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DRYING CHARACTERISTICS AND QUALITY OF PEAR UNDER HYBRID DRYING (MID-INFRARED-FREEZE DRYING)

Author(s):
T. Antal

Affiliation:
University of Nyíregyháza, Institute of Engineering and Agricultural Sciences, Department of Vehicle and Agricultural Engineering, Kótaji Str. 9-11., H-4400 Nyiregyhaza, Hungary.

Email address:
antal.tamas@nye.hu

Abstract

This article provides results of an experimental investigation of hybrid- (MIR-FD), mid-infrared- (MIR) and freeze drying (FD) on the drying characteristics, energy consumption and quality parameters of pear. Rehydration ratio, color, texture were measured to evaluate the quality of dried pear products. Mid-infrared-freeze drying (MIR-FD) had the higher drying rate, which reduced the drying time by 14.3-42.9% compared with FD method. Two empirical models were chosen to fit the drying curves. The MIR-FD pear had darker color, better rehydration capacity and lower hardness than single stage of FD products. Above all, the MIR50-60°C-FD was suggested as the best drying method for pear in this study.

Keywords

combined drying, freeze drying, drying kinetics, energy uptake, quality

1. Introduction

The pears (Pyrus communis L.) are pomaces fruit-tree species of the Rosaceae family. The pear is a fruit much appreciated for its characteristic flavor, crispness and sweetness. Most pears are eaten fresh and in processed forms: purées, juice, jams, dried, and in other forms [1].

Freeze-drying (FD), also denoted as lyophilization, has long been known as the best drying method for preserving the high-price products, the heat-sensitive materials [2, 3]. The FD is a dehydration process in which the solvent and/or suspension medium is crystallized at a low temperature and then sublimated from the solid state directly into the vapor phase [4]. FD has been reported to be an ideal method due to minimal shrinkage resulting in a porous product with excellent rehydration capacity, soft texture, bright color, superior taste, while the low temperatures used ensures good retention of nutrients [5]. However, the FD has long drying time, high energy uptake and costly process, a judicious combination with other dehydration methods. According to [6] the cost of FD has been found to be at least one order of magnitude higher than conventional drying system.

Infrared drying (IR) supplies energy directly to the surface of the material and thus causes its rapid heating. The heat is transferred further towards the material inside by heat conduction [7]. The depth of penetration of radiation depends upon the characteristics of the sample and wavelength of radiation [8]. IR has many advantages compared to the widely used hot air drying. Such as, high heat transfer coefficients, short process time, quick response time, faster drying rate, uniform product heating and low energy cost are the characteristic properties of IR [6]. Moreover, drying of food products by IR enhances the quality of the dried products. According to [9] the wavelength of medium-wave- or mid-infrared radiation drying (MIR) is in the range of 1-4 μm which covers the maximum absorption wavelength of water molecule. The high heating speed is one of the most apparent advantages of MIR. The MIR is often employed to control the final moisture content of industrial product, mainly because MIR is heat-efficient, convenient and safe. For the penetrability of MIR is strong and it would be more effective in drying products. Therefore, the MIR can decrease a duration of drying [10].

The infrared drying has other advantages, for example the easy combination of the IR with convective, vibration, vacuum, freeze and microwave technologies; simplicity of the equipment and versatility [11]. The minimizing the energy consumption and enhancing the product quality of FD by combination of infrared or microwave drying were investigated by many researchers [12].

Hybrid drying (IR-FD) is a modern technique that combines all of the advantages of different drying methods, in terms of enhanced product quality and reduction in operational time and in energy consumption [6].

The mathematical model of drying kinetics is an important tool used to optimize management of operating parameters and to predict performance of a drying system. Numerous mathematical models, theoretical, empirical and semi-empirical, have been proposed to estimate the drying

characteristics of food products. These mathematical models, allow prediction of simultaneous heat and mass transfer during drying and are applied to simulate the drying curves [13, 14]. Several empirical models for drying kinetics in falling rate drying period are available in the scientific literature [15].

Product color is one of the most important sensory attributes of dried food. The mechanism of browning for many agricultural and horticultural products can be enzymatic and non-enzymatic (Maillard browning) source [16].

Texture, defined as a sensory property is percepted by humans using senses of touch and pressure, is a multi-parameter attribute related to the structure of the biomaterial [17].

The rehydration characteristics of a dried biomaterial are used as a quality index. According to [18] the degree of rehydration is dependent on the degree of cellular and structural disruption of treated material by different drying methods.

To our knowledge, no work is available the effect of mid-infrared-freeze drying on dehydration and quality characteristics of pear. Therefore, this present study was undertaken to investigate the MIR, FD and MIR-FD drying characteristics of pear, to determine the effect of hybrid-, FD and MIR drying on the specific energy consumption. In addition, the aim of our work is to evaluate the effect of different drying technology on the physical and mechanical parameters of pear dice.

2. Material and method

Sample preparation

The raw pear Packham's Triumph species (Pyrus communis L.) employed in the experiments were purchased from the grower (Apagy, Hungary) and stored in a refrigerator (5°C). The pears were washed with tap water, hand-peeled and cored with a knife, and then cut into cubes of 5 mm thickness using a hand-operated slicer. The free water on the surface of samples was removed with an absorbent filler paper. They were stored at a temperature of 5°C until the drying experiments.

The samples were divided into ten groups, each group of samples weighed 100 g. The initial mass of pear cubes was measured using a balance (model JKH-500, Jadever Co., New Taipei, Taiwan) with 0.1 g precision. The prepared pear samples were put into dryers after cutting to avoid surface enzymatic browning.

Determination of moisture content

Moisture content of the raw and dried pear dices was determined by the gravimetric method (model LP306, LaborMIM, Budapest, Hungary). At regular time intervals (30 min) during the drying process, samples were taken out and dried in the oven for 8 h at 105°C until constant weight. Weighing was performed on a digital balance (JKH-500, Jadever Co., New Taipei, Taiwan) and then moisture content was calculated.

Moisture content was expressed in wet matter (g 100 g fresh matter^{-1}, %) and in dry matter (kg moisture kg dry matter^{-1}). The initial moisture content of the pear was found to be 81.03% (wet basis: w.b.), 4.271 kgH_2O kg dry matter^{-1} (dry basis: d.b.). The tests were performed in triplicate.

Drying experiments

The pear cubes were dried by different drying methods with the optimal drying technology until the final moisture content (2-2.5%, wet basis: w.b.). The applied drying methods are described below-mentioned. The drying process was continued until a constant moisture content was recorded (The samples was dried until it reached the equilibrium moisture content). The moisture loss was recorded at 1 min intervals during the drying process in order to determine the drying curves. The experimental data sets from the different drying runs were expressed as moisture ratio (MR) versus drying time (t).

All the experiments were repeated thrice and the average of three results for each treatment was used in this paper. The dried products – before quality assessment – were cooled and packed in low-density polyethylene (LDPE) bags that were heat-sealed.

1. Mid-infrared drying (MIR). A quartz infrared heater, with nearly 80% efficiency in converting electrical energy to infrared energy was used for effective drying. The chamber wall was formed from aluminized steel, with a length of 15 cm, a breadth of 15 cm, and a height of 25 cm, equipped with a single door opening at the top, which allowed insertion and removal of the sample. In the drying chamber, a pair of quartz glass emitters (220 V, maximum power of per lamp 300 W) was positioned above the sample support. Infrared radiation, with wavelengths expressed in microns, can be accurately measured, controlled, and applied to the product. The wavelength of radiation between 2.4-3.0 μm and the heating intensity were maintained between 3-5.5 kW m^{-2}. The quartz glass emitter is located at a distance of 15 cm from the pear cubes surface. The sample tray was supported on a balance (a precision of ± 0.1 g, model Precisa, Precisa Instruments AG, Dietikon, Switzerland) to monitor the sample weight change during drying. The samples were spread uniformly in a monolayer on the aluminum tray. A vent was provided at the top of the chamber for the exit of moist air.

