุณหภูมิ 70^{0}C และ การอบแห้งด้วยไมโครเวฟสุญญากาศที่ระดับความเข้มของไมโครเวฟ 4.8 $W.g^{-1}$ และ 6.4 $W.g^{-1}$ ในการศึกษาครั้งนี้ พบว่า การอบแห้งแบบไมโครเวฟสุญญากาศสามารถเพิ่มค่าคงที่อัตราการอบแห้งและส่งผลให้เวลาในการอบแห้งของใบสะระแหน่และส้มสายน้ำผึ้งลดลง เมื่อเปรียบเทียบกับการอบแห้งแบบลมร้อน นอกจากนั้น ใบสะระแหน่และส้มสายน้ำผึ้งที่ได้จากการอบแห้งแบบไมโครเวฟสุญญากาศมีความสว่างของสีมากกว่าใบสะระแหน่และส้มสายน้ำผึ้งที่ได้จากการอบแห้งแบบลมร้อนอย่างมีนัยสำคัญ ($p\leq0.05$) แต่การเพิ่มความเข้มของกำลังไมโครเวฟ ทำให้ปริมาณวิตามินเอในส้มอบแห้งลดลง และส่งผลให้ค่าความสว่างของส้มลดลง สำหรับโครงสร้าง พบว่า ส้มสายน้ำผึ้งที่ได้จากการอบแห้งแบบไมโครเวฟสุญญากาศมีลักษณะพอง แต่ส้มสายน้ำผึ้งที่ได้จากการอบแห้งแบบลมร้อนมีลักษณะนุ่มและแน่น จากภาพถ่ายพื้นผิวแบบส่องกราด พบว่า ใบสะระแหน่ที่ได้จากการอบแห้งแบบไมโครเวฟสุญญากาศมีโครงสร้างรูพรุนสม่ำเสมอและมากกว่าใบสะระแหน่ที่ได้จากการอบแห้งแบบลมร้อน ดังนั้น ค่าคงที่อัตราการคืนตัวของใบสะระแหน่ที่ได้จากการอบแห้งแบบไมโครเวฟสุญญากาศที่ระดับ 9.6 $W.g^{-1}$ and 11.2 $W.g^{-1}$ จึงมากกว่า ค่าคงที่อัตราการคืนตัวของใบสะระแหน่ที่ได้จากการอบแห้งแบบลมร้อนที่ 70^{0}C อย่างมีนัยสำคัญ ($p\leq0.05$)

คำหลัก : การอบแห้ง ไมโครเวฟ ใบสะระแหน่ ส้มสายน้ำผึ้ง แบบจำลอง

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Executive summary

Project Code: MRG5080227

Project Title: Drying process development of fruit and vegetable using microwave assisted technology

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Background

Fruits and vegetables were perishable materials. Their shelf-life was short. Sometimes, there was also over-supplied problem during season. Conventional method to preserve fruit and vegetable was either sun drying or hot air drying. However, their colour degraded significantly because of heating for long period. To decrease the drying time, air temperature should be increased. In addition, microwave drying may be applied to shorten drying process. Microwave drying was regarded as a rapid dehydration process. To improve process efficiency and quality of dried fruits and vegetables, this study aimed to determine the characteristics of microwave vacuum drying of mint leaves and osmotically dehydrated mandarin, in comparison with conventional hot air drying and their effects on the color and structure of the dried products.

Objectives

1) To describe drying characteristics of microwave vacuum dried and hot air dried fruit and vegetable using mathematical models
2) To determine quality of microwave vacuum dried and hot air dried fruit and vegetable

Methodology

1) Microwave assisted drying of mint leaves

Mint (*Mentha cordifolia* Opiz ex Fresen) leaves were dried using either a microwave vacuum dryer (MarchCool, Thailand) or a tray dryer (Frecon, BWS-serie). The microwave vacuum dryer was operated at three microwave power outputs: 1,600 W (MV1600), 1,920 W (MV1920) and 2,240W (MV1920), all with controlled pressure at 13.33 kPa and controlled frequency at 2,450 MHz for 15 minutes. To compare with the microwave vacuum drying, the hot air drying with 1.0 $m.s^{-1}$ flow velocity was conducted at two temperatures: 60^0C (HA60) and 70^0C (HA70) for 120 minutes, in order to reduce the moisture content to a similar level to that of the microwave vacuum drying.

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2) Microwave assisted drying of osmotically dehydrated mandarin

Mandarin (*Sai-Namphaung*) was peeled and soaked in osmotic solutions containing sucrose and glycerol in the ratio of 9:1, 7:3 and 5:5, respectively. After osmotic dehydration, mandarin was dried under various conditions including hot air drying at 70^0C for 6 hours (HA70), microwave vacuum drying at 1280 W microwave power (6.4 $W.g^{-1}$power intensity) for 5 minutes and microwave vacuum drying at 960 W microwave power (4.8 $W.g^{-1}$power intensity) for 7 minutes.

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Introduction

Fruits and vegetables were perishable materials. Their shelf-life was short. Sometimes, there was also over-supplied problem during season. Conventional method to preserve fruit and vegetable was either sun drying or hot air drying. However, their colour degraded significantly because of heating for long period. To decrease the drying time, air temperature should be increased. In addition, microwave drying may be applied. Microwave drying may be regarded as a rapid dehydration process. During the process, moisture content was reduced, as well as, loss factor of dried materials decreased. The local pressure and temperature could be increased and speed up the drying process (Cheng et al., 2006). Increasing microwave power also increased dehydration rate of carrot (Wang and Xi, 2005) and mint (Ozbek and Dadali, 2007). Moreover, the rehydration rate was increased by increasing the microwave power at the second stage (Wang and Xi, 2005). However, too rapid mass transfer could damage the texture in some cases. In addition, non-uniformity of electromagnetic field could create hot spots during microwave drying. At the final stage of drying, product temperature might be increased rapidly to the level that caused scorching (Zhang et al., 2006). Burning of dried whole strawberries was found when rated power of 600 W was applied (Venkatachalapathy and Raghavan, 2000). To dry mushroom from 7.5% moisture content to 2.0% moisture content, microwave drying provided the fastest diffusion coefficient of 331.02×10^{-6} $m^2 s^{-1}$ whereas vacuum drying provided the slowest rate of 0.3225×10^{-6} $m^2 s^{-1}$. However microwave drying produced poorer quality of dried products (Walde et al., 2006).

To overcome the limitation of microwave drying, microwave assisted vacuum drying has been used for drying fruits and vegetables. The advantage was to speed up drying process, to increase mass transfer by an increased pressure gradient between inner and outer layers and to maintain drying process at low temperature (Pere and Rodier, 2002). Compared to conventional hot air drying of mushroom, microwave assisted vacuum drying could reduce the drying time by 70-90% as well as rehydration characteristics were improved (Giri and Prasad, 2007). From scanning electron microscope (SEM) results, the microstructure of microwave-vacuum dried potato was characterized by large porous and irregular structure whereas the microstructure of hot air dried potato was characterized by tight packing and strong connection between cells.

Therefore, the microwave-vacuum dried potato showed higher reconstitution ability during rehydration than the hot air dried potato (Bondaruk et al., 2007). For drying of lactose powder, McMinn (2004) found that water diffusivity under hot air drying was in the range of 0.350×10^{-9} $m^2.s^{-1}$ to 1.467×10^{-9} $m^2.s^{-1}$ whereas water diffusivity under microwave-vacuum drying was in the range of 3.255×10^{-9} $m^2.s^{-1}$ to 6.110×10^{-9} $m^2.s^{-1}$. Moisture diffusion rate could be enhanced by reducing pressure. Moreover the reduced pressure could increase puffing characteristics and crispness of fish slides and reduce burnt spots (Zhang et al., 2007). According to a two-dimensional finite element model, puffing of dough during microwave-vacuum drying was caused by firstly the difference between air pressure in the dough and air pressure in the chamber and secondly vaporization due to an increased dough temperature (Ressing et al., 2007).

As regards color, Drouzas et al. (1999) found significant improvement of lightness of microwave vacuum dried model pectin gel, compared to hot air dried samples. On drying potato, Bondaruk et al. (2007) also observed that the color of the product was significantly lighter when drying with microwave at 24 kPa, compared to drying with microwave at atmospheric pressure. Another advantage of microwave when it was applied to vacuum drying was increased mass loads of vacuum dryers (Hu et al.(2006). This was due to the intensive energy of the microwave system. Microwave drying requires only 20-35% of floor space, compared with hot air drying (Wang and Xi, 2005).

To improve process efficiency and quality of dried fruit and vegetable, this study aimed to use microwave vacuum drying for mint leaves (*Mentha cordifolia* Opiz ex Fresen) and madarin (*Sai-Namphaung*). The characteristics of microwave assisted vacuum drying of mint leaves and mandarin were determined in comparison with conventional hot air drying. In addition, effect of drying condition on the color and structure of the dried samples was investigated.

Objectives

1) To describe drying characteristics of microwave vacuum dried and hot air dried fruit and vegetable using mathematical models

2) To determine quality of microwave vacuum dried and hot air dried fruit and vegetable

Methodology

1) Microwave assisted drying of mint leaves

Mint (*Mentha cordifolia* Opiz ex Fresen) leaves were washed and dried using either a microwave vacuum dryer (MarchCool, Thailand) or a tray dryer (Frecon, BWS-serie). Thickness of the fresh mint leaves were measured by a micrometer (Mitutoyo, Japan; ±0.01mm). For the microwave vacuum drying, 200 grams mint leaves were used per batch. The microwave vacuum dryer was operated at three microwave power outputs: 1,600 W (MV1600), 1,920 W (MV1920) and 2,240W (MV1920), all with controlled pressure at 13.33 kPa and controlled frequency at 2,450 MHz for 15 minutes. To compare with the microwave vacuum drying, the hot air drying with 1.0 m.s^{-1} flow velocity was conducted at two temperatures: 60^{0}C (HA60) and 70^{0}C (HA70) for 120 minutes, in order to reduce the moisture content to a similar level to that of the microwave vacuum drying.

1.1 Drying characterization

Moisture content of microwave vacuum dried mint leaves and hot air dried mint leaves was analyzed using the AOAC oven method (AOAC, 2000) throughout the drying process. Drying rate was defined as:

$$Drying\_rate = \frac{X_i - X_{i-1}}{\Delta t} \qquad (1)$$

Where X_i is moisture content dry basis (kg water. Kg dry solid^{-1}) at time i and t is time interval (minute).

The change of moisture in mint leaves during drying was expressed as moisture ratio defined as:

$$Moisture\_ratio = \frac{X_i - X_e}{X_0 - X_e} \quad (2)$$

As the thickness of mint leaves was very small, the most frequently used thin layer models including Lewis's model (Equation 3) and Page's model (Equation 4) (Jayas et al., 1990) were applied for describing the drying mechanism.

The kinetic constant of Lewis's model could be used to quantify the rate of moisture change during various drying conditions.

$$\frac{X_i - X_e}{X_0 - X_e} = \exp(kt) \quad (3)$$

Where k is kinetic constant (min^{-1}), X_0 is initial moisture content dry basis (kg water. kg dry $solid^{-1}$), X_e is equilibrium moisture content dry basis (kg water. kg dry $solid^{-1}$), X_i is moisture content dry basis (kg water. kg dry $solid^{-1}$) at time i and t is time interval (minute).

As an improvement over Lewis's model, Page's model was characterized by k and n where n was defined as a dimensionless exponential index:

$$\frac{X_i - X_e}{X_0 - X_e} = \exp(kt^n) \quad (4)$$

Fitness of each model was evaluated by comparing between the modeled moisture ratio and the experimental data. Correlation coefficient (R) and root mean square error (RMSE) were calculated to determine the model performance.

Based on Fick's law and assumptions of symmetric mass transfer with respect to the centre, constant diffusion coefficient and no shrinkage, effective moisture diffusivity of water in mint leaves was estimated from change of moisture ratio along with drying time by using modified Crank's equation (Singh and Heldman, 2001) as shown in the following equation.

$$\frac{X_i - X_e}{X_0 - X_e} = \frac{8}{\pi^2}\sum_{n=1}^{\infty}\frac{1}{(2n-1)^2}\cdot\exp(-\frac{(2n-1)^2\pi^2\cdot D_{eff}}{4L^2}.t) \quad (5)$$

Where D_{eff} is the effective moisture diffusivity ($m^2.s^{-1}$), L is half thickness of mint leaves (0.19×10^{-3}m) and t is drying time (s).

1.2 Color measurement

Mint leaves were dried for various times and collected to examine change of color by using a spectrophotometer (Minolta CM-3500d). Color was determined in the CIE system. The values of L*, a* and b* present darkness-lightness, greenness-redness and blueness-yellowness. Change of color was estimated by:

$$\Delta E = \sqrt{(L_i^* - L_0^*)^2 + (a_i^* - a_0^*) + (b_i^* + b_0^*)} \quad (6)$$

Where ΔE is color change, L_0^* and L_i^* are lightness values at initial time and time i, respectively, a_0^* and a_i^* are greenness-redness values at initial time and time i, respectively, and b_0^* and b_i^* are blueness-yellowness values at initial time and time i, respectively.

1.3 Structural characteristic of dried mint leaves

The cross section at the middle of dried mint leaves samples was investigated using a Scanning Electron Microscope (Hitachi TM-1000, Japan) with an accelerating voltage of 15 kV. Magnification was adjusted to 500×.

1.4 Rehydration characteristics of dried mint leaves

Dried mint leaves (10 g) produced under various drying conditions were rehydrated at 30^0C for 15 minutes by being immersed in 80 g water. Rehydration rate was described by:

$$\frac{W_t - W_e}{W_0 - W_e} = \exp(-kt) \quad (7)$$

Where W_0 is initial weight (g), W_e is equilibrium weight (g), W_t is weight (g) after rehydration for t minutes, k is rehydration rate constant (min^{-1}), and t is rehydration time (min).

Fitness of equation 7 was evaluated by comparing between the modeled weight after rehydration and the experimental data. Correlation coefficient (R) and root mean square error (RMSE) were calculated to determine the performance.

