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Intermittent and Continuous Microwave-Convective Air Drying of Potato (Lady rosetta): Drying Kinetics, Energy Consumption and Product Quality

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Abstract: In this research, effectiveness of various microwave-convective air drying treatments was compared to establish the most favourable drying condition for potato in terms of drying time, energy consumption and dried product quality. Quality parameters were colour (*L*a*b** coordinates), and sensory properties (visual appearance, colour, texture and overall acceptance). The microwave-convective drying treatments were done in the intermittent and continuous modes at 697.87 W output power. Results show that both the continuous and intermittent microwave-convective air drying gave good quality product compared to convective air drying. In terms of drying time, energy consumption and dried product quality, the combination of intermittent-convective air drying with pulse ratio of 2.0 and 55°C drying air temperature was determined as the most favourable drying method for potato. According to results of this research, this drying technique provided considerable savings in drying time and energy consumption when compared to convective air drying and could be successfully used to produce dried potato without quality loss.

Key words: energy consumption, intermittent microwave drying, potato, colour, sensory quality

INTRODUCTION

Drying processes are energy intensive unit operations and used as an essential production step in various industrial applications. Convective dryers require high energy input and account for about 85% of all industrial dryers (Mujumdar and Beke, 2003) which has been reported to account for anywhere from 12 to 20% of the energy consumption in the industrial sector (Raghavan *et al.*, 2004). Some enhancements such as recycling of exhaust heat, two or multi stage drying and implementation of different modes of heat transfer have been made to improve the efficiencies of conventional drying systems. There has been many unsolved issues of such drying systems namely low energy efficiency, lengthy drying time during falling rate period, high processing temperatures, large floor space requirements, etc. Therefore, there is increasing demand on research and developments dealing with design and applications of energy efficient, environment-friendly advanced drying systems with less floor space, short drying time as well as high quality dried products.

Microwave drying is rapid, more uniform and energy efficient compared to conventional hot air drying systems (Maskan, 2000).

In convective drying, because of the temperature gradient, heat energy is gradually transferred from surface to inner sections of the material being dried. Thus, rapid reduction of surface moisture and consequent shrinkage often results in limited moisture and heat transfer. Because of this undesirable effect of convective hot air drying systems, two-thirds of the time may be spent to remove the last one-third of the moisture content (Al-Duri and McIntyre, 1992).

Heating and drying with microwaves is distinctly different from so-called convection drying as the electromagnetic waves can penetrate deep into material causing volumetric heating targeting mostly water (Drouzas *et al.*, 1999; Moreno *et al.*, 2000; Torringa *et al.*, 2001; Nindo *et al.*, 2003; Beaudry *et al.*, 2003; Venkatesh and Raghavan, 2004). Due to the rapid internal heat generation throughout the volume of the material being dried, the moisture within the product is heated instantaneously. Then the increase in internal pressure drives out the moisture from the interior of the material to the surface where evaporation occurs. Thus, the microwave drying eliminates the heat transfer problem often encountered with convective air drying.

It requires less floor space (20-35%), increases drying efficiency and provides very rapid drying without overheating the atmosphere or the surface of drying installations (Wang *et al.*, 2004). Moreover, numbers of recent scientific researches on microwave drying have been increasing by virtue of its following unique features; more uniform drying, relatively minor migration of water-soluble constituents during drying, low temperature drying in combination with vacuum and improved product quality.

It is reported that the microwave drying could successfully be applied in drying of high moisture content agricultural crops like fruits and vegetables such as potato (Bouraout *et al.*, 1994), apple (Funebo and Ohlsson, 1998), mushroom (Torringa *et al.*, 2001), carrot (Litvin *et al.*, 1998), banana (Maskan, 2000), garlis (Sharma and Prasad, 2001), asparagus (Nindo *et al.*, 2003), parsley (Soysal, 2004). Nevertheless, most of these studies have been done at a research level and have not been adopted industrial scale (Nijhuis *et al.*, 1998). Microwave drying of agricultural crops is still in its initial phase of acceptance in industrial scale. Most important reasons for impeding wide spread use of this hopeful technology are the high investment cost compared to conventional systems and lack of documented energy analysis in most of the publications to date (Raghavan *et al.*, 2004; Changrue *et al.*, 2004). Several strategies have been suggested and applied by some researchers to improve the energy utilisation in microwave drying (Gunasekaran, 1999; Kaensup *et al.*, 2002; Beaudry *et al.*, 2003). These are: (a) combination of microwave and conventional drying systems; (b) microwave vacuum drying to lower the drying air temperature; and (c) intermittent applications of microwave energy instead of continuous exposure to avoid overheating and improve energy efficiency.