The experiments were carried out for 40-70°C drying temperatures. The emitter temperature and relative humidity were measured by Testo 4510 type meter (Testo GmbH, Lenzkirch, Germany) in the drying chamber. Another temperature probe was inserted into the sample to measure the product temperature (K-type thermocouple, Testo GmbH, Lenzkirch, Germany). However, the relative humidity was not controlled during the laboratory test. The samples were dehydrated until they reached the final moisture content (2.1-2.5%, w.b.).

2. Freeze drying (FD) was performed in a laboratory-scale Armfield FT-33 freeze-dryer (Armfield Ltd., Ringwood, UK). In the FD process, the pear dices were spread uniformly in a single layer on a stainless steel tray. The pear samples (100 g) were frozen at -24°C in a freezing/heating chamber and freeze dried to a moisture content of 2.06% (w.b.) at an absolute pressure of 85-95

Pa with a chamber temperature of 23°C and a condenser temperature of -47°C. In all experiments, temperature of the condenser and the chamber pressure were maintained at constant parameter. Thermocouples (four pieces) of freeze drier were inserted into the pear cubes.

The weight loss of the samples was followed by a data logger (ES-138, Emalog, Budapest, Hungary) and a RS-232 attached to a PC computer, acquired the data readings from platform cell (PAB-01, Emalog, Budapest, Hungary), which is placed within the sample chamber.

3. Hybrid or combined drying (MIR-FD): The pear samples were dried by FD drier by coupling with the MIR devices before the freeze drying step until the final moisture content was between 2.18-2.45% (w. b.). The samples after pre-drying procedure (MIR) were immediately placed into the FD, this is the so-called change point. The change points were placed in drying curve before reach to inflexion point of MIR curve. After the achievement of the inflexion point the color of the samples changed darkening – this phenomenon was determined using ColorLite sph900 colorimeter (ColorLite GmbH, Katlenburg-Lindau, Germany).

The experimental samples dried by MIR at 40°C for 5 min (MIR40°C-FD), MIR at 50°C for 5 min (MIR50°C -FD), MIR at 60°C for 5 min (MIR60°C -FD) and MIR at 70°C for 5 min (MIR70°C -FD) then dried by FD were chosen for further quality evaluation. The drying parameters are in agreement with above-mentioned ones (points of 1-2).

Mathematical models

There are several empirical approaches for modeling the drying kinetics. Henderson and Pabis (exponential) and third-degree polynomial models were used to fit the drying curves (MR versus drying time) in this study.

The Henderson and Pabis model was developed based on approximation that diffusion controls the drying process. This model has been used to describe various food and agricultural materials [19] (Eq. 1).

$$MR = a \cdot e^{-k \cdot t} \tag{1}$$

Another model, which is used for thin-layer drying studies, is the third-degree polynomial (Eq. 2). The model was successfully used to describe the freeze-drying characteristics of fruits and vegetables [20].

$$MR = a \cdot t^3 + b \cdot t^2 + c \cdot t + d \tag{2}$$

where *MR* is the dimensionless moisture ratio, *a, b, c, d* is the drying coefficients, *k* is the drying constant, *t* is the drying time (min, h).

The moisture content of samples is defined by (Eq. 3):

$$M_t = \frac{m_t - m_f}{m_f} \tag{3}$$

where M_t is the moisture content at time t on dry basis (kg H_2O kg dm^{-1}), m_t is the weight of material at specific t (kg), and m_f is the dry matter weight of the material (kg).

The dimensionless moisture ratio (MR) was calculated as (Eq. 4):

$$MR = \frac{M_t - M_e}{M_0 - M_e} \tag{4}$$

where M_t is the moisture content at time t on dry basis (kg H_2O kg dm^{-1}), Me is the equilibrium moisture content (kg H_2O kg dm^{-1}), and M_0 is the initial moisture content (kg H_2O kg dm^{-1}).

The moisture ratio (MR) was simplified to M_t/M_o instead of $(M_t-M_e)/(M_0-M_e)$ since M_e is relatively small as compared with M_0 – in case of all drying methods.

The coefficient of determination (R^2) and root mean square error (RMSE) were calculated to evaluate the fitting of two models to experimental data. The higher values of the R^2 and the lower values of the RMSE were chosen for goodness of fit. These statistical parameters can be calculated as (Eqs. 5, 6):

$$R^2 = 1 - \left[\frac{\Sigma_1^n \left(MR_{\exp_i} - MR_{pre_1} \right)^2}{\Sigma_1^n \left(MR_{ave} - MR_{pre_i} \right)^2} \right] \tag{5}$$

$$RMSE = \sqrt{\frac{1}{n} \cdot \sum_{i=1}^{N} (MR_{\exp_i} - MR_{pre_i})^2} \tag{6}$$

where *n* is the number of observations, *exp* is the experimental data, *pre* is the predicted data, *ave* is the average data, and *MR* is the moisture ratio.

Specific energy consumption

The total electrical power consumption (E, kWh) during FD, MIR and MIR-FD was measured by an energy-cost-checker (model EKM 265, Conrad Electronic GmbH, Hirschau, Germany).

Analysis was performed in triplicate. The specific energy consumption (SEC) expressed electrical power consumption requires for evaporation of one kilogram of water from specimen and was calculated according to Eq. 7.

$$SEC = \frac{E \times 3600}{W_0 - W_f} \tag{7}$$

where *SEC* is the specific energy consumption (MJ kg H_2O^{-1}), E is electrical power consumption from the energy-cost-checker (kWh), W_0 is the initial mass of the raw material (kg) and W_f is the final mass of the dried sample (kg).

Hardness test

The texture characteristics of the fresh and dehydrated pear were measured using a CT3-4500 (Brookfield Engineering

Laboratories, Middleboro, USA) texture analyzer fitted with a spherical probe. Compression test was carried out to generate a plot of force (N) vs. time (s). This plot was used to determine the value of hardness. The parameters that have been used were the followings: 8 kg force load cell, 2 mm s^{-1} test speed, 20 mm travel distance and 4 mm diameter of cylindrical probe. The maximum depth of penetration was 3 mm and trigger force was 4.5 g. A 115 mm diameter plate (rotary base table) was used as a base while compressing the pear samples.

The samples were kept in a room temperature at 21°C until analysis. The penetrometer measurements are reported in Newton's (N).

Ten samples were tested and the average values were reported.

Color of products

The color of pear cubes was measured just before and immediately after drying treatment using a ColorLite sph900 colorimeter (ColorLite GmbH, Katlenburg-Lindau, Germany). The colorimeter (illuminant D65, 10° observer angle) was calibrated against a standard ceramic white tile. For each drying experiment the color measurement was performed on ten dried samples and the color values were compared with those of fresh samples (control). The powder obtained by grinding the dried material in a domestic mixer was used for color estimation. The spectrophotometer was supplied with special adapter. MA38 adapter converts the scanning spot from 3.5 to 38 mm. This device can be used to measure pear powders (the samples were examined from different points).