1.5 Sensorial quality of dried mint leaves

By using 10 trained panelists, intensity of quality attributes including darkness, shrinkage, rank aroma and cool aroma of dried mint leaves was evaluated. To test the appearance and aroma attributes, 2 g samples were served on white bowls.

2) Microwave assisted drying of osmotically dehydrated mandarin

Mandarin (*Sai-Namphaung*) was peeled and soaked in osmotic solutions containing sucrose and glycerol in the ratio of 9:1, 7:3 and 5:5, respectively. Initial concentration of osmotic agents was controlled at 60 ^{0}Brix. The ratio between sample and osmotic solution was 1:5. Osmotic solution was agitated at 40 rpm. After osmotic dehydration, mandarin was dried under various conditions including hot air drying at 70^{0}C for 6 hours (HA70), microwave vacuum drying at 1280 W microwave power (6.4 $W.g^{-1}$ power intensity) for 5 minutes and microwave vacuum drying at 960 W microwave power (4.8 $W.g^{-1}$ power intensity) for 7 minutes.

2.1 Water loss and solid gain during osmotic dehydration

During osmotic dehydration, water loss and solid gain was determined as:

During osmotic dehydration, water loss and solid gain could be calculated by Equations 8 and 9 (Kaymak-Ertekin and Sultanoglu, 2000).

$$Weight\_loss = \frac{M_0 X_0^w - M_t X_t^w}{M_0} \times 100 \quad (8)$$

$$Solid\_gain = \frac{M_0 X_0^{ts} - M_t X_t^{ts}}{M_0} \times 100 \quad (9)$$

where M_0 and M_t are mass of sample at time 0 and t, respectively.

X_0^{ts} and X_t^{ts} are total solid concentration at time 0 and t, respectively.

X_0^{w} and X_t^{w} are water concentration at time 0 and t, respectively

2.2 Mass diffusivity during *osmotic dehydration*

Based on Fick's law and assumptions of symmetric mass transfer with respect to the centre, constant diffusion coefficient and no shrinkage, effective moisture diffusivity of water in mandarin was estimated from change of moisture ratio along with process time by using modified Crank's equation (Singh and Heldman, 2001) as shown in the following equation.

$$\frac{X_i - X_e}{X_0 - X_e} = \frac{8}{\pi^2} \sum_{n=1}^{\infty} \frac{1}{(2n-1)^2} \cdot \exp(-\frac{(2n-1)^2 \pi^2 \cdot D_{eff}}{4L^2} .t) \quad (10)$$

Where D_{eff} is the effective moisture diffusivity ($m^2.s^{-1}$), L is half thickness of mandarin and t is time (s).

2.3 Drying characterization

Moisture content of microwave vacuum dried mandarin and hot air dried mandarin was analyzed using the AOAC oven method (AOAC, 2000) throughout the drying process. The change of moisture in osmotically dehydrated mandarin during drying was expressed as moisture ratio defined as:

$$Moisture\_ratio = \frac{X_i - X_e}{X_0 - X_e} \quad (11)$$

The kinetic constant of Lewis's model could be used to quantify the rate of moisture change during various drying conditions.

$$\frac{X_i - X_e}{X_0 - X_e} = \exp(kt) \quad (12)$$

Where k is kinetic constant (min^{-1}), X_0 is initial moisture content dry basis (kg water. kg dry solid^{-1}), X_e is equilibrium moisture content dry basis (kg water. kg dry solid^{-1}), X_i is moisture content dry basis (kg water. kg dry solid^{-1}) at time i and t is time interval (minute).

2.4 Color measurement

Osmotically dehydrated mandarin was dried under various conditions. The final products were collected to examine color by using a spectrophotometer (Minolta CM-3500d). Color was determined in the CIE system. The values of L*, C and h present darkness-lightness, chroma and hue.

2.5 Vitamin A of dried mandarin

Vitamin A (Beta carotene) content of dried mandarin was determined using In house method (AOAC, 1997).

2.6 Textural characteristic of dried mandarin

Hardness of hot air dried and microwave vacuum dried mandarin was determined using a Lloyd texture analyzer (TA 500).

Results and Discussion

1) Microwave assisted drying of mint leaves

1.1 Drying characteristics during microwave vacuum drying and hot air drying

Figure 1 shows how the moisture content of mint leaves was decreased with increased drying time under various drying conditions. At the beginning of a drying process, mint leaves with an average initial moisture content of 9.4331$\pm$0.0188 kg water/kg dry solid were heated up. Hot air drying at 60^0C and 70^0C required 90 and 60 minutes respectively whereas microwave vacuum drying at 1,600W, 1,920W and 2,240W required 10, 12 and 13 minutes respectively for reducing the moisture content to less than 0.1 kg water/kg dry sample. Change of drying rate is shown in Figure 2.

It can be seen from Figure 2 that significant differences in drying rate were found between the two drying methods, i.e. microwave vacuum drying and hot air drying. At the beginning when moisture content was high, the drying rate under all drying conditions increased with time. In microwave vacuum drying, it could be explained that high microwave energy absorption was found when significant amount of dipole molecules was available. With significant microwave energy absorption, heat was generated to increase the product's temperature to meet the boiling point temperature. At this stage, mass transfer was dominated by vaporization. After the drying rate reached its maximum level, falling drying rate period occurred. Lack of a constant drying rate period was also observed in other studies of microwave drying of porous materials (Sander, 2007). Comparing to the microwave drying of mint leaves under atmospheric pressure in Ozbek and Dadali (2007), the microwave vacuum drying in the present study tended to produced higher maximum drying rate. The maximum drying rates were approximately 0.5, 1.5 and 3.0 kg water. kg dry solid^{-1}, when the microwave intensity of 7.2 W.g^{-1}, 14.4 W.g^{-1} and 36.0 W.g^{-1} were applied respectively. In our present study, maximum drying rates of 1.9, 2.1 and 2.5 kg water. kg dry solid^{-1} were obtained when the microwave intensity of 8.0 W.g^{-1}, 9.5 W.g^{-1} and 11.2 W.g^{-1} were applied, respectively, with the pressure controlled at 13.33 kPa.

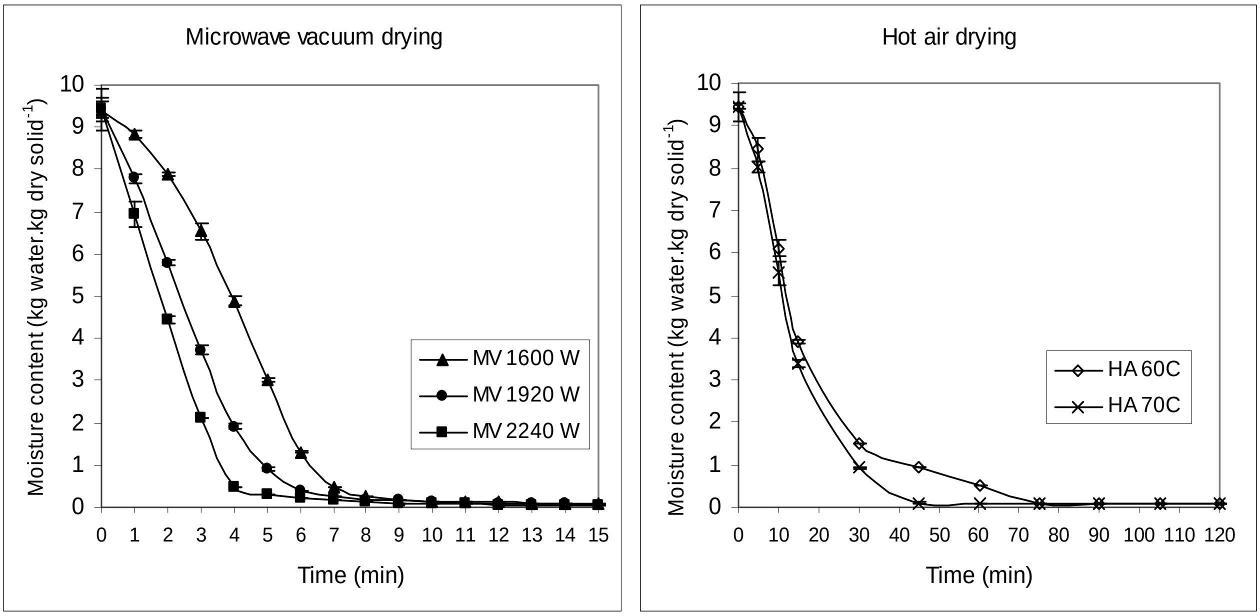


Figure 1 Moisture degradation during microwave assisted vacuum drying (MV) and hot air drying (HA)

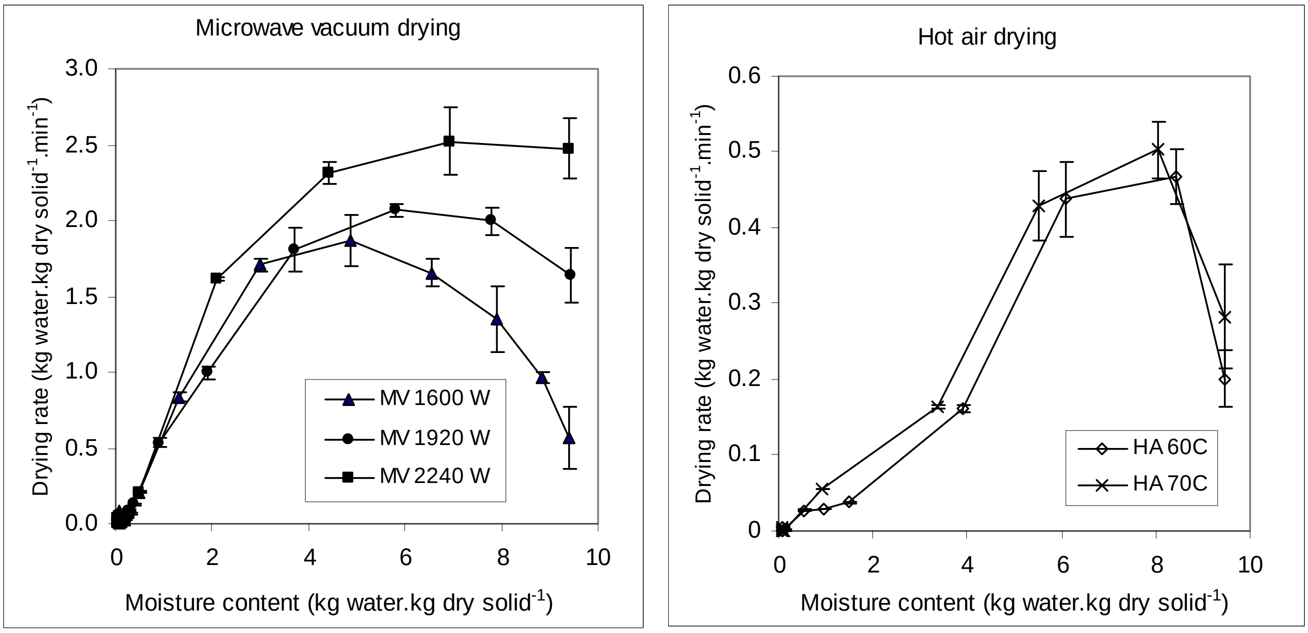


Figure 2 Drying rate of microwave assisted vacuum drying and hot air drying

The drying rate later decreased when moisture content decreased, although surface barrier was not an issue for microwave vacuum drying at this stage. This was due to the decreased absorption of microwave energy and decreased dielectric loss constant of relatively dried mint leaves. In addition, some energy was used for breaking away bounded water which required higher energy than free water. However, the absorbed energy was still large enough to vaporize water and continuously increase the product's temperature. Therefore, burnt spots could be found at the last stage of drying.

Increasing the microwave power from 1600 W to 2240 W tended to increase the drying rate. Similar effect of microwave power was found in drying of carrot (Wang and Xi, 2005), mint leaves (Ozbek and Dadali, 2007), osmotically dehydrated banana (Pereira et al., 2007) and cooked soybean (Gowen et al., 2008). However, by increasing air temperature from 60^{0}C to 70^{0}C, the drying rates were not significantly improved. Comparing to the microwave assisted vacuum drying, the hot air drying yielded significantly lower drying rates. This was possibly due to the effect of microwave power output, which transferred heat faster at depth, rather than the vacuum condition (Cui et al., 2004; Bondaruk et al., 2007). With the increased drying rate, the microwave could therefore be used to shorten the drying process of mint leaves by 85-95%. Giri and Prasad (2007) also found 70-90% reduction in drying time of mushroom drying.

Based on thin layer models including Lewis's model, Page's model and Fick's model, moisture ratio was estimated as shown in Figures 3, 4 and 5, respectively. All models yielded results in good agreement with the experimental ones, indicated by high correlation coefficients and low root mean square errors (RMSE) in Table 1. For Lewis's model, better fit was found in the falling drying rate period, compared with the heating up period. This was due to that the model was analogous to the Newton's law to explain the mechanism during the falling rate period when the drying rate of porous samples was proportional to the difference between moisture content and equilibrium moisture content (Sander, 2007). Therefore, the model did not describe the drying kinetics well during heating up and the constant rate period. Similarly, Fick's model only fit the experimental data during the falling drying rate period. As the drying process was dominated by the falling drying rate period, the overall model performance over the whole drying period was reasonably good.

