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Comparative study of three drying methods: freeze, hot air-assisted freeze and infrared-assisted freeze modes

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Abstract. The dehydration tests were conducted at three drying methods to evaluate the drying curves and the energy uptake. Apple (*Malus domestica* L.) cubes were dried under different processing conditions applying freeze drying (FD), freeze drying assisted by hot air and freeze drying assisted by infrared radiation. Control samples were produced using regular freeze drying without the pre-drying. Hot air combined with freeze drying (HAD-FD) at 60 and 80°C air temperatures was investigated. The infrared-freeze drying (IR-FD) is a relatively new processing method. The *Idared* apple cubes were dried with 5 kW m^{-2} IR power intensity. It was observed that the infrared power level and hot air temperature affected the drying rate and time of freeze drying. The infrared radiation heating had a higher drying rate than hot air during the pre-dehydration. The water activity, colour, firmness and rehydration ratio (RR) of finished products were measured. The dried material produced with IR-FD had desirable colour, higher rehydration rate and lower firmness than dried by HAD-FD ones. The quality of single-stage FD samples was close to IR-FD materials. It was observed that the IR-FD method drastically decreased the energy consumption, compared to FD and HAD-FD drying treatments. The mathematical models such as Henderson-Pabis and third-degree polynomial are used to describe the drying kinetics of food material. It was found that those mathematical models performed adequately in predicting the changes of moisture ratio.

Key words: Combination or hybrid drying, quality assessment, energy uptake, modelling.

INTRODUCTION

Apple is an important material for many food products and apple plantations are cultivated all over the world in many countries. Apple is a high moisture food with moisture content of 80–85% (in w.b.). Unsuitable preservation and storage methods cause losses of fruits which range from 10% to 30% (Togrul, 2005).

The technique of drying is probably the oldest method of food preservation practiced by mankind. Drying of foods is mainly aimed at reducing the moisture to extend the shelf life. The major challenge during dehydration of food is to reduce the energy consumption and the water content of the material to the desired level without substantial loss of colour, appearance, flavour, taste and chemical components. In prepare of functional foods and ready-to-eat foods, freeze-drying or lyophilisation (FD) method is used generally. Freeze drying is a dehydration operation with the sublimation of ice from frozen material. Because of the absence of liquid water and the low temperature (approx. 20°C) used in the operation process, most of deterioration and microbiological reaction are stopped (Lin et al., 2007). Three main steps are involved in

FD process: freezing, sublimation and desorption. In this method shrinkage is eliminated, minimum loss of flavour, aroma, vitamins, and near-perfect preservation results are obtained. Although freeze drying can be applied to manufacture products with complete structural retention, it is an expensive process, due to its long drying time (approx. 20–30h) (Antal et al., 2014). In recent years, freeze drying is combined with various other dehydration methods such as hot air, infrared radiation, microwave and microwave-vacuum.

Foodstuffs with high moisture content can be effectively dried using combination methods, as it provides the synergistic effect. Hybrid drying, like hot air-freeze drying (Xu et al., 2005) and infrared-freeze drying (Wang et al., 2014) have been successfully employed in order to improve the effectiveness of dehydration. Pan et al. (2008) used sequential infrared and freeze drying to produce high-quality dried fruits at reduced cost. The products dried using infrared-freeze drying had better colour, higher shrinkage, higher crispiness but poor rehydration capacity compared to those produced by using single stage freeze drying. According to earlier reports, hot air (HAD) pre-drying can reduce by about half the drying time needed for traditional freeze drying (Kumar et al., 2001). The optimization of IR and HAD application for FD operation is an innovative development that can amplify drying efficiency, shorten drying time and enhance product quality (Chakraborty et al., 2011).

Hot air drying (HAD) is the most commonly employed commercial technique for drying vegetables and fruits, in which heat is transferred from the hot air to the product by convection, and evaporated water is transported to the air also by convection (Lewicki, 1998). However, the major disadvantage associated with hot air dehydrating is the long drying time even at temperatures near 60°C, resulting in the degradation of material quality (Kumar et al., 2005).

