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Ultrasound-assisted intensification of a hybrid intermittent microwave - hot air drying process of potato: Quality aspects and energy consumption

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ABSTRACT

The objective of this study was to intensify combined intermittent microwave – low temperature (40 °C) hot air drying with ultrasound. The process variables were ultrasound time (40 kHz for 0, 10, 20 and 30 min), microwave power (360, 600 and 900 W), and microwave pulse ratio (1, 2, 3 and 4). Results showed that the highest reduction in moisture content was observed in the samples pretreated with ultrasound for 10 min and then dried at 900 W microwave with the pulse ratio of 4. As ultrasound time, microwave power and pulse ratio increased, significant increases were noticed in D_{eff} by 4.89, 16.44 and 20.7%, respectively. Moreover, shrinkage was lower in the samples pretreated with lower ultrasound time and microwave pulse ratio. Besides, bulk density reduced when the microwave power was increased due to lower volume reduction. In addition, the highest increase in rehydration (32.23%) was observed in the samples dried using the high-power intermittent microwave. Finally, the highest significant reduction in specific energy consumption as a result of increased microwave power was 23.32%. In general, results of this study demonstrated that the ultrasound-intensified combined intermittent microwave – low temperature hot air drying may be a suitable alternative for industrial applications.

1. Introduction

Potato (*Solanum tuberosum*) is from the family *Solanacea* and is the fourth most important crop after wheat, maize, and rice in the world thanks to its high fiber, energy, vitamins, and mineral contents [1]. The high moisture content of fruits and vegetables negatively affects the efficiency of their transportation cycle and storage. Microbial growth, change of color, off-flavor development, and reduction in nutritional value are a number of prevalent storage-related causes of quality degradation that render the product unacceptable for fresh consumption. It is thus useful to remove moisture or dry by simultaneous heat and mass transfer processes to extensively increase longevity, facilitate transportation, preserve quality, reduce post-harvest losses, and also produce dried products for direct consumption. Drying is one of the most common thermal methods under controlled conditions for improving food properties through moisture evaporation. This, in turn, minimizes physicochemical changes during storage. Products with longer shelf-life, lower weight and volume, no need for cold storage, and lower transportation and packaging costs are the beneficial outputs of the drying process [2]. In general, this process should reduce moisture content to the extent that reduces the water activity so that the food products can reach a steady state in terms of microbial and enzyme activities [3]. Potato faces large losses in developing countries due to poor harvest and storage practices. It is thus essential to produce dried potatoes to increase its shelf life and reduce its losses. A large number of potato products are marketed in the form of dried and fried products in the industry. Dried potatoes are one of the important food products with broad applications in preparation and processing of ready meals [1].

Traditionally, agricultural products were dried in the sun, which was a convenient low-cost method. Such systems, however, have drawbacks including quality degradation, uncontrollable ambient conditions, large space and cost requirements, non-uniform dried output, long drying time, and contamination. Convective hot air drying is the most popular drying technique and one of the oldest alternatives to conventional drying and preservation methods that enhances the product longevity. More than 85% of the industrial dryers are convective [4]. In this method, hot air passes through the food product and evaporates its moisture content to a target level [1]. The main challenge in hot air drying is the use of high temperatures during long periods, which leaves undesired effects on the qualitative properties of the product such as reduced rehydration. In addition, it has serious disadvantages including high energy consumption due to the low conductivity of foods, reduction in nutritional value, color change, hardened surface, and shrinkage [5]. These shortcomings have encouraged more interest in modern methods that can improve quality, increase

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efficiency, and reduce energy consumption [6].

Moisture removal during convective hot air drying is largely affected by hot air conditions and also food properties. The temperature of the passing hot air and the temperature of the food have a large effect on the qualitative characteristics of foods such as vitamins, flavor, color, texture, and nutritional composition. Hot air drying destroys temperature-sensitive compounds and also declines the quality of major sensory characteristics of the dried product. Although shortening the drying time, high drying temperatures can reduce the quality of products, thermally damage their surface, and increase energy consumption. The other disadvantages of convective hot air drying are fast surface moisture removal and shrinkage [7]. On the other hand, the use of low-temperature hot air can lengthen the drying process but helps preserve vitamins, improve color and texture, and thus improve marketability. Additionally, moisture is removed more slowly at lower temperatures, which in turn prevents from surface hardening. In hybrid drying techniques, lower temperatures can also improve product rehydration [7].

Different pretreatments are useful in addressing problems associated with hot air drying such as long drying time, high process costs, and low final quality. A widely used pretreatment before the hot air process is the use of ultrasonic waves [8]. Ultrasound waves are generated by the mechanical waves traveling through solids, liquids and gases. This is a non-thermal technique with broad applications in the food industry. It has been established that ultrasound pretreatment prior to the drying of fruits and vegetables positively affects the drying rate and qualitative characteristics of the dried products [9]. The ultrasound technology mechanically generates waves at a frequency above the human hearing range. These waves are in the form of vibrations at a frequency between 20 and 500 kHz [10]. Ultrasound waves are used in food processing, analysis and quality control and, depending on their frequency range, are divided into two groups: low-energy ultrasound (high frequency and low power) and high-energy ultrasound (low frequency and high power) [10]. High-frequency ultrasound (more than 100 kHz) is used as a non-destructive method to control food quality, analyze their physicochemical properties, and monitor food changes during the process. On the other hand, low-frequency ultrasound (20–100 kHz) is applied to break down cellular structures in order to trigger and inhibit chemical or physical changes in foods, which finally strengthens heat and mass transfer during different processes. Low-frequency ultrasound can be used in food processes such as drying, freezing, melting, extraction, filtration, and crystallization [11]. This technique is also applied as a pretreatment prior to hot air drying in order to improve the qualitative properties of the dried products by enhancing heat and mass transfer phenomena [12]. The ultrasound pretreatment can be done by submerging the fruit in distilled water or in a hypertonic solution [13].

In addition, microwave drying has attracted a great deal of attention as a suitable technique to improve the dried product quality [3]. Advantages of microwave drying over hot air drying include high drying rate, reduced shrinkage, increased rehydration, and improved dried food quality. Moreover, less energy is consumed due to its shorter drying time [3]. The microwave frequencies used for drying are 915 and 2450 MHz, with the latter being more popular. Microwave-dried products have satisfactory qualitative properties such as higher porosity, higher rehydration capacity, and less shrinkage. This method saves energy by reducing the process time [3]. Therefore, the microwave drying technique is a solution to compensate for the disadvantages of the hot air drying [4]. Microwave drying has better results than hot air drying in terms of faster drying and minimum heating at spots with lower moisture content. As a result of the latter advantage, the spots, where less energy is required for moisture removal, are not overheated. Microwave drying reduces the critical moisture content and lengthens the constant-rate drying period. Hot air performs relatively efficiently in removing the free water on or near the surface, whereas the unique function of microwaves is internal heating as an effective way to remove bound water from inner layers [7]. In microwave drying, internal heating causes the moisture to move from inner layers to the surface. However, if microwaves are not applied correctly, the final product will have a poor quality. This is because continuous microwave application leads to accumulation of microwaves with a similar waveform within specific locations inside the oven and forms hot spots. This, in turn, applies more heat to a specific parts of the food and reduces the final quality. Accordingly, microwaves are rarely used alone for drying and are usually coupled with other drying techniques (such as hot air drying, freeze drying, and vacuum drying) to bring about better uniformity with a faster and more efficient process. Microwave drying coupled with hot air drying has been used on several agricultural crops such as carrot, potato, garlic, and mushroom.

On the other hand, the main problem of the continuous microwave is the non-uniform temperature and moisture distribution, which can develop hot and cold spots and reduce the product quality. In general, non-uniform heating can cause uneven drying. Some of the causes of non-uniformity from microwave drying can be unbalanced exposure of samples to microwaves, dissimilar sample compositions, and uneven geometry. In order to reduce the unwanted effects, microwaves can be applied intermittently [14]. The intermittent microwave is applied by turning on/off its source within certain time periods. This prevents uneven heating by allowing temperature and moisture redistribution during the off times and consequently improves product quality and reduces energy consumption [3]. Moreover, the rehydration ratio of foods dried using the intermittent method is higher than that of those dried by the continuous method. Additionally, the bulk density of samples dried with the intermittent method is lower due to the redistribution of temperature and moisture during the off times [4]. Therefore, intermittent microwave application is suggested as an alternative for preventing uneven temperature distribution and improving product quality through uniform heating.

Research on the drying of food products using the intermittent microwave has been on the rise recently in the food industry. To the best of our knowledge, in the literature, there is no report on the effect of the simultaneous application of intermittent microwave and forced convection of hot air on the drying of ultrasound-pretreated potato samples. Antonio et al. [15] studied the drying process of potato slices with and without osmotic dehydration, and evaluated the optimum high temperature and short time (HTST) process, and effects of sample pretreatment on drying rate. Processing time was the most significant variable influencing moisture content and rehydration. The shortest convective drying time corresponded to the sample treated only by the HTST process. Doymaz [16] studied the effect of blanching and temperature on drying time, effective moisture diffusivity, activation energy and rehydration ratio of potato slices. The author observed that both the drying temperature and blanching affected the drying kinetics and different properties of the samples. Dehghannya et al. [1] investigated the combined effect of osmotic dehydration and intermittent microwave and hot-air drying on quantitative and qualitative properties of potato slices. Results showed that the hybrid drying process decreased drying time by up to about 54%. The lowest shrinkage and the highest rehydration was observed in the 900 W microwave power and pulse ratio of 4. The maximum of 63.27% reduction in energy consumption was noticed when using the 900 W power level compared to the hot-air drying. The objective of this study was to investigate the influence of ultrasound-assisted intensification of hybrid intermittent microwave – hot air drying process on a number of quantitative and qualitative properties of potato cubes (*i.e.* drying kinetics, D_{eff}, shrinkage, bulk density, rehydration, and specific energy consumption).

2. Materials and methods

2.1. Raw materials and equipment

Potato samples (var. Agria) were purchased from a local market and were stored at 4–6 °C. In order to maximize repeatability and provide equal experimental conditions, all potato samples were purchased from one place and one variety. In this study, a hybrid microwave – hot air dryer (LG SolarDOM, model SD-3855SCR, Korea, internal dimensions: 480 × 392 × 527 mm^3, capacity: 38 L) with adjustable microwave power (90, 180, 360, 600 and 900 W at a frequency of 2450 MHz), equipped with temperature control (40–230 °C) and also a rotating tray (2.5 rpm) was used, which was designed for household uses. For moisture content measurements, a smart oven equipped with an air circulation blower was used (Fan Azma Gostar, model BM120, Iran, capacity: 120 L). A 22 L smart bain-marie (Fan Azma Gostar, model WM22, Iran) with a microcontroller for precise temperature control (± 1 °C) was employed for blanching purposes. A 50 mL pycnometer was also designed and used to measure sample volumes using the toluene displacement method [17].

2.2. Sample preparation

The samples were kept at room temperature to reach a temperature balance before every experiment. Large and hard potatoes were selected for each experimental run in order to prevent them from being crushed during cutting and from texture collapse during blanching with hot water. The potatoes were then washed with tap water, peeled and sliced into 1.2 cm long cubes using a manual cutter. After weighing the samples, they were blanched for 5 min in a bain-marie at 100 °C and were then immediately cooled down in 5 °C cold water to eliminate the excess heat [1]. Finally, the water on the samples was wiped by a moisture-absorbent pad.

2.3. Ultrasound pretreatment

In this study, the samples were pretreated in a beaker in a 9.5 L ultrasonic bath (AS ONE, model US-4R, Japan) (H × W × D = 36.5 × 30.5 × 26.2 cm^3) using a 40 kHz frequency at room temperature (25 °C) for four different treatment times (0 or control, 10, 20 and 30 min) [8]. To prepare the samples pretreated with ultrasound, 150 g potato cubes were placed in a 250 mL beaker containing distilled water inside the ultrasonic bath. The weight ratio of potato to distilled water was 1–4. Potato slices were removed from the beaker at the end of the treatment duration, and their surface moisture was gently wiped by an absorbent pad [8].

2.4. Drying experiments

The ultrasound-pretreated potato samples were dried using the hybrid microwave and forced convection method under three power levels (360, 600 and 900 W) and four pulse ratios (1, 2, 3 and 4) (Table 1) to analyze the effect of the process on the quality of the dried potato slices. The following equation shows pulse ratio (PR) [5]:

$$PR = \frac{t_{on} + t_{off}}{t_{on}} \quad (1)$$

where t_{on} is the microwave on-time (s), and t_{off} shows the microwave off-time (s).

The hybrid microwave – hot air drying technique can be carried out in three different ways [3]: (1) Use of microwaves at the beginning of the drying process where the inner layers of the product are quickly heated up to form a vapor stream from inside to the surface. In the next stage, a hot-air stream is applied to carry away the vapors from around the product. (2) Use of microwaves in the middle stage where the moisture content of surface areas is removed from the product but the inner moisture content still remains. Microwaves, at this point, can generate internal heat and thus increase the vapor pressure. (3) Microwaves can be applied at the final stage of the process to help to remove bound water and reduce shrinkage. This is done within the falling-rate drying period or at a low moisture content, and the outgoing vapor stream can prevent shrinkage.

In this study, the samples were first exposed to microwaves and were then dried using the hot air method at 40 °C and airflow velocity of 1 m/s. The process was terminated once the moisture content of samples reached 0.2 g water/g dry solid.

2.5. Qualitative and quantitative measurements

2.5.1. Moisture content

To measure moisture content (MC), the samples were dried in an oven at 105 °C for 24 h and under atmospheric pressure until reaching a constant weight. Moisture content (d.b.) was determined as follows [1]:

$$MC\ (d.b.) = \frac{M_w}{M_s} \quad (2)$$

where M_W is water mass (g) and M_S is the mass of solids in dried sample (g).