An important factor characterizing the variation of color in the test sample is total color difference. The total color change (ΔE) was evaluated as (Eq. 8):

$$\Delta E = \sqrt{(L_0 - L)^2 + (a_0 - a)^2 + (b_0 - b)^2} \quad (8)$$

where L^* is the degree of lightness (100) and darkness (0), a^* is the degree of redness (+) and greenness (-) and b^* is the degree of yellowness (+) and blueness (-). Subscript 'zero' refers to the color reading of fresh pear cubes. This is my basis for comparison. A larger ΔE value denotes greater color change from the control (fresh) sample.

All experiments were performed in triplicate and the average values were reported.

Rehydration ratio

The measurement of the water rehydration ratio was based on the following procedure. 100 ml of distilled water was brought to a temperature of 30°C in a constant temperature water bath. Then a precisely weighed 0.5 g sample of the dried material was placed in a plastic vessel and immersed for 90 min. Afterwards the samples were taken out (when the time reached 5, 10, 30, 60 and 90 min) and blotted with tissue paper to eliminate excess water on the surface.

The weights of dried and rehydrated specimens were measured with an electronic digital balance (model JKH-500, Jadever Co., New Taipei, Taiwan) having a sensitivity of 0.1 g. The RR values were determined in triplicate.

$$RR = \frac{W_r}{W_d} \quad (9)$$

Rehydration ratio (RR) of dehydrated samples was estimated using the equation given below (Eq. 9).

where W_r is the drained weight of the rehydrated sample (g), and Wd is the weight of the dry sample used for rehydration (g).

Statistical analysis

Data analyses were determined using the PASW Statistics 18 software (IBM Corp., Armonk, USA), and analyses of variance were conducted by ANOVA procedure, Duncan test. Mean values were considered to be significantly different when $P<0.05$.

Formal statistical analyses on all collected data were performed via Microsoft Excel v. 2013 (Microsoft Corporation, Redmond, USA) software.

Table 1. Effect of drying methods on moisture content of product and operational time

Drying method (Symbol)	Infrared pre-drying period [min]	Freeze finish-drying period [h]	Product moisture content [%, w.b.]	Total drying time [min]	Reduction in FD drying time [%]
FD	-	21	2,06	1260^{h}	-
MIR40°C-FD	5	17,92	2,21	1080^{g}	14,28^{d}
MIR50°C-FD	5	15,92	2,18	960^{f}	23,81^{c}
MIR60°C-FD	5	12,92	2,22	780^{e}	38,1^{b}
MIR70°C-FD	5	11,92	2,45	720^{d}	42,85^{a}
MIR40°C	20	-	2,34	20^{c}	-
MIR50°C	19	-	2,22	19^{c}	-
MIR60°C	16	-	2,49	16^{b}	-
MIR70°C	14	-	2,11	14^{a}	-

Means with different letters in the same column were significantly different at the level ($P<0.05$)
FD, freeze-drying; MIR-FD, mid-infrared-assisted freeze-drying; MIR, mid-infrared drying.

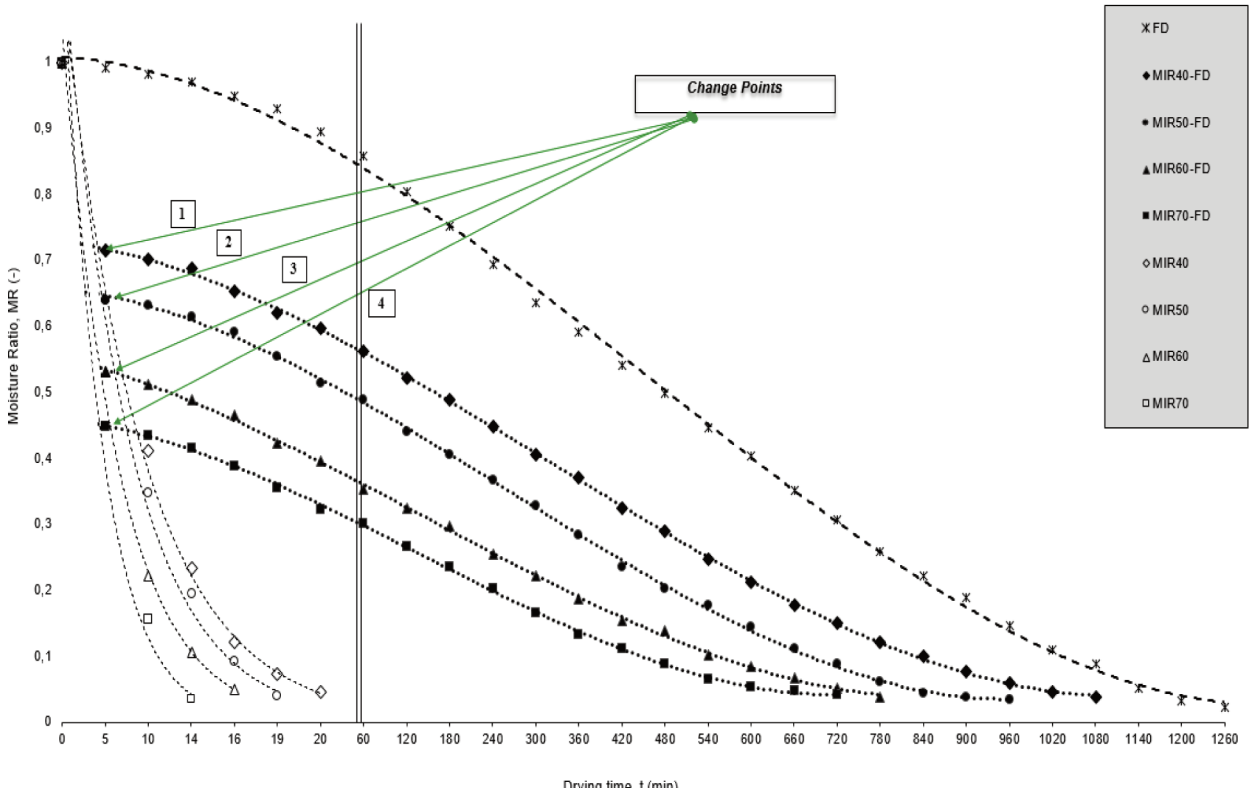


Figure 1. Drying curve of pear cubes

3. Results and discussion

Drying kinetics of different drying methods

Pear cubes with initial moisture content of 81.03% (w.b.) or 4.271 kgH_2O kgdry matter-1 (d.b.) were dried following three different drying methods i.e. mid-infrared (MIR), freeze-drying (FD) and combined mid-infrared-freeze drying (MIR-FD) to a final moisture content of 2.06-2.49% (w.b.) or 0.09-0.21 kgH_2O kg dry matter^{-1} (d.b.) (Table 1).

Drying curves of samples dried using MIR, FD and MIR-FD are compared in Figure 1.

The moisture content decreased continuously with drying time. This figure shows the drying values observed and estimated by the Henderson-Pabis and the third-degree polynomial models. The change points were placed in drying curve before reach to inflexion point of curve and the falling rate period.

As shown in Figure 1, the drying time to reach the final moisture content (2.11-2.49%, w.b.) using MIR at 40°C, 50°C, 60°C and 70°C was 20 min, 19 min, 16 min and 14 min, respectively. Therefore, the MIR operational time of the pear was very short.

In the early stage of MIR, the moisture content decreased more rapidly and subsequently slowly reduced with increase in drying time. This was due to the high drying rates in the early stages. During pear drying with MIR, no constant rate period was observed. From Figure 1, it can be observed that the moisture content decreases with drying time following an exponential decay. A similar trend was seen in studies grape [21].