Recent research results showed that the microwave assisted drying applications such as microwave-convective drying, microwave freeze drying and microwave finish drying after osmotic or convective drying could increase the drying efficiency and product quality, considerably (Nijhuis *et al.*, 1998). Nevertheless, it is also reported that the continuous exposure of microwave during microwave assisted drying lead to considerable quality losses caused by temperature increase within the product. Vacuum-microwave drying has successfully been applied to prevent temperature increase, improve product quality and energy efficiency by shortening total microwave exposure time. Despite these advantages, additional equipments required for vacuum application increased the investment and operational costs and restricted to it's adaptation to continuous conveyor drying systems. At this point, it has been suggested that intermittent supply of energy during microwave drying can reduce total drying costs and improve energy utilisation as well as quality of dried product (Carabin, 1990). The idea of intermittent drying is not new. First studies on intermittent drying have been carried out in the years of 1933 (Gunasekaran, 1999). In this technique, the energy for drying intermittently turned on and off. It improves energy efficiency and product quality (Farkas and Rendik, 1997). In recent years, adopting this technique to microwave drying has been proved to several fruits and gave very good results.

It clear that the product temperature during drying is an important key to achieve a good quality dried products (Changrue *et al.*, 2004). To obtain suitable product temperature, following issues has often been raised in recent studies; intermittent application of microwave energy instead of continuous exposure, combining microwave and convective drying and determination of optimal working conditions concerning energy utilisation and product quality during intermittent microwave-convective drying (Venkatachalapathy, 1998; Gunasekaran, 1999; Beaudry *et al.*, 2003; Sunjka *et al.*, 2004).

Therefore, the aim of this study was to compare the effectiveness of intermittent microwave-convective drying with continuous microwave-convective and convective drying in terms of dried product quality, drying kinetics and specific energy consumption.

MATERIAL and METHODS

Material

Lady Rosetta variety potatoes which are very good for chipping used in drying experiments were supplied from Doğa Seed Company, Eskişehir, Turkey, and immediately stored at 4.0±0.1°C. Prior to drying, potatoes were taken out of storage, peeled with a knife, and cut into 3.5 mm thick slices with a slicing machine. Experimental drying system consists of a modified house hold microwave oven (Beko MD 1593), fan, air heater, continuous weighing system and control and power measuring systems (Figure 1). Air was heated by 1250 W electric resistant heater. The drying system had a programmable logic controller (PLC) system to control the intermittence time of microwave application in desired time intervals. The PLC control unit also controlled the fan, glass turntable and air temperature between 40 to 100°C. The temperature of the air inside the air duct was measured using a PT100 platinum resistance temperature sensor. In each drying experiment, about 200 g fresh material was dried at a constant air flow speed of 1 m/s. A digital balance (Sartorius TE3102S, Germany, 3100±0.01 g) was placed under the rotating glass tray (diameter: 314 mm, mass: 1150 g) to continuously measure the mass of the material being dried without stopping the drying procedure. The glass turntable on which the material was placed continuously turned (5 min^{-1}) during the drying procedure to obtain a uniform distribution of the microwave energy in the material, and to assure homogenized drying. Three replicates were carried out for each experiment.

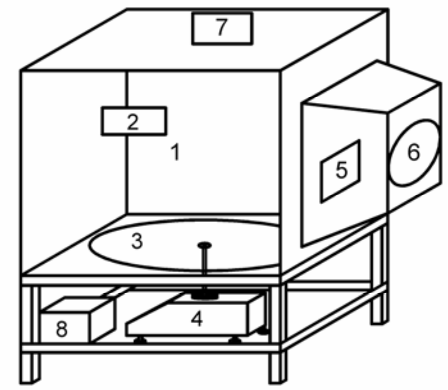

Figure 1. Schematic view of Experimental drying system (1) Drying chamber, (2) Magnetron, (3) Rotating glass tray, (4) Digital balance, (5) Air entrance, (6) Fan and heating unit, (7) Moist air exit opening, (8) PLC control unit and digital Wattmeter

Method

Microwave Oven Power Measurement

International Microwave Power Institute (IMPI) 2-liter test was used to determine the microwave oven power (Buffler, 1993). The oven was operated at the highest power (100%) with a load of 2000±5 g of water placed in 2 parallel 1 liter glass beakers. The initial water temperature was adjusted to 20±2 ºC. The beakers were placed in the centre of the oven side by side in the width dimensions of the cavity. The oven was turned on for 2 min and 2 s. Final temperatures of water were measured immediately after the oven was turned off. The power measurement was replicated three times and calculated by using equation 1 as follows:

$$P_w = \frac{mC_p(\Delta T_1 + \Delta T_2)}{2\Delta t} \qquad [1]$$

where P_m is the average measured microwave power in W, ΔT_1 and ΔT_2 are the temperature rises of the water in the two beakers calculated by subtracting the initial water temperature from the final temperature in °C, m is the total mass of water in kg, c_p is the specific heat of water in J/kg°C, and Δt is time in s. The average power outputs of the microwave ovens were measured as P_w=697.87±7.90 W.