2.5.2. Effective moisture diffusion coefficient (D_{eff})

The dominant phenomenon during the drying process is the moisture diffusion to surface for evaporation. The moisture variations can be thus expressed using Fick's equation for unsteady-state diffusion [5]. This equation can be solved as follows by assuming moisture migration through diffusion, negligible shrinkage, constant D_{eff}, and uniform distribution of the initial moisture across the sample:

$$MR = \frac{M_t - M_e}{M_0 - M_e} = \frac{8}{\pi^2} \sum_{n=1}^{\infty} \frac{1}{2n-1} \exp\left(\frac{-(2n-1)^2 \pi^2 D_{eff}}{4L^2}\right)t \quad (3)$$

In Eq. (3), M_t is the sample moisture content (g water/g dry solid) at time t (s), M_0 is the initial sample moisture content (g water/g dry solid), M_e is the equilibrium moisture content (EMC) (g water/g dry solid), n is the number of terms in the series, D_{eff} shows the effective moisture diffusion coefficient (m^2/s), and L is the half thickness of the sample (m). For long drying times, only the first term of the series is considered as the effect of the other terms on D_{eff} becomes negligible. By considering that M_e is negligible compared to M_t and M_0, Eq. (3) can be written as follows [1]:

$$MR = \frac{M_t}{M_0} = \frac{8}{\pi^2} \exp\left(\frac{-\pi^2 D_{eff}}{4L^2}\right) \quad (4)$$

By taking logarithm from both sides of Eq. (4), the following relation is obtained:

Table 1
On/off times at different microwave powers and pulse ratios.

	360 W	600 W	900 W
Pulse ratio	Time (min)		
1	37 min on (37 min total)	23 min on (23 min total)	14 min on (14 min total)
2	1 min on/1 min off (74 min total)	1 min on/1 min off (46 min total)	1 min on/1 min off (28 min total)
3	1 min on/2 min off (111 min total)	1 min on/2 min off (69 min total)	1 min on/2 min off (42 min total)
4	1 min on/3 min off (148 min total)	1 min on/3 min off (92 min total)	1 min on/3 min off (56 min total)

$$\ln(\mathrm{MR}) = \ln\left(\frac{8}{\pi^2}\right) - \left(\frac{\pi^2 D_{eff}}{4L^2}\right)t \tag{5}$$

D_{eff} can be obtained by plotting the ln(MR) curve versus time and then calculating its slope from Eq. (6):

$$\mathrm{Slope} = \frac{\pi^2 D_{eff}}{4L^2} \tag{6}$$

$$D_{eff} = \frac{\mathrm{Slope} \times 4L^2}{\pi^2} \tag{7}$$

2.5.3. Shrinkage

In general, shrinkage represents volume changes as expressed by the following equation [17]:

$$S = \left(1 - \frac{V_t}{V_0}\right) \times 100 \tag{8}$$

In this equation, S is shrinkage, V_t sample volume (cm^3) at time *t* (s), and V_0 the initial volume of the sample (cm^3). The volume was measured by placing the samples in a pycnometer half-full with toluene, once their raw and dried weights were recorded, and then filling it up with toluene. The food sample volume was determined by the following equations [17]:

$$V = V_f - \frac{M_{sf}}{\rho_s} \tag{9}$$

$$M_{sf} = M_{t+s} - M_f - M \tag{10}$$

In these relations, V_f is the pycnometer volume (cm^3), M_{sf} shows the weight of the toluene for filling the pycnometer (g), M_{t+s} is the weight of pycnometer plus the weights of the sample and toluene (g), M_f is the weight of pycnometer (g), M is the weight of the sample (g), and ρ_s shows the density of toluene (0.87 g/cm^3 at 20 °C).

2.5.4. Bulk density

For fresh and dried potatoes, bulk density was determined by dividing the sample weight by its volume according to the following equation [18]:

$$\rho_b = \frac{m_t}{V_t} \tag{11}$$

where m_t represents sample weight (g) and V_t is sample volume (cm^3).

2.5.5. Rehydration

To measure rehydration ratio, the dried potato samples were immersed in 500 mL of boiling water for 20 min. Then, the samples were taken and wiped with absorbent pads to remove the excess water. The rehydration percent of dried samples was measured using the following equation [19]:

$$R(\%) = \frac{M_t - M_0}{M_0} \times 100 \tag{12}$$

where M_t and M_0 are the weight (g) of dried samples after and before rehydration, respectively.

2.5.6. Specific energy consumption

Specific energy consumption (E) of the hybrid microwave – hot air dryer was determined as follows [5,7]:

$$E_1 = \frac{P t_m}{PR \times M_1} \tag{13}$$

$$E_2 = \frac{A V_a \rho_a \Delta H t_c}{M_2} \tag{14}$$

$$\Delta H = (C_{p,a} + W C_{p,v})(T_{in} - T_{amb}) + W\lambda \tag{15}$$

$$E = E_1 + E_2 \tag{16}$$

where E_1 is the microwave energy consumption (kJ), E_2 is the energy consumption by the hot air dryer (kJ), P is the microwave power (W), t_m shows the microwave drying time (s), PR is the pulse ratio (dimensionless), M_1 stands for the amount of moisture removed by microwaves (kg), A is the sample container area (m^2), V_a represents air velocity (m/s), ρ_a is air density (kg/m^3), ΔH is air enthalpy (kJ/kg dry air), t_c is the drying time with hot air (s), M_2 shows the amount of moisture removed by hot air flow (kg), $C_{p,a}$ is specific heat of air (kJ/kg °C), W shows the absolute humidity of air (kg water vapor/kg dry air), $C_{p,v}$ is the specific heat of water vapor (kJ/kg °C), t_{in} is the internal air temperature of the dryer (°C), T_{amb} is the ambient air temperature (°C), and λ is latent heat of vaporization (kJ/kg water vapor).

2.5.7. Statistical analysis

A factorial experiment (4 × 3 × 4: ultrasound time, microwave power and pulse ratio) with a randomized complete design was used to analyze the effect of ultrasound pretreatment at 4 levels (0 or control, 10, 20 and 30 min), microwave power at 3 levels (360, 600 and 900 W), and pulse ratio at 4 levels (1, 2, 3 and 4) each with three replications (144 treatments). The effect of each variable on the qualitative and quantitative properties (*i.e.* drying kinetics, D_{eff}, shrinkage, bulk density, rehydration, and specific energy consumption) was analyzed. Means were compared using Duncan's multiple range test ($p < 5\%$). Results were statistically analyzed in SAS (version 9.4).

3. Results and discussion

3.1. Drying kinetics

Fig. 1(a–d) presents the effect of different pulse ratios at the 360 W microwave power on the kinetics of the drying process for the potato samples pretreated under different ultrasound times. Moisture content consistently decreased in all treatments as the drying time advanced. The steep slope at the microwave drying stage indicates the substantial effect of microwave energy on moisture reduction in potato samples. In microwave drying, internal (volumetric) heating causes the moisture migration to the surface [7]. Microwaves produce heat through two mechanisms: ionic polarization and dipole rotation. In ionic polarization, an electrical field is applied to make ions move and collide with each other. As a result, their kinetic energy is converted into heat inside the food product. Dipole rotation occurs when polar molecules such as water are present in foods. In the presence of a magnetic field, the molecules change direction with the variations in the field. The continuous changes in the electric field and thus in direction cause friction and consequently produce heat. Therefore, the higher the number of polar molecules, the higher the heat production. In microwave heating, unlike traditional methods, heat flows from inside to outside and depends on the dielectric properties of foods. This helps reach a target temperature faster.

Generally, the final moisture content of the samples pretreated with 10, 20 and 30 min of ultrasound exposure was 12, 8 and 3% lower than the control samples, respectively (Table 2). This was in agreement with the results reported by Dehghannya et al. [8] and Garcia-Noguera et al. [20]. Ultrasound waves intensify moisture flow turbulence on the surface and inside samples by developing numerous vibrations and reduce the thickness of the boundary layer on the sample surface. This improves heat and mass transfer phenomena and reduces resistance to moisture movement. In addition, the ultrasonic energy penetrates into the samples to create a sponge effect, which helps to expand the capillary tubes for moisture diffusion, besides helping the water molecules inside the sample to overcome their internal cohesion and thus migrate to the surface [14].

In general, ultrasound waves form micro air bubbles inside a liquid medium, which later burst causing the cavitation phenomenon. The asymmetric bursting of bubbles near the food surface transfers the fast and eruptive wave streams to the surface and develops a sponge effect

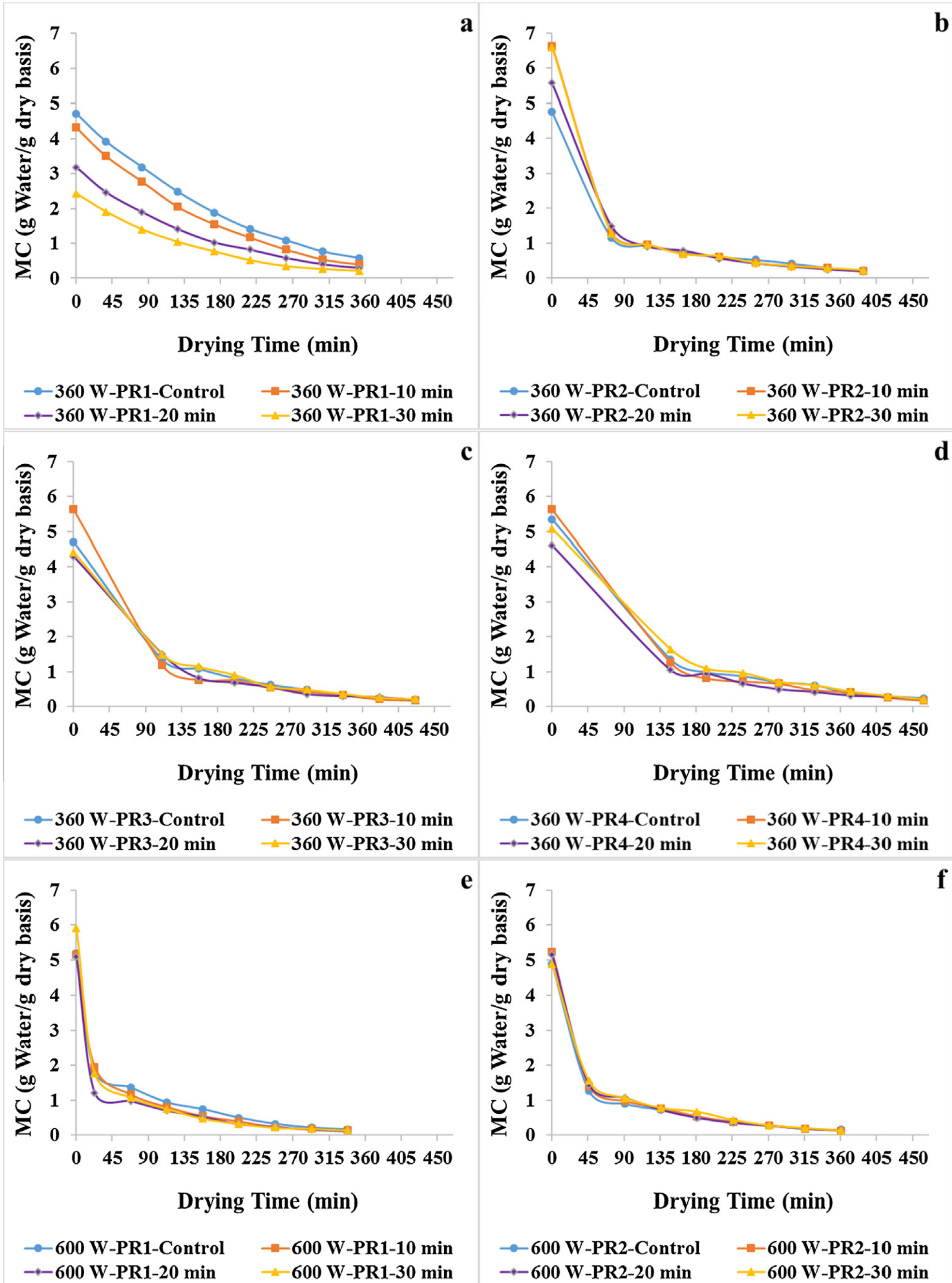

Fig. 1. Drying kinetics of potato samples pretreated with ultrasound for of 0 (control), 10, 20 and 30 min during microwave – convective hot air drying at 360 W (a–d), 600 W (e–h) and 900 W (i–l) with different pulse ratios (PR).

(intermittent contractions and expansions) that forms microscopic channels to help transfer moisture from the inner layers during the drying process [21,22]. Microstructure analysis has shown that the ultrasound treatment leads to cellular disruption and formation of larger cavities. This improves the drying rate by providing an easier moisture removal path, which in turn can accelerate moisture migration to the surface and thus reduces the drying time [17]. Other ultrasound effects include the creation of compressive stress and deformation of porous solids, which are both responsible for creating microscopic channels, decreasing the boundary diffusion layer, and enhancing the convective mass transfer in foods [23].

As shown in Table 2, the highest moisture reduction was observed in the samples pretreated for 10 min. Nowacka and Wedzik [11] studied the ultrasound-pretreated carrot structure (10, 20 and 30 min) and found that the micro-channels are specially developed in the samples that were exposed to shorter pretreatment times. This result might show that the micro-channels were created at the beginning of the ultrasound pretreatment (10 min) and, as the exposure time was increased, were merged with each other (neighboring cells) to form larger spaces [11]. Therefore, probably, the number of micro-channels was higher at the beginning of the ultrasound process (10 min) than the end of the 30 min treatment. This higher number finally increased moisture reduction in the potato samples.