Table 1. Model performance

Model	Model performance	MV1600	MV1920	MV2240	HA60	HA70
Lewis	R	0.9321	0.9825	0.9874	0.9935	0.9932
	RMSE	0.1716	0.0724	0.0527	0.0457	0.0477
Page	R	0.9954	0.9962	0.9934	0.9927	0.9969
	RMSE	0.0385	0.0307	0.0366	0.0458	0.0298
Fick	R	0.9640	0.9821	0.9837	0.9872	0.9869
	RMSE	0.1456	0.0866	0.0712	0.0844	0.08424

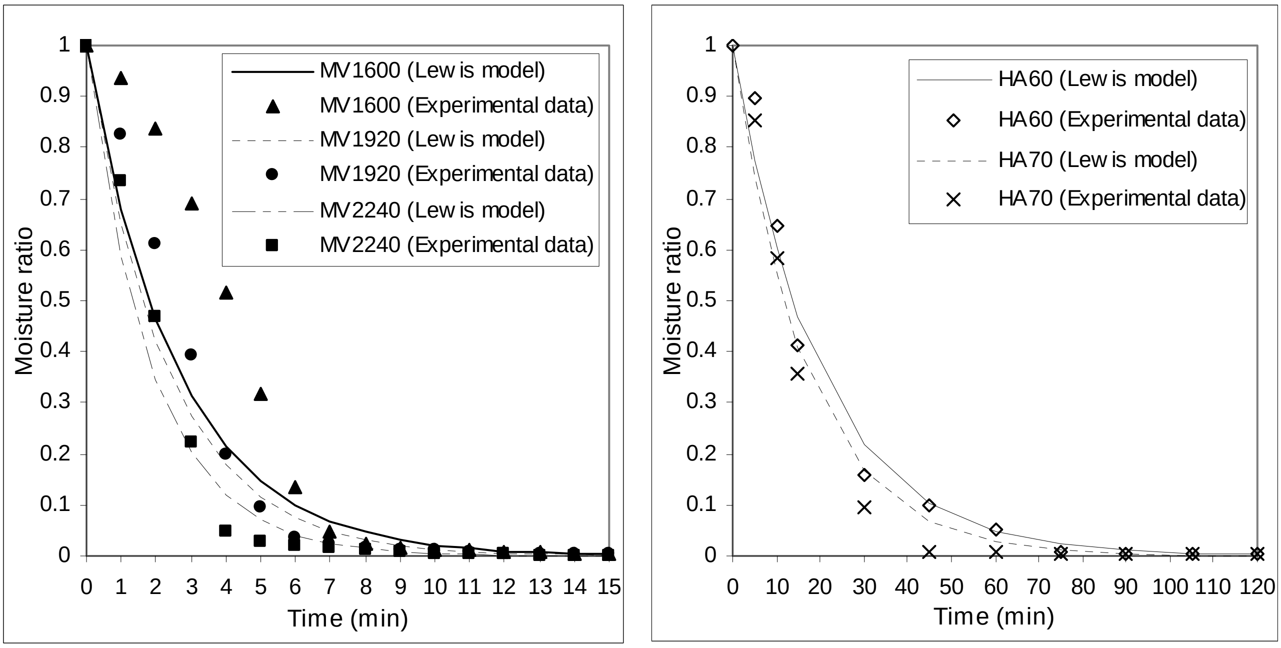


Figure 3 Simulated moisture ratio during drying from Lewis's model

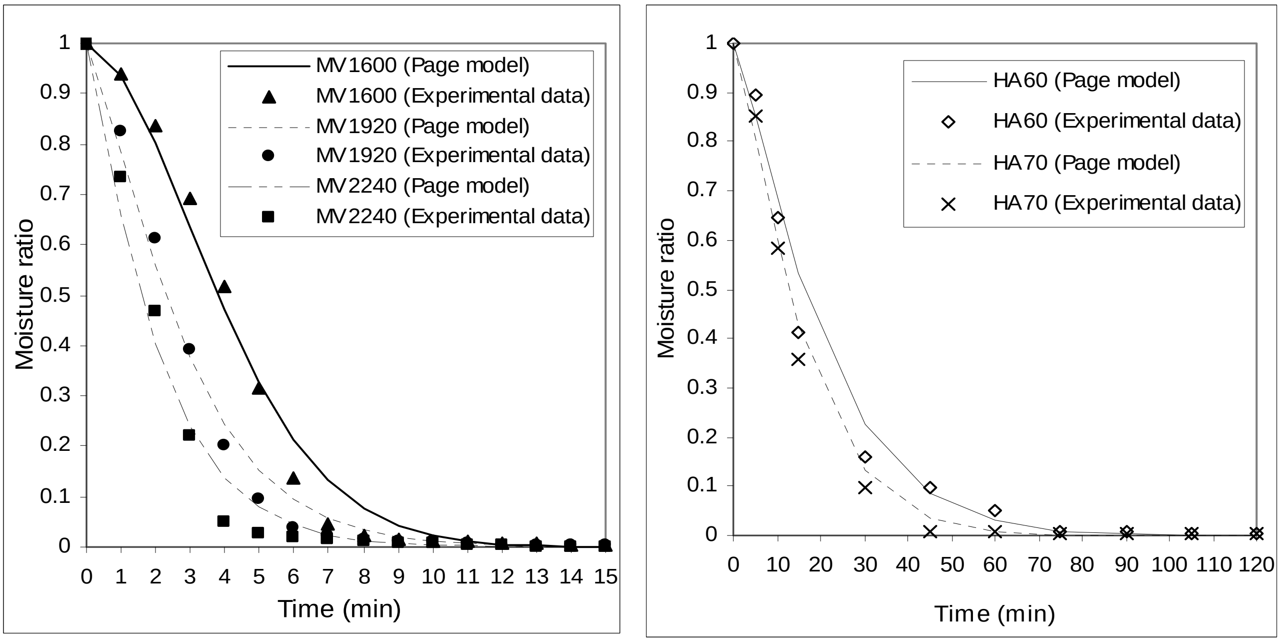


Figure 4 Simulated moisture ratio during drying from Page's model

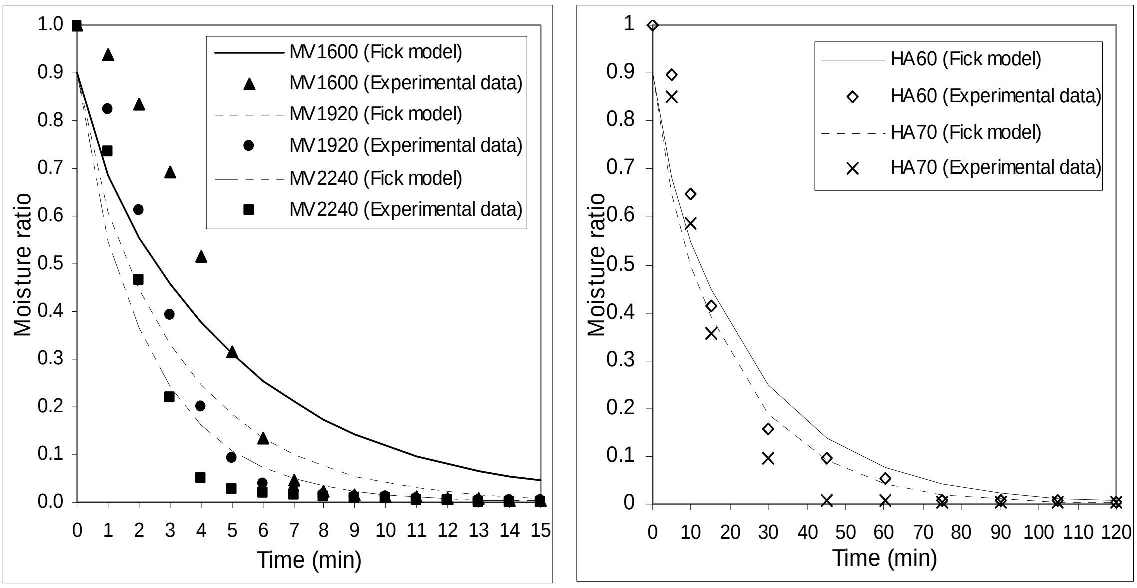


Figure 5 Simulated moisture ratio during drying from Fick's model

From Lewis's model which was a first-order kinetic model, kinetic constant could be used to demonstrate a relatively quicker drying mechanism when microwave was applied with vacuum condition, compared to hot air drying (Table 2). From Page's model, n was found to be greater than 1.0 which means that the relationship between moisture ratio and time was unlikely a first-order kinetic. Therefore Page's model offered improved predictability of drying kinetics over Lewis's model, regardless of heat supply methods. This is in line with the use of Page's model for drying of green bean (Doymaz, 2005), kiwi fruits (Simal et al., 2005) and cooked soybean (Gowen et al., 2008).

Table 2. Model parameters

Model	Model parameters	MV1600 (Power intensity: 8.0 $W.g^{-1}$)	MV1920 (Power intensity: 9.6 $W.g^{-1}$)	MV2240 (Power intensity: 11.2 $W.g^{-1}$)	HA60	HA70
Lewis	k (min^{-1})	0.3852	0.4307	0.5322	0.0508	0.0598
Page	n	1.7669	1.2708	1.1250	1.2463	1.2447
	k (min^{-1})	0.0649	0.2423	0.4168	0.0215	0.0291
Fick	D_{eff} ($m^2.s^{-1}$)	4.6999×10^{-11}	7.2620×10^{-11}	9.7838×10^{-11}	0.9648×10^{-11}	1.1900×10^{-11}

Based on Fick's second law, effective moisture diffusivity was calculated from equation 5, as shown in Table 2. From previous studies of microwave drying of mint leaves (Ozbek and Dadali, 2007), the effective moisture diffusivities at power intensity of 7.2 $W.g^{-1}$ and 14.4 $W.g^{-1}$ were 0.3982×10^{-10} and 0.9253×10^{-10} $m^2.s^{-1}$, respectively, To obtain similar effective moisture diffusivities (i.e. 0.9253×10^{-10} $m^2.s^{-1}$ and 0.9784×10^{-10} $m^2.s^{-1}$), the microwave drying in Ozbek and Dadali (2007) required an power intensity of 14.4 $W.g^{-1}$, whereas the microwave vacuum drying in this study required only 11.2 $W.g^{-1}$. McMinn (2004) also observed an increase of the effective moisture diffusivity in microwave dried lactose powder when pressure was decreased. For the hot air drying, the effective moisture diffusivity was slightly improved when air temperature was increased from 60^0C to 70^0C. The effective moisture diffusivity during the hot air drying at 60^0C and 70^0C from the present study was higher than the effective moisture diffusivity (0.5129×10^{-12}-2.945×10^{-12} $m^2.s^{-1}$) reported in a previous study where experiments were conducted at 30-50^0C on *Mentha crispa* L (Park et al., 2002). Comparing to the hot air drying, the effective moisture diffusivity was significantly improved when microwave vacuum drying was applied to drying mint leaves.

1.2 Degradation of color during drying

Lightness (L*-value), greenness (negative a*-value) and yellowness (positive b*-value) of fresh mint leaves were 35.39±1.36, -10.23±0.88, and 26.92±1.01, respectively. As shown in Figure 6, after the microwave vacuum drying for 15 minutes, the lightness and yellowness of the dried mint leaves were significantly increased, possibly because of chlorophyll degradation. The obtained dried mint color was light green-yellow. In contrast, after the hot air drying, the lightness was decreased and the redness was increased, resulting in dark green-brown color. The degree of color change was dependent on drying temperature, drying time and oxygen level. High temperature could lead to the replacement of magnesium in the chlorophyll by hydrogen, thereby converting Chlorophylls to pheophytins (Rudra et al., 2008).

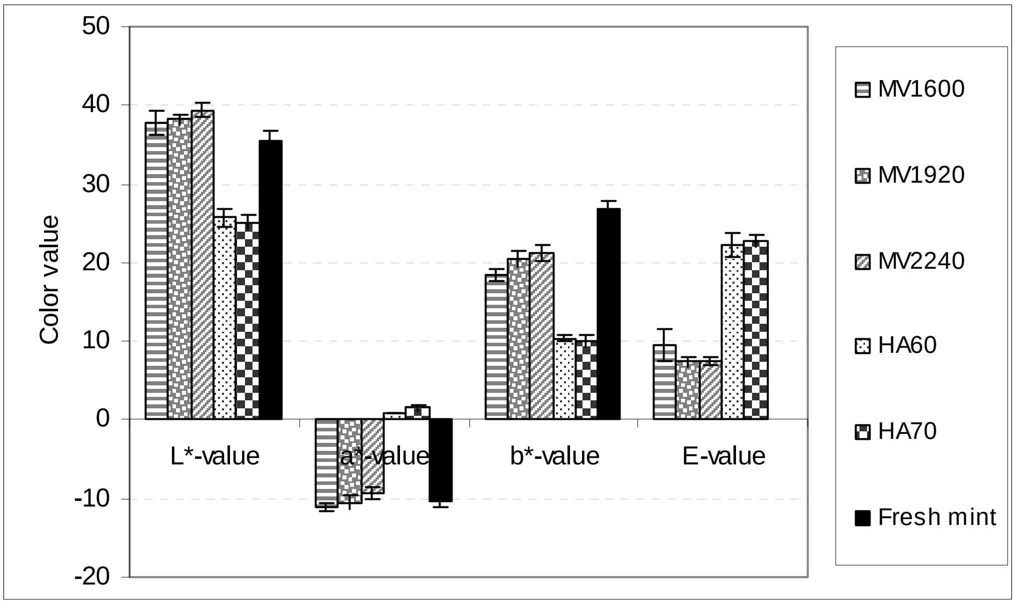


Figure 6 Color degradation during microwave assisted vacuum drying and hot air drying

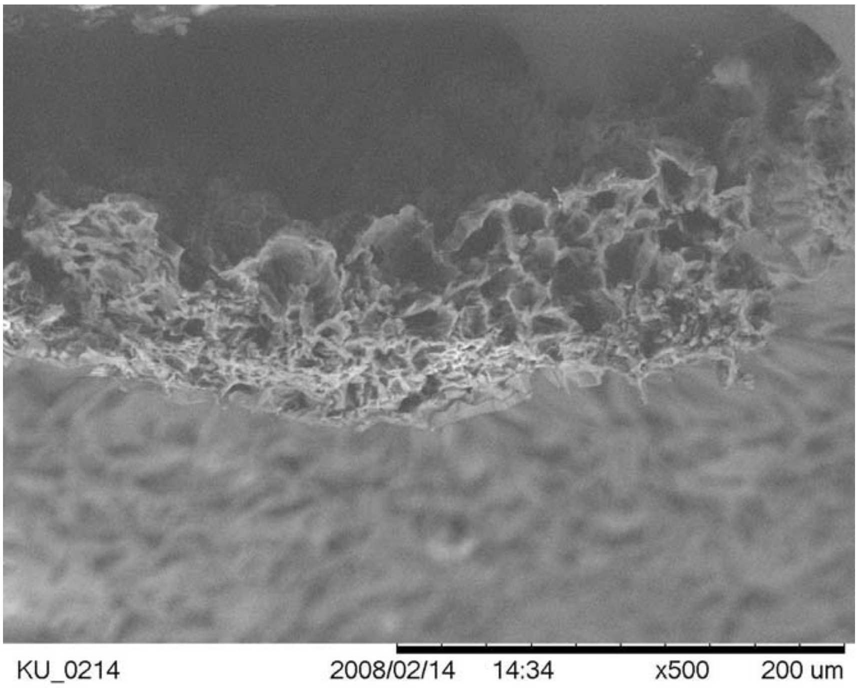
For hot air drying at 60^0C and 70^0C, color (L*, a*, b* and E) of the dried mint leaves was not significantly different ($p>0.05$). Both drying temperatures yielded positive a* values, thus redness appeared. Insignificant impact of drying temperature in this range on the color of hot air dried products was observed in a previous study of drying dasheen leaves. However, the impact on color change was increased when temperature was increased from 40-50^0C to 60-70^0C (Maharaj and Sankat, 1996).