Calculation of Specific Energy Consumption

The specific energy consumption which is the energy required to vaporize the unit mass of water from the sample was calculated by using equation 2 as follows:

$$Q_s = \frac{Q_t}{m_w} \qquad [2]$$

where Q_s is the specific energy consumption in MJ.kg^{-1}[H_2O], Q_t is the consumed energy (to dry the material which is the combination of the energy to power the magnetron, fan, rotating glass tray motor, lighting, measurement and control units) in MJ, m_w is the mass of vaporized water in kg [H_2O].

Colour Analysis

The colour of fresh and dried potatoes was quantified by using a Minolta (CR-400) Chromameter (Osaka, Japan). The colour meter was set to CIE Standard Illuminant C. Top and bottom surface colour of potato slices was measured. The colour of the fresh potato slices was measured after removing surface moisture by paper towel. $L*$, $a*$ and $b*$ values were measured to describe three dimensional colour space and interpreted as follows: $L*$ is the brightness/lightness or whiteness ranging from no reflection for black (L=0) to perfect diffuse reflection for white (*L*=100). The value *a** is the redness ranging from negative values for green to positive values for red. The value *b* is the yellowness ranging from negative values for blue and positive values for yellow. The data were presented as means of 12 independent measurements for each treatment.

Sensory Analysis

Potatoes dried with different microwave and convective treatments were evaluated for visual appearance, colour, texture and product acceptability using a 9-point scale with 8 trained panellists. Visual appearance and product acceptability were evaluated only using hedonic scale. On the hedonic scale, 9 corresponded to like extremely, 5 to neither like nor dislike and 1 to extremely dislike. The samples were coded with a random 3 digit number and served to selected panellists using completely randomized design. Five samples were served to the panelists at each session. The testing was done in a clean, quiet, air-conditioned and odour free room where each panellist used separate tables during judgments.

Statistical Analysis

One way ANOVA and Tukey multiple comparison test at %5 levels of significance were applied to data using SPSS statistic program.

Drying Procedure

In this research, several drying applications namely continuous microwave-convective drying (T=25°C), intermittent microwave-convective drying (T=25°C, 55°C, 60°C and 65°C) and convective air drying, T=55°C, 60°C and 65°C) were compared to each other. The pulse ratio (PR) for intermittent microwave drying treatments was calculated using the equation 3:

$$PR = \frac{t_{on} + t_{off}}{t_{on}} \qquad [3]$$

where PR is the pulse ratio, t_{on} is the microwave on time in s, and t_{off} is the microwave off time in s.

According to Equation 3, microwave pulse ratios applied in this study were as follows:

PR=1.0 continuously on
PR=2.0 15 s on, 15 s off
PR=2.5 30 s on, 45 s off
PR=3.0 30 s on, 60 s off

RESULTS AND DISCUSSION

Drying Kinetics

Continuous microwave-convective drying treatments yielded lowest drying time (12 min) and highest drying rate (Figure 2 and 3). Drying time of intermittent microwave-convective air drying treatments were 14 to 28 minutes higher than continuous application. Increasing the microwave pulse ratio (PR) resulted in an increase in drying times and a decrease in drying rates (Figure 2 and 3).

Depending on the PR values, 1 to 2 min decrease in drying time of intermittent microwave-convective drying treatments were obtained by increasing the air temperature from 25°C to 65°C (Figure 2).

It is clear from figure 3 that the drying rate curves showed bumpy patterns in intermittent microwave-convective air drying treatments. On the other hand, continuous microwave-convective drying proved no such trend (Figure 3). These bumpy patterns gradually increased with the increase in PR and convective air temperature. Possible explanation of this situation would be the temperature and moisture levelling effect of intermittent microwave-convective air drying method. It is well known that the fast temperature increase occurred inside the dried product during continuous microwave drying often causes burning in the edge of product and case hardening due to shrinkage. These undesirable effects mainly caused by the heterogeneous moisture and temperature distribution inside material being dried with continuous microwave application could be eliminated by the intermittent application of microwave energy. This technique allows more effective and stable moisture and heat transfer during microwave drying. The power off times provides the rest time necessary for moisture and temperature distribution within the product, reduces the microwave exposure time, prevents the temperature increase inside product and yields the higher product quality (Yongsawatdigul and Gunasekaran, 1996; Gunasekaran, 1999).