At the same time, as shown in Table 2, moisture content had an inverse correlation with pulse ratio. This was in agreement with the results reported by Dehghannya et al. [1]. The positive effect of intermittent microwave on moisture reduction during the drying of potato samples provides a tempering period during microwave off-time that

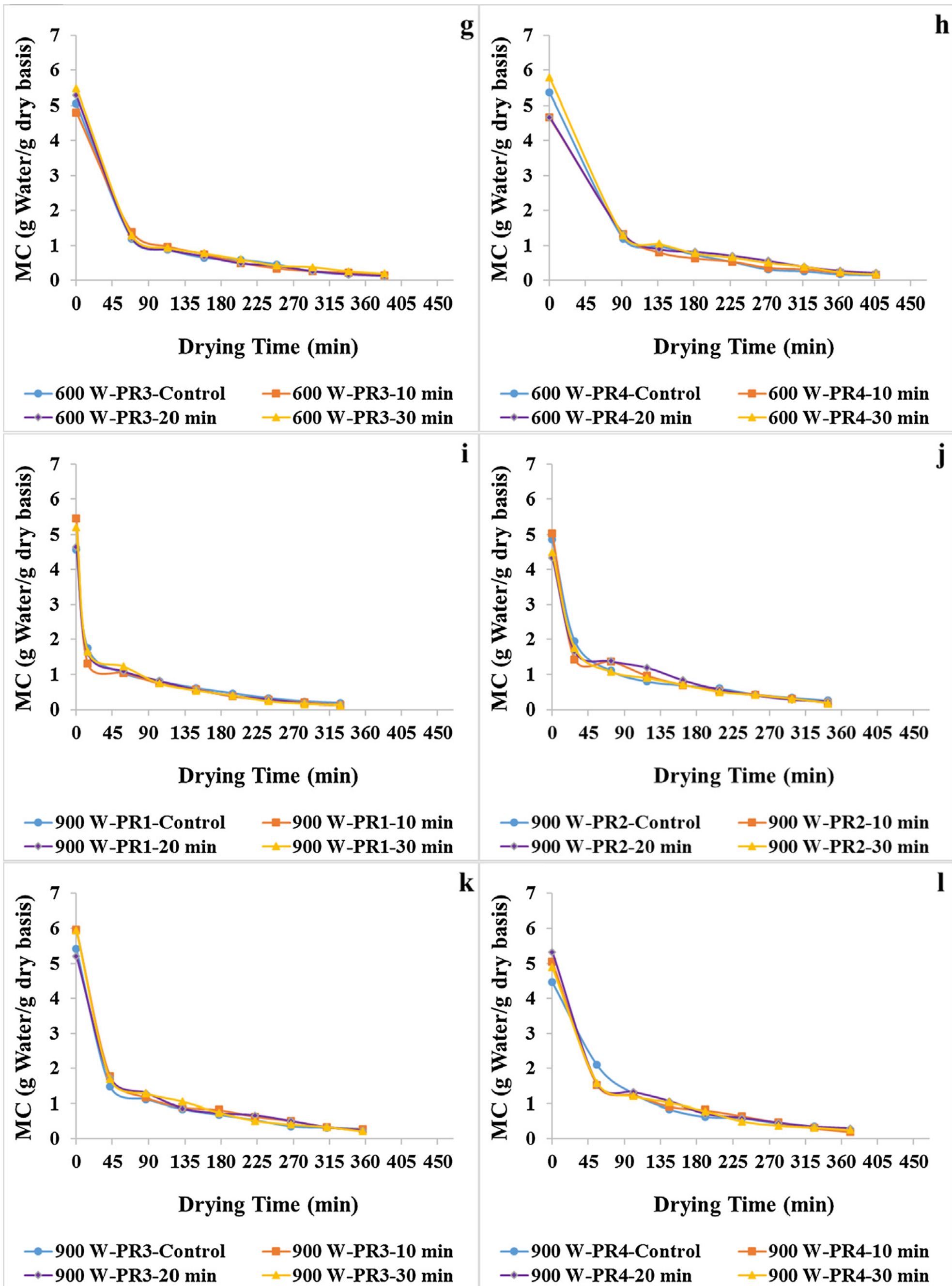

Fig. 1. (*continued*)

allows temperature and moisture to redistribute throughout the product. This contributes to the faster removal of moisture during the next on-time [4]. In general, the higher off-time at larger pulse ratios (*e.g.* PR = 4) facilitates moisture migration from center to the surface of the potato samples, and more moisture is then removed during the next microwave exposure episode.

Fig. 1 displays the effect of microwave power levels (600 (e–h) and 900 W (i–l)) on the drying kinetics of the potato samples pretreated under different ultrasound times (0, 10, 20 and 30 min) and pulse ratios (1, 2, 3 and 4). The moisture content of potato samples decreased when the microwave power was increased. The reduction was statistically significant for the 900 W level (Table 2). These results were consistent with other similar studies on the effect of microwave power on the moisture content of potato [1] and quince [7]. This can be due to the increased internal vapor pressure with the increase in microwave power and thus faster moisture removal [24]. As shown in Fig. 1, there is an inverse correlation between the initial moisture content and drying time, and the results indicated that, when the microwave power was increased from 360 to 900 W, the time required to reach the target moisture content reduced (Table 3). At the 900 W power, more heat is generated in the sample that accelerates mass transfer, and, as a result of the high microwave power, the final moisture content of potato samples was 77% lower than the 360 W treatment (Table 2). This can be due to the high mass transfer rate inside the samples during high-power microwave drying as a result of higher heat generation. Accordingly, internal heating creates a large vapor pressure gradient between the surface and inner parts of the samples and contributes to the higher outward migration of inner moisture [25].

Table 2
Mean comparison of various indexes including moisture content (MC), effective moisture diffusion coefficient (D_{eff}), bulk density (BD), shrinkage (Sh), rehydration ratio (RR) and specific energy consumption (SEC) of samples as influenced by different process variables.

Process variables		MC[1]	D_{eff}[2]	BD[3] $\times 10^3$	Sh[4]	RR[5]	SEC[6] $\times 10^3$
Ultrasonication time (min)	0 (Control)	0.187[a]	1.146×10^{-7a}	0.958[a]	71.804[b]	209.750[a]	281.11[a]
	10	0.163[a]	1.205×10^{-7a}	0.969[a]	73.393[ab]	208.210[a]	280.31[a]
	20	0.171[a]	1.164×10^{-7a}	0.978[a]	75.481[a]	180.00[b]	269.87[a]
	30	0.181[a]	1.167×10^{-7b}	1.111[a]	76.349[a]	225.020[a]	264.27[a]
Microwave pulse ratio	1	0.193[a]	1.053×10^{-7d}	0.740[c]	69.143[c]	244.51[a]	254.04[b]
	2	0.181[a]	1.118×10^{-7c}	0.791[c]	69.217[c]	214.32[b]	295.50[a]
	3	0.177[a]	1.183×10^{-7b}	1.056[b]	76.349[b]	198.79[b]	287.55[a]
	4	0.151[a]	1.328×10^{-7a}	1.428[a]	82.317[a]	165.36[c]	258.47[b]
Microwave power (W)	360	0.191[a]	1.082×10^{-7a}	1.053[a]	75.181[a]	161.115[c]	318.90[a]
	600	0.188[a]	1.295×10^{-7b}	1.047[a]	73.268[a]	218.366[b]	258.23[b]
	900	0.147[a]	1.171×10^{-7c}	0.912[a]	74.321[a]	237.752[a]	244.54[b]

*For each process variable, different letters in the same column indicate a significant difference ($p < 0.05$).
[1] Moisture content (g water/g dry solid).
[2] Effective moisture diffusion coefficient (m^2/s).
[3] Bulk density (kg/m^3).
[4] Shrinkage (%).
[5] Rehydration ratio (%).
[6] Specific energy consumption (MJ/kg).

3.2. Effective moisture diffusion coefficient (D_{eff})

Fig. 2(a–d) shows ln(MR) values versus the drying time for potato samples in the microwave – hot air method under 360 W microwave power using different pulse ratios and ultrasound pretreatment times. By using the slope from these figures, the D_{eff} values of potato samples dried under different experimental conditions were calculated using Eqs. (6) and (7). According to these equations, which indicate a direct relationship between slope and D_{eff}, as the slope decreased, D_{eff} also decreased.

Generally, by increasing the ultrasound time from 10 to 30 min, D_{eff} of potato samples increased by 4.89, 1.54 and 1.38%, respectively, compared to the control treatment (Table 2). Only the increase from the 30 min treatment time was statistically significant. Similar behavior of D_{eff} was also reported in ultrasound pretreated samples of melons [13], banana [26,27], apple [22], and plum [8]. The ultrasound pretreatment strengthens cavitation, and the formation of micro-channels increases mass transfer (moisture removal) and D_{eff} [8]. Additionally, according to Table 2, the moisture reduction in the samples pretreated for 10 min was more than other samples, and this was attributed to more micro-channel formation in this pretreatment time. Since the increase in D_{eff} depends on the formation of microscopic channels within the sample texture [22], increased D_{eff} of the potato samples pretreated for 10 min was considerable compared to other time samples (20 and 30 min) (Table 2). In a similar study, Rodrigues and Fernandes [13] reported the effects of ultrasound pretreatment on moisture removal from melons. The pretreatment involved an ultrasound bath (25 kHz) at 30 °C for 10, 20 and 30 min. The samples were dried in an oven at 60 °C where airflow was blown on the dryer walls at a volumetric flow rate of 0.12 m^3/s. Results showed that D_{eff} increased by 39.3% following 30 min of ultrasound pretreatment. This was attributed to the formation of micro-channels during the ultrasound pretreatment. The increased D_{eff} reduced drying time by 25% in this study.

Moreover, D_{eff} significantly increased as the pulse ratio was increased from 1 to 4 (Table 2). This result was in agreement with the results reported by Aghilinategh et al. [4]. This can be due to the reduced internal stress with the increase in pulse ratio, which subsequently facilitated moisture removal [7]. As the off-time increased, the moisture migration from the center to the surface became easier, and by applying microwave energy in the next stage, moisture removal intensified at the beginning of each drying period, which, in turn, increased D_{eff} [28].

Fig. 2 also presents ln(MR) values versus the drying times of potato samples in the microwave – hot air drying method using 600 (e–h) and 900 W (i–l) microwave powers and different pulse ratios on the samples pretreated for different ultrasound exposure times. D_{eff} significantly increased as the microwave power was increased from 360 to 900 W (Table 2). Increased D_{eff} as a result of increasing the microwave power was in agreement with the results of Sharma and Prasad [24] and Aghilinategh et al. [28]. Higher microwave powers raise the internal vapor pressure and develop a porous structure and higher vapor permeability, which finally increase D_{eff} due to faster heating of potato samples (Table 4). In addition, results showed that the 600 W microwave power had the highest D_{eff}, and the 360 W treatment had the lowest value in this regard (Table 2). The reason for the higher D_{eff} value at the 600 W level than the 900 W level was probably the longer microwave exposure time in the 600 W treatment (23 min) than the 900 W one (14 min) (Table 1).

In a similar study, Sharma and Prasad [24] analyzed D_{eff} variations in cloves of garlic dried using the microwave – hot air technique. The study used different levels of microwave power (10, 20, 30 and 40 W), hot air temperature (40, 50, 60 and 70 °C) and airflow velocity (1 and 2 m/s). Results revealed that, at a constant airflow velocity, D_{eff} increased as moisture content decreased by increasing hot air temperature and microwave power. However, other parameters being constant, D_{eff} decreased when airflow velocity increased. It was also found that D_{eff} has an inverse correlation with moisture content during the microwave – hot air drying. This supports the idea that vapor permeability is higher at lower moisture content levels, which can help maintain the porous structure. The sample temperature at the beginning of the drying process raises rapidly due to the higher absorption of the microwave heat, as a sample with high moisture content has a high moisture removal rate. This leads to increased vapor pressure that opens the pores. At the first drying stage, liquid moisture diffusion is the dominant transfer mechanism. As the process advances, vapor diffusion becomes the dominant moisture transfer mechanism at the final stage.

3.3. Shrinkage

Fig. 3(a–d) presents shrinkage versus the microwave – hot air drying times of potato samples using the 360 W microwave power and different pulse ratios for the ultrasound-pretreated samples. According to the figure, shrinkage increased in all samples as the drying time advanced and more moisture was removed leading to a reduction in samples' volume. At the beginning of the process, the shrinkage rate was higher because of the higher moisture content of the samples. As

Table 3
Magnitudes of moisture content after ultrasound pretreatment (MC-U), moisture content after microwave drying (MC-MD), final moisture content (MC-F), drying time considering microwave "on" time (DT-ON) and drying time considering microwave "on" and "off" times (DT-ON-OFF) of samples as influenced by ultrasonication time (UT), microwave pulse ratio (PR) and power (P).