It is observed that the total drying time required for FD is the longest (1260 min), followed by MIR40°C-FD (1080 min), MIR50°C-FD (960 min), MIR60°C-FD (780 min), and MIR70°C-FD (720 min), which yielded the shortest time (Table 1). Figure 1 showed that drying was completed after 720 min for MIR70°C-FD, and this represents a 42.85% reduction of drying time in comparison with FD. Thus, the MIR pre-drying lessened the drying time significantly ($P<0.05$). Drying time used in MIR-assisted FD drying was 57.14-85.71% of that in FD drying (Table 1).

The MIR-FD drying curves can be divided into two drying stages, i.e. mid-infrared and freeze-drying parts. In the first stage, the dimensionless moisture ratio (MR) of pear decreased sharply, while reached the change point (at 5 min), for example at MIR40°C pre-drying (from 1 to 0.71), at MIR50°C pre-drying (from 1 to 0.64), at MIR60°C pre-drying (from 1 to 0.53) and at MIR70°C pre-drying (from 1 to 0.45) – i.e. MIR pre-drying described with a high drying rate. The change point shows where joined the various drying methods in succession. It can be observed that if the change points – at MIR-FD – decreases, the drying time decreases significantly ($p<0.05$) (Table 1).

In the second stage, the drying rate of FD finish-drying exhibited a slow decrease to equilibrium moisture content of dried samples – i.e. FD finish-drying described with a low drying rate. Therefore, freeze-drying was applied after change point, when the moisture content of pear was reduced to 3.05 (1), 2.73 (2), 2.27 (3) and 1.91 kgH_2O kg dry matter^{-1} (4), respectively (Figure 1). Overall, MIR-FD had a significantly higher drying rate than FD, but were significantly lower than MIR drying. These results were also observed by [22]. The decrease in the total drying time with increase of IR intensity from 3 to 5.5 kW m^{-2} was associated with an increase in water migration inside the pear caused by MIR pre-drying.

Changes in the drying rate (DR is expressed as the amount of the evaporated moisture over time: kgwater·kg solid^{-1}·min^{-1}) with drying time for different drying methods are shown in Figure 2.

The critical point (peak) divides the drying curves into two parts at FD curve. At the beginning of the drying process, the DR was progressively increased while reached the critical point (so called initial heating period). The drying rate gradually decreased with drying time after the critical point (540 min), and kept almost constant at the end of the dehydration process (so called falling rate period).

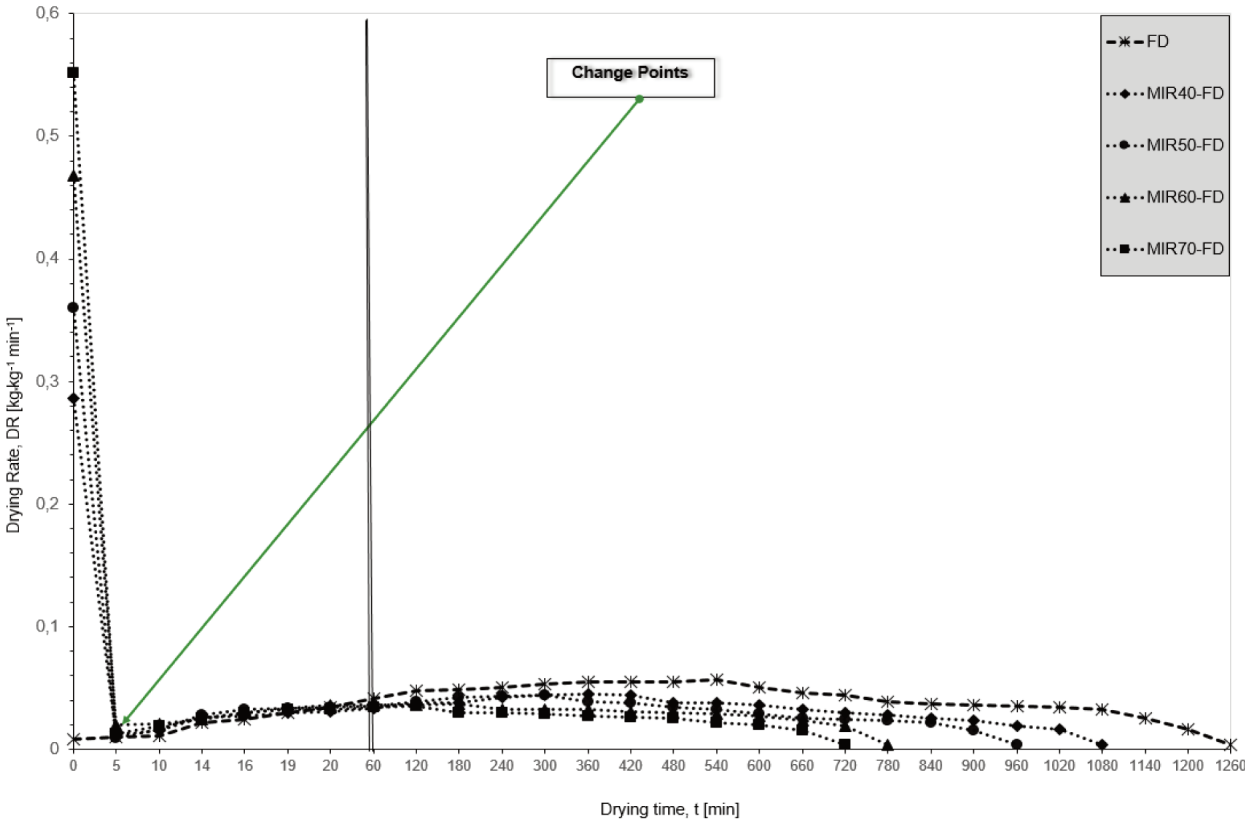


Figure 2. Drying rate curve of pear cubes

Compared with MIR-FD, a drying stage of constant rate period in FD can be observed (between 300 and 480 min). The drying rate of MIR-FD was obviously higher than that of FD. It was observed that the highest drying rate of MIR 70°C-FD was 0.552 kg·kg^{-1} min^{-1} (at the initation of MIR pre-drying), while that of FD was 0.057 kg·kg^{-1} min^{-1}(at the 540 min drying time of FD), indicating that the MIR70°C-FD drying rate was about 9.7 times higher than FD drying rate. This phenomenon due to drying temperature (infrared intensity) of MIR. It was found that the drying rates increased from 0.28 to 0.55 kg·kg^{-1} min^{-1} with an increase in IR intensity at MIR pre-drying. The results were in conjunction with [23], in which the drying rate increased with the increase of drying temperature, and consequently reduced the operational time.

The increased molecular vibration in the exposed material due to absorption of radiation generates heat simultaneously at the surface and in the inner layers of the product. The rapid heating of the sample increased the rate of water removal [24].

A big fluctuation was observed in the MIR-FD drying curve and this might be due to the intermittent working mode of the combined mid-infrared pre-drying and freeze finish-drying method. During the drying, DR were high (0.28-0.55 kg·kg^{-1} min^{-1}) at the beginning of the process, and after that they intensely decreased approx. 0.01-0.02 kg·kg^{-1} min^{-1} at the change point.