In drying of corn, Shivhare *et al.* (1992) reported that the total drying time increased in intermittent microwave application compared to continuous application, while the product quality improved and energy consumption reduced by reducing total microwave exposure time.

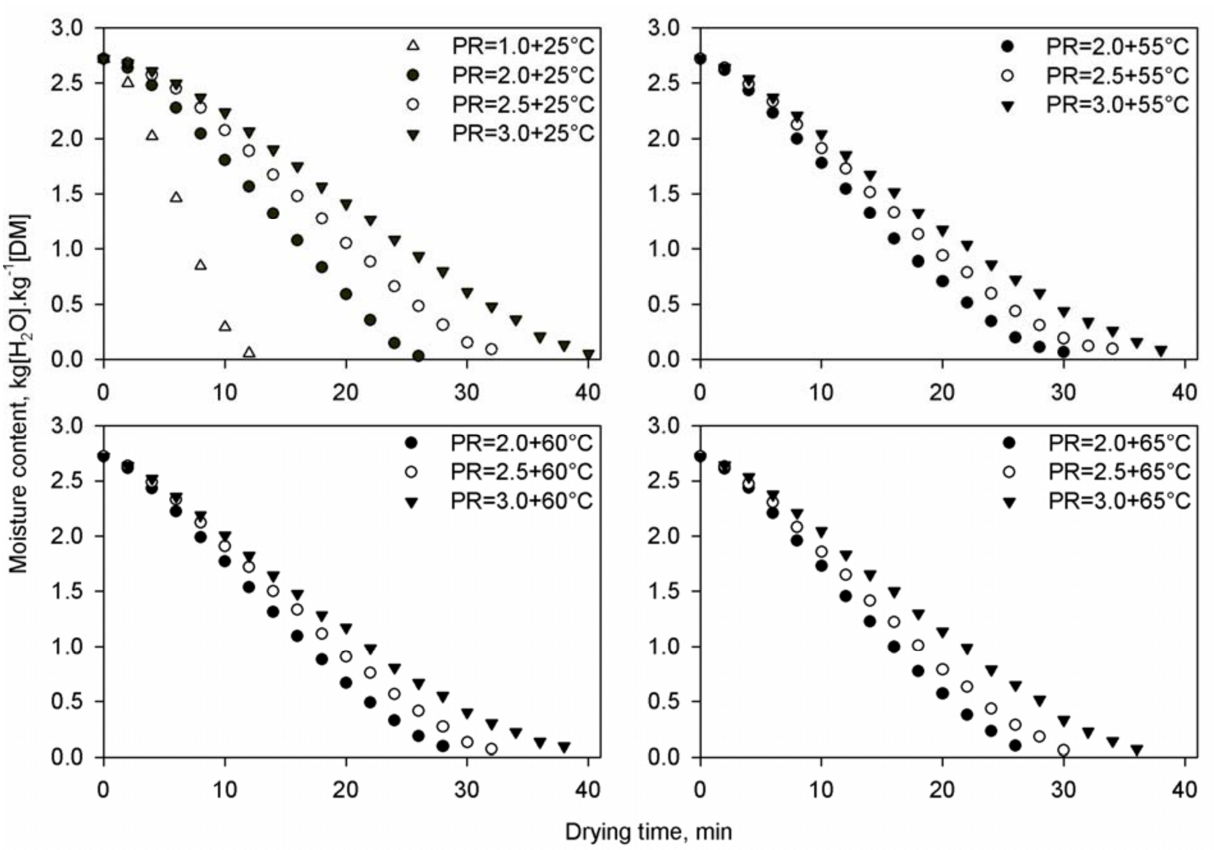

Figure 2. Relationship between the moisture content and drying time for various microwave-convective drying treatments (Mass of dried products) 200 g, (DM) dry matter, (P_w=697.87 W), (slice thickness) 3.5 mm, (v_h) 1 m/s

On the other hand, convective air drying at 65°C yielded lowest drying time (215 min) and highest drying rate among the convective air drying treatments (Figure 4 and 5). As expected, decreasing the drying air temperature resulted in a decrease in drying times and an increase in drying rates. The convective air drying at 55°C which reduced the potato slice moisture content from 2.72 to 0.15 kg [H_2O].kg^{-1}[DM] took 260 min. The convective air drying treatments was about 19 to 24 times longer than the continuous-microwave convective drying. On the other hand, it was about 6 to 11 times longer than the intermittent microwave-convective air drying treatments depending on the microwave output power, PR and the dying temperature.