Infrared (IR) drying is based on the action of IR wavelength radiation from heat source, which interacts with the internal structure of the sample and thus increases its temperature and favours the evaporation of its moisture (Celma et al., 2008). During drying, the infrared rays penetrate into the wet sample to a certain depth and increase their temperature without heating the surrounding air. Then, the diffusion rate of the water through the material increases and consequently the radiation properties of the samples are changed due to decreasing moisture content, which diffused out of the materials into the air (Laohavanich & Wongpichet, 2008). IR drying is gaining popularity in food processing because of its inherent advantages over hot air drying. IR drying has many advantages including uniform heating, high heat transfer rate, reduced processing time and energy uptake and improved product quality (Sandu, 1986; Vishwanathan et al., 2013).

The objectives of this research were to compare the freeze drying with the combination drying (IR-FD and HAD-FD), for apple, considering drying time, energy consumption, change of physical properties (colour, water activity, rehydration rate and hardness), and additionally to find a model to describe the FD, HAD-FD and IR-FD drying characteristics.

To our knowledge, no work or little detailed information is available the effect of hybrid drying (HAD-FD and IR-FD) on the quality and drying characteristic of apple.

MATERIALS AND METHODS

Raw material

Ripe *Idared* apples (*Malus domestica* L.) were picked from the orchard near Nyíregyháza and stored in a refrigerator (5°C) until use. The apples were cored with a household tool, washed with tap water and cut into cubes with 5 mm thickness. The cause of relatively thin sample: Increases in thickness reduce the penetration of the IR radiation and thereby decreases the drying rate (Kumar et al., 2005).

The samples were divided into nine groups, each group of samples weighed 100 g. The initial mass of apple cubes was measured using a balance (model JKH-500, Jadever Co., Taiwan) with 0.1 g precision. The sliced apple samples were subjected to dryers immediately after cutting to avoid surface enzymatic browning.

Determination of moisture content

Moisture content of the raw and dried apple dices was determined by the gravimetric method (model LP306, LaborMIM, Hungary). At regular time intervals during the drying process, samples were taken out and dried for 8 h at 105°C until constant weight. Weighing was performed on a digital balance (JKH-500, Jadever Co., Taiwan) and then moisture content was calculated. Moisture content was expressed in wet matter (g 100 g^{-1} fresh matter, %) and in dry matter (kg moisture kg dry $matter^{-1}$). The initial moisture content of the apple was found to be 84.8% (wet basis: w.b.), 5.578 kg H_2O kg dry $matter^{-1}$ (dry basis: d.b.). The tests were performed in triplicate.

Drying procedure

The apple slices were dried by different drying methods with the optimal drying technology until final moisture content (5–6%, wet basis: w.b.). The applied drying methods are described under-mentioned. The drying process was continued until no moisture content was recorded (The samples was dried until it reached the equilibrium moisture content, otherwise no change in 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 – was cooled and packed in low-density polyethylene (LDPE) bags that were heat-sealed.

Convective drying (HAD) was carried out in a hot-air dryer (model LP306, LaborMIM, Hungary) at 60 and 80°C with an air flow rate of 1 m/s. Air humidity was regulated at ≈20%. The samples (100 g) were spread uniformly, in single layer on the trays of dryer. After 1h, the trays were taken out of the equipment, weighed, and then put back in the dryer. During the drying process, the weight of the apple cubes was recorded to construct a drying curve, and the temperature (material and air), air velocity, air humidity was measured using a Testo 4510 type meter (Testo GmbH, Germany). The mass was measured on an analytical balance (model JKH-500, Jadever Co., Taiwan) with a precision of ± 0.1 g. The apples were dehydrated until they reached the final moisture content (6%, w.b.).

Infrared drying (IR) was conducted by 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 was maintained at 5 kW m^{-2} (Infrared intensity is usually expressed as radiation power per unit area). The quartz glass emitter is located at a distance of 15 cm from the apple surface. The sample tray was supported on a balance (a precision of ± 0.1 g, model Precisa, Precisa Instruments AG, Swiss) to monitor the sample weight change during drying. The samples were spread uniformly in a monolayer on the aluminium tray. A vent was provided at the top of the chamber for the exit of moist air. The experiment was carried out for 60°C drying temperature. The emitter temperature and relative humidity was measured by Testo 4510 type meter (Testo GmbH, Germany) at the top of chamber. However, the relative humidity was not controlled during the laboratory test.