Comparing to the microwave vacuum drying, the hot air drying yielded dried mint leaves being darker, less green and more yellow. As a result, ΔE values of the air dried samples were significantly higher than those of the microwave vacuum dried ones ($p \leq 0.05$). This could be due to shorter drying time and vacuum condition (13.33 kPa) of the microwave vacuum drying. This result agreed with Onayemi and Okeibuno Badifu (1987) in which slower rate of chlorophyll degradation was found with shorter drying process. Improvement of color was also found with decreasing pressure in drying of model fruit gel (Drouzas et al., 1999) and potato (Bondaruk et al., 2007).

1.3 Structural characteristics of dried mint leaves

Figure 7 shows the microstructure of dried mint leaves investigated by using SEM. From the scanning electron micrographs, the microstructure of microwave vacuum dried mint leaves was more porous and open than that of hot air dried ones. The more porous structure was possibly from massive and fast vaporization during microwave-vacuum drying. Vapor bubbles could increase total pressure gradient inside mint leaves and therefore enhanced the porosity. Increasing microwave power tended to increase evaporation rate, thereby preventing shrinkage and case hardening. This could also explain the improvement in rehydration of dried mushroom by using microwave-vacuum drying as reported in Giri and Prasad (2007).

a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2008/02/14
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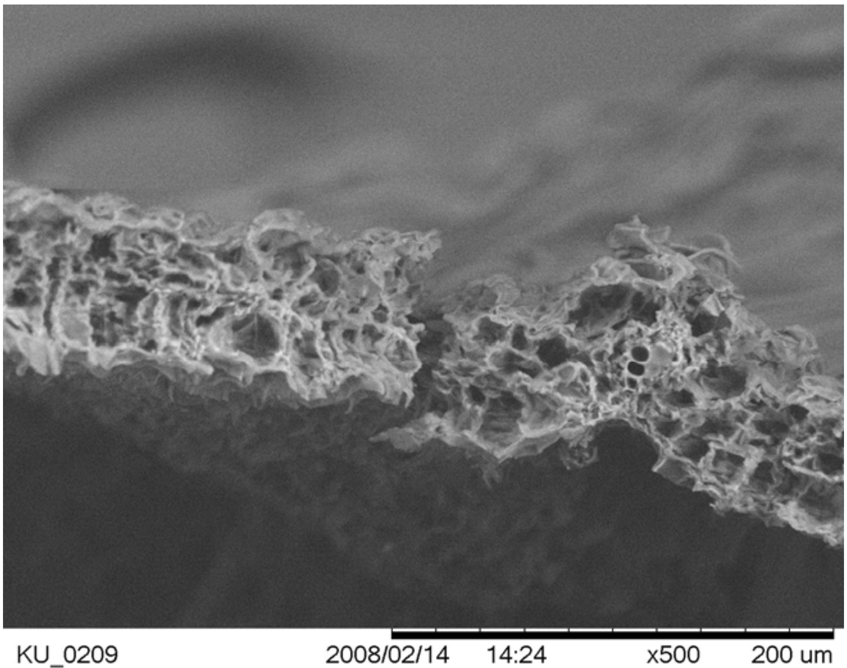
x500
200 um

b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x500
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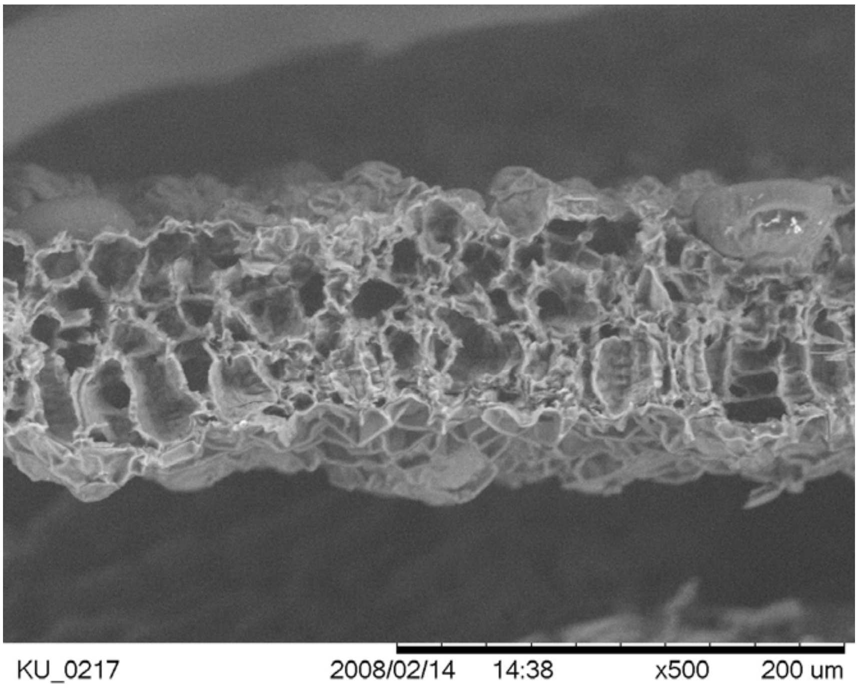
c


KU_0217
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14:38
x500
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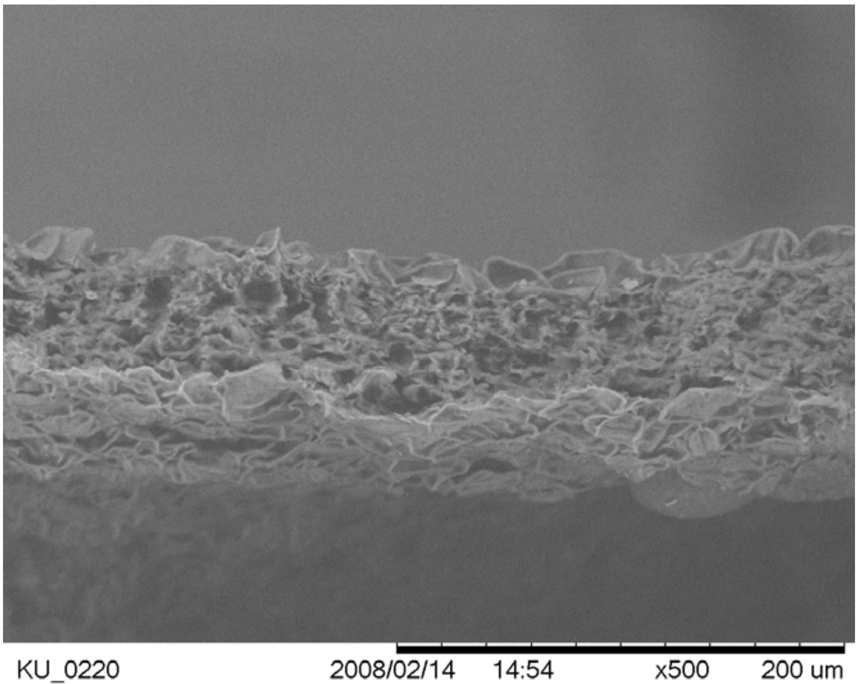
d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x500
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e

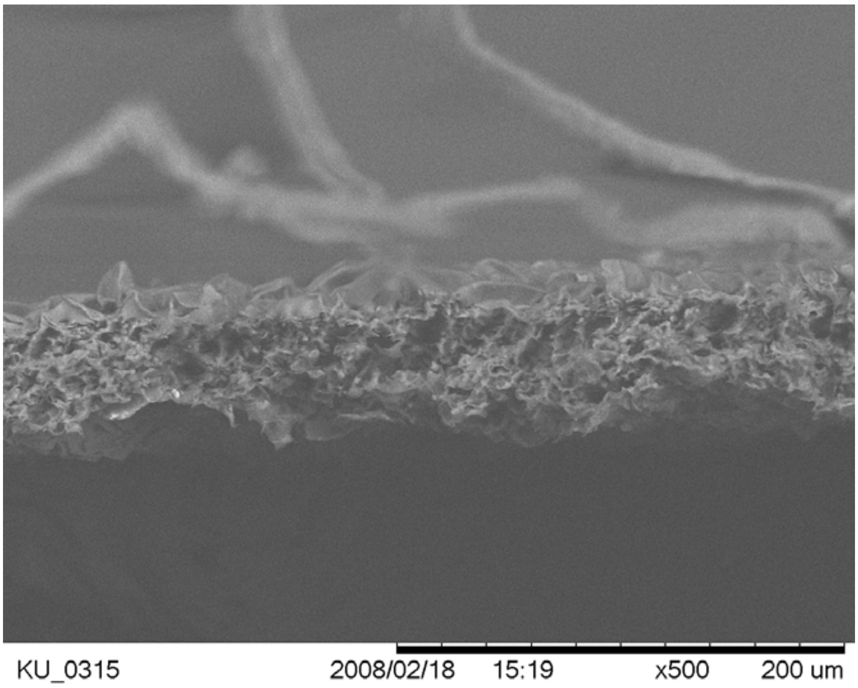

Figure 7 Scanning electron micrograph of dried mint leaves, a: microwave-vacuum drying at 1600W, b: microwave vacuum drying at 1920W, c: microwave-vacuum drying at 2240W, d: hot air drying at 60^{0}C and e: hot air drying at 70^{0}C.

Hot air drying at both 60^{0}C and 70^{0}C yielded packed structure. Difference in microstructure between hot air drying at 60^{0}C and 70^{0}C was not clearly visible. Insignificant difference in structure was also reported on dried cooked rice that was dried at 50^{0}C, 80^{0}C and 120^{0}C, respectively (Luangmalawat et al., 2008).

1.4 Rehydration characteristics of dried mint leaves

As shown in Table 3, the microwave vacuum drying at 1920 W and 2240 W yielded significantly higher rehydration rates than the hot air drying at 60^{0}C and 70^{0}C. This result agreed to Giri and Prasad (2007) in which an improvement in rehydration of dried mushroom by microwave vacuum drying was observed over hot air drying. For the microwave vacuum drying, increasing microwave power tended to increase the rehydration rate. In contrast, change in the rehydration rate was insignificant when the drying temperature was increased from 60^{0}C to 70^{0}C. Insignificant impact of drying temperature in the range of 50-100^{0}C on rehydration of dried cooked rice was also observed in a previous study (Luangmalawat et al., 2008).

Table 3 Rehydration rate of dried mint leaves

Drying condition	MV1600	MV1920	MV2240	HA60	HA70
Rehydration rate (k: min^{-1})	0.2533bc	0.2839ab	0.3177a	0.2214c	0.2215c
R	0.9980	0.9980	0.9961	0.9949	0.9930
RMSE	1.0470	0.7935	1.2472	2.2711	2.1774

a-c means significant difference within the same row ($p \leq 0.05$)

1.5 Sensorial quality of dried mint leaves

By using 10 trained panelists, intensity of quality attributes of dried mint leaves were evaluated, as shown in Table 4. Hot air dried sample were darker than those of microwave vacuum drying. The result coincided with the instrumental analysis in Figure 6. However, microwave vacuum dried mint leaves showed more shrinkage, due to intensive microwave heating. For aroma intensity, microwave vacuum dried samples could keep cool aroma, when microwave powers were 1600 W and 1920 W. Increasing microwave power to 2240 W, cool aroma was reduced to be closed to that of hot air dried samples.

Table 4 Quality attributes of dried mint leaves

Attributes of dried mint leaves	MV1600	MV1920	MV2240	HA60	HA70
Appearance					
1. Darkness	5.47$\pm$0.01	5.92$\pm$0.14	7.45$\pm$0.24	10.96$\pm$0.13	10.78$\pm$0.62
2. Shrinkage	7.94$\pm$0.35	8.82$\pm$0.73	9.47$\pm$0.24	5.05$\pm$0.43	5.15$\pm$0.07
Aroma					
1. Rank aroma	7.69$\pm$0.19	8.57$\pm$0.59	7.50$\pm$0.84	8.88$\pm$0.43	8.06$\pm$0.55
2. Cool aroma	7.78$\pm$0.49	6.21$\pm$0.16	4.65$\pm$0.57	5.20$\pm$0.41	4.92$\pm$0.69

2.) Microwave assisted drying of osmotically dehydrated mandarin

2.1 Water loss and solid gain during osmotic dehydration of mandarin.

Figure 8 presents the profiles of water loss and solid gain of mandarin during osmotic dehydration. Increasing glycerol from 9:1 to 5:5 in the osmotic agent could significantly increase water loss (Table 5). In addition, the solid gain was significantly increased, because of the lower molecular weight of glycerol, compared with sucrose. This coincided with Azoubel et al. (2004) that found increased water loss and solid gain in osmotically dehydrated tomato when NaCl was used instead of sucrose. Nonetheless, comparing between 5:5 and 7:3 sucrose and glycerol ratios, there was no significant difference in solid gain.

a.

b.