UT[1]	PR[2]	P[3]	MC-U[4]	MC-MD[5]	MC-F[6]	DT-ON[7]	DT-ON-OFF[8]
0	1	360	$5.872^{abc} \pm 0.973$	$1.243^{cdef} \pm 0.040$	$0.189^{abcd} \pm 0.098$	292^{abcd}	$292^{hijklmn}$
10	1	360	$6.088^{abc} \pm 0.087$	$1.266^{cdef} \pm 0.024$	$0.163^{abcd} \pm 0.083$	277^{abcd}	$277^{jklmnop}$
20	1	360	$6.141^{ab} \pm 0.163$	$1.662^{abcde} \pm 0.040$	$0.172^{abcd} \pm 0.093$	307^{abc}	307^{hijklm}
30	1	360	$5.516^{abc} \pm 0.797$	$1.545^{abcdef} \pm 0.037$	$0.181^{abcd} \pm 0.093$	292^{abcd}	$292^{hijklmn}$
0	1	600	$5.187^{abc} \pm 0.600$	$1.816^{abc} \pm 0.025$	$0.161^{abcd} \pm 0.09$	263^{abcd}	263^{klmnop}
10	1	600	$5.148^{abc} \pm 0.705$	$1.953^{ab} \pm 0.025$	$0.132^{bcd} \pm 0.06$	248^{bcd}	248^{mnop}
20	1	600	$5.100^{abc} \pm 0.775$	$1.214^{cdef} \pm 0.019$	$0.115^{d} \pm 0.06$	218^{d}	218^{p}
30	1	600	$5.913^{abc} \pm 0.026$	$1.765^{abcd} \pm 0.088$	$0.134^{bcd} \pm 0.06$	233^{cd}	233^{nop}
0	1	900	$4.572^{bc} \pm 0.312$	$1.753^{abcde} \pm 0.047$	$0.178^{abcd} \pm 0.09$	269^{abcd}	269^{klmnop}
10	1	900	$5.470^{abc} \pm 0.760$	$1.309^{cdef} \pm 0.059$	$0.127^{cd} \pm 0.07$	254^{bcd}	254^{lmnop}
20	1	900	$4.642^{bc} \pm 0.515$	$1.621^{abcdef} \pm 0.018$	$0.135^{bcd} \pm 0.09$	269^{abcd}	269^{klmnop}
30	1	900	$5.215^{abc} \pm 0.925$	$1.657^{abcde} \pm 0.025$	$0.127^{bcd} \pm 0.06$	224^{d}	224^{p}
0	2	360	$4.759^{bc} \pm 0.388$	$1.154^{ef} \pm 0.038$	$0.208^{abcd} \pm 0.110$	322^{ab}	359^{bcdefg}
10	2	360	$6.630^{a} \pm 0.557$	$1.306^{cdef} \pm 0.025$	$0.190^{abcd} \pm 0.006$	322^{ab}	359^{bcdefg}
20	2	360	$5.570^{abc} \pm 0.923$	$1.482^{cdef} \pm 0.026$	$0.179^{abcd} \pm 0.016$	292^{abcd}	$329^{cdefghijk}$
30	2	360	$6.597^{a} \pm 0.528$	$1.271^{cdef} \pm 0.013$	$0.222^{abcd} \pm 0.018$	292^{abcd}	$329^{cdefghijk}$
0	2	600	$4.887^{abc} \pm 0.655$	$1.267^{cdef} \pm 0.048$	$0.148^{abcd} \pm 0.07$	263^{abcd}	$286^{ijklmno}$
10	2	600	$5.299^{abc} \pm 0.750$	$1.409^{bcdef} \pm 0.020$	$0.124^{cd} \pm 0.07$	248^{bcd}	271^{klmnop}
20	2	600	$5.153^{abc} \pm 0.584$	$1.444^{bcdef} \pm 0.035$	$0.124^{cd} \pm 0.06$	248^{bcd}	271^{klmnop}
30	2	600	$4.883^{abc} \pm 0.480$	$1.554^{abcdef} \pm 0.022$	$0.127^{cd} \pm 0.07$	263^{abcd}	$286^{ijklmno}$
0	2	900	$4.859^{abc} \pm 0.434$	$1.953^{ab} \pm 0.019$	$0.253^{a} \pm 0.16$	314^{ab}	$328^{cdefghijk}$
10	2	900	$5.025^{abc} \pm 0.533$	$1.423^{bcdef} \pm 0.051$	$0.180^{abcd} \pm 0.09$	299^{abc}	$313^{efghijklm}$
20	2	900	$4.343^{c} \pm 0.250$	$1.658^{abcde} \pm 0.055$	$0.233^{abc} \pm 0.16$	284^{abcd}	$298^{ghijklm}$
30	2	900	$4.490^{bc} \pm 0.306$	$1.747^{abcde} \pm 0.063$	$0.184^{abcd} \pm 0.11$	299^{abc}	$313^{efghijklm}$
0	3	360	$4.713^{bc} \pm 0.365$	$1.338^{cdef} \pm 0.013$	$0.190^{abcd} \pm 0.014$	337^{a}	411^{ab}
10	3	360	$5.631^{abc} \pm 0.238$	$1.180^{def} \pm 0.090$	$0.172^{abcd} \pm 0.087$	292^{abcd}	366^{bcdef}
20	3	360	$4.299^{c} \pm 0.203$	$1.494^{bcdef} \pm 0.039$	$0.185^{abcd} \pm 0.097$	277^{abcd}	$351^{bcdefghi}$
30	3	360	$4.415^{bc} \pm 0.290$	$1.482^{bcdef} \pm 0.038$	$0.207^{abcd} \pm 0.014$	307^{abc}	381^{abcd}
0	3	600	$5.046^{abc} \pm 0.566$	$1.192^{def} \pm 0.026$	$0.130^{bcd} \pm 0.07$	248^{bcd}	$294^{ghijklmn}$
10	3	600	$4.804^{bc} \pm 0.569$	$1.383^{bcdef} \pm 0.021$	$0.140^{bcd} \pm 0.07$	233^{cd}	$279^{jklmnop}$
20	3	600	$5.287^{abc} \pm 0.724$	$1.214^{cdef} \pm 0.065$	$0.123^{d} \pm 0.06$	248^{bcd}	$294^{ghijklmn}$
30	3	600	$5.482^{abc} \pm 0.810$	$1.290^{cdef} \pm 0.058$	$0.194^{abcd} \pm 0.11$	308^{abc}	$354^{bcdefgh}$
0	3	900	$5.419^{abc} \pm 0.241$	$1.483^{bcdef} \pm 0.040$	$0.200^{abcd} \pm 0.10$	284^{abcd}	$312^{efghijklm}$
10	3	900	$5.973^{abc} \pm 0.115$	$1.778^{abcd} \pm 0.024$	$0.200^{abcd} \pm 0.11$	314^{ab}	$342^{cdefghij}$
20	3	900	$5.215^{abc} \pm 0.971$	$1.730^{abcde} \pm 0.971$	$0.179^{abcd} \pm 0.09$	314^{ab}	$342^{cdefghij}$
30	3	900	$5.954^{abc} \pm 0.131$	$1.699^{abcde} \pm 0.109$	$0.211^{abcd} \pm 0.11$	314^{ab}	$342^{cdefghij}$
0	4	360	$5.346^{abc} \pm 0.703$	$1.340^{cdef} \pm 0.037$	$0.237^{ab} \pm 0.019$	322^{ab}	433^{a}
10	4	360	$5.628^{abc} \pm 0.824$	$1.258^{cdef} \pm 0.037$	$0.172^{abcd} \pm 0.100$	322^{ab}	433^{a}
20	4	360	$4.607^{bc} \pm 0.461$	$1.042^{f} \pm 0.025$	$0.202^{abcd} \pm 0.100$	277^{abcd}	388^{abc}
30	4	360	$5.075^{abc} \pm 0.543$	$1.636^{abcdef} \pm 0.024$	$0.199^{abcde} \pm 0.10$	322^{ab}	433^{a}
0	4	600	$5.357^{abc} \pm 0.687$	$1.190^{def} \pm 0.039$	$0.152^{abcd} \pm 0.09$	233^{cd}	$302^{fghijklm}$
10	4	600	$4.660^{bc} \pm 0.362$	$1.330^{cdef} \pm 0.038$	$0.167^{abcd} \pm 0.008$	248^{bcd}	$317^{defghijkl}$
20	4	600	$4.672^{bc} \pm 0.348$	$1.320^{cdef} \pm 0.013$	$0.208^{abcd} \pm 0.100$	308^{abc}	377^{abcde}
30	4	600	$5.787^{abc} \pm 0.912$	$1.275^{cdef} \pm 0.014$	$0.176^{abcd} \pm 0.100$	308^{abc}	377^{abcde}
0	4	900	$4.470^{bc} \pm 0.241$	$2.092^{a} \pm 0.068$	$0.199^{abcd} \pm 0.10$	314^{ab}	$356^{bcdefgh}$
10	4	900	$5.052^{abc} \pm 0.624$	$1.526^{abcdef} \pm 0.013$	$0.196^{abcd} \pm 0.11$	284^{abcd}	$326^{cdefghijk}$
20	4	900	$5.326^{abc} \pm 0.030$	$1.542^{abcdef} \pm 0.013$	$0.202^{abcd} \pm 0.11$	314^{ab}	$356^{bcdefgh}$
30	4	900	$4.897^{abc} \pm 0.542$	$1.577^{abcdef} \pm 0.020$	$0.208^{abcd} \pm 0.10$	284^{abcd}	$326^{cdefghijk}$

[*] Different letters in the same column indicate a significant difference ($p < 0.05$).
[1] Ultrasonication time (min).
[2] Pulse ratio.
[3] Power (W).
[4] Moisture content after ultrasound pretreatment (g water/g dry solid).
[5] Moisture content after microwave drying (g water/g dry solid).
[6] Final moisture content (g water/g dry solid).
[7] Drying time considering microwave "on" time (min).
[8] Drying time considering microwave "on" and "off" times (min).

the moisture content decreased, shrinkage rate also reduced.

In general, shrinkage increased significantly compared to the control samples when the ultrasound treatment time increased (Table 2). This parameter was lower in the samples pretreated for 10 min than those pretreated for 20 and 30 min. This is because of the higher D_{eff} of the 10-min pretreated samples than other ones (Table 2). Nowacka et al. [22] reported that shrinkage was higher by 6–20% in ultrasound-pretreated samples than the controls. The ultrasound pretreatment destroys cell walls, changes tissue structure, and thus creates surface stress and cracks in the tissue [9]. Therefore, more moisture is removed and as a result, shrinkage is increased. Since volume change and thus shrinkage was larger in ultrasound pretreated samples than the

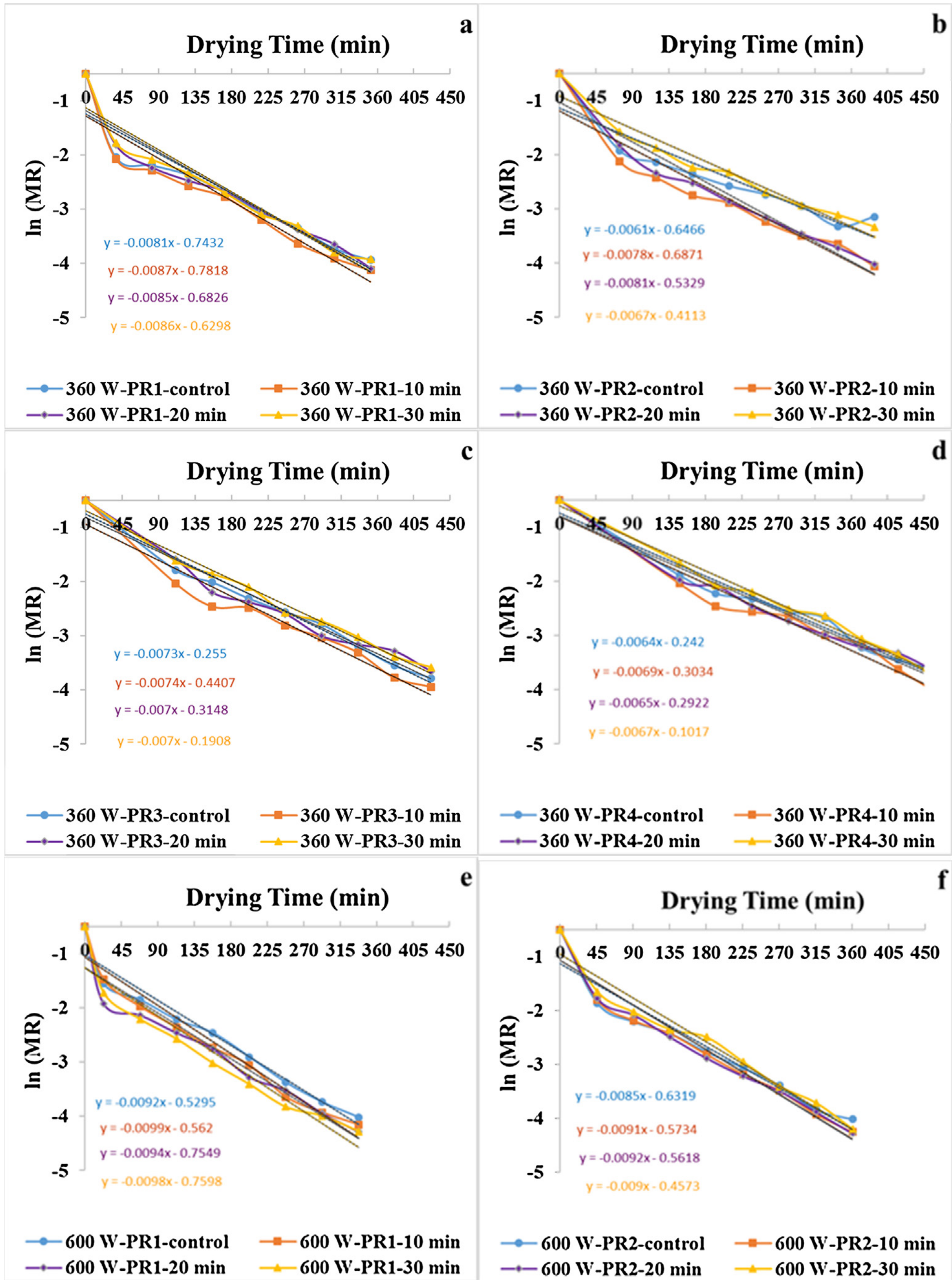

Fig. 2. Ln (MR) versus drying time of potato samples pretreated with ultrasound for of 0 (control), 10, 20 and 30 min during microwave – convective hot air drying at 360 W (a–d), 600 W (e–h) and 900 W (i–l) with different pulse ratios (PR).

controls, the higher shrinkage of the pretreated samples continued throughout the process (Fig. 3(a–d)).

On the other hand, results showed that shrinkage increased by increasing pulse ratio from 1 to 4 (Table 2). When higher pulse ratios were used, the drying time was also longer (Table 3), which in turn increased shrinkage in the samples. Ultrasound causes the cellular structure to collapse [17], and the larger shrinkage as a result of the collapsed structure indicates the structural damages to the samples. Considering the effect of ultrasound on increased shrinkage (Table 2), the ultrasound-pretreated samples displayed the same increasing trend, again, under higher pulse ratios.

Fig. 3 presents shrinkage versus the microwave – hot air drying times of potato samples using the 600 (e–h) and 900 W (i–l) powers and different pulse ratios for the ultrasound-pretreated samples. According to these figures, the ultrasound-caused initial shrinkage of the pretreated samples was higher (Table 2), which also gave rise to more shrinkage after the microwave stage. As the microwave power was increased from 360 to 900 W, shrinkage decreased (Table 2) although it was not statistically significant. Reduced shrinkage at higher microwave power levels was in agreement with the results reported by Maskan [29]. This is because high-power microwave drying accelerates drying of sample crusts compared to their cores and reduces the drying time and thus shrinkage [25].