The DR decreases continuously with drying time in falling rate period (This is a first falling rate period.). Drying rate under MIR-FD conditions increased from change points, this is a heating period. The values of critical point (peak) of MIR40-70°C-FD at the second stages of drying: 0.045 kg·kg^{-1}·min^{-1} (360 min), 0.044 kg·kg^{-1}·min^{-1} (300 min), 0.037 kg·kg^{-1}·min^{-1} (180 min), 0.035 kg·kg^{-1}·min^{-1} (120 min), respectively. The DR of MIR-FD was very low, gradually declined after critical point of the drying process (This is a second falling rate period). When the moisture content of pear cubes reached to final values, the values of DR at FD, MIR40°C-FD, MIR50°C-FD, MIR60°C-FD, and MIR70°C-FD were 0.0032, 0.004, 0.0038, 0.004 and 0.0044 kg·kg^{-1}·min-1, respectively.

Taking it all round, the MIR-assisted FD drying is considered to be more efficient than FD drying alone, because of a synergistic effect. For MIR drying, the heat efficiency is high, the rate of heat loss is low, and the DR is quicker than that of FD drying.

The variation of dimensionless moisture ratio (MR) with drying time was fitted using two models, including Henderson and Pabis and third-degree polynomial models. The statistical parameters which estimated the model performance and the model constants are shown in Table 2.

The coefficient of determination (R^2) and root mean square error (RMSE) were used to assess how well the models characterized the drying kinetics. The R^2 values for all models were above 0.98. According to the statistical analysis, it was observed that the Henderson and Pabis and third-degree polynomial models presented high values of R^2 and low values of RMSE. The Henderson and Pabis model clearly fitted experimental data of MIR. The values of R^2 and RMSE of the Henderson and Pabis model for MIR dehydrated pear were in the range of 0.9807 to 0.9982, 0.0175 to 0.0465 which indicates the model suitable for describing the drying characteristics of the pear during MIR dying.

A higher drying constant (k) demonstrates a higher drying rate at MIR drying. The values of k and a of the Henderson and Pabis model is higher with increasing in drying temperature (from 40°C to 70°C).

It was observed that the R^2 and RMSE of the third-degree polynomial were in the range of 0.9991 to 0.9998, 0.0067 to 0.0143. Thus, it adequately fit the experimental data for the freeze-drying of the pear cubes.

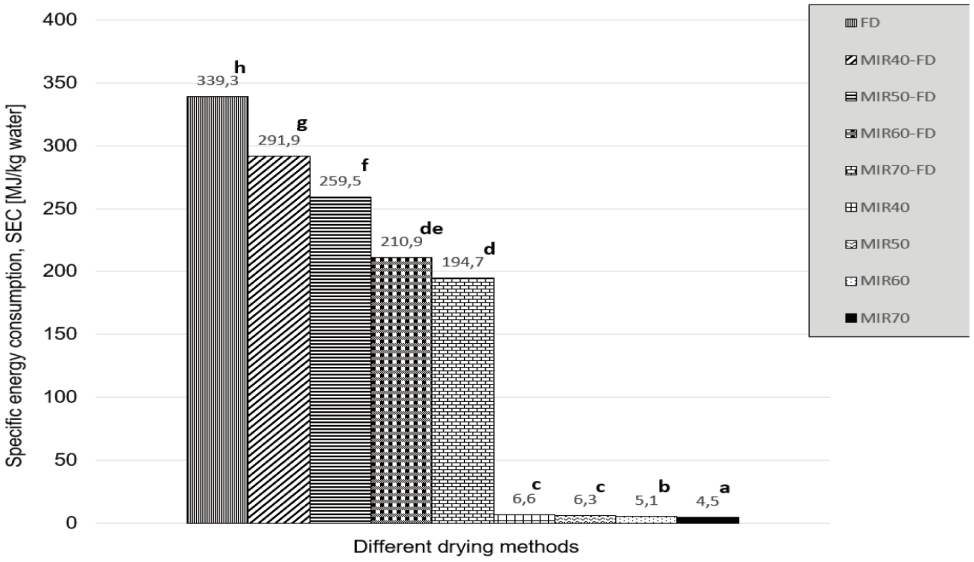
The thin-layer drying models, i.e. Henderson and Pabis and third-degree polynomial models were found to represent the drying kinetics of pear cubes with high R^2 and low RMSE values for all drying conditions.

The model's predicted data were described as curves in Figure 1 and these predicted curves fitted the experimental values very well.

Table 2. Model constants and statistical results obtained from the drying models

Drying method (Symbol)	Model constants					Evaluation criteria	
	k	a	b	c	d	R^2	RMSE
FD	-	0,000085	-0,003736	0,003312	1,008756	0,999102	0,014366
MIR40°C-FD	-	0,000079	-0,002938	-0,003406	0,735488	0,999852	0,006789
MIR50°C-FD	-	0,000103	-0,003547	-0,000284	0,660602	0,999513	0,009134
MIR60°C-FD	-	0,000086	-0,002444	-0,011792	0,567067	0,999428	0,010235
MIR70°C-FD	-	0,000123	-0,003439	-0,001170	0,464552	0,999469	0,010156
MIR40°C	0,539804	1,925862	-	-	-	0,995577	0,029865
MIR50°C	0,642646	2,208593	-	-	-	0,989468	0,042268
MIR60°C	0,761415	2,241401	-	-	-	0,998230	0,017542
MIR70°C	1,111216	3,577709	-	-	-	0,980729	0,046543

FD, freeze-drying; MIR-FD, mid-infrared-assisted freeze-drying; MIR, mid-infrared drying



Means with different letters were significantly different at the level (*P<0.05)*

Figure 3. Specific energy consumptions of pear under various dehydration conditions

uptake of different dryers

The specific energy consumption (SEC) during different drying processes are summarized in Figure 3. The SEC values were varied between 4.5 and 339.3 MJ·kg water^{-1} for all drying conditions. The maximum SEC occurred at the FD drying (339.3 MJ·kg water^{-1} – FD had the longest drying time). In the case of the FD process, the longest drying time resulted the highest SEC.

It can be seen from Figure 3 that the SEC linearly increased with the drying temperature decreased in MIR (pre-drying). It was observed that the SEC of MIR-FD was significantly lower (P<0.05) than that of the FD. The SEC

in the MIR70°C-FD was 194.7 MJ·kg water^{-1}, which was lower than of 42.62% in pure FD drying.

Among all of the drying operations, the SEC of MIR70°C was 4.5 MJ·kg water^{-1}, which was the lowest – it was less, than of 98.67% in single stage of FD dehydration. The MIR drying had significantly lower ($P<0.05$) drying time and energy consumption compared with other drying methods. These results are in agreement with those reported by [25].

It was stated that increasing mid-infrared radiation or drying temperature reduced the operational time, thereby reducing the specific energy consumption. Similar results have also been reported by [26].

Hardness of pear product

The effects of MIR, FD and MIR-FD drying methods on the texture of pear cubes are reported in Figure 4.