Changrue *et al.* (2004) stated that the product temperature during microwave drying is an important key to achieve a good quality dried products. As seen on Figure 6, considerable temperature increase in drying chamber was observed during the last stage of continuous microwave-convective drying. Such an increase in drying chamber temperature increased the product temperature and lead to local hot spots formation in dried products. Moreover, as compared to continuous application, relatively small temperature increase during the last stage of intermittent microwave-convective drying was observed (Figure 6). These results were in close agreement with previous studies (Yongsawatdigul and Gunasekaran, 1996; Venkatachalapathy, 1998; Gunasekaran, 1999; Beaudry *et al.*, 2003; Sunjka *et al.*, 2004).

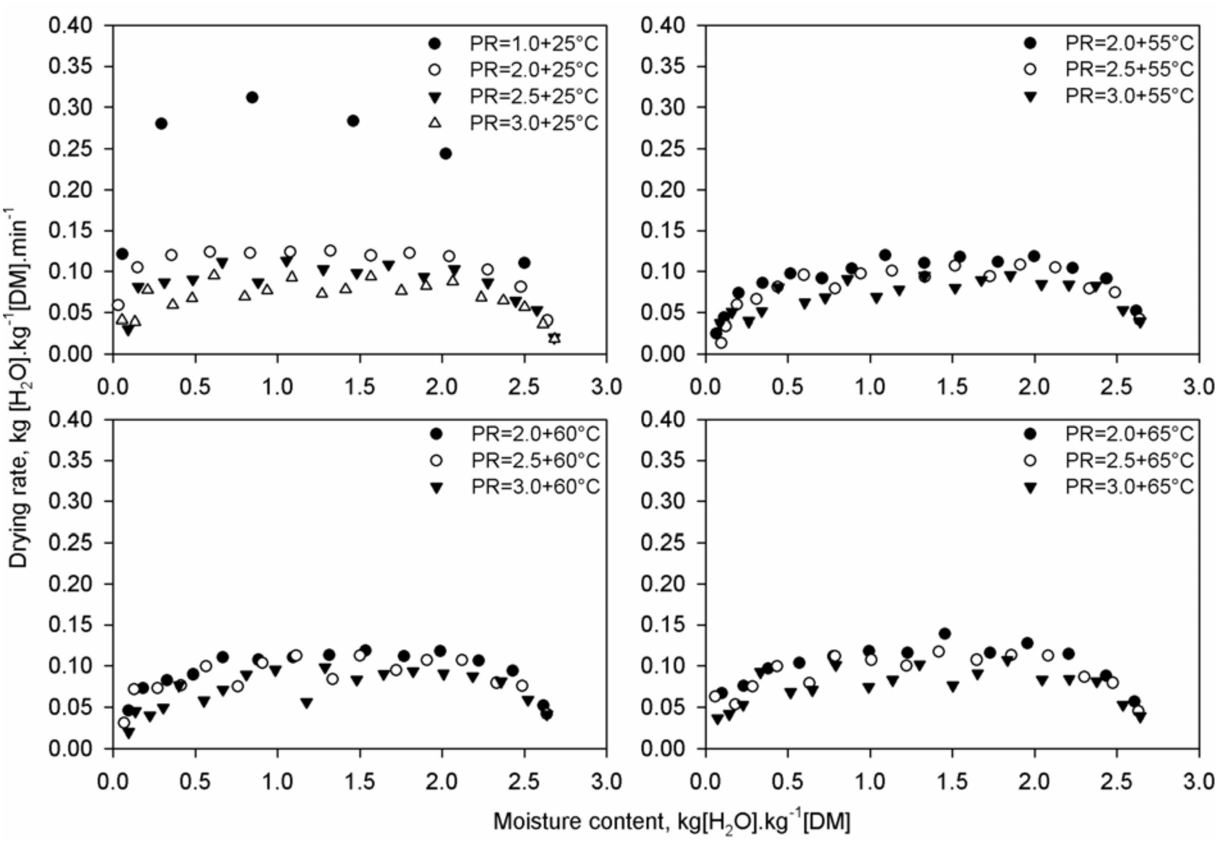

Figure 3. Relationship between drying rate and moisture content for various microwave-convective drying treatments (Mass of dried products) 200 g, (DM) dry matter, (P_w=697.87 W), (slice thickness) 3.5 mm, (v_h) 1 m/s