3.4. Bulk density

Fig. 4(a–d) shows bulk density at different ultrasound times using 360 W microwave power with different pulse ratios. In general, results

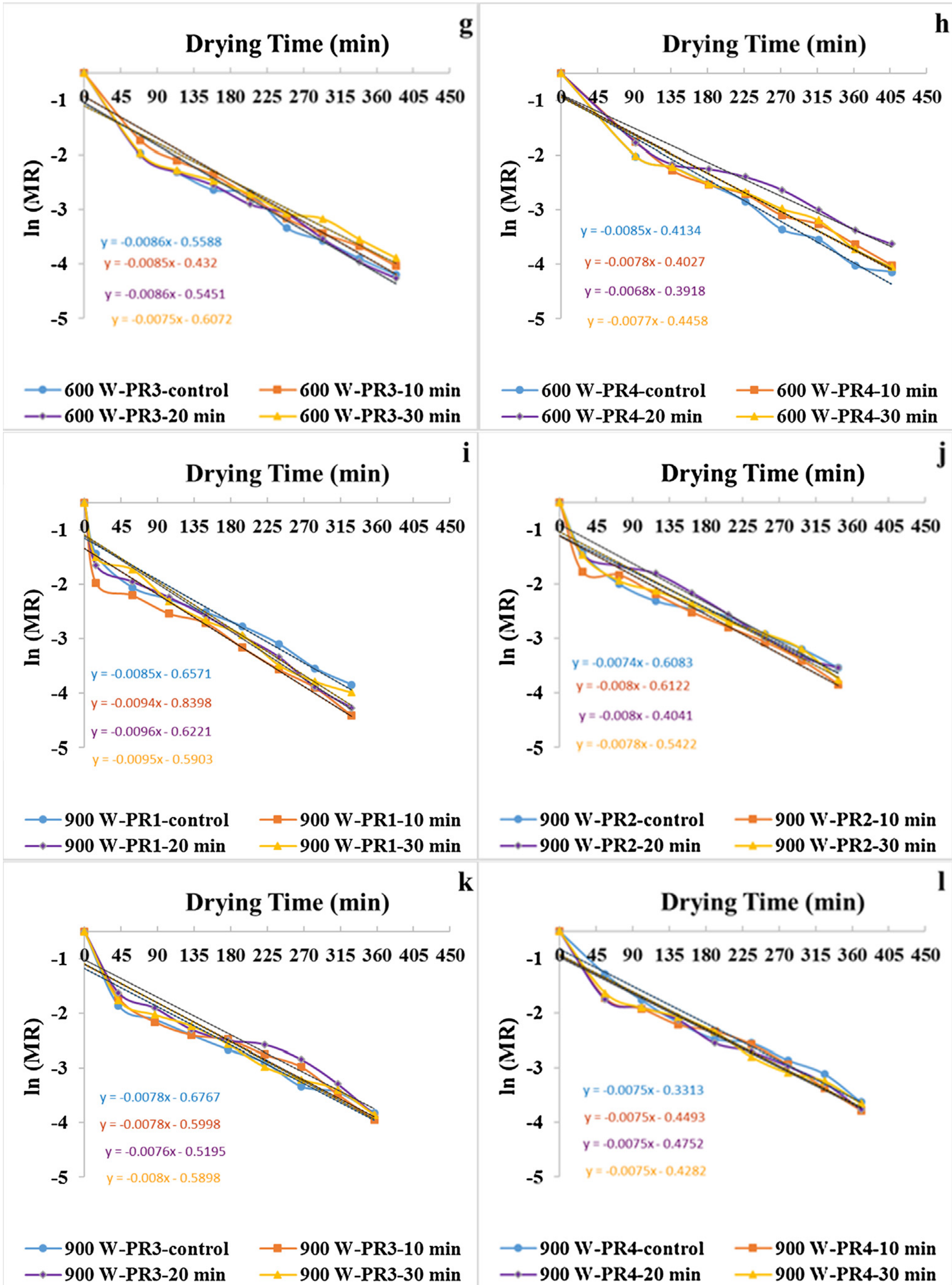

Fig. 2. (*continued*)

showed that the control samples had the lowest bulk density, and this parameter increased non-significantly as the ultrasound time increased (Table 2). This result was in agreement with those reported by Rodrigues et al. [30]. The microstructural analysis has shown that the ultrasonic waves disrupt the cellular structure and create more pores in the ultrasound-pretreated samples than the controls. As a result, the drying rate is higher due to the better moisture removal paths [30]. These changes finally lead to better moisture diffusion and higher bulk density [18]. Since shrinkage from moisture removal affects bulk density [22], and since shrinkage increased as the ultrasound treatment time increased (Table 2), the increased bulk density can be justified (Table 2). Factors such as moisture removal and shrinkage reduce the sample volume during drying producing a sample with a higher amount of solids per unit volume and thus higher bulk density [18]. It should be noted that the food moisture is a combination of free and confined water. Given that confined water in food products contains stronger bonds with dried solids, it has a higher density than pure water.

Additionally, bulk density generally increased significantly by increasing the pulse ratio (Table 2). As pulse ratio was increased, a significant reduction in moisture content of potato samples was observed (Table 2). This, in turn, increased shrinkage (Table 2) due to the decrease in potato volumes and, therefore, increased bulk density. Guiné and Castro [31] also reported increased bulk density as a result of a decrease in moisture content.

Fig. 4 shows bulk density kinetics at different ultrasound times using 360 (e–h) and 600 W (i–l) microwave powers with different pulse ratios. The bulk density reduced as the microwave power was raised from 360 to 900 W (Table 2). This result was in agreement with the results of Aghilinategh et al. [4]. In general, by increasing the microwave power, the bulk density of dried samples decreases as their porosity increases

Table 4
Magnitudes of effective moisture diffusion coefficient (D_{eff}) at different ultrasonication time [UT (min)], microwave pulse ratios [PR] and powers [P (W)].

UT[1]	PR[2]	P[3]	D_{eff} (m^2/s)
0	1	360	$1.220 \times 10^{-7\mathrm{abcdefghij}} \pm 8.915 \times 10^{-9}$
10	1	360	$1.264 \times 10^{-7\mathrm{abcdef}} \pm 4.690 \times 10^{-9}$
20	1	360	$1.235 \times 10^{-7\mathrm{abcdefgh}} \pm 7.197 \times 10^{-9}$
30	1	360	$1.249 \times 10^{-7\mathrm{abcdefgh}} \pm 5.524 \times 10^{-9}$
0	1	600	$1.347 \times 10^{-7\mathrm{abc}} \pm 2.233 \times 10^{-8}$
10	1	600	$1.434 \times 10^{-7\mathrm{a}} \pm 1.025 \times 10^{-8}$
20	1	600	$1.371 \times 10^{-7\mathrm{ab}} \pm 0$
30	1	600	$1.434 \times 10^{-7\mathrm{a}} \pm 1.188 \times 10^{-8}$
0	1	900	$1.225 \times 10^{-7\mathrm{abcdefghij}} \pm 5.261 \times 10^{-9}$
10	1	900	$1.347 \times 10^{-7\mathrm{abc}} \pm 1.241 \times 10^{-8}$
20	1	900	$1.371 \times 10^{-7\mathrm{ab}} \pm 1.392 \times 10^{-8}$
30	1	900	$1.434 \times 10^{-7\mathrm{a}} \pm 9.493 \times 10^{-9}$
0	2	360	$9.921 \times 10^{-8\mathrm{hijk}} \pm 3.860 \times 10^{-9}$
10	2	360	$1.133 \times 10^{-7\mathrm{cdefghijk}} \pm 1.356 \times 10^{-8}$
20	2	360	$1.186 \times 10^{-7\mathrm{abcdefghijk}} \pm 2.746 \times 10^{-9}$
30	2	360	$9.775 \times 10^{-8\mathrm{ijk}} \pm 8.124 \times 10^{-9}$
0	2	600	$1.240 \times 10^{-7\mathrm{abcdefgh}} \pm 1.052 \times 10^{-8}$
10	2	600	$1.323 \times 10^{-7\mathrm{abcd}} \pm 1.847 \times 10^{-8}$
20	2	600	$1.347 \times 10^{-7\mathrm{abc}} \pm 1.035 \times 10^{-8}$
30	2	600	$1.317 \times 10^{-7\mathrm{abcde}} \pm 1.170 \times 10^{-8}$
0	2	900	$1.079 \times 10^{-7\mathrm{cdefghijk}} \pm 1.297 \times 10^{-8}$
10	2	900	$1.293 \times 10^{-7\mathrm{abcde}} \pm 3.466 \times 10^{-8}$
20	2	900	$1.162 \times 10^{-7\mathrm{bcdefghijk}} \pm 2.715 \times 10^{-8}$
30	2	900	$1.138 \times 10^{-7\mathrm{bcdefghijk}} \pm 9.112 \times 10^{-9}$
0	3	360	$1.084 \times 10^{-7\mathrm{defghijk}} \pm 1.765 \times 10^{-8}$
10	3	360	$1.074 \times 10^{-7\mathrm{defghijk}} \pm 1.859 \times 10^{-8}$
20	3	360	$1.021 \times 10^{-7\mathrm{fghijk}} \pm 1.247 \times 10^{-8}$
30	3	360	$1.026 \times 10^{-7\mathrm{fghijk}} \pm 1.095 \times 10^{-8}$
0	3	600	$1.235 \times 10^{-7\mathrm{abcdefghi}} \pm 8.036 \times 10^{-9}$
10	3	600	$1.235 \times 10^{-7\mathrm{abcdefghi}} \pm 2.151 \times 10^{-8}$
20	3	600	$1.259 \times 10^{-7\mathrm{abcdefg}} \pm 8.036 \times 10^{-9}$
30	3	600	$1.094 \times 10^{-7\mathrm{cdefghijk}} \pm 1.822 \times 10^{-8}$
0	3	900	$1.074 \times 10^{-7\mathrm{defghijk}} \pm 1.943 \times 10^{-8}$
10	3	900	$1.094 \times 10^{-7\mathrm{cdefghijk}} \pm 1.644 \times 10^{-8}$
20	3	900	$1.060 \times 10^{-7\mathrm{efghijk}} \pm 4.457 \times 10^{-9}$
30	3	900	$1.162 \times 10^{-7\mathrm{bcdefghijk}} \pm 1.607 \times 10^{-8}$
0	4	360	$9.386 \times 10^{-8\mathrm{k}} \pm 5.524 \times 10^{-9}$
10	4	360	$9.970 \times 10^{-7\mathrm{hijk}} \pm 7.487 \times 10^{-9}$
20	4	360	$9.386 \times 10^{-8\mathrm{k}} \pm 5.124 \times 10^{-9}$
30	4	360	$9.726 \times 10^{-8\mathrm{jk}} \pm 7.487 \times 10^{-9}$
0	4	600	$1.235 \times 10^{-7\mathrm{abcdefghi}} \pm 1.179 \times 10^{-8}$
10	4	600	$1.147 \times 10^{-7\mathrm{bcdefghijk}} \pm 2.739 \times 10^{-8}$
20	4	600	$1.001 \times 10^{-7\mathrm{ghijk}} \pm 6.739 \times 10^{-9}$
30	4	600	$1.118 \times 10^{-7\mathrm{bcdefghijk}} \pm 1.387 \times 10^{-8}$
0	4	900	$1.084 \times 10^{-7\mathrm{defghijk}} \pm 1.560 \times 10^{-8}$
10	4	900	$1.108 \times 10^{-7\mathrm{cdefghijk}} \pm 1.407 \times 10^{-8}$
20	4	900	$1.021 \times 10^{-7\mathrm{fghijk}} \pm 1.437 \times 10^{-8}$
30	4	900	$1.079 \times 10^{-7\mathrm{defghijk}} \pm 5.261 \times 10^{-9}$

*Different letters in the same column indicate a significant difference ($p < 0.05$).
[1] Ultrasonication time (min).
[2] Pulse ratio.
[3] Power (W).

[25]. This can be due to the increased internal water vapor pressure at higher microwave powers and formation of a non-compact structure because of the vapor traveling through the food product [4]. Moreover, results revealed that the lower bulk density from higher microwave powers can be a result of the lower shrinkage (less volume reduction) of the samples dried by higher microwave powers (Table 2).

3.5. Rehydration

Fig. 5(a–d) shows rehydration variations at different ultrasound times using 360 W microwave power with different pulse ratios. The negative values at the start of each curve at t = 0 were due to the immersion of potato samples in distilled water during ultrasound pretreatment. Rehydration decreased as the ultrasound time was increased from 10 to 20 min, however, it increased again when the ultrasound time was further increased to 30 min (Table 2). Consistent with these results were those reported by Nowacka et al. [22] who found that the potatoes receiving ultrasound pretreatment for 30 min had the highest rehydration than the 10 and 20 min treatments. The rehydration ratio depends on the extent of cellular rupture and destruction in food products during the ultrasound pretreatment phase [22]. Nowacka et al. [22] carried out a microstructural analysis and found that the samples receiving longer pretreatment (30 min) had the highest cellular damage compared to those receiving 10 and 20 min treatments. Therefore, it is likely that the increased rehydration after 30 min of ultrasound pretreatment is due to the larger extent of the cellular damage and the lower resistance of broken cells against moisture leaving the product [9]. On the other hand, the lowest rehydration ratio belonged to the samples pretreated for 20 min (Table 2). This can be a result of the lower D_{eff} of these samples compared to those pretreated for 10 and 30 min (Table 2).

In a similar investigation, Nowacka et al. [22] studied ultrasound pretreatment during drying of apple slices and its effect on physical properties. Ultrasound waves with a 35 kHz frequency were applied for 10, 20 and 30 min in an ultrasonic bath. The apple slices were then dried with hot air at 70 °C under an airflow of 1.5 m/s. The pretreatment reduced the drying time by 31–40%. Its effects on other parameters were as follows: 11% more shrinkage, 6–20% less bulk density, and 9–14% more porosity than the control samples. Results also showed that the samples receiving 30 min of ultrasound pretreatment were dried faster than other samples, whereas samples exposed to 20 min of ultrasound pretreatment had the longest drying time. In general, the ultrasound pretreatment, facilitated moisture removal and increased D_{eff} through the formation of microscopic channels. D_{eff} was higher in the samples pretreated for 10 and 30 min which was 18% greater than the control samples. Moreover, ultrasound improved rehydration. The highest moisture content during rehydration was observed in the samples pretreated for 30 min, however, rehydration could not be completed in these samples. The overall results revealed that the rehydration ratio increased up to saturation as the rehydration time was increased.

In addition, rehydration ratio and pulse ratio had a generally significant inverse correlation (Table 2). The increased shrinkage at higher pulse ratios (Table 2) causes an irreversible tissue breakdown, which leads to the loss of texture integrity, the formation of a dense texture, shrinkage of capillary tubes, and reduced hydrophilicity. Reduced hydrophilicity can, in turn, lower the rehydration ratio of potato samples during drying [25]. In general, a texture with higher shrinkage has a lower capacity for rehydration.