Freeze drying (FD) was performed in a laboratory-scale Armfield FT-33 freeze-dryer (Armfield Ltd., England). In the FD process, the apple dices were spread uniformly in a single layer on a stainless steel tray. The apple samples (100 g) were frozen at -21°C in a freezing/heating chamber and freeze dried to a moisture content of 5–6% (w.b.) at an absolute pressure of 85–90 Pa with a chamber temperature of 20°C and a condenser temperature of -48°C. Thermocouples (four pieces) of freeze drier were inserted into the apple cubes. The weight loss of the samples was followed by a data logger and a RS-232 attached to a PC computer, acquired the data readings from platform cell, which is placed within the sample chamber.

For **hybrid or combination drying** the apple samples were dried by FD drier by coupling with the HAD and IR devices before the freeze drying step until the final moisture content was between 4.88–6.03% (w/w). The samples after pre-drying procedure (HAD, IR) immediately placed into the FD. The experimental samples dried by HAD at 60°C for 3 h (HAD-FD1), HAD at 80°C for 3 h (HAD-FD2), IR at 60°C for 3 min (IR-FD3), IR at 60°C for 4 min (IR-FD4) and IR at 60°C for 5 min (IR-FD5) then dried by FD were chosen for further quality evaluation. The drying parameters are in agreement with above-mentioned ones (points of 1–3). The Table 1 demonstrates the main details of different drying process.

Table 1. Applied drying experiments

Abbreviation	Definition of the process	Drying temp., IR intensity	Pre-drying time
FD	single-stage of freeze drying	–	–
HAD-FD1	hot air pre- and freeze finish-drying	60°C	3 h
HAD-FD2	hot air pre- and freeze finish-drying	80°C	3 h
IR-FD3	infrared pre- and freeze finish-drying	60°C, 5 kW m^{-2}	3 min
IR-FD4	infrared pre- and freeze finish-drying	60°C, 5 kW m^{-2}	4 min
IR-FD5	infrared pre- and freeze finish-drying	60°C, 5 kW m^{-2}	5 min

Mathematical modelling of drying curve

Mathematical modelling of drying is important for optimum management of operating parameters and prediction of performance of the drying system (Jain & Pathare, 2004). There are several empirical approaches for modelling 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 (Table 2). The moisture content of samples is defined by (1):

$$M_t = \frac{m_t - m_f}{m_f}, \quad (1)$$

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

The dimensionless moisture ratio (MR) was calculated as (2):

$$MR = \frac{M_t - M_e}{M_0 - M_e}, \quad (2)$$

where: M_t – the moisture content at time t on dry basis; M_e – the equilibrium moisture content, kg H_2O kg dm^{-1}; M_0 – the initial moisture content, kg H_2O kg dm^{-1}.

For infrared drying, Fasina et al. (1998) explained that the M_e has been numerically set zero, since prolonged exposure of food to IR radiation eventually causes the burning of the samples, which happens only at nearly zero moisture content. Therefore the moisture ratio (MR) was simplified to M_t/M_o instead of $(M_t-M_e)/(M_0-M_e)$–not only at IR. The selected mathematical models are identified in Table 2.

Table 2. Mathematical models for modelling drying of apple

Model designation	Model equation	Reference
Henderson and Pabis	$MR = a \cdot e^{-k \cdot t}$	Doymaz, 2012
Third-degree polynomial	$MR = a \cdot t^3 + b \cdot t^2 + c \cdot t + d$	Antal et al., 2014

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

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 (3, 4):

$$R^2 = \frac{residual\ sum\ of\ squares}{corrected\ total\ sum\ of\ squares}, \quad (3)$$

$$RMSE = \sqrt{\frac{1}{N} \cdot \sum_{i=1}^{N} (MR_{\exp_i} - MR_{pre_i})^2}\ , \qquad (4)$$

where: N – the number of observations; *exp* – the experimental data; *pre* **–** the predicted data; MR – moisture ratio.