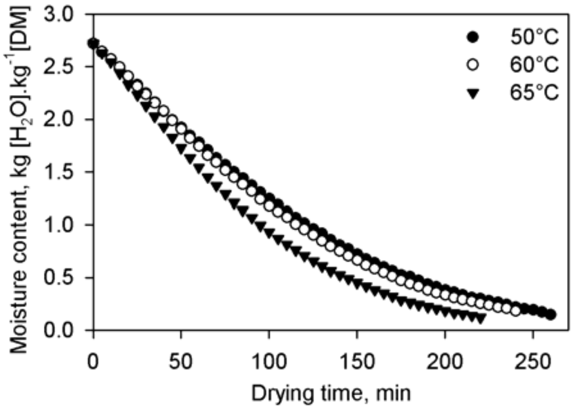

Figure 4. Relationship between moisture content and drying time for convective air drying treatments (Mass of dried products) 200 g, (DM) dry matter, (slice thickness) 3.5 mm, (v_h) 1 m/s

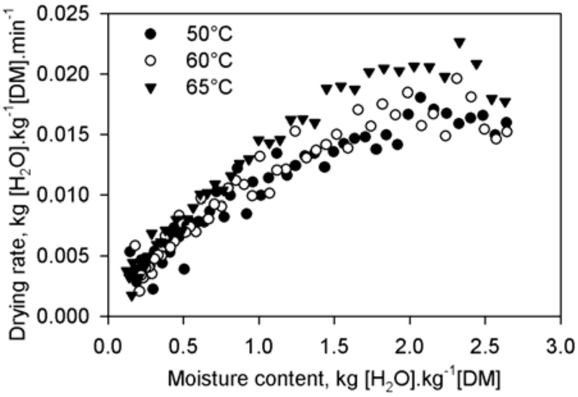

Figure 5. Relationship between drying rate and moisture content for convective air drying treatments (Mass of dried products) 200 g, (DM) dry matter, (slice thickness) 3.5 mm, (v_h) 1 m/s