Fig. 5 shows rehydration variations at different ultrasound times using 600 (e–h) and 900 W (i–l) microwave powers with different pulse ratios. As shown, at the microwave drying phase (Table 1), the rehydration ratio of the potato samples increased rapidly. Microwave application in drying increases the internal pressure of the samples creating a puffy structure. This structure can increase the rehydration capacity and improve the reconstruction of the dried structure [4]. Moreover, the rehydration ratio increased as the microwave power was increased from 360 to 900 W. This increase was statistically significant (Table 2). This result was in agreement with the results reported by Maskan [29] and Wang and Xi [32]. This can be due to the increased internal vapor pressure at higher microwave powers and formation of a non-compact structure because of the vapor traveling through the food product, shorter microwave exposure time (Table 1), and reduced shrinkage [32]. In other words, at higher microwave powers, the sample structure was changed and became more porous due to faster heating and better moisture removal, and thus the rehydration ratio

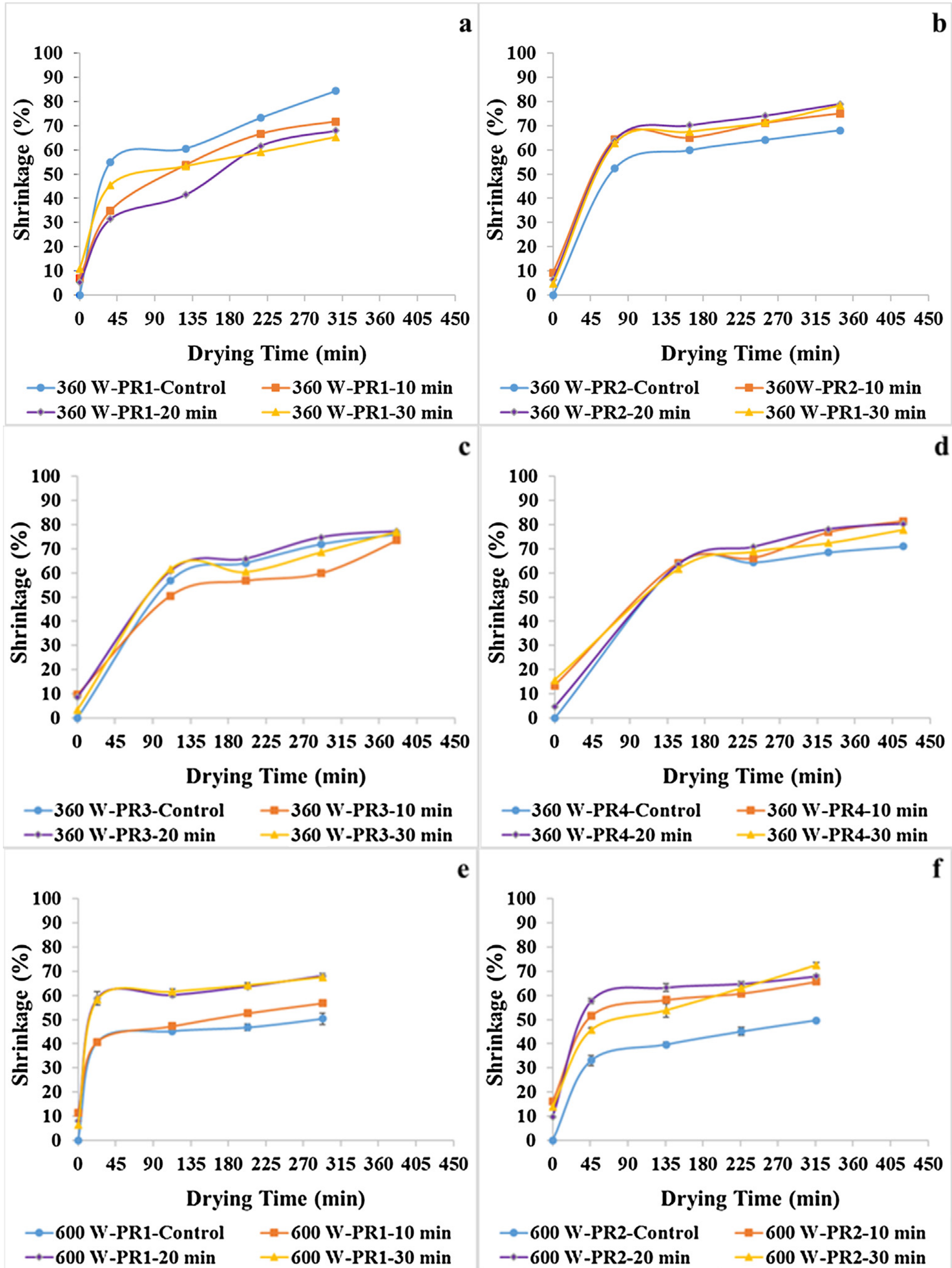

Fig. 3. Shrinkage variations of potato samples pretreated with ultrasound for of 0 (control), 10, 20 and 30 min during microwave – convective hot air drying at 360 W (a–d), 600 W (e–h) and 900 W (i–l) with different pulse ratios (PR).

increased [7].

In a similar study, Maskan [29] studied the effect of microwave drying, hot air drying, and hybrid microwave – hot air drying on rehydration and shrinkage of kiwi fruits. The study conditions were a 60 °C air flowing at 1.29 m/s and microwave power of 210 W. Results showed that the drying time of the microwave drying was 89% shorter than that of hot air drying. This was suggested to be a result of fast infiltration of heat into the inner parts of the product and thus faster water vapor removal. Moreover, the hybrid microwave – hot air method had a drying time 40% lower than the hot air method. The lowest shrinkage was observed in the hybrid method. The highest shrinkage, however, belonged to the microwave drying, which was a result of high internal heat generation and thus fast removal of moisture from the fruit structure. The microwave-dried kiwi fruit slices had a lower rehydration ratio, whereas the highest rehydration was observed in the samples dried using the hybrid technique due to their lower shrinkage. In general, the samples dried with the hybrid microwave – hot air method showed the best quality with the lowest shrinkage and highest rehydration. In another study, Wang and Xi [32] studied a two-stage microwave drying of carrot with different thicknesses using different microwave powers. Six different sample thicknesses (1.5, 3, 4.5, 6, 7.5, and 9 mm) and three microwave power levels (120, 160 and 240 W) were used. It was reported that, for a constant carrot thickness, higher microwave power led to higher porosity and rehydration ratio due to faster heating and improved moisture removal. Moreover, the rehydration ratio reduced as the sample thickness was increased. For thicker samples, the time required to reach the target moisture content was longer, and the moisture removal rate was slower. The thermal energy generated during microwave drying facilitates moisture movement inside the product, which increases the moisture removal rate.

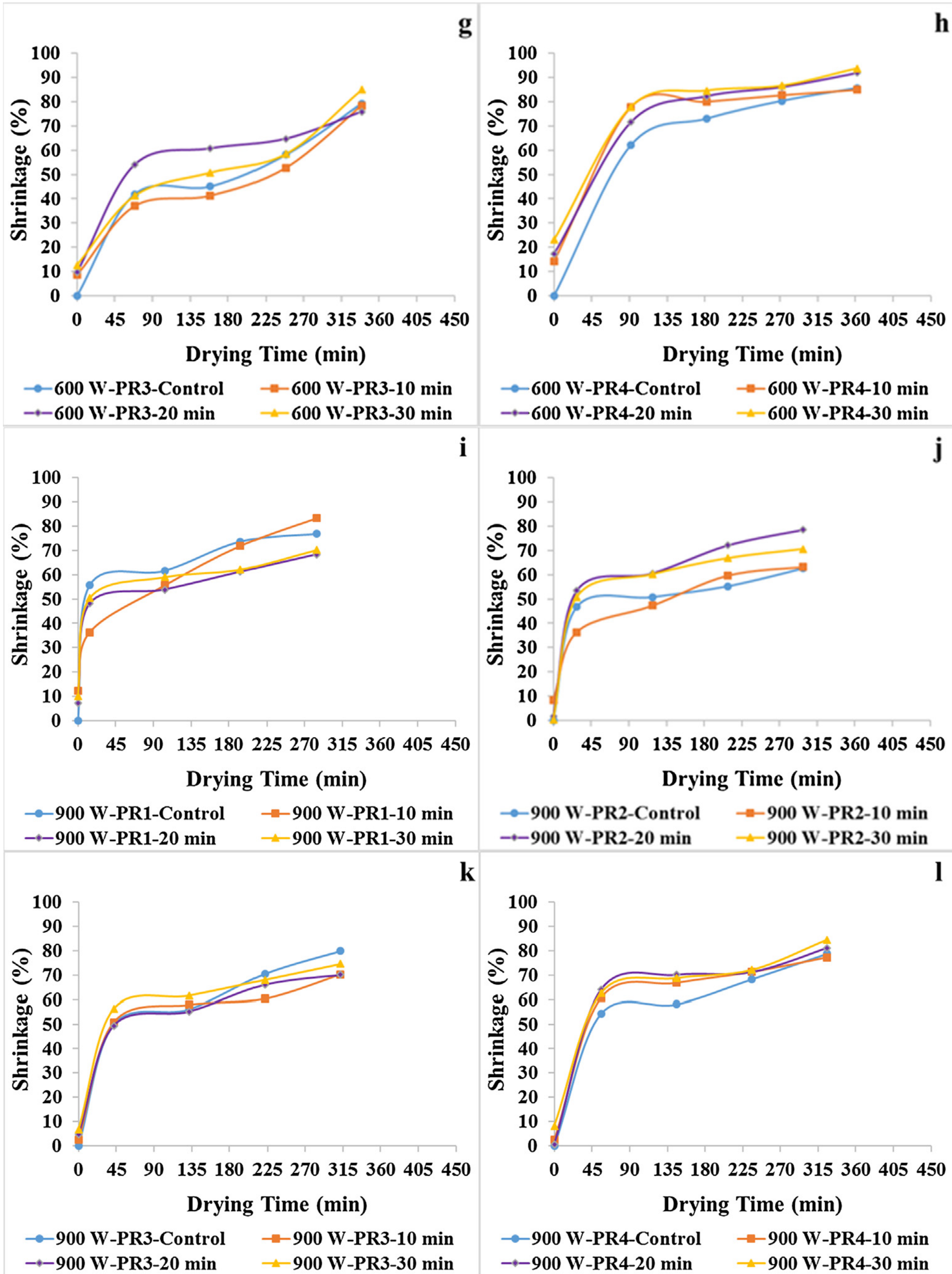

Fig. 3. (*continued*)

Additionally, the microwave energy required for moisture transfer was higher in thicker samples. This was attributed to the volumetric heating and the increased internal pressure that are followed by turbulence inside samples.

In another similar study, Horuz and Maskan [25] studied pomegranate arils drying using both continuous microwave and hot air techniques. They analyzed the drying behavior, shrinkage, bulk density and rehydration of samples. Samples were dried using three temperatures (50, 60 and 70 °C) at an airflow velocity of 1 m/s. Three microwave power levels (210, 350 and 490 W) were also considered. The drying rate of the microwave technique was higher than hot air drying. This was due to the high mass transfer rate inside the samples during microwave drying. In fact, internal heating creates a high vapor pressure gradient between the surface and inner parts of the samples. Finally, microwaves contribute to the outward movement of inner moisture. Moreover, air temperature and microwave power had a considerable effect on the drying rate. At higher temperatures of hot air and higher levels of microwave power, the drying time was shorter due to faster moisture removal. It was reported that shrinkage was higher in hot air-dried samples than in microwave-dried ones. In fact, high-power microwave drying caused faster drying of product crusts than their cores and reduced the drying time and thus shrinkage. Shrinkage of hot air-dried samples at 50, 60 and 70 °C was 78.57, 77.06 and 75.62%, respectively. The highest shrinkage occurred at 50 °C, which was due to its longer process time. Shrinkage of microwave-dried samples using 210, 350 and 490 W was 65.45, 65.22 and 54.55%, respectively. Similarly, the highest shrinkage belonged to the 210 W treatment due to its slower drying rate. The bulk density of the hot air-dried samples was also higher than microwave-dried ones due to its longer drying time. The lowest bulk density belonged to microwave-dried samples as a result of their lower shrinkage than hot air-dried samples. It was found that bulk density decreases with the air temperature and microwave

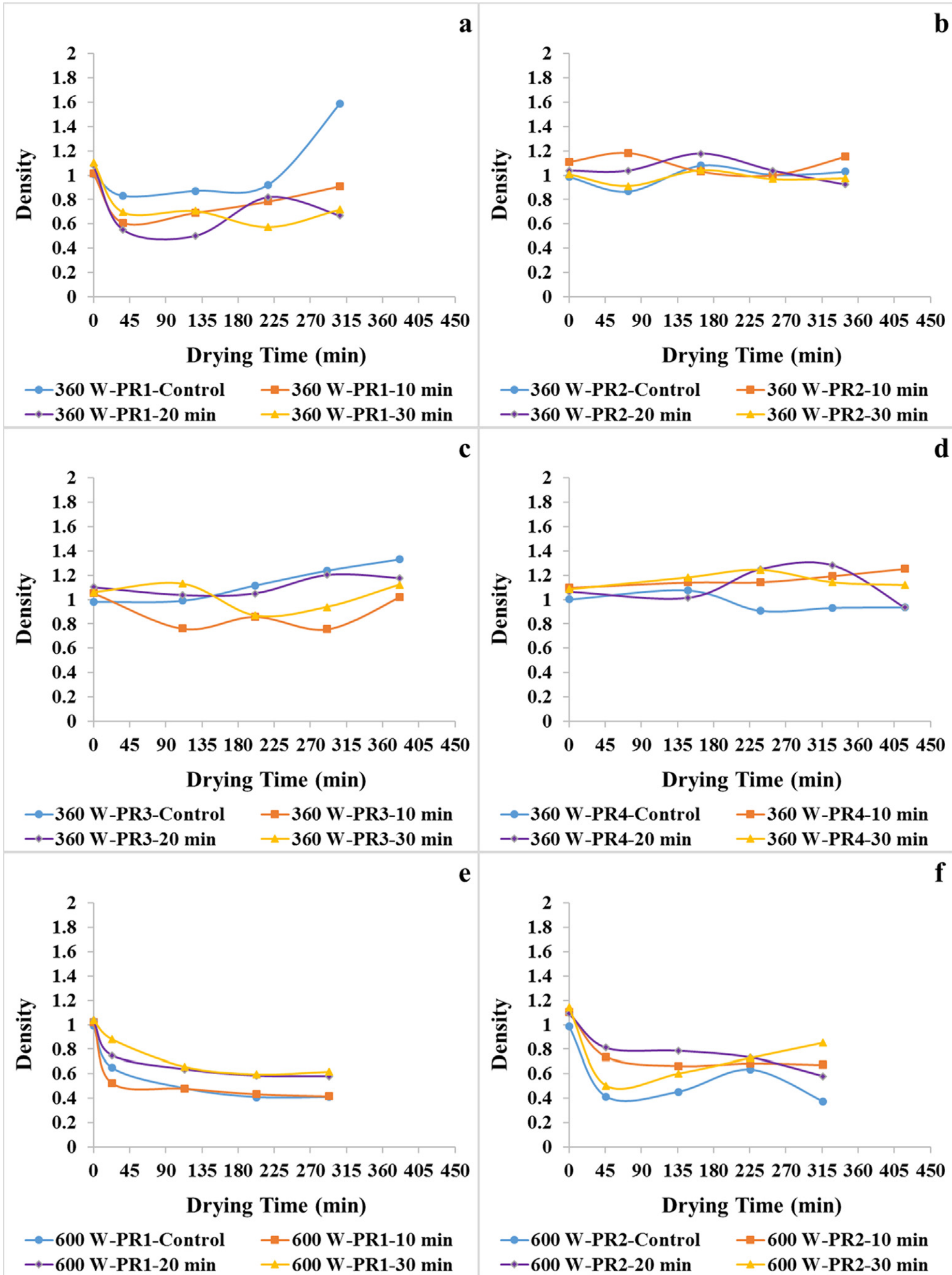

Fig. 4. Density variations of potato samples pretreated with ultrasound for of 0 (control), 10, 20 and 30 min during microwave – convective hot air drying at 360 W (a–d), 600 W (e–h) and 900 W (i–l) with different pulse ratios (PR).

power. The highest bulk density belonged to the hot air-dried samples at 50 °C due to the long drying time of this treatment. The highest bulk density was also observed in the samples dried with the microwave power of 210 W. The lower porosity and longer drying time were the causes for this result. In general, by increasing the microwave power, bulk density of dried samples decreased as their porosity increased. At the same time, the rehydration rate of the microwave-dried samples was higher but the difference was not statistically significant. According to the results, the rehydration ratio was lower in the samples dried at 70 °C than at 60 °C, which can be explained by the severe shrinkage and structural collapse of the samples dried at higher temperatures. In addition, the rehydration ratio decreased as the microwave power increased. High-power microwave drying can cause irreversible collapsing in the texture leading to the loss of texture integrity and formation of a compact collapsed texture that contributes to the shrinkage of capillary channels and reduced hydrophilicity. Reduced hydrophilic properties can, in turn, decrease the rehydration ratio. The statistical analysis, however, revealed that the drying temperature and microwave power had no significant effect on rehydration.