Measuring of energy uptake of driers

Energy used in the drying and heating process is important for production processes in the industrial and household sectors. However, the price of energy is extremely expensive; therefore, there are a strong incentive to invent processes that will use energy efficiently. Currently, widely used drying processes are complicated and inefficient; moreover, it is generally damaging to the environment. What is needed is a simplified, lower-cost approach to this process one that will be replicable in a range of situations (Jindarat et al., 2011). The total energy consumption (E, kWh) during FD, HAD-FD and IR-FD was measured by an energy-cost-checker (model EKM 265, Conrad Electronic GmbH, Germany). Analysis was performed in triplicate.

Colour measurement

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

An important factor characterizing the variation of colour in the test sample is total colour difference. The total colour change (ΔE) was evaluated as (5):

$$\Delta E = \sqrt{(L_0 - L)^2 + (a_0 - a)^2 + (b_0 - b)^2}\ , \qquad (5)$$

where: L^* – the degree of lightness (100) and darkness (0); a^* – the degree of redness (+) and greenness (–); b^*– the degree of yellowness (+) and blueness (–). Subscript 'zero' refers to the colour reading of fresh apple cubes as the control. A larger ΔE value denotes greater colour change from the control (fresh) sample.

Both chroma (C) and hue (h) are derived from a* and b* using the following equations (6, 7):

$$C = \sqrt{a^2 + b^2} \qquad (6)$$

$$h = \arctan\left(\frac{b}{a}\right) \qquad (7)$$

The chroma describes the vividness or dullness of a colour. The hue angle (h) an indicator of browning colour, expresses the colour nuance and values are defined as follows: red-purple: 0°, yellow: 90°, bluish-green: 180°, and blue: 270°.

Determination of water activity (a_w)

The water activity (a_w) shows how tightly the water is bound in the food material. Low water activity foods are those with water activity levels lower than 0.8. Therefore, the targeted a_w of dried products was 0.6, the general level limits for the growth of yeast, molds and bacteria (Shi et al., 2008). Approximately 3 g of chopped dried apple samples were placed in the sample holder of a Novasina Labmaster (model CH-8853, Novasina AG, Switzerland) a_w-meter. The temperature and duration for testing were at 25°C and 30 min. The tests were replicated three times.

Texture (hardness) test

Texture is considered one of the most important criteria concerning eating quality of dried apple cubes (Deng & Zhao, 2008). The texture characteristics of the fresh and dehydrated apple were measured using a CT3-4500 (Brookfield Engineering Laboratories, Middleboro, USA) texture analyser 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 following: 4.5 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 10 g. A 115 mm diameter plate (rotary base table) was used as a base while compressing the apple samples. The samples were kept in a room temperature at 23°C until analysis. The penetrometer measurements are reported in Newtons (N). Ten samples were tested and the average values were reported.

Rehydration capacity process

The rehydration characteristics of the dried material are always used as an index of structural quality, and it largely depends on the dehydration conditions employed (Vishwanathan et al., 2010).The measurement of the water rehydration ratio was based on the following procedure. 100 ml of distilled water was brought to a temperature of 22°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 30 and 60 min. Afterwards, the samples were taken out (when the time reached 30 and 60 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, Taiwan) having a sensitivity of 0.1 g. The RR values were determined in triplicate. Rehydration ratio (RR) of dehydrated samples was estimated using the equation given below (8):

$$RR = \frac{W_r}{W_d}, \quad (8)$$

where: W_r – the drained weight of the rehydrated sample, g; W_d – the weight of the dry sample used for rehydration, g.

Statistical analysis

Data analyses were determined using the PASW Statistics 18 software (IBM Corp., USA), and analyses of variance were conducted by ANOVA procedure, Duncan test. Mean values were considered significantly different when $P < 0.05$. The parameters of model were calculated using Table Curve 2D Windows v. 2.03 (Jandle Scientific, San Rafael, CA)

RESULTS AND DISCUSSION

Drying kinetics of FD, HAD-FD and IR-FD drying

The time required for drying the apple and the final moisture content of sample under different dehydration modes is presented in Table 3. The reduction in drying time was between 45.5% and 27.3% with hybrid drying (IR-FD and HAD-FD), respectively as compared to freeze drying (FD).