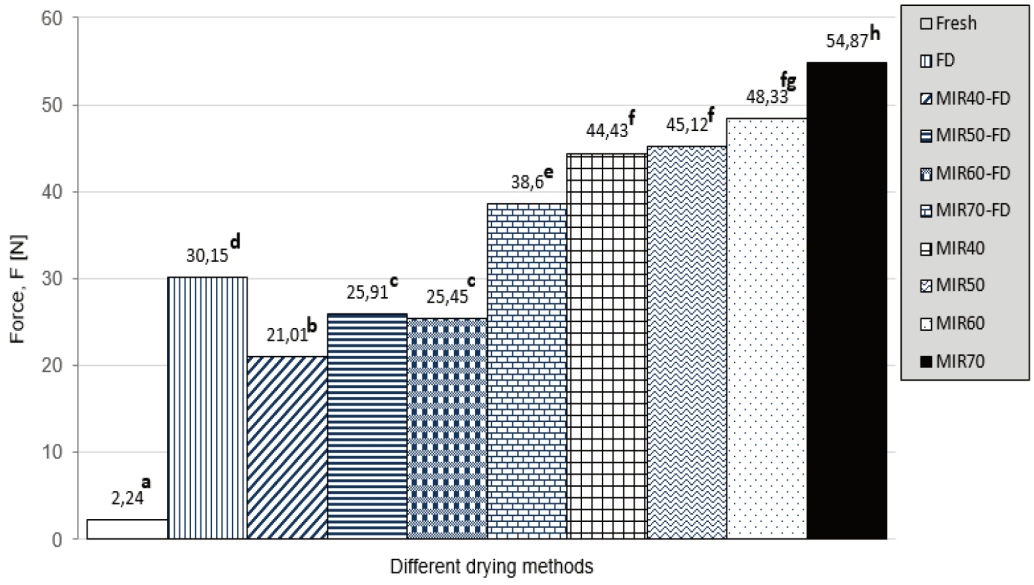


Figure 4. Effect of different drying methods on the hardness of pear cubes

The statistical analysis showed that the effects of drying temperature and drying methods on the firmness were significant ($P<0.05$). The hardness force values for FD, MIR40°C-FD, MIR50°C-FD, MIR60°C-FD, MIR70°C-FD, MIR40°C, MIR50°C, MIR60°C and MIR70°C pears were 30.15, 21.01, 25.91, 25.45, 38.6, 44.43, 45.12, 48.33 and 54.87 N, respectively. It was evidenced that the hardness of biomaterials dried by MIR was higher than for those dried using MIR-FD and FD. Moreover, the hardness of fresh pear (2.24 N) was significantly lower ($P<0.05$) than that of dried products treated by all drying methods.

The pear dehydrated by MIR40-60°C-FD methods show significantly lower ($P<0.05$) firmness values than FD dried sample. This fact can be explained by the drying uniformity and short drying time.

The shorter operational time of MIR pre-drying might have contributed to the better texture quality of the finish product. According to [27] in case of the MIR pre-drying the surface moisture evaporates faster and the inside of the biomaterial retains a porous honeycomb structure. This fact leads to softening of the texture.

The statistical analysis of the biomaterial showed no significant differences ($P>0.05$) between MIR50°C-FD and MIR60°C-FD dried pears.

It can be observed that the FD product result in a clearly porous structure, which explain relatively low firmness of freeze-drying (30.15 N) [28].

The results showed that the higher drying rate and IR power during MIR70°C resulted in significantly higher ($P<0.05$) firmness of the products compared to MIR40-60°C. The results of hardness at MIR40°C, MIR50°C and MIR60°C products showed no significant ($P>0.05$) differences in texture between drying methods. It can be observed, that increasing drying temperature and IR intensity, the hardness values increased ($P>0.05$) at MIR-FD and MIR drying (except of MIR60°C-FD).

Effect of drying on product color

Table 3 presents the color parameters of MIR, FD and MIR-FD dried and fresh pear samples. Color of fresh pear cubes before processing is: L^* =73.59, a^*= 0.22, b^*= 16.86, respectively. Compared to the control (raw material), the L^* and b^* values decreased and the a^* values increased significantly for MIR and MIR-FD dried products. Preferred colors are those closest to the original color of fresh pear cubes.

In general, MIR-FD dried pears were darker (+L^*), redder (+a^*) and less yellow (+b^*) in color than the undried pears. The FD dried product were lighter (+L^*), slightly redder (+a^*) and less yellow (+b^*) than fresh pear cubes.

The L^* values were ranged between 56.97 and 78.18 and a^* values between 2.05 and 8.97 and b^* values between 11.65 and 16.67 for dried pear cubes. The total color

change (ΔE) of pear cubes, calculated from Eq. 8 is colorimetric parameters used extensively to describe the variation of colors in foods during drying. The ΔE of dried pear was in a range between 4.95 and 19.49.

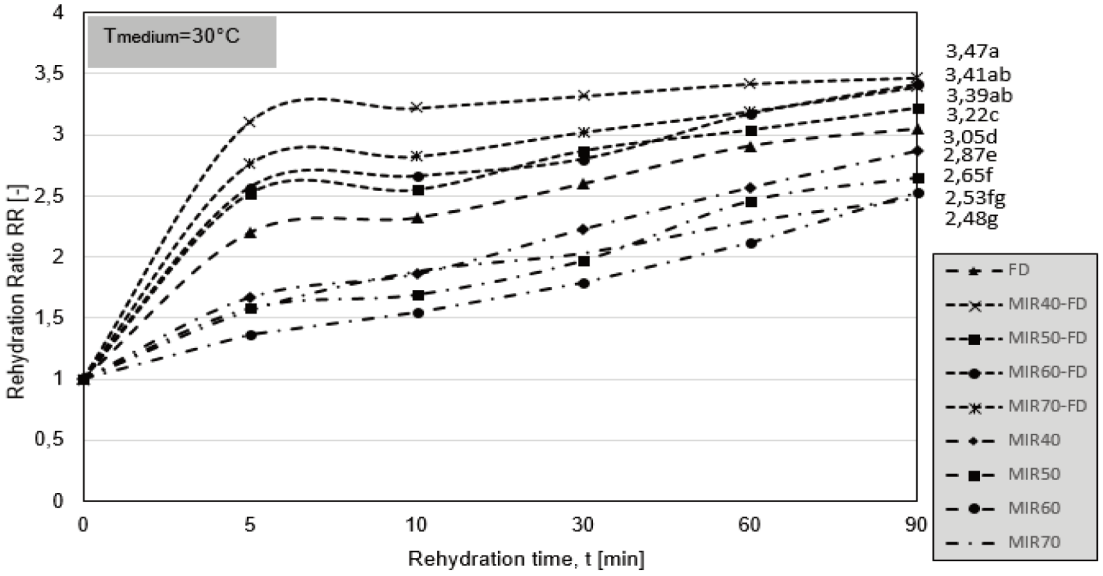
Table 3. Color values of the pear samples produced by using different drying methods

Description	Color parameters			
	L	a	b	ΔE
Fresh material	73,59	0,22	16,86	---
FD	78,18	2,05	16,60	4,95[a]
MIR40°C-FD	71,73	5,29	16,67	5,4[ab]
MIR50°C-FD	66,82	6,45	15,83	9,25[d]
MIR60°C-FD	67,71	4,91	15,82	7,59[c]
MIR70°C-FD	63,83	6,01	14,60	11,56[e]
MIR40°C	60,66	7,23	13,40	15,11[f]
MIR50°C	58,67	7,56	12,52	17,18[h]
MIR60°C	59,23	7,13	12,98	16,40[fg]
MIR70°C	56,97	8,97	11,65	19,49[i]

Means with different letters in the same column were significantly different at the level (P<0.05)
FD, freeze-drying; MIR-FD, mid-infrared-assisted freeze-drying; MIR, mid-infrared drying.

The FD dried pear exhibited the highest L* value and the lowest ΔE value, followed by MIR-FD and MIR pear showed the lowest L* value and the highest *ΔE* value. High L* value (78.18) of FD pear indicated that the brightness coordinate faded due to freezing process in FD drying. Freezing rate during FD drying is one of the causes of significant *ΔE* (4.95) changes in FD products. The b* values of the samples (16.60 and 16.67) showed that the FD and MIR40°C-FD pear cubes resembled the fresh product. This can be explained by the sensitivity of pear to temperature. The FD and MIR40°C-FD drying caused little color change compared with the raw pear cubes. During the FD process, the Maillard reaction was inactivated.