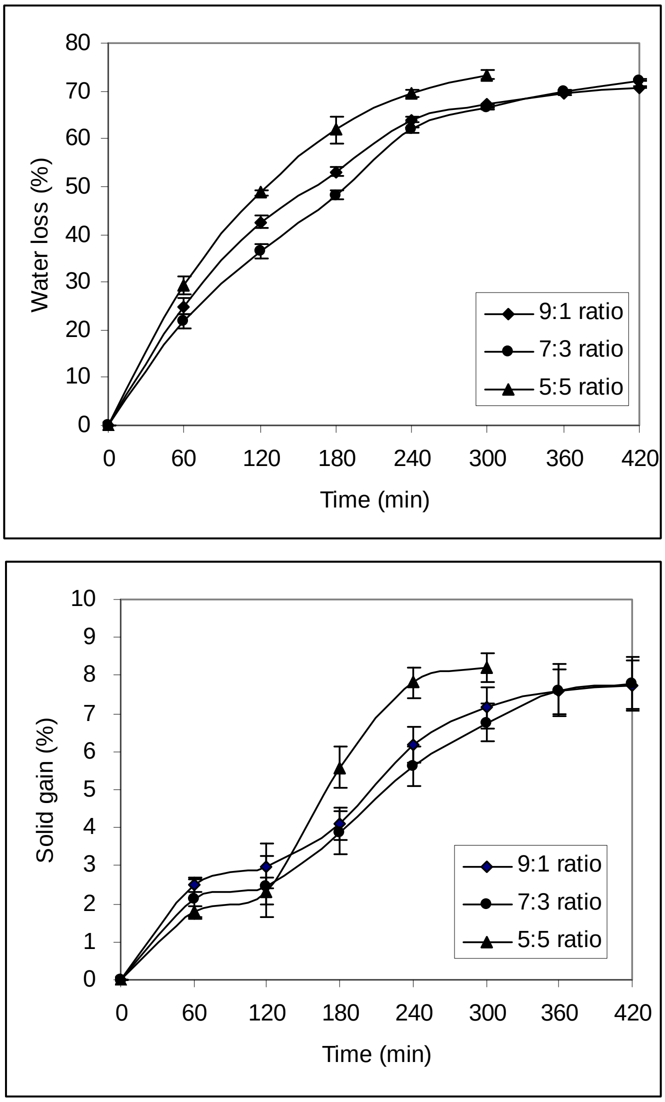

Figure 8 Water loss (a) and solid gain (b) during osmotic dehydration

Table 5 Water loss and solid gain during osmotic dehydration

Time (min)	Water loss (%)			Solid Gain (%)		
	Sucrose:Glycerol = 9:1	Sucrose:Glycerol = 7:3	Sucrose:Glycerol = 5:5	Sucrose:Glycerol = 9:1	Sucrose:Glycerol = 7:3	Sucrose:Glycerol = 5:5
60	$24.90^{b} \pm 1.59$	$21.74^{c} \pm 1.35$	$29.39^{a} \pm 1.83$	$2.50^{a} \pm 0.17$	$2.14^{ab} \pm 0.52$	$1.79^{b} \pm 0.12$
120	$42.58^{b} \pm 1.44$	$36.47^{c} \pm 1.17$	$48.69^{a} \pm 0.66$	$2.99^{ns} \pm 0.57$	$2.46^{ns} \pm 0.82$	$2.33^{ns} \pm 0.35$
180	$53.06^{b} \pm 0.94$	$48.21^{c} \pm 1.65$	$61.84^{a} \pm 2.76$	$4.10^{b} \pm 0.43$	$3.86^{b} \pm 0.55$	$5.59^{a} \pm 0.55$
240	$63.98^{b} \pm 0.50$	$61.82^{c} \pm 1.14$	$69.58^{a} \pm 0.71$	$6.17^{b} \pm 0.47$	$5.63^{b} \pm 0.53$	$7.81^{a} \pm 0.40$
300	$67.06^{b} \pm 0.13$	$66.37^{b} \pm 1.12$	$73.30^{a} \pm 0.93$	$7.16^{b} \pm 0.54$	$6.77^{b} \pm 0.48$	$8.19^{a} \pm 0.38$
360	$69.46^{ns} \pm 0.37$	$69.99^{ns} \pm 0.77$	-	$7.58^{ns} \pm 0.59$	$7.61^{ns} \pm 0.69$	-
420	$70.75^{b} \pm 0.37$	$72.23^{a} \pm 0.53$	-	$7.73^{ns} \pm 0.67$	$7.79^{ns} \pm 0.69$	-

a-c means significant difference within the same row ($p \leq 0.05$)

ns means non-significant difference within the same row ($p>0.05$)

2.2 Mass diffusivity during osmotic dehydration of mandarin.

Based on Fick's second law, effective moisture diffusivity was calculated, as shown in Table 6. Increasing glycerol ratio in osmotic solution from 9:1 to 5:5 tended to increase effective moisture diffusivity. This was in agreement with the water loss profiles during osmotic dehydration.

Table 6 Effective diffusivity during osmotic dehydration

Sucrose: Glycerol ratio	9:1	7:3	5:5
D_{eff} ($m^2.s^{-1}$)	7.2620×10^{-12}	7.0301×10^{-12}	1.0738×10^{-11}
RMSE	0.0443	0.0622	0.0510
r^2	0.9818	0.9749	0.9852

2.3 Drying characteristics of osmotically dehydrated mandarin

Osmotically dehydrated mandarin was dried in either a convective drying oven at $70^{0}C$ for 360 minutes or microwave vacuum oven. The drying kinetic rate constant of Lewis's model could be used to quantify kinetics of moisture change during drying (Table 7).

Table 7 Drying kinetic rate constant of osmotically dehydrated mandarin

Drying condition	Sucrose : Glycerol ratio	k (min^{-1})	RMSE	r^2
HA70	9:1	-0.0111	0.0706	0.9869
	7:3	-0.0121	0.0470	0.9950
	5:5	-0.0120	0.0498	0.9932
MV1280 (6.4 $W.g^{-1}$ power intensity)	9:1	-0.4706	0.0879	0.9529
	7:3	-0.6826	0.1290	0.9168
	5:5	-0.5332	0.1002	0.9443
MV960 (4.8 $W.g^{-1}$ power intensity)	9:1	-0.2705	0.0981	0.9500
	7:3	-0.3879	0.1165	0.9322
	5:5	-0.3962	0.1388	0.9061

By using osmotic dehydration as a pretreatment step for water removal, the moisture content of mandarin was reduced. The kinetic rate constants were in the range of 0.0111 and 0.0121 min^{-1}, when hot air drying was used. When microwave vacuum drying was applied, the drying kinetic rate constant was increased to the range of 0.2705 and 0.6826 min^{-1}. Therefore, drying time was reduced from 360 minutes of hot air drying to 5-7 minutes of microwave vacuum drying. In addition, increasing microwave power from 960 W to 1280 W could improve drying kinetic rate constant. As a result, drying time was decreased by 2 minutes. Pereira et al. (2007) also found that increasing the microwave power at the last drying stage could speed up the drying rate of osmotically dehydrated banana.

2.4) Quality of dried mandarin.

Osmotically dehydrated mandarin from various osmotic agents was dried under various conditions. The appearance of the final product was shown in Figure 9. Quality of dried mandarin was shown in Tables 8-10.

Before drying, the lightness (L*-value), Chroma (C-value) and hue (h-value) of fresh mandarin were 46.43, 14.12 and 73.58 respectively. After drying, intensity of color was increased due to water loss. From h-value, the samples were changed from yellow to yellow-red after drying. Comparing to hot air drying, microwave vacuum drying could yield significantly lighter dried mandarin ($p \leq 0.05$). This was possibly due to the applied vacuum condition and short drying time in microwave vacuum drying. However, increasing microwave power tended to reduce the lightness. In addition, decreasing sucrose:glycerol ratio significantly reduced the lightness of dried mandarin ($p \leq 0.05$).

a) Sucrose: glycerol ratio = 9:1

HA70 MV960 MV1280

b) Sucrose: glycerol ratio = 7:3

HA70 MV960 MV1280

c) Sucrose: glycerol ratio = 5:5

HA70 MV960 MV1280

Figure 9 Dried mandarin from various drying conditions

Table 8 Color of osmotically dehydrated mandarin after drying

Drying condition	Sucrose : Glycerol ratio	L*	C	h
HA70 360 min	9:1	$47.46^{f} \pm 1.33$	$45.19^{de} \pm 3.11$	$56.82^{g} \pm 2.61$
	7:3	$46.50^{g} \pm 1.11$	$44.31^{f} \pm 4.37$	$60.28^{e} \pm 1.02$
	5:5	$44.08^{h} \pm 1.14$	$45.16^{de} \pm 2.69$	$57.59^{f} \pm 1.47$
MV1280 5 min	9:1	$53.96^{b} \pm 2.12$	$49.57^{ab} \pm 3.00$	$62.67^{a} \pm 1.65$
	7:3	$50.35^{cd} \pm 1.47$	$49.26^{bc} \pm 1.48$	$61.67^{bc} \pm 0.82$
	5:5	$48.34^{e} \pm 0.97$	$48.06^{c} \pm 1.02$	$60.67^{de} \pm 1.04$
MV960 7 min	9:1	$55.34^{a} \pm 1.63$	$50.66^{a} \pm 2.33$	$62.07^{ab} \pm 0.56$
	7:3	$50.78^{c} \pm 1.68$	$48.97^{bc} \pm 1.34$	$61.94^{abc} \pm 0.85$
	5:5	$49.87^{d} \pm 1.77$	$46.31^{d} \pm 1.65$	$61.19^{cd} \pm 1.77$

a-f means significant difference within the same column ($p \leq 0.05$)

For hue, h-values of microwave vacuum dried samples were significantly higher than those of hot air dried samples ($p \leq 0.05$). Increasing microwave power from 960 W to 1280 W produced non-significant difference of hue. However, reducing the sucrose ratio in osmotic solution significantly decreased h-value after drying. This was possibly due to the increased loss of vitamin A. Likewise, C-values of hot air dried samples were less than those of microwave vacuum drying ($p \leq 0.05$).

Regarding vitamin A: Beta-carotene content of dried mandarin (Table 9), increasing sucrose: glycerol ratio in osmotic solution could maintain vitamin A content of dried mandarin. Similarly, in the study of tomato drying, Shi et al. (1999) explained that sucrose could strengthen the binding force of lycopene in the matrix. In addition, sucrose could prevent oxidation of lycopene. Therefore, red color in tomato could be maintained.

Carotenoid was one of components involving coloration of mandarin. Pretreatment with sucrose during osmotic dehydration possibly slowed down the solubility of carotene. Therefore, color of dried mandarin could be preserved. Ruiz et al. (2005) also found a linear relationship between color and carotene content of apricot.

Table 9 Vitamin A content of osmotically dehydrated mandarin after drying

Drying condition	Sucrose : Glycerol ratio	Vitamin A (μg/100g)
HA70	9:1	553.02[c] ± 4.19
	7:3	493.04[d] ± 7.33
	5:5	75.83[g] ± 2.56
MV1280 (6.4 $W.g^{-1}$ power intensity)	9:1	760.16[b] ± 8.83
	7:3	332.14[f] ± 0.48
	5:5	64.25[g] ± 2.50
MV960 (4.8 $W.g^{-1}$ power intensity)	9:1	1104.15[a] ±15.75
	7:3	444.48[e] ± 45.44
	5:5	55.77[g] ± 0.68

a-g means significant difference within the same column ($p \leq 0.05$)

Generally, the solubility of carotene could be increased when process temperature was increased during drying (Karabulut et al., 2007). For microwave vacuum drying, increased microwave power caused an increased loss of vitamin A and thereby an increased color darkness of dried samples. However, effect of microwave power on chroma and hue was not significantly observed. This was possibly because of shorter process when the increased microwave power was supplied. Comparing to the hot air drying, the microwave vacuum drying could maintain higher vitamin A content, when 9:1 sucrose and glycerol ratio was used in the osmotic solution. As carotene could be lost due to oxidation, vacuum condition and shorter drying process in the microwave vacuum drying could help maintaining the vitamin A content and thereby product color. Karatas and Kamisli (2007) also observed brown apricot in infrared drying (20-90 minutes), but natural color in microwave drying (3-8 minutes). However, increasing ratio of glycerol to 5:5 could reduce vitamin A content significantly ($p \leq 0.05$). Consequently, effect of drying method on vitamin A content became non-significant.

For texture, pre-water removal by osmotic dehydration could reduce the hardness of dried samples. In this study, increased glycerol ratio in osmotic solution significantly reduced the hardness of dried samples (Table 10). Glycerol could function as humectant in dried mandarin. Therefore, the moist characteristic of dried sample was increased when glycerol ratio was increased. Similarly, drying without osmotic dehydration yielded the dried carrot characterized by 3 times compression strength of the one with osmotic dehydration (Stepien, 2008).

For hot air drying, dried samples were soft; as well as, hardness was in the range of 0.08 and 0.22 N. As microwave vacuum dried samples contained puffing structure, their outer layers were thick and hard, in order to prevent collapsing. Increased microwave power did not show significant effect on hardness of dried samples.

Table 10 Hardness of osmotically dehydrated mandarin after drying

Drying condition	Sucrose : Glycerol ratio	Hardness (N)
HA70	9:1	0.22[c] ± 0.04
	7:3	0.11[d] ± 0.03
	5:5	0.08[d] ± 0.03
MV1280 (6.4 $W.g^{-1}$ power intensity)	9:1	0.49[a] ± 0.11
	7:3	0.31[b] ± 0.06
	5:5	0.25[c] ± 0.04
MV960 (4.8 $W.g^{-1}$ power intensity)	9:1	0.52[a] ± 0.13
	7:3	0.35[b] ± 0.08
	5:5	0.22[c] ± 0.05

a-d means significant difference within the same column ($p \leq 0.05$)

After drying, all pretreated mandarin contained less than 0.6 water activity. The product became shelf-stable. Likewise, Heredia et al. (2007) found more shelf stable dried tomato when osmotic dehydration was used as pretreatment before the microwave vacuum drying.

Conclusions

Microwave vacuum drying was used to dry mint leaves and osmotically dehydrated mandarin and compared with conventional hot air drying. Characteristics of the dried samples were determined. The changes of moisture ratio have been described by using Lewis's model, Page's model and Fick's model, respectively. Based on Fick's second law, effective moisture diffusivity was calculated by Crank's equation.