The Fig. 1 shows that the traditional FD process required the longest drying time (22 h). This is because FD, under vacuum conditions, supplies the sublimation heat by conduction. The rate of heat transfer is slow and thus drying takes a long time (Duan et al., 2012).

The required HAD-FD1-2 and IR-FD3-5 drying times for obtaining the final products were 16, 14, 14, 12 hours, respectively. The infrared-assisted freeze drying (IR-FD4-5) reduced the drying time considerably over hot air-assisted freeze drying (HAD-FD1-2) in both the cases. The results showed the synergistic effect of IR-FD drying. The reduction in drying time could lead to consuming lesser energy for processing.

Table 3. Effect of drying methods on moisture content, drying time of dehydrated apple

Drying method (Symbol)	Final moisture cont. (%, w.b. and d.b.)		Total drying time (h)	Reduction in FD time (%)
FD	5.78	0.151	22^{d}	–
HAD-FD1	6.03	0.180	16^{c}	27.27^{c}
HAD-FD2	5.98	0.167	14^{b}	36.36^{b}
IR-FD3	4.88	0.109	14^{b}	36.36^{b}
IR-FD4	5.11	0.130	12^{a}	45.45^{a}
IR-FD5	5.07	0.126	12^{a}	45.45^{a}

Means with different letters in the same column were significantly different at the level $P < 0.05$.

The apple cubes of initial moisture content of 84.8% (w.b.) was dried to the final moisture content of 4.88–6.03% (w.b.) until no further changes in their mass were observed. The final moisture content of the IR-FD3 treated apple was lower than the apple dried with other modes.

Two drying model have been used to describe drying kinetics. The model constants and coefficients of this models used for moisture ratio change with time are presented in Table 4. An increase in drying temperature resulted in higher values of k in cases of HAD, as it largely depends on the hot air temperature.

The acceptability of the model is based on a value for the coefficient of determination (R^2) which should be close to one, and low values for the root mean square error (RMSE). The values of R^2 and RMSE of the third-degree polynomial model are between 0.9923–0.9996 and 0.017204–0.005328, respectively. Similarly, the values R^2

and RMSE of the Henderson-Pabis model are between 0.9550–0.9864 and 0.096721–0.026763, respectively.

Consequently, it can be stated that the Henderson-Pabis and polynomial models gives an adequate description of the drying characteristic. The high values of R^2 (> 0.95) and low parameters of RMSE (< 0.1) indicated that the calculated results were in good agreement with the experimental data. Therefore, these models can be proposed for predicting changes in moisture ratio with time.

The changes in the moisture ratio (MR) with time during HAD, IR, HAD-FD and IR-FD of apple cubes are given in Figs 1–2. In addition, Figs 1–2 shows the variation of the MR calculated with the selected models, with change points (This point shows where joined the various drying methods in succession). The change points were placed in drying curve before reach to inflexion point of curve and the falling rate period. The dimensionless moisture contents of the products at change points for HAD-FD1-2 and IR-FD3-5 were 1.952, 1.394 and 3.904, 2.510, 1.952, respectively. In Figs. 1–2, it was observed that when the change point is higher, the drying time of HAD-FD and IR-FD increased significantly.

Table 4. Curve fitting criteria for drying models

Drying	Model parameters					Statistic	
method	k	a	b	c	d	R^2	RMSE
FD	–	0.000186	-0.00607	-0.00115	1.015071	0.9996	0.005328
HAD1	0.483	2.0407	–	–	–	0.9864	0.026763
HAD2	0.634	2.4694	–	–	–	0.9762	0.064325
HAD-FD1	–	0.000104	-0.00293	-0.00133	0.383225	0.9991	0.007651
HAD-FD2	–	0.000041	0.000745	-0.04705	0.427263	0.9923	0.017204
IR	0.559	2.3757	–	–	–	0.9550	0.096721
IR-FD3	–	0.000073	-0.00286	-0.00077	0.704602	0.9995	0.005991
IR-FD4	–	0.0000938	-0.00355	0.014072	0.455318	0.9988	0.009663
IR-FD5	–	0.000020	-0.00045	-0.01713	0.417317	0.9980	0.010974

The drying curve begins with a warm-up period (at IR and HAD), where the material is heated. In freezing period (at FD) the material is cooled. As the sample warm up (freezing – 0.5 h after warm up at FD), the drying rate increases to a peak drying rate that is maintained for a period of time known as the constant drying rate period. Eventually, the moisture content of the material drops to a level known as critical moisture content, where the high rate of evaporation cannot be maintained. This is the beginning of the falling drying rate period (Haghi, 2001). Constant drying rate period was not detected or very brief stage in IR drying curve. This could be because of the quick drying on the surface of sample at high temperature (Pan et al., 2008).