Moreover, in another study, the effects of intermittent microwave, continuous microwave, and hot air drying techniques on the qualitative characteristics (*e.g.* drying rate, bulk density, and rehydration ratio) of dried apple samples were compared by Aghilinategh et al. [4]. The experimental variables were temperature (40, 50, 60, 70 and 80 °C), pulse ratio (2, 3, and 6), microwave power (200, 300 and 600 W), and airflow velocity (0.5, 1 and 2 m/s). The continuous microwave drying showed the fastest drying process than intermittent microwave and hot air drying. As the microwave power and air temperature were increased, D_{eff} showed an increase. The highest D_{eff} was reported for the continuous microwave treatment whereas the lowest D_{eff} value

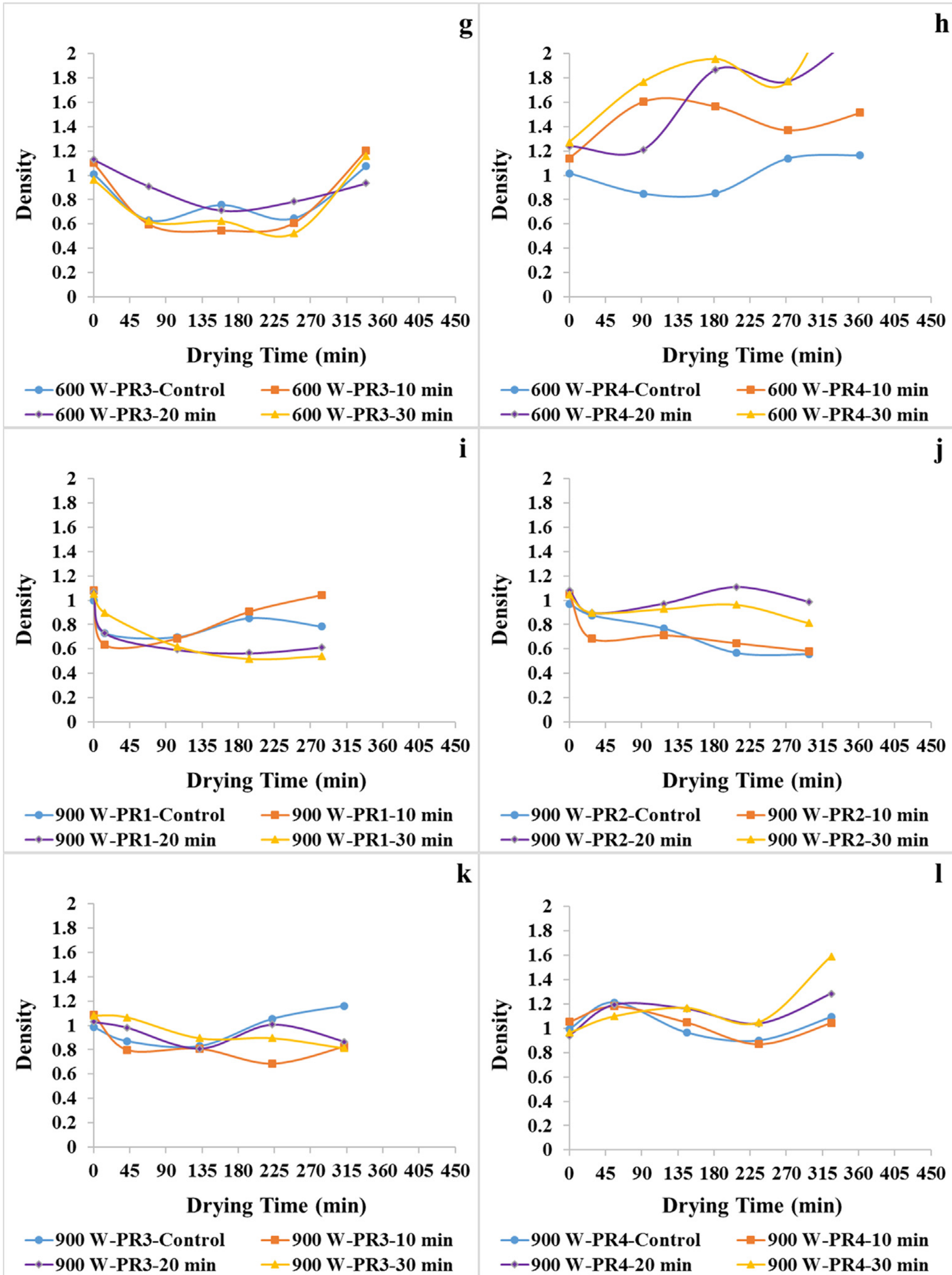

Fig. 4. (*continued*)

belonged to the hot air drying treatment. In fact, the temperature was raised higher in the continuous treatment than in the other treatments, and thus the vapor pressure was more increased contributing to higher moisture diffusion towards the surface. Results showed that intermittent microwave-dried samples had the lowest bulk density and highest rehydration ratio than microwave- and hot air-dried ones. During intermittent microwave drying, internal pressure can produce pores in foods, which in turn reduces bulk density and increases rehydration ratio. Bulk density was lower at higher microwave powers, temperatures, and airflow velocities. This was due to the higher porosity of the samples dried under such conditions.

3.6. Specific energy consumption

Specific energy consumption values for the control and pretreated samples dried at different microwave powers and pulse ratios are given in Table 5. Compared to the control treatment, specific energy consumption decreased when the ultrasound time was raised from 10 to 30 min (Table 2). This can be due to the shorter drying time (Table 3) at higher D_{eff} of ultrasound-pretreated samples than the control samples (Table 2). The ultrasound pretreatment creates microscopic channels in the potato texture that facilitates moisture removal, reduces the drying time, and finally decreases specific energy consumption [26,27]. In general, ultrasound pretreatment can reduce production costs by reducing the required drying time. In a similar study, Fernandes and Rodrigues [27] also focused on the effects of ultrasound pretreatment on moisture removal from banana slices. The pretreatment involved an ultrasound bath (25 kHz) at 30 °C for 10, 20 and 30 min. The samples were dried in an oven at 60 °C and relative humidity of 16%. Results showed an increase in D_{eff} in ultrasound-pretreated samples. This increase led to an 11% reduction in the drying time and finally improved energy consumption and reduced costs. In another study, Azoubel et al.

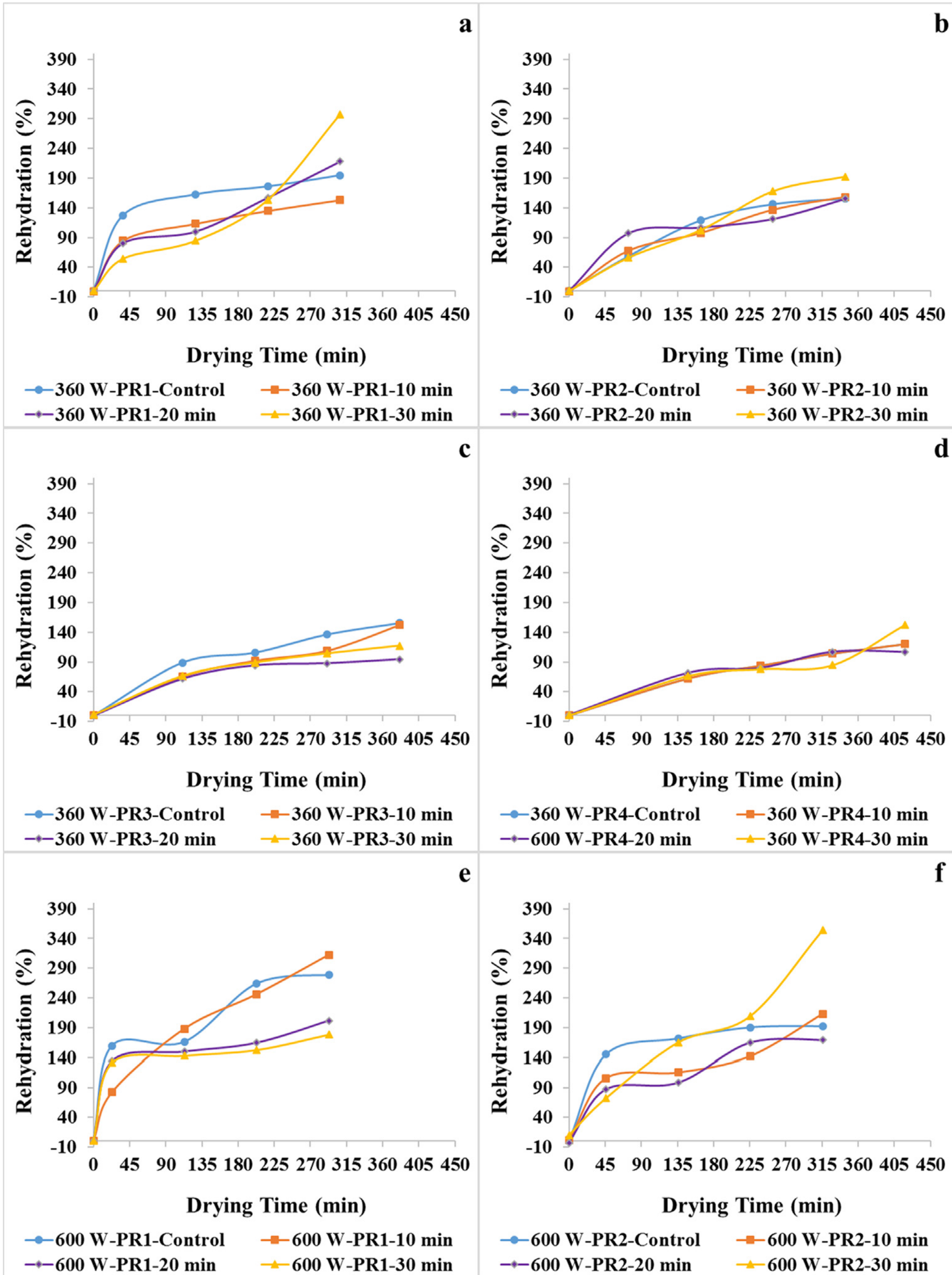

Fig. 5. Rehydration variations of potato samples pretreated with ultrasound for of 0 (control), 10, 20 and 30 min during microwave – convective hot air drying at 360 W (a–d), 600 W (e–h) and 900 W (i–l) with different pulse ratios (PR).

[26] modeled the drying kinetics of ultrasound-pretreated banana samples. The modeling was carried out based on the diffusion model (Fick's second law) for moisture transfer. The samples were pretreated in an ultrasound bath (25 kHz) at 30 °C for 10, 20 and 30 min. Drying was done in a fixed-bed dryer using two temperatures (50 and 70 °C) at an airflow velocity of 3 m/s. By increasing the temperature and using ultrasound pretreatment, D_{eff} increased and, in turn, reduced the drying time bringing about energy saving and cost reduction.

In addition, by increasing pulse ratio from 1 to 4, specific energy consumption generally showed non-significant increases (Table 2). This can be explained by the longer drying time required for drying potato samples when pulse ratio was increased from 1 to 4 (Table 3). Specific energy consumption also significantly decreased (23.32%) by increasing microwave power from 360 to 900 W (Table 2). This finding was in agreement with the results from Jindarat et al. [33]. The lowest specific energy consumption value was observed at 900 W. This can be due to the shorter microwave application time at higher powers (Table 1). At higher microwave powers, microwaves better infiltrate into the samples, and kinetic energy of water molecules is more effectively converted to thermal energy generating more heat throughout the sample volume. As a result of these variations, the 900 W power can save more energy [33].