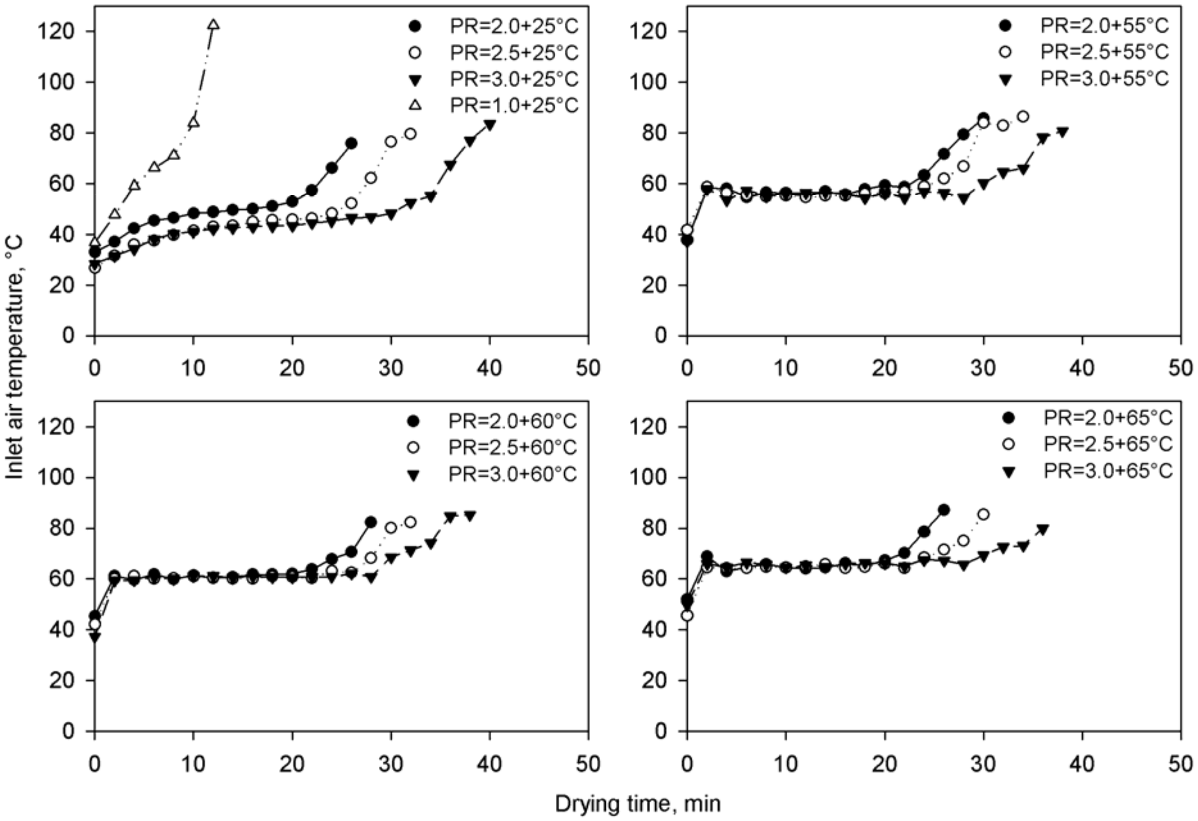

Figure 6. Relationship between inlet air temperature and drying time for various microwave-convective drying treatments (Mass of dried products) 200 g, (DM) dry matter, (P_w=697.87 W), (slice thickness) 3.5 mm, (v_h) 1 m/s

Specific Energy Consumption

In terms of specific energy consumption, there were no significant differences among continuous microwave-convective drying, PR=2.0+25°C and PR=2.5+25°C drying treatments ($p>0.05$) (Table 1). On the other hand, specific energy consumption values for intermittent microwave-convective dryings conducted above 25°C air temperature and convective air drying treatments were significantly differed from both continuous and intermittent dryings at 25°C ($p\leq0.05$).

The specific energy consumption values for convective air drying treatments were about 5.2 to 5.6 times higher than the continuous-microwave convective drying (Table 1). On the other hand, it was about 4.4 to 5.3 times higher than the intermittent microwave-convective air drying treatments depending on the microwave output power, PR and the dying temperature (Table 1). Similar findings were reported by several authors. For example, in the research of Tulasidas . (1995), the specific energy consumption value was about 81.15-90.35 MJ kg^{-1} [H_2O] for convective drying of grapes. It is stated that under similar convective conditions by he implementation of microwave, the energy consumption reduced to values ranging from 7.11 to 24.32 MJ kg^{-1}[H_2O] depending on the process conditions. Yongsawatdigul and Gunasekaran (1996) studied microwave-vacuum drying of cranberries and showed the intermittent application of microwave energy is more energy efficient than continuous application. The most suitable value of specific energy consumption was obtained at microwave power cycle of 30 s on/150 s off at 250 W microwave power output. The mean value of specific energy consumption under this condition was 2.66 MJ kg^{-1} [H_2O] that indicates an improvement of about 40-60% over conventional hot air drying and about 46% over continuous microwave-vacuum drying (4.90 MJ kg^{-1}[H_2O]).

Table 1. Specific energy consumption values for various drying treatments (n=3; P_w=697.87 W)

Drying treatments		Specific energy consumption (MJ.kg^{-1} H_2O)
Microwave convective air drying	PR=1.0+25°C	6.97±0.21 a*
	PR=2.0+25°C	7.44±0.18 ab
	PR=2.5+25°C	7.87±0.34 ab
	PR=3.0+25°C	8.28±0.21 bc
	PR=2.0+55°C	8.95±0.52 cd
	PR=2.0+60°C	9.28±0.20 de
	PR=2.0+65°C	9.47±0.14 de
	PR=2.5+55°C	9.78±0.05 de
	PR=2.5+60°C	9.72±0.13 de
	PR=2.5+65°C	10.07±0.07 ef
	PR=3.0+55°C	10.12±0.21 ef
	PR=3.0+60°C	10.27±0.33 ef
	PR=3.0+65°C	10.78±0.14 f
Convective air drying	55°C	36.33±0.50 g
	60° C	38.46±0.30 h
	65°C	39.37±0.78 h

* Tukey test: values with the same letter(s) are not significantly different (p>0.05).

Beaudry *et al.* (2003) used combined microwave–hot air drying for finish drying of osmotically dehydrated cranberries and compared the effects of power densities (0·75, 1·0, 1·25 W/g and power cycles of 30 s on/30 s off and 30 s on/60 s off at 750 W microwave output power) on the specific energy consumption and the quality of product. It was concluded that both microwave cycling period and applied power density in intermittent microwave drying influenced the energy consumption. It was further stated that the combination of 0·75 W/g with cycling period of 30 s on/60 s off was appropriate to dry cranberries in terms of energy efficiency (9·0 MJ kg^{-1} [H_2O]) and quality of dried product.

Colour

Table 2 shows the colour parameters of fresh and dried products. No significant difference was found between the lightness of fresh and dried products (p>0.05). Greenish yellow colour of fresh potato slices (-a*, *b**) was changed to reddish yellow (*a**, *b**). The colours of products dried with microwave-convective drying were light yellow. Convective air drying resulted in dense yellow product colour (Table 2).