For mint leaves, the effective moisture diffusivity was significantly increased when microwave drying was applied under vacuum condition, compared with hot air drying. Regarding color, the microwave vacuum dried mint leaves were light-green/yellow whereas the hot air dried mint leaves were dark-brown. From the SEM results, the microwave vacuum dried mint leaves had highly porous microstructure whereas the hot air dried mint leaves had packed microstructure. Rehydration tests confirmed that the rehydration rates of the microwave vacuum dried mint leaves were higher than those of the hot air dried ones.

For mandarin, microwave vacuum drying could increase kinetic rate constant and thereby shortened drying time, compared to hot air drying. Increasing microwave power could increase kinetic rate constant of moisture loss. However, it significantly decreased vitamin A content ($p \leq 0.05$). Similar to dried mint leaves, microwave vacuum drying yielded significantly lighter color ($p \leq 0.05$). Hue and chroma values were also higher than those from hot air drying. As microwave vacuum drying yielded puffing characteristics, thick and hard outer layer of dried samples were observed. In contrast, hot air dried sample was soft. Pre-water removal by osmotic dehydration using increased ratio of glycerol could reduce hardness of dried samples. In addition, increased ratio of glycerol could increase water loss and effective mass diffusivity and thereby possibly reduce the pre-water removal process time. However, increasing glycerol ratio by decreasing glucose ratio in the osmotic solution significantly increased loss of vitamin A content of dried mandarin ($p \leq 0.05$).

From this study, microwave drying under vacuum condition was proved to be a potential technique to improve dried fruit and vegetable. Pre-water removal by osmotic dehydration should be applied for fruit drying to reduce drying time and burning spot during microwave drying.

Recommendations

Microwave vacuum drying was good at decreasing drying time and maintaining natural color. It could produce dried products with quick rehydration characteristics, due to its porous structure. However, to develop dried products for direct consumption without the need of rehydration, it requires some further study to develop techniques to improve the texture, flavor and taste. Treatment of materials before and after microwave vacuum drying, e.g. osmotic dehydration, should be investigated further to develop verities of product characteristics that are good for consumption without rehydration.

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Characterization of microwave vacuum drying and hot air drying of mint leaves (*Mentha cordifolia* Opiz ex Fresen)

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ABSTRACT

Mint (*Mentha cordifolia* Opiz ex Fresen) was subjected to microwave vacuum drying and hot air drying, respectively. For microwave vacuum drying, three microwave intensities i.e. 8.0 W g^{-1}, 9.6 W g^{-1} and 11.2 W g^{-1} were applied with pressure controlled at 13.33 kPa. For hot air drying, two drying temperatures of 60 °C and 70 °C were examined. Lewis's, Page's and Fick's models were used to describe drying kinetics under various drying conditions. Effective moisture diffusivities were determined to be 4.6999×10^{-11}, 7.2620×10^{-11}, 9.7838×10^{-11}, 0.9648×10^{-11} and 1.1900×10^{-11} m^2 s^{-1} for microwave vacuum drying at 8.0 W g^{-1}, 9.6 W g^{-1} and 11.2 W g^{-1}, hot air drying at 60 °C and 70 °C, respectively. The microwave vacuum drying could reduce drying time of mint leaves by 85–90%, compared with the hot air drying. In addition, color change during drying was investigated. Lightness, greenness and yellowness of the microwave vacuum dried mint leaves were higher than those of the hot air dried mint leaves. From scanning electron micrographs, the microwave vacuum dried mint leaves had a more porous and uniform structure than the hot air dried ones. From rehydration test at 30 °C, rehydration rate constants of the dried mint leaves by the microwave vacuum drying at 9.6 W g^{-1} and 11.2 W g^{-1} microwave intensity were significantly higher than those by the hot air drying at 60 °C and 70 °C ($p \leqslant 0.05$).

1. Introduction

Mint (*Mentha cordifolia* Opiz ex Fresen) was one of the popular Thai kitchen herbs due to its unique aroma and benefits to human health such as helping to relieve from colds, flu, fever, motion sickness and poor digestion problems (Ozbek and Dadali, 2007). To preserve it, mint leaves were conventionally dried using either sun drying or hot air drying. Its color degrades significantly because of heating for long period. To decrease the drying time, air temperature should be increased. In addition, microwave drying may be applied. Microwave drying may be regarded as a rapid dehydration process. During the process, moisture content was reduced, as well as, loss factor of dried materials decreased. The local pressure and temperature could be increased and speed up the drying process (Cheng et al., 2006). Increasing microwave power also increased dehydration rate of carrot (Wang and Xi, 2005) and mint (Ozbek and Dadali, 2007). Moreover, the rehydration rate was increased by increasing the microwave power at the second stage (Wang and Xi, 2005). However, too rapid mass transfer could damage the texture in some cases. In addition, non-uniformity of electromagnetic field could create hot spots during microwave drying. At the final stage of drying, product temperature might be increased rapidly to the level that causes scorching (Zhang et al., 2006). Burning of dried whole strawberries was found when rated power of 600 W was applied (Venkatachalapathy and Raghavan, 2000). To dry mushroom from 7.5% moisture content to 2.0% moisture content, microwave drying provided the fastest diffusion coefficient of 331.02×10^{-6} m^2 s^{-1} whereas vacuum drying provided the slowest rate of 0.3225×10^{-6} m^2 s^{-1}. However, microwave drying produced poorer quality of dried products (Walde et al., 2006).

To overcome the limitation of microwave drying, microwave assisted vacuum drying has been used for drying fruits and vegetables. The advantage was to speed up drying process, to increase mass transfer by an increased pressure gradient between inner and outer layers and to maintain drying process at low temperature (Pere and Rodier, 2002). Compared to conventional hot air drying of mushroom, microwave assisted vacuum drying could reduce the drying time by 70–90% as well as rehydration characteristics were improved (Giri and Prasad, 2007). From scanning electron microscope (SEM) results, the microstructure of microwave vacuum dried potato was characterized by large porous and irregular structure whereas the microstructure of hot air dried potato was characterized by tight packing and strong connection between cells. Therefore, the microwave vacuum dried potato showed higher reconstitution ability during rehydration than the hot air dried potato (Bondaruk et al., 2007). For drying of lactose

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powder, McMinn (2004) found that water diffusivity under hot air drying was in the range of 0.350×10^{-9}–1.467×10^{-9} m^2 s^{-1} whereas water diffusivity under microwave vacuum drying was in the range of 3.255×10^{-9} m^2 s^{-1}–6.110×10^{-9} m^2 s^{-1}. Moisture diffusion rate could be enhanced by reducing pressure. Moreover, the reduced pressure could increase puffing characteristics and crispness of fish slides and reduce burnt spots (Zhang et al., 2007). According to a two-dimensional finite element model, puffing of dough during microwave vacuum drying was caused by firstly the difference between air pressure in the dough and air pressure in the chamber and secondly vaporization due to an increased dough temperature (Ressing et al., 2007).

As regards color, Drouzas et al. (1999) found significant improvement of lightness of microwave vacuum dried model pectin gel, compared to hot air dried samples. On drying potato, Bondaruk et al. (2007) also observed that the color of the product was significantly lighter when drying with microwave at 24 kPa, compared to drying with microwave at atmospheric pressure. Another advantage of microwave when it was applied to vacuum drying was increased mass loads of vacuum dryers (Hu et al., 2006). This was due to the intensive energy of the microwave system. Microwave drying requires only 20–35% of floor space, compared with hot air drying (Wang and Xi, 2005).

As described in the above, microwave assisted vacuum drying showed a high potential in improving process efficiency and quality of dried products. This study aimed to determine the characteristics of microwave assisted vacuum drying of mint leaves in comparison with conventional hot air drying and their effects on the color and structure of the dried leaves.

2. Materials and methods

Mint (*M. cordifolia* Opiz ex Fresen) leaves were washed and dried using either a tray dryer (Frecon, BWS-series) or a microwave vacuum dryer (MarchCool, Thailand). The microwave vacuum dryer consisted of three pairs of magnetrons with a 360° rotating load basket (Fig. 1). Thickness of the fresh mint leaves were measured by a micrometer (Mitutoyo, Japan; ±0.01 mm). For the microwave vacuum drying, 200 g of mint leaves were used per batch. The microwave vacuum dryer was operated at three microwave power outputs: 1600 W (MV1600), 1920 W (MV1920) and 2240 W (MV1920) or microwave intensities: 8.0 W g^{-1}, 9.6 W g^{-1} and 11.2 W g^{-1}, all with controlled pressure of 13.33 kPa and controlled frequency of 2450 MHz for 15 min. To compare with the microwave vacuum drying, the hot air drying with 1.0 m s^{-1} flow velocity was conducted at two temperatures: 60 °C (HA60) and 70 °C (HA70) for 120 min, in order to reduce the moisture content to a similar level to that of the microwave vacuum drying.

2.1. Drying characterization

Moisture content of microwave vacuum dried mint leaves and hot air dried mint leaves was analyzed using the AOAC oven method (AOAC, 2000) throughout the drying process. Drying rate was defined as

$$\text{Drying rate} = \frac{X_i - X_{i-1}}{\Delta t} \tag{1}$$

where X_i is moisture content dry basis (kg water kg dry solid^{-1}) at time i and t is time interval (min).

The change of moisture in mint leaves during drying was expressed as moisture ratio defined as

$$\text{Moisture ratio} = \frac{X_i - X_e}{X_0 - X_e} \tag{2}$$

As the thickness of mint leaves was very small, the most frequently used thin layer models including Lewis's model (Eq. (3)) and Page's model (Eq. (4)) (Jayas et al., 1990) were applied for describing the drying mechanism.

The kinetic constant of Lewis's model could be used to quantify the rate of moisture change during various drying conditions:

$$\frac{X_i - X_e}{X_0 - X_e} = \exp(kt) \tag{3}$$

where k is kinetic constant (min^{-1}), X_0 is initial moisture content dry basis (kg water kg dry solid^{-1}), X_e is equilibrium moisture content dry basis (kg water kg dry solid^{-1}), X_i is moisture content dry basis (kg water kg dry solid^{-1}) at time i and t is time interval (min).

As an improvement over Lewis's model, Page's model was characterized by k and n where n was defined as a dimensionless exponential index:

$$\frac{X_i - X_e}{X_0 - X_e} = \exp(kt^n) \tag{4}$$

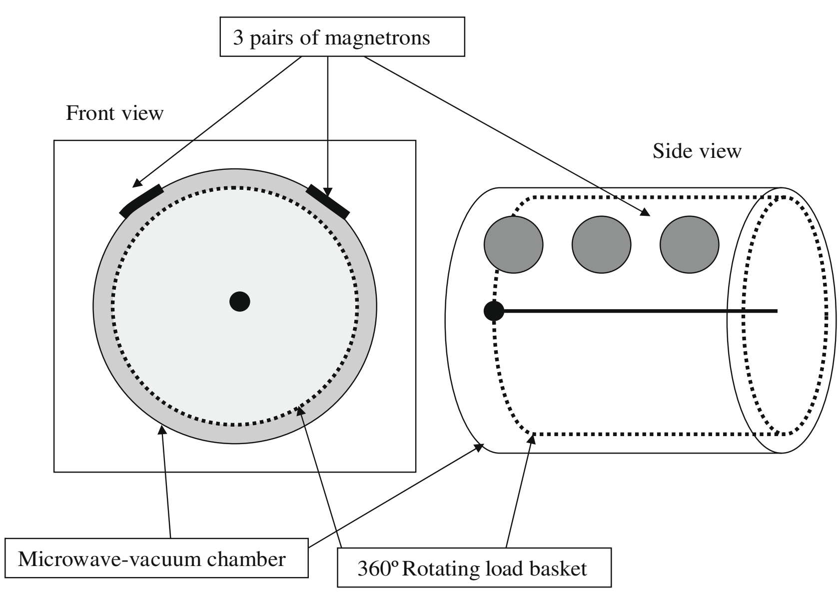

Fig. 1. Illustration of a microwave vacuum dryer.

Fitness of each model was evaluated by comparing between the modeled moisture ratio and the experimental data. Correlation coefficient (R) and root mean square error (RMSE) were calculated to determine the model performance.

Based on Fick's law and assumptions of symmetric mass transfer with respect to the centre, constant diffusion coefficient and no shrinkage, effective moisture diffusivity of water in mint leaves was estimated from change of moisture ratio along with drying time by using modified Crank's equation (Singh and Heldman, 2001) as shown in the following equation:

$$\frac{X_i - X_e}{X_0 - X_e} = \frac{8}{\pi^2}\sum_{n=1}^{\infty}\frac{1}{(2n-1)^2}\cdot\exp\left(-\frac{(2n-1)^2\pi^2\cdot D_{eff}}{4L^2}\cdot t\right) \quad (5)$$

where D_{eff} is the effective moisture diffusivity ($m^2\,s^{-1}$), L is half thickness of mint leaves (0.19×10^{-3} m) and t is drying time (s).

2.2. Color measurement

Mint leaves were dried for various times and collected to examine change of color by using a spectrophotometer (Minolta CM-3500d). Color was determined in the CIE system. The values of L^*, a^* and b^* present darkness–lightness, greenness–redness and blueness–yellowness. Change of color was estimated by

$$\Delta E = \sqrt{(L_i^* - L_0^*)^2 + (a_i^* - a_0^*)^2 + (b_i^* - b_0^*)^2} \quad (6)$$

where ΔE is color change, L_0^* and L_i^* are lightness values at initial time and time i, respectively, a_0^* and a_i^* are greenness–redness values at initial time and time i, respectively, and b_0^* and b_i^* are blueness–yellowness values at initial time and time i, respectively.

2.3. Structural characteristic of dried mint leaves

The cross section at the middle of dried mint leaves samples was investigated using a scanning electron microscope (Hitachi TM-1000, Japan) with an accelerating voltage of 15 kV. Magnification was adjusted to 500×.

2.4. Rehydration characteristics of dried mint leaves

Dried mint leaves (10 g) produced under various drying conditions were rehydrated at 30 °C for 15 min by being immersed in 80 g water. Rehydration rate was described by

$$\frac{W_t - W_e}{W_0 - W_e} = \exp(-kt) \quad (7)$$

where W_0 is initial weight (g), W_e is equilibrium weight (g), W_t is weight (g) after rehydration for *t min*, k is rehydration rate constant (min^{-1}), and t is rehydration time (min).