In a similar study, Zhao et al. [34] used different combinations of microwave and hot air variables to study the drying of carrots using the hybrid intermittent microwave – hot air method. The studied parameters were D_{eff}, drying time, rehydration ratio, and energy consumption. The drying conditions were as follows: 1. Hot air at 60 °C and airflow velocity of 5 m/s; 2. Hot air at 60 °C, airflow velocity of 5 m/s, and microwave power of 140 W; 3. Hot air at 60 °C, airflow velocity of 5 m/s, and microwave power of 175 W; 4. Microwave power of 175 W

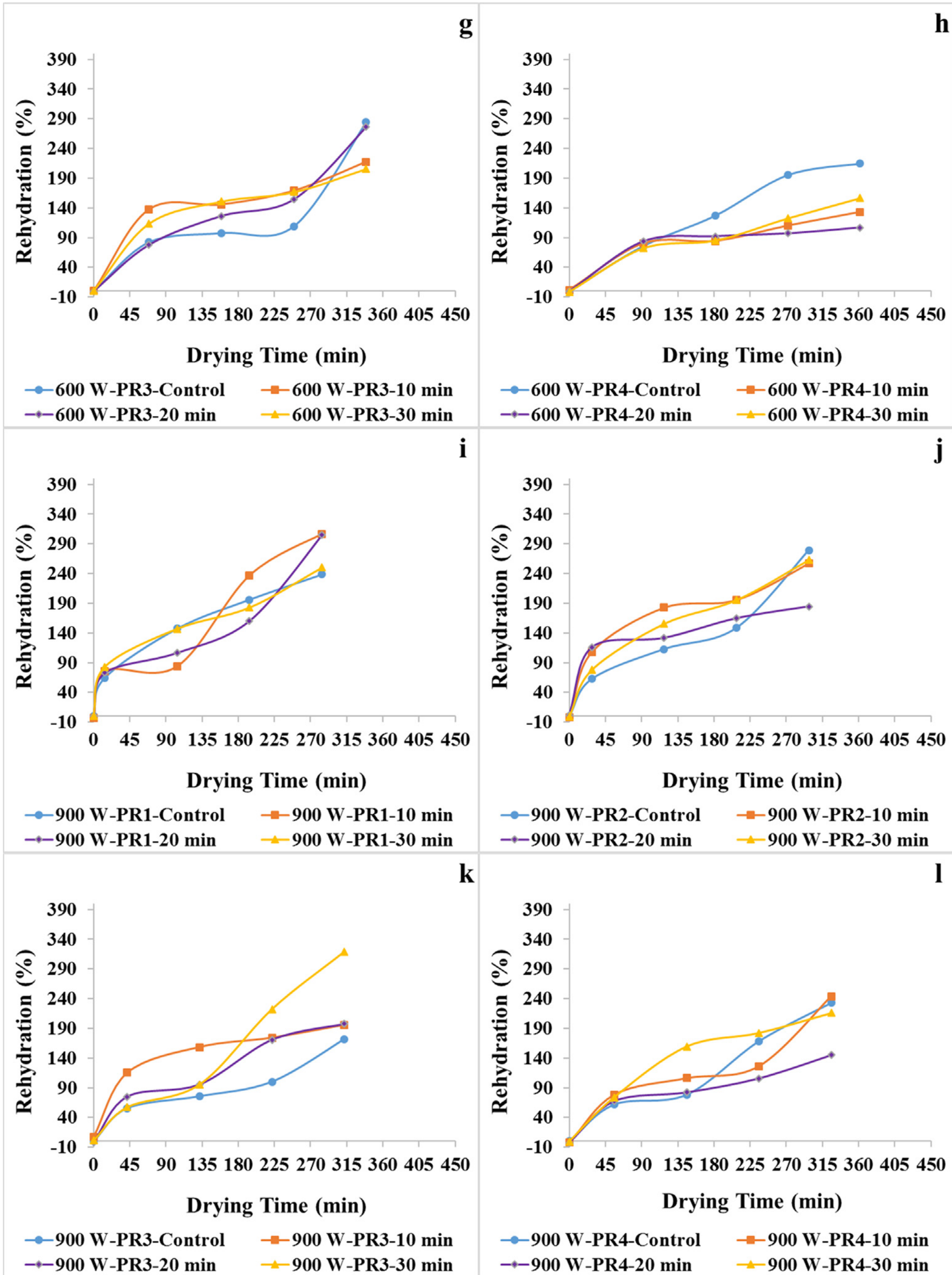

Fig. 5. (*continued*)

followed by microwave power of 140 W; and 5. Intermittent microwave in two stages using pulse ratio of 4 at the beginning and pulse ratio of 5 at the next stage followed by hot-air flow at 60 °C. All experiments under these conditions were continued until reaching 0.1 g_{water}/g_{solids}. Results showed that energy consumption and drying time the treatment 5 were lower than the other 4 treatments, and the samples dried under these conditions had the highest rehydration rate than the samples from other treatments. The hybrid microwave – hot air drying method showed the highest drying rate among other methods. The combination of intermittent microwave and hot air caused internal and external heating, which enhanced heat and mass transfer and finally higher energy efficiency. Moreover, the samples dried using treatment 5 had the highest D_{eff} value than other samples. Because, in this method, the combination of intermittent microwave and hot air developed a temperature balance between the surface and inner layers of samples providing temperature uniformity throughout the sample. At the same time, the samples dried using the hybrid intermittent microwave and hot air technique showed the highest rehydration ratio than the samples dried by microwave or hot air methods alone. This can be due to the fact that food products lose a great amount of water during the first microwave phase because of their high moisture content, and this can cause high volumetric heating and internal pressure. This mechanism finally results in turbulence in the samples reducing their rehydration ratio. However, the hybrid intermittent microwave – hot air method is more useful because it reduces the irreversible physical changes due to using lower temperatures.

4. Conclusions

Fruits and vegetables such as potato have secured a special position in the human diet, and the drying process as a food preservation technique can affect their physicochemical properties. It is thus

Table 5
Specific energy consumption of microwave drying [SE-MD ($\times 10^3$ MJ/kg)], specific energy consumption of hot-air drying [SE-HA ($\times 10^3$ MJ/kg)] and total specific energy consumption [SE-Total ($\times 10^3$ MJ/kg)] at different ultrasonication time [UT (min)], microwave pulse ratios [PR] and powers [P (W)].

UT[1]	PR[2]	P[3]	SE-MD[4]	SE-HA[5]	SE-Total[6]
0	1	360	0.603^{bcdefghijk} ± 0.042	360.53^{ab} ± 23.5	361.07^{ab} ± 23.6
10	1	360	0.574^{cdefghijkl} ± 0.040	376.59^{a} ± 27.1	377.07^{a} ± 27.1
20	1	360	0.617^{bcdefghijkl} ± 0.043	257.38^{defghi} ± 16.6	257.92^{defghi} ± 16.7
30	1	360	0.696^{abcdefg} ± 0.048	294.82^{abcdefg} ± 18.2	295.39^{abcdefg} ± 18.2
0	1	600	0.824^{abcd} ± 0.139	204.81^{ghij} ± 35.5	205.42^{ghij} ± 35.6
10	1	600	0.870^{abc} ± 0.147	163.98^{ij} ± 26.9	164.61^{ij} ± 27
20	1	600	0.715^{abcdef} ± 0.121	225.17^{fghij} ± 44.5	225.72^{fghij} ± 44.6
30	1	600	0.670^{abcdefghij} ± 0.113	168.43^{ij} ± 30	168.96^{ij} ± 30.1
0	1	900	0.907^{a} ± 0.040	247.38^{defghi} ± 9.7	248.2^{defghi} ± 9.8
10	1	900	0.658^{abcdefghijk} ± 0.027	280.02^{bcdefgh} ± 10.8	280.60^{bcdefgh} ± 10.8
20	1	900	0.905^{ab} ± 0.037	230.32^{efghij} ± 8.6	231.10^{efghij} ± 8.6
30	1	900	0.769^{abcde} ± 0.031	231.77^{efghij} ± 8.3	232.46^{efghij} ± 8.4
0	2	360	0.487^{efghijkl} ± 0.145	370.02^{a} ± 49.7	379.5^{a} ± 49.6
10	2	360	0.330^{kl} ± 0.098	359.52^{abcd} ± 42.2	359.85^{abc} ± 42.1
20	2	360	0.429^{fghijkl} ± 0.128	275.73^{bcdefgh} ± 36.1	276.18^{bcdefgh} ± 36
30	2	360	0.330^{kl} ± 0.098	341.66^{abcd} ± 44.9	342.03^{abcd} ± 44.8
0	2	600	0.575^{cdefghijkl} ± 0.275	307.95^{abcdef} ± 51.4	308.5^{abcdef} ± 51.5
10	2	600	0.544^{cdefghijkl} ± 0.260	266.58^{bcdefgh} ± 44.7	267.11^{bcdefgh} ± 44.8
20	2	600	0.561^{cdefghijkl} ± 0.268	273.19^{bcdefgh} ± 43.5	273.72^{bcdefgh} ± 43.6
30	2	600	0.625^{bcdefghijkl} ± 0.299	278.24^{bcdefgh} ± 40.3	278.81^{bcdefgh} 40.4
0	2	900	0.638^{bcdefghijkl} ± 0.351	264.41^{bcdefgh} ± 31.2	264.96^{bcdefgh} ± 31.5
10	2	900	0.514^{defghijkl} ± 0.283	275.71^{bcdefgh} ± 36.5	267.16b^{cdefgh} ± 36.8
20	2	900	0.690^{abcdefgh} ± 0.379	251.8^{defghi} ± 31.9	252.39^{defghi} ± 32.2
30	2	900	0.675^{abcdefghi} ± 0.371	266.16^{bcdefgh} ± 33.9	266.73^{bcdefgh} ± 34.2
0	3	360	0.497^{defghijkl} ± 0.331	327.38^{abcde} ± 41.9	327.82^{abcde} ± 41.8
10	3	360	0.337^{ghijkl} ± 0.251	359.19^{abc} ± 47.7	359.53^{abc} ± 47.7
20	3	360	0.598^{bcdefghijkl} ± 0.398	304.37^{abcdef} ± 30.6	304.90^{abcdef} ± 30.6
30	3	360	0.572^{cdefghijkl} ± 0.380	279.96^{bcdefgh} ± 37.7	280.47^{bcdefgh} ± 37.7
0	3	600	0.378^{ghijkl} ± 0.220	257.52^{defghi} ± 27.2	257.87^{defghi} ± 27
10	3	600	0.426^{fghijkl} ± 0.248	238.36^{efghij} ± 23.2	238.75^{efghij} ± 23
20	3	600	0.358^{hijkl} ± 0.208	262.98^{cdefgh} ± 26.5	263.31^{cdefgh} ± 26.3
30	3	600	0.348^{ijkl} ± 0.202	297.02^{abcdefg} ± 31.6	297.26^{abcdefg} ± 31.4
0	3	900	0.378^{ghijkl} ± 0.289	289.63^{abcdefgh} ± 33.7	290.05^{abcdefgh} ± 33.9
10	3	900	0.355^{hijkl} ± 0.271	272.64^{bcdefgh} ± 27.4	273^{bcdefgh} ± 27.6
20	3	900	0.427^{fghijkl} ± 0.327	275.28^{bcdefgh} ± 27.8	275.7^{bcdefgh} ± 28.1
30	3	900	0.349^{ijkl} ± 0.268	281.52^{bc}defgh ± 29	281.88^{bcdefgh} ± 29.2
0	4	360	0.338^{jkl} ± 0.283	296.21^{abcdefg} ± 11.2	296.81^{abcdefg} ± 11
10	4	360	0.310^{l} ± 0.259	264.32^{bcdefgh} ± 28.7	264.92^{bcdefgh} ± 28.7
20	4	360	0.380^{ghijkl} ± 0.318	383.85^{a} ± 14.7	384.45^{a} ± 14.4
30	4	360	0.394^{fghijkl} ± 0.329	233.91^{efghij} ± 8.6	234.5^{efghij} ± 8.3
0	4	600	0.380^{ghijkl} ± 0.388	280.97^{bcdefgh} ± 50.6	281.61^{bcdefgh} ± 51
10	4	600	0.475^{efghijkl} ± 0.486	304.01^{abcdef} ± 54.2	304.63^{abcdef} ± 54.7
20	4	600	0.472^{efghijkl} ± 0.483	296.56^{abcdefg} ± 56.6	297.26^{abcdefg} ± 57.1
30	4	600	0.351^{ijkl} ± 0.359	297.56^{abcdefg} ± 57.3	298.11^{abcdefg} ± 57.7
0	4	900	0.602^{bcdefghijkl} ± 0.538	151.03^{j} ± 15.9	151.53^{j} ± 16.1
10	4	900	0.406^{fghijkl} ± 0.363	197.14^{hij} ± 22.7	197.48^{hij} ± 22.8
20	4	900	0.378^{ghijkl} ± 0.338	195.52^{hij} ± 22.5	195.83^{hij} ± 226
30	4	900	0.431^{fghijkl} ± 0.386	194.17^{hij} ± 22	194.52^{hij} ± 22.2

[*] Different letters in the same column indicate a significant difference ($p < 0.05$).
[1] Ultrasonication time (min).
[2] Pulse ratio.
[3] Power (W).
[4] Specific energy consumption of microwave drying ($\times 10^3$ MJ/kg).
[5] Specific energy consumption of hot-air drying ($\times 10^3$ MJ/kg).
[6] Total specific energy consumption ($\times 10^3$ MJ/kg).

important to optimize the quality of dried potato slices and energy efficiency. The topic's significance has been the driver for the growing advances in the food drying methods. The findings from analyzing the effect of the intermittent microwave – forced convection hot air drying of potato slices pretreated with ultrasound showed that the ultrasound pretreatment can reduce the drying time due to better moisture removal. In general, ultrasound-pretreated samples in all treatments (10, 20 and 30 min) had a shorter drying time than the control samples, and as the pretreatment time increased, the drying time decreased. By increasing the ultrasound time from 10 to 30 min, an increase was observed in D_{eff} of potato samples. D_{eff} was also increased by increasing the microwave power and pulse ratio. At higher power outputs and pulse ratios, the highest increase in D_{eff} was 52.4 and 54.9%, respectively. Shrinkage also indicated a direct relationship with ultrasound time, microwave power, pulse ratio. In addition, bulk density increased with ultrasound time and pulse ratio; however, bulk density followed a falling trend at higher microwave power levels. Rehydration was also higher at higher ultrasound times and microwave powers. It was, however, lower at higher pulse ratios. The highest rehydration ratio was found in the samples dried with intermittent microwave (900 W). Accordingly, as the microwave power was increased, a statistically significant 32.23% increase was observed in the rehydration ratio. Finally, the highest specific energy consumption belonged to the drying of control samples (without ultrasound pretreatment) due to its longer drying time. In general, specific energy consumption had an inverse relationship with ultrasound time. As a result, the lowest specific energy consumption was recorded in the samples receiving 30 min of ultrasound pretreatment. The use of microwave – hot air drying at 900 W reduced specific energy consumption compared to the 360 and 600 W powers. Pulse ratio had also a direct correlation with specific energy consumption. This behavior was caused by the substantial reduction in the drying time, which reduced the overall energy consumption.

Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ultras.2019.02.005.

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