Sensory Evaluation

Convective air dried potato samples received the lowest scores in terms of sensory quality compared to microwave-convective-drying treatments (Table 3). Considerable amount of browning was observed in convective air dried product. Darker appearance of these products was possibly due to the final moisture content of these products which was about 0.13 kg [H_2O].kg^{-1}[DM].

Table 2. Measured colour parameters of fresh and dried product (n=12; P_w=697.87 W)

Drying treatments		*L**	*a**	*b**	h
Fresh	-	68.04 a**	-2.50 a	18.00 ab	97.94 b
Microwave-convective air drying	PR=1.0+25°C	65.08 a	4.87 b	27.78 d	80.66 a
	PR=2.0+25°C	69.00 a	1.30 ab	24.59 cd	87.21 ab
	PR=2.5+25°C	67.96 a	1.68 ab	25.12 cd	86.37 ab
	PR=3.0+25°C	65.47 a	2.04 ab	23.39 c	84.91 a
	PR=2.0+55°C	64.67 a	1.01 ab	23.07 c	87.45 ab
	PR=2.0+60°C	66.18 a	2.12 ab	23.87 cd	85.45 a
	PR=2.0+65°C	67.30 a	0.56 ab	24.23 cd	88.46 ab
	PR=2.5+55°C	66.84 a	1.67 ab	24.13 cd	85.87 a
	PR=2.5+60°C	64.83 a	1.00 ab	22.47 c	87.61 ab
	PR=2.5+65°C	65.74 a	1.20 ab	22.71 c	86.76 ab
	PR=3.0+55°C	64.99 a	0.42 ab	22.85 c	88.94 ab
	PR=3.0+60°C	65.94 a	0.44 ab	24.07 cd	88.93 ab
	PR=3.0+65°C	61.79 a	1.43 ab	21.40 bc	86.25 ab
Convective air drying	55°C	65.56 a	3.02 b	16.04 a	79.28 a
	60°C	64.84 a	2.78 b	15.71 a	79.59 a
	65°C	69.27 a	2.08 ab	16.90 a	82.99 a

** Tukey test: values with the same letter(s) in the same column are not significantly different (p>0.05).

Table 3. Effects of various drying treatments on sensory properties of potato (n=8; P_w=697.87 W)

Drying treatments		Visual appearance	Colour	Texture	Overall acceptance
Microwave-convective air drying	PR=1.0+25°C	6.1 ab	6.5 ab	5.9 a	6.1 a
	PR=2.0+25°C	6.1 ab	6.5 ab	6.1 a	6.0 a
	PR=2.5+25°C	4.5 abcd	4.4 abcd	5.8 a	4.8 abc
	PR=3.0+25°C	4.6 abc	4.5 abc	6.0 a	4.9 ab
	PR=2.0+55°C	7.0 a	6.8 a	6.2 a	6.5 a
	PR=2.0+60°C	5.1 ab	5.1 abc	5.5 ab	5.1 a
	PR=2.0+65°C	6.1 ab	6.0 abc	5.8 a	6.0 a
	PR=2.5+55°C	4.1 bcd	3.9 cde	5.9 a	4.8 abc
	PR=2.5+60°C	6.1 ab	6.0 abc	6.1 a	6.2 a
	PR=2.5+65°C	4.6 abc	4.1 bcde	5.1 ab	4.8 abc
	PR=3.0+55°C	5.1 ab	4.6 abc	6.1 a	5.2 a
	PR=3.0+60°C	4.5 abcd	4.5 abc	5.9 a	5.2 a
	PR=3.0+65°C	5.9 ab	6.0 abc	6.4 a	6.0 a
Convective air drying	55°C	2.5 cd	1.9 e	2.2 c	2.2 bc
	60°C	2.0 d	2.0 de	2.9 bc	2.1 c
	65°C	2.4 cd	1.8 e	2.8 bc	2.2 bc

* Tukey test: values with the same letter(s) in the same column are not significantly different (p>0.05).

In terms of sensory properties of dried products, no significant differences were found among continuous microwave-convective drying and intermittent microwave-convective drying treatments (p>0.05). It is clear that the intermittent microwave–convective drying at 55°C with a PR of 2.0 produced high quality dried potato with better sensory attributes namely visual appearance, colour, texture and overall acceptance (Table 3).

Results showed that the intermittent microwave–convective drying at 55°C with a PR of 2.0 provided optimum drying conditions for potato (L. Rosetta variety) considering drying time, drying rate, energy consumption and dried product quality.

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