The color of MIR40°C-FD product was the closest to that of the FD samples. There were no significant differences (P>0.05) observed in the total color difference (*ΔE*) among the two drying methods. It is clear that lower drying temperature (IR intensity) and longer operational time of FD finish-drying maintained the original color of fresh pear cubes better. This can be explained by the short drying times and relatively low temperatures in case of MIR pre-drying which did not promote browning reactions.



Means with different letters were significantly different at the level (*P<0.05)*

Figure 5. Effect of different drying methods on the rehydration characteristics of pear

It can be seen that the L* value (71.73) of dried product by MIR40°C-FD is very similar to fresh material. Drying temperatures were above 40°C at MIR-FD, rendering the possibility to the Maillard browning (so called non-

enzymatic browning). It was observed that the L^* value is relevant to browning in the products. In the case of L^* value, it was found that drying temperature and drying methods were the significant factors influencing the changes in brightness.

However, at the end of the drying the total color difference for MIR-FD at 40°C-70°C was the significantly ($P<0.05$) less than that for MIR drying at same drying temperature. The higher drying temperature (higher emission peak wavelength) may be the reason for deterioration of color of pear during MIR from 40°C to 70°C. The present color results indicated that the MIR products were darker (browner and redder) than those of the FD and MIR-FD samples. The MIR products provided the highest a^* and lowest L^* and b^* values due to charring. The Maillard reaction and caramelization, may also occur due to heat during the MIR drying process. As the IR power increased, the ΔE values of the MIR and MIR-FD samples increased significantly ($P<0.05$) – except of MIR60°C and MIR60°C-FD.

Rehydration capacity

The Rehydration Ratio (RR) values of pear cubes dried by MIR, FD and MIR-FD are shown is Figure 5.

The end of the rehydration process the RR values for pear cubes dried with MIR40°C-FD, MIR60°C-FD, MIR70°C-FD, MIR50°C-FD, FD, MIR40°C, MIR50°C, MIR60°C and MIR70°C were 3.47, 3.41, 3.39, 3.22, 3.05, 2.87, 2.65, 2.53 and 2.48, respectively. The RR of the biomaterial dried by MIR-FD was the highest, followed by FD and MIR dried pear dices, and there was significant difference ($P<0.05$) between each methods. Opposite trend was observed in the previous study [25]. The MIR-FD was found to be inferior compared to the FD-MIR as the former tended to produce products with a collapse surface layer and poor rehydration capacity.

From Figure 5 we can see that the highest RR values in dried pear cubes by MIR-FD was because fewer physical and chemical changes occurred in the MIR-FD process due to shorter drying time and uniform heating compared to FD. The MIR pre-drying shows great promise in this respect. There were no significant differences ($P>0.05$) observed between MIR40°C-FD, MIR60°C-FD and MIR70°C-FD dried products. The water uptake curve of MIR-FD samples was suddenly jumped during the first 5 minutes of the rehydration procedure. This is because of the fast rehydration achieved with MIR-assisted FD materials. When the rehydration time was increased from 5 to 60 min, the RR of pear cubes was rose slightly at MIR-FD. All of the MIR-FD and FD samples showed stabilization in rehydration curve from 60 to 90 min – the samples became saturated.

Faster drying with IR and quicker diffusion of water vapor from the pear might help the sample retains its porous, less dense structure, increasing its ability to absorb more water during rehydration process [29]. Roknul et al. [30] was observed some porous spaces in the tissue cells of the material dried by IR. This phenomenon can be explained by the fact that during IR, some swelling occurs in the tissue cells due to the absorbance of IR radiation, especially in a thin-layer on the sample surface.

The relatively higher rehydration capacity of FD products (RR=3.05) might be the result of such enhanced porous structures and prevention of tissue collapse. It was observed that the RR of FD after relatively rapid water uptake (at the beginning of rehydration process) gradually increased until reached the constant state at 60 min.

The pear cubes dried by MIR showed the significantly ($P<0.05$) lowest RR (between 2.48 and 2.87), but the values of RR is not negligible. The RR of MIR-FD sample almost doubled than the MIR samples when the rehydration process was reached 5 and 10 min. In addition, when the soaking time was increased from 10 min to 90 min, the RR of samples was increased slightly at MIR. The RR was found to decrease with increasing IR intensity levels (drying temperature) at MIR drying. Data indicated that increasing IR intensity level from 3 to 5.5 kW m^{-2} exhibited a decline in RR of MIR40°C-70°C from 2.87 to 2.48.

The difference in rehydration attribute was related to surface hardening and the degree of structural damage which occurred during dehydration.

4. Conclusion

Three drying methods, i.e. mid-infrared-freeze drying (MIR-FD), freeze-drying (FD) and mid-infrared drying (MIR) were used in the preparation of pear cubes at four different drying temperatures (40, 50, 60 and 70°C) and the drying kinetics, the specific energy consumption (SEC), physical and mechanical properties of product (rehydration, color and texture) was investigated.

Application of mid-infrared-freeze drying enhanced the drying rate and significantly reduced ($P<0.05$) the operational time and SEC for pear samples. The dehydration rate (DR) of MIR-FD for pear cubes was higher than FD and was lower than MIR. The total drying time required for MIR-FD methods was 720-1080 min, reduced by 43-14% compared to pure FD (1260 min). Moreover, the operational time of MIR70°C-FD was the shortest, followed by MIR60°C-FD, MIR50°C-FD and MIR40°C-FD. It was found that the drying rate increases substantially with the increase in infrared drying temperature (intensity level).

In order to explain the drying behavior of pear, two thin-layer drying models were used. The drying kinetics were well-fitted by Henderson and Pabis model and third-degree polynomial model could adequate describe the dehydration behavior of pear under MIR, FD and MIR-FD conditions.

The MIR-FD products had softer texture (except of MIR70°C-FD) and better rehydration capacity than the FD and MIR samples. In terms of physical attributes of product, FD showed the better color. Pears dried by MIR had the worst quality, but cost the lowest SEC.

Hence, taking into account the drying characteristics and the product quality attributes, the combined mid-infrared pre- and freeze finish-drying (optimum condition: MIR50-60°C-FD) was the best method for industrial processing of

pear and commercial-scale application. On the basis of our results, it can be recommended that the MIR pre-drying temperature of pear should not exceed 60°C during the dehydration process.

References

[1] Kolniak-Ostek J.: 2016. Identification and quantification of polyphenolic compounds in ten pear cultivars by UPLC-PDA-Q/TOF-MS. Journal of Food Composition and Analysis, Vol. 49, pp. 65-77. http://dx.doi.org/10.1016/j.jfca.2016.04.004

[2] Wojdyło A., Figiel A., Oszmiański J.: 2009. Effect of drying methods with the application of vacuum microwaves on the bioactive compounds, color, and antioxidant activity of strawberry fruits. Journal of Agricultural and Food Chemistry, Vol. 57, Issue 4, pp. 1337-1343.
http://dx.doi.org/10.1021/jf802507

[3] Kerekes B., Antal T.: 2006. Drying methods of fruits and vegetables. Hungarian Agricultural Engineering, Vol. 19, pp. 43-45. Published online: ISSN 0864-7410

[4] Ciurzynska A., Lenart A.: 2011. Freeze drying – application in food processing and biotechnology – a review. Polish Journal of Food and Nutrition Science, Vol. 61, Issue 3, pp. 165-171. http://dx.doi.org/10.2478/v10222-011-0017-5