Fitness of Eq. (7) was evaluated by comparing between the modeled weight after rehydration and the experimental data. Correlation coefficient (R) and root mean square error (RMSE) were calculated to determine the performance.

3. Results and discussion

3.1. Drying characteristics during microwave vacuum drying and hot air drying

Fig. 2 shows how the moisture content of mint leaves was decreased with increased drying time under various drying conditions. At the beginning of a drying process, mint leaves with an average initial moisture content of 9.4331 ± 0.0188 kg water kg dry solid^{-1} were heated up. Hot air drying at 60 °C and 70 °C required 90 and 60 min, respectively whereas microwave vacuum drying at 1600 W, 1920 W and 2240 W required 13, 12 and 10 min, respectively for reducing the moisture content to less than 0.1 kg water/kg dry sample. Change of drying rate is shown in Fig. 3. For the microwave vacuum drying, it is worth to note that the power values were microwave powers supplied by the oven without considering reflected powers from the mint leaves.

It can be seen from Fig. 3 that significant differences in drying rate were found between the two drying methods, i.e. microwave vacuum drying and hot air drying. At the beginning when moisture content was high, the drying rate under all drying conditions increased with time. In microwave vacuum drying, it could be explained that high microwave energy absorption was found when significant amount of dipole molecules were available. With significant microwave energy absorption, heat was generated to increase the product's temperature to meet the water boiling point temperature (51.7 °C). At this stage, mass transfer was dominated by vaporization. After the drying rate reached its maximum level, falling drying rate period occurred. Lack of a constant drying rate period was also observed in other studies of microwave drying of porous materials (Sander, 2007). Comparing to the microwave drying of mint leaves under atmospheric pressure in Ozbek and Dadali (2007), the microwave vacuum drying in the present study tends

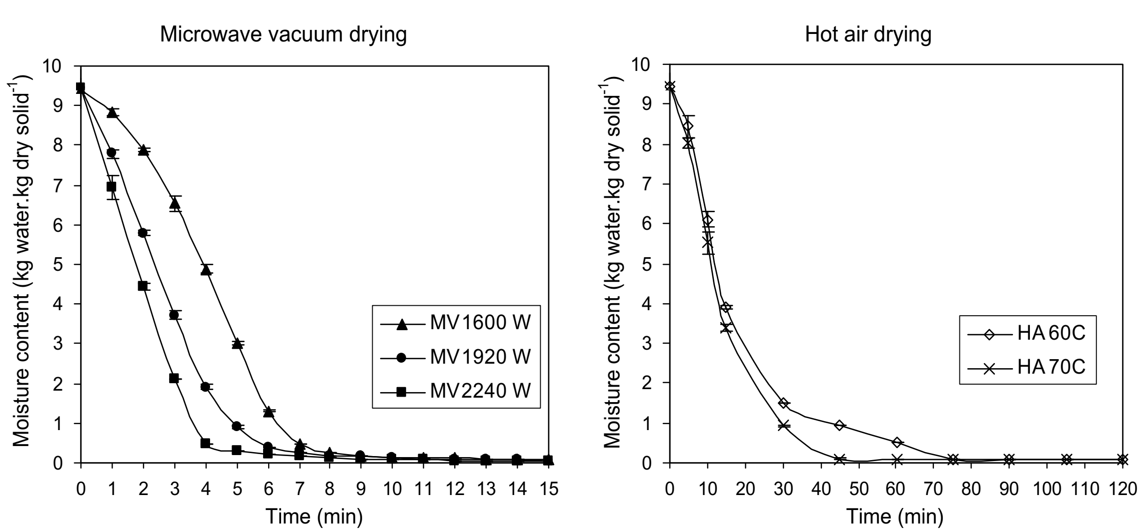

Fig. 2. Moisture degradation during microwave assisted vacuum drying (MV) and hot air drying (HA).

to produce higher drying rate. The maximum drying rates were approximately 0.5, 1.5 and 3.0 kg water kg dry solid^{-1} min^{-1}, when the microwave intensity of 7.2 W g^{-1}, 14.4 W g^{-1} and 36.0 W g^{-1} were applied, respectively. In our present study, maximum drying rates of 1.9, 2.1 and 2.5 kg water kg dry solid^{-1} min^{-1} were obtained when the microwave intensity of 8.0 W g^{-1}, 9.5 W g^{-1} and 11.2 W g^{-1} were applied, respectively, with the pressure controlled at 13.33 kPa.

The drying rate later decreased when moisture content decreased, although surface barrier was not an issue for microwave vacuum drying at this stage. This was due to the decreased absorption of microwave energy and decreased dielectric loss constant of relatively dried mint leaves. In addition, some energy was used for breaking away bound water which required higher energy than free water. However, the absorbed energy was still large enough to vaporize water and continuously increase the product's temperature. Therefore, burnt spots could be found at the last stage of drying.

Increasing the microwave power from 1600 W to 2240 W tends to increase the drying rate. Similar effect of microwave power was found in drying of carrot (Wang and Xi, 2005), mint leaves (Ozbek and Dadali, 2007), osmotically dehydrated banana (Pereira et al., 2007) and cooked soybean (Gowen et al., 2008). However, by increasing air temperature from 60 °C to 70 °C, the drying rates were not significantly improved. Comparing to the microwave assisted vacuum drying, the hot air drying yielded significantly lower drying rates. This was possibly due to the effect of microwave power output, which achieved higher heat transfer depth than the vacuum condition (Bondaruk et al., 2007; Cui et al., 2004). With the increased drying rate, the microwave could therefore be used to shorten the drying process of mint leaves by 85–95%. Giri and Prasad (2007) also found 70–90% reduction in drying time of mushroom drying.

Based on thin layer models including Lewis's model, Page's model and Fick's model, moisture ratio was estimated as shown in Figs. 4–6, respectively. All models yielded results in good agree-

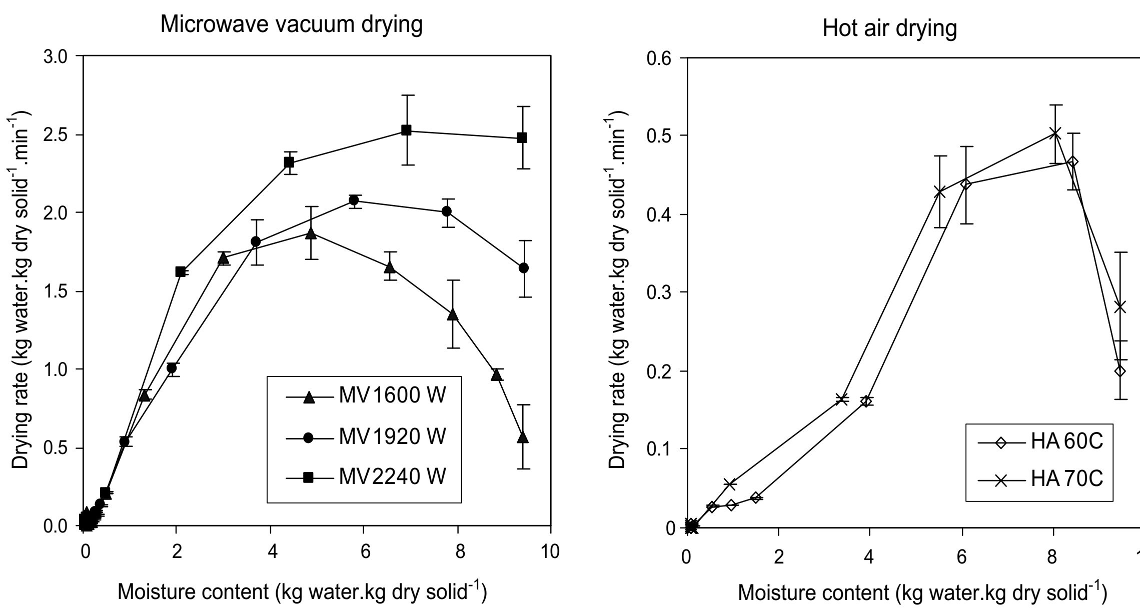

Fig. 3. Drying rate of microwave assisted vacuum drying and hot air drying.

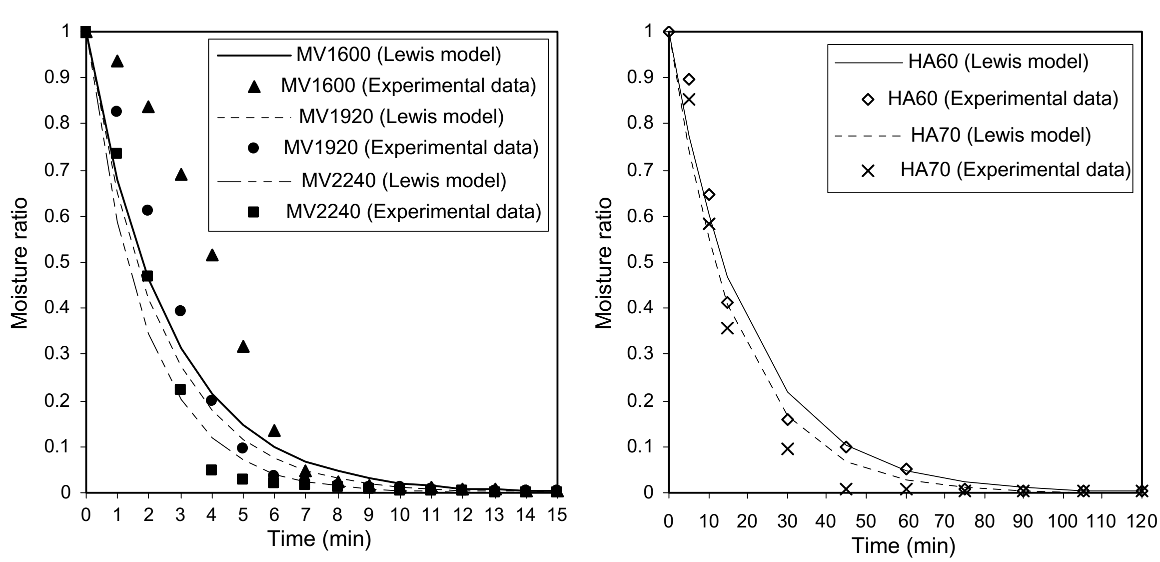

Fig. 4. Simulated moisture ratio during drying from Lewis's model.

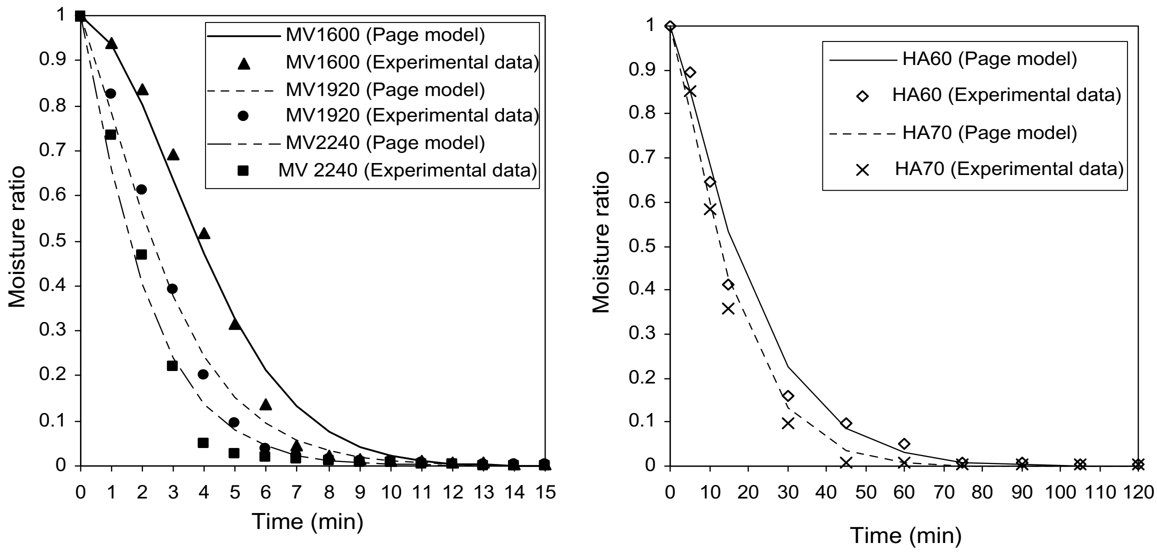

Fig. 5. Simulated moisture ratio during drying from Page's model.

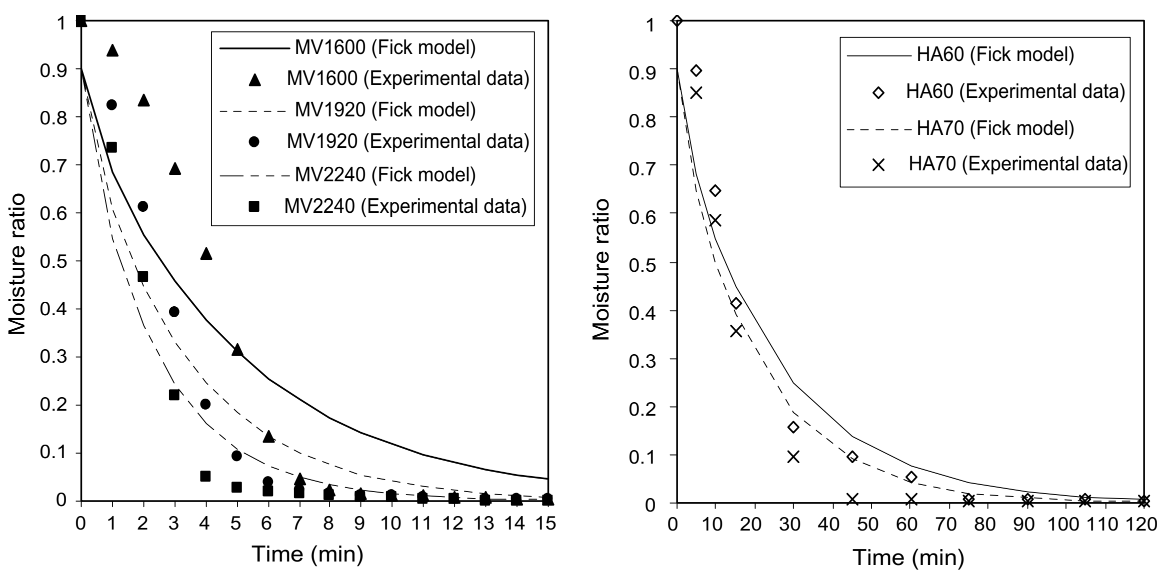

Fig. 6. Simulated moisture ratio during drying from Fick's model.

ment with the experimental ones, indicated by high correlation coefficients and low root mean square errors (RMSE) in Table 1. For Lewis's model, better fit was found in the falling drying rate period, compared with the heating up period. In the falling drying rate period, drying rate was proportional to the difference between moisture content and equilibrium moisture content. Thus, it followed Newton's law which Lewis's model was based on (Sander, 2007). Similarly, Fick's model only fit the experimental data during the falling drying rate period. As the drying process was dominated by the falling drying rate period, the overall model performance over the whole drying period was reasonably good.