It can be observed that the moisture ratio decreases with drying time. The effect of temperature on drying is significant in case of hot air drying (HAD). By increasing the temperature from 60°C to 80°C, drying time is decreased 2 hours. However, very high air temperature (higher than 80°C) could lead to steady of the product resulting in its weak quality (Kerekes & Antal, 2006). As seen from Fig. 1, MR of HAD decreased exponentially with time, which shows a typical drying trend.

Hybrid drying had a higher average rate of mass transfer, which is resulted in a shorter drying time over the FD drying. The free water (large amount of moisture) is removed quickly during beginning of IR and HAD process, therefore accelerated the drying rate of FD.

IR drying had much higher drying rate compared with the HAD drying under same drying temperature (60°C). The HAD is a slow process relying on heat conduction from outer surface towards the interior. The rapid diffusion of moisture and direct heat transfer to the material due to infrared drying (IR) resulted in a faster drying process. Since quartz glass emitter heating provides mid-infrared radiation which means high penetration depth, radiation was accumulated in the material (inner layer). According to Nowak & Lewicki (2004), the drying kinetics of apple with infrared energy was dependent on distance between emitters and surface of sample. A decrease in IR-FD processing time by nearly 14.3% was observed when IR drying time was increased from 3 to 4–5 min. The MR of IR decreased exponentially with drying time (Tirawanichakul et al., 2008). Wang et al. (2014) reported that mid-infrared-assisted freeze dried mushroom had lower energy uptake compared to FD product. It is observed that electricity consumption of IR-FD4 and IR-FD5 are almost equal. This is due to same drying time at FD finish-drying (12 h), which is increased additionaly by 4 and 5 min treatment time (at IR pre-drying).

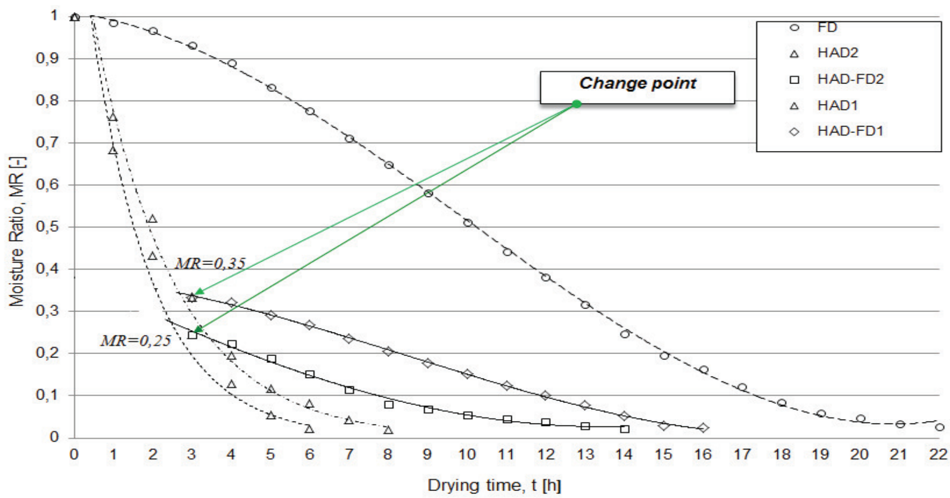

Figure 1. Variation of experimental and predicted moisture ratio with drying time at HAD-FD.

Lin et al. (2007) stated that application of far infrared (wavelength range up to 4 μm) in freeze drying of yam slices could reduce drying time by 25%. Similarly, it can be seen that IR heating was positive effect on moisture loss in the infrared-assisted freeze drying (Fig. 2).