[5] Ratti C.: 2001. Hot air and freeze-drying of high-value foods: a review. Journal of Food Engineering, Vol. 49, Issue 9, pp. 311-319. http://dx.doi.org/10.1016/S0260-8774(00)00228-4

[6] Chou S. K., Chua K. J. 2001. New hybrid drying technologies for heat sensitive foodstuffs. Trends Food Science and Technology, Vol. 12, Issue 10, 359-369.
http://dx.doi.org/10.1016/S0924-2244(01)00102-9

[7] Lechtanska J. M., Szadzinska J., Kowalski S. J.: 2015. Microwave- and infrared-assisted convective drying of green pepper: Quality and energy considerations. Chemical Engineering and Processing: Process Intensification, Vol. 98, pp. 155-164.
http://dx.doi.org/10.1016/j.cep.2015.10.001

[8] Hebbar H. U., Rastogi N. K.: 2001. Mass transfer during infrared drying of cashew kernel. Journal of Food Engineering, Vol. 47, Issue 1, pp. 1-5.
http://dx.doi.org/10.1016/S0260-8774(00)00088-1

[9] Chen Q., Bi J., Wu X., Yi J., Zhou L., Zhou Y.: 2015. Drying kinetics and quality attributes of jujube (Zizyphus jujube Miller) slices dried by hot-air and short- and medium-wave infrared radiation. LWT – Food Science and Technology, Vol. 64, Issue 2, pp. 759-766.
http://dx.doi.org/10.1016/j.lwt.2015.06.071

[10] Wang L., Zhang M., Fang Z., Xu, B.: 2014. Application of intermediate-wave infrared drying in preparation of mushroom chewing tablets. Drying Technology Vol. 32, Issue 15, pp. 1820-1827.
http://dx.doi.org/10.1080/07373937.2014.949347

[11] Riadh M. S., Ahmad S. A. B., Marhaban M. H., Soh, A. C. 2015. Infrared heating in food drying: An overview. Drying Technology, Vol. 33, Issue 3, pp. 322-335. http://dx.doi.org/10.1080/07373937.2014.951124

[12] Chong C. H., Figiel A., Law C. L., Wojdylo A.: 2014. Combined drying of apple cubes by using of heat pump, vacuum-microwave, and intermittent techniques. Food Bioprocess Technology, Vol. 7, Issue 4, pp. 975-989.
http://dx.doi.org/10.1007/s11947-013-1123-7

[13] Poós T., Örvös M.: 2012. Heat and mass transfer in agitated, co-, or countercurrent conductive–convective heated drum dryer. Drying Technology, Vol. 30, Issue 13, pp. 1457-1468.
http://dx.doi.org/10.1080/07373937.2012.689402

[14] Mészáros Cs., Farkas I., Bálint Á.: 2001. A new application of percolation theory for coupled transport phenomena through porous media. Mathematics and Computers in Simulation, Vol. 56, pp. 395–404.
http://dx.doi.org/10.1016/S0378-4754(01)00310-X

[15] Beke J., Kurják Z., Bessenyei K.: 2012. Konvekciós szárítási modellek alkalmazási lehetőségei a mikrohullámú szárítási folyamatokban. Mezőgazdasági Technika, Vol. 53, Issue 7, pp. 30-32.

[16] Pekke M. A., Pan Z., Atungulu G. G., Smith, G., Thompson J. F.: 2013. Drying characteristics and quality of bananas under infrared radiation heating. International Journal of Agricultural and Biological Engineering, Vol. 6, Issue 3, pp. 58-70.
http://dx.doi.org/10.3965/j.ijabe.20130603.008

[17] Szczesniak A. S.: 2002. Texture is a sensory property. Food Quality and Preference, Vol. 13, Issue 4, pp. 215-225.
http://dx.doi.org/10.1016/S0950-3293(01)00039-8

[18] Krokida M. K., Marinos-Kouris D.: 2003. Rehydration kinetics of dehydrated products. Journal of Food Engineering, Vol. 57, Issue 1, pp. 1-7.
http://dx.doi.org/10.1016/S0260-8774(02)00214-5

[19] Henderson S. M., Pabis S.: 1961. Grain drying theory II: Temperature effects on drying coefficients. Journal of Agricultural Engineering Research, Vol. 6, Issue 3, pp. 169-174.

[20] Antal T., Kerekes B.: 2015. Investigation of hot air- and infrared-assisted freeze-drying of apple. Journal of Food Processing and Preservation, Vol. 40, Issue 2, pp. 257-269. http://dx.doi.org/10.1111/jfpp.12603

[21] Celma A.R., López-Rodríguez F., Blázquez F. C.: 2009. Experimental modelling of infrared drying of industrial grape by-products. Food and Bioproducts Processing, Vol. 87, Issue 4, pp. 247-253.
http://dx.doi.org/10.1016/j.fbp.2008.10.005

[22] Lin Y. P., Tsen J. H., King V. A. E.: 2005. Effects of far-infrared radiation on the freeze-drying of sweet potato. Journal of Food Engineering, Vol. 68, Issue 2, pp. 249-255.
http://dx.doi.org/10.1016/j.jfoodeng.2004.05.037

[23] Sharma G. P., Verma R. C., Pathare P. B.: 2005. Thin-layer infrared radiation drying of onion slices. Journal of Food Engineering, Vol. 67, Issue 3, pp. 361-366.
http://dx.doi.org/10.1016/j.jfoodeng.2004.05.002

[24] Puente-Diaz L., Ah-Hen K., Vega-Gálvez A., Lemus-Mondaca R., Di Scala K.: 2013. Combined infrared-convective drying of Murta (Ugni molinae Turcz) Berries: Kinetic Modelling and quality assessment. Drying Technology, Vol. 31, Issue 3, pp. 329-338.
http://dx.doi.org/10.1080/07373937.2012.736113

[25] Wang H., Zhang M., Adhikari B.: 2015. Drying of shiitake mushroom by combining freeze-drying and mid-infrared radiation. Food and Bioproducts Processing, Vol. 94, pp. 507-517.
http://dx.doi.org/10.1016/j.fbp.2014.07.008
[26] Ning X., Lee J., Han C.: 2015. Drying characteristics and quality of red ginseng using far-infrared rays. Journal of Ginseng Research, Vol. 39, Issue 4, pp. 371-375.
http://dx.doi.org/10.1016/j.jgr.2015.04.001
[27] Wang H., Zhang M. Mujumdar A. S.: 2014. Comparison of three new drying methods for drying characteristics and quality of shiitake mushroom (Lentinus edodes). Drying Technology, Vol. 32, Issue 15, pp. 1791-1802.
http://dx.doi.org/10.1080/07373937.2014.947426
[28] Ferenczi S., Czukor B., Cserhalmi Zs.: 2014. Evaluation of microwave vacuum drying combined with hot-air drying and compared with freeze- and hot-air drying by the quality of the dried apple product. Periodica Polytechnica. Chemical Engineering, Vol. 58, Issue 2, pp. 111-116. http://dx.doi.org/10.3311/PPch.7082
[29] Nasiroglu S., Kocabiyik H.: 2009. Thin-layer infrared radiation drying of red pepper slices. Journal of Food Process Enginering, Vol 32, Issue 1, pp. 1-16.
http://dx.doi.org/10.1111/j.1745-4530.2007.00195.x
[30] Roknul A. S. M., Zhang M., Mujumdar A. S., Wang Y.: 2014. A comparative study for four drying methods on drying time and quality characteristics of stem lettuce slices (Lactuca sativa L.). Drying Technology, Vol. 32, Issue 6, pp. 657-666.
http://dx.doi.org/10.1080/07373937.2013.850435