Table 1
Model performance.

Model	Model performance	MV1600	MV1920	MV2240	HA60	HA70
Lewis	*R*	0.9321	0.9825	0.9874	0.9935	0.9932
	RMSE	0.1716	0.0724	0.0527	0.0457	0.0477
Page	*R*	0.9954	0.9962	0.9934	0.9927	0.9969
	RMSE	0.0385	0.0307	0.0366	0.0458	0.0298
Fick	*R*	0.9640	0.9821	0.9837	0.9872	0.9869
	RMSE	0.1456	0.0866	0.0712	0.0844	0.08424

From Lewis's model which was a first-order kinetic model, kinetic constant could be used to demonstrate a relatively quicker drying mechanism when microwave was applied with vacuum condition, compared to hot air drying (Table 2). From Page's model, n was found to be greater than 1.0 which means that the relationship between moisture ratio and time was unlikely a first-order kinetic. Therefore, Page's model offered improved predictability of drying kinetics over Lewis's model, regardless of heat supply methods. This is in line with the use of Page's model for drying of green bean (Doymaz, 2005), kiwi fruits (Simal et al., 2005) and cooked soybean (Gowen et al., 2008).

Based on Fick's second law, effective moisture diffusivity was calculated from Eq. (5), as shown in Table 2. From previous studies of microwave drying of mint leaves (Ozbek and Dadali, 2007), the

Table 2
Model parameters.

Model	Model parameters	MV1600 (Power intensity: 8.0 W g^{-1})	MV1920 (Power intensity: 9.6 W g^{-1})	MV2240 (Power intensity: 11.2 W g^{-1})	HA60	HA70
Lewis	k (min^{-1})	0.3852	0.4307	0.5322	0.0508	0.0598
Page	n	1.7669	1.2708	1.1250	1.2463	1.2447
	k (min^{-1})	0.0649	0.2423	0.4168	0.0215	0.0291
Fick	D_{eff} ($m^2\ s^{-1}$)	4.6999×10^{-11}	7.2620×10^{-11}	9.7838×10^{-11}	0.9648×10^{-11}	1.1900×10^{-11}

effective moisture diffusivities at power intensity of 7.2 W g^{-1} and 14.4 W g^{-1} were 0.3982×10^{-10} and 0.9253×10^{-10} $m^2\ s^{-1}$, respectively. To obtain similar effective moisture diffusivities (i.e. 0.9253×10^{-10} $m^2\ s^{-1}$ and 0.9784×10^{-10} $m^2\ s^{-1}$), the microwave drying in Ozbek and Dadali (2007) required an power intensity of 14.4 W g^{-1}, whereas the microwave vacuum drying in this study required only 11.2 W g^{-1}. McMinn (2004) also observed an increase of the effective moisture diffusivity in microwave dried lactose powder when pressure was decreased. For the hot air drying, the effective moisture diffusivity was slightly improved when air temperature was increased from 60 °C to 70 °C. The effective moisture diffusivity during the hot air drying at 60 °C and 70 °C from the present study was higher than the effective moisture diffusivity (0.5129×10^{-12}–2.945×10^{-12} $m^2\ s^{-1}$) reported in a previous study where experiments were conducted at 30–50 °C on *Mentha crispa* L. (Park et al., 2002). Comparing to the hot air drying, the effective moisture diffusivity was significantly improved when microwave vacuum drying was applied to drying mint leaves.

3.2. Degradation of color during drying

Lightness (L^*-value), greenness (negative a^*-value) and yellowness (positive b^*-value) of fresh mint leaves were 35.39 ± 1.36, −10.23 ± 0.88, and 26.92 ± 1.01, respectively. As shown in Fig. 7, after the microwave vacuum drying for 15 min, the lightness and yellowness of the dried mint leaves were significantly increased, possibly because of chlorophyll degradation. The obtained dried mint color was light green–yellow. In contrast, after the hot air drying, the lightness was decreased and the redness was increased, resulting in dark green–brown color. The degree of color change was dependent on drying temperature, drying time and oxygen level. High temperature could lead to the replacement of magnesium in the chlorophyll by hydrogen, thereby converting Chlorophylls to pheophytins (Rudra et al., 2008).

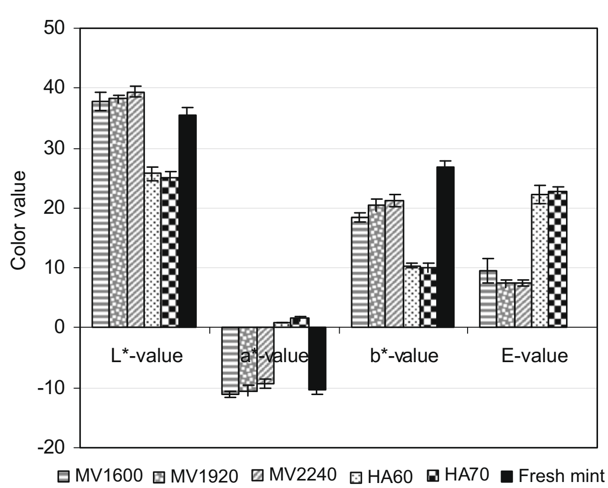

Fig. 7. Color degradation during microwave assisted vacuum drying and hot air drying.

For hot air drying at 60 °C and 70 °C, color (L^*, a^*, b^* and E) of the dried mint leaves was not significantly different ($p > 0.05$). Both drying temperatures yielded positive a^* values, thus redness appeared. Insignificant impact of drying temperature in this range on the color of hot air dried products was observed in a previous study of drying dasheen leaves. However, the impact on color change was increased when temperature was increased from 40–50 °C to 60–70 °C (Maharaj and Sankat, 1996).

Comparing to the microwave vacuum drying, the hot air drying yielded dried mint leaves being darker, less green and more yellow. As a result, ΔE values of the air dried samples were significantly higher than those of the microwave vacuum dried ones ($p \leqslant 0.05$). This could be due to shorter drying time and vacuum condition (13.33 kPa) of the microwave vacuum drying. This result agreed with Onayemi and Okeibuno Badifu (1987) in which slower rate of chlorophyll degradation was found with shorter drying process. Improvement in color was also found with decreasing pressure in drying of model fruit gel (Drouzas et al., 1999) and potato (Bondaruk et al., 2007).

3.3. Structural characteristics of dried mint leaves

Fig. 8 shows the microstructure of dried mint leaves investigated by using SEM. From the scanning electron micrographs, the microstructure of microwave vacuum dried mint leaves (Fig. 8a–c) was more porous and open than that of hot air dried ones (Fig. 8d and e). The more porous structure was possibly from massive and fast vaporization during microwave vacuum drying. Vapor bubbles could increase total pressure gradient inside mint leaves and therefore enhanced the porosity. Increasing microwave power tended to increase evaporation rate, thereby preventing shrinkage and case hardening. This could also explain the improvement in rehydration of dried mushroom by using microwave vacuum drying as reported in Giri and Prasad (2007).

Hot air drying at both 60 °C and 70 °C yielded packed structure. Difference in microstructure between hot air drying at 60 °C and 70 °C was not clearly visible. Insignificant difference in structure was also reported on dried cooked rice that was dried at 50 °C, 80 °C and 120 °C, respectively (Luangmalawat et al., 2008).

3.4. Rehydration characteristics of dried mint leaves

As shown in Table 3, the microwave vacuum drying at 1920 W and 2240 W yielded significantly higher rehydration rates than the hot air drying at 60 °C and 70 °C. This result agreed to Giri and Prasad (2007) in which an improvement in rehydration of dried mushroom by microwave vacuum drying was observed over hot air drying. For the microwave vacuum drying, increasing microwave power tended to increase the rehydration rate. In contrast, change in the rehydration rate was insignificant when the drying temperature was increased from 60 °C to 70 °C. Insignificant impact of drying temperature in the range of 50–100 °C on rehydration of dried cooked rice was also observed in a previous study (Luangmalawat et al., 2008).

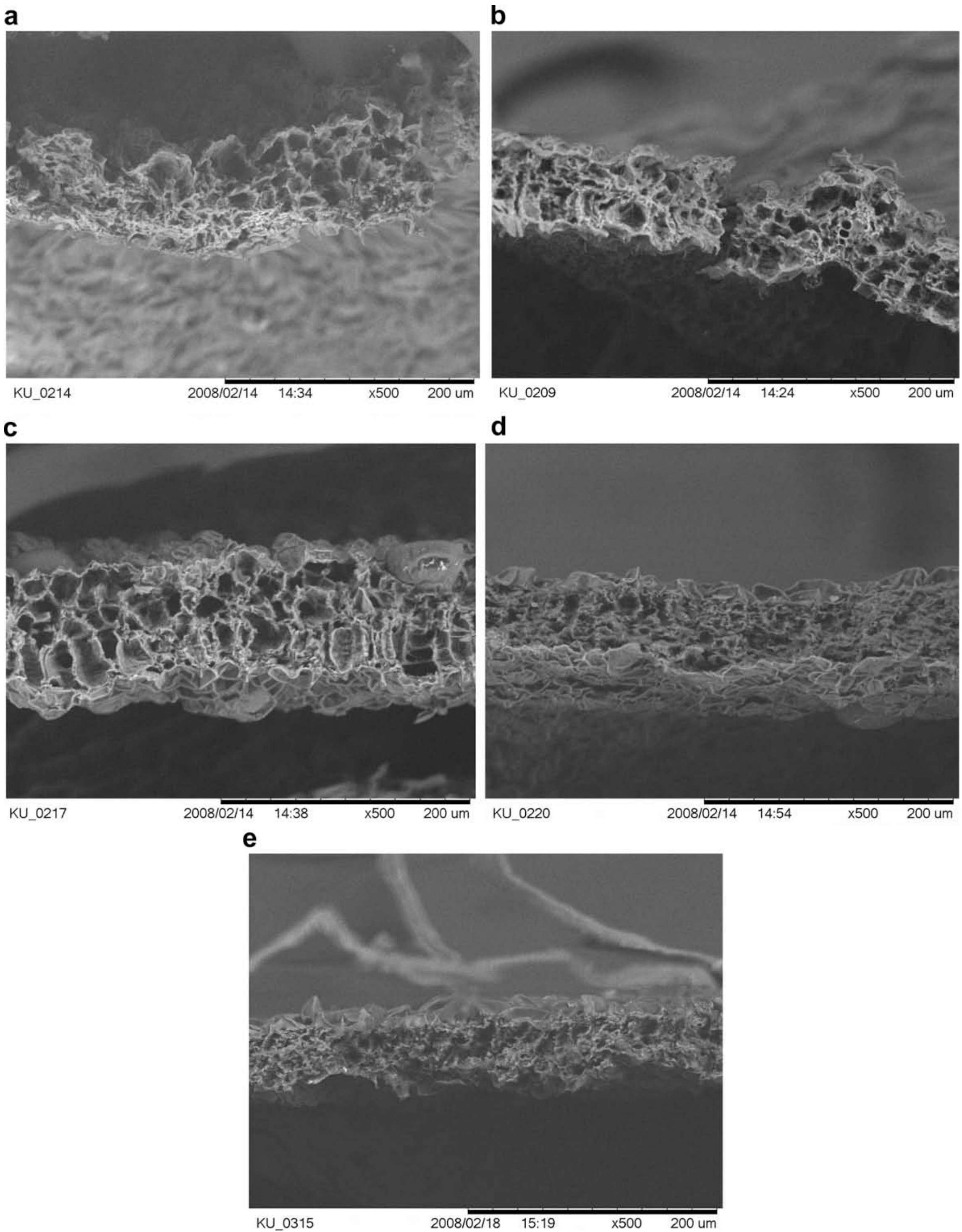

Fig. 8. Scanning electron micrograph of dried mint leaves: (a) microwave vacuum drying at 1600 W, (b) microwave vacuum drying at 1920 W, (c) microwave vacuum drying at 2240 W, (d) hot air drying at 60 °C and (e) hot air drying at 70 °C.

Table 3
Rehydration rate of dried mint leaves.

Drying condition	MV1600	MV1920	MV2240	HA60	HA70
Rehydration rate (k: min^{-1})	0.2533^{bc}	0.2839^{ab}	0.3177^{a}	0.2214^{c}	0.2215^{c}
R	0.9980	0.9980	0.9961	0.9949	0.9930
RMSE	1.0470	0.7935	1.2472	2.2711	2.1774

a–c means significant difference within the same row ($p \leqslant 0.05$).

4. Conclusions

Characteristics of the microwave vacuum drying and hot air drying of mint leaves were determined. The changes of moisture ratio have been described by using Lewis's model, Page's model and Fick's model, respectively. Page's model yielded the best description. Based on Fick's second law, effective moisture diffusivity was calculated by Crank's equation. The effective moisture diffusivity was significantly increased when microwave drying was applied under vacuum condition, compared with hot air drying. For color, the microwave vacuum dried mint leaves were light-green/yellow whereas the hot air dried mint leaves were dark-brown. From the SEM results, the microwave vacuum dried mint leaves had highly porous microstructure whereas the hot air dried mint leaves had packed microstructure. Rehydration tests confirmed that the rehydration rates of the microwave vacuum dried mint leaves were higher than those of the hot air dried ones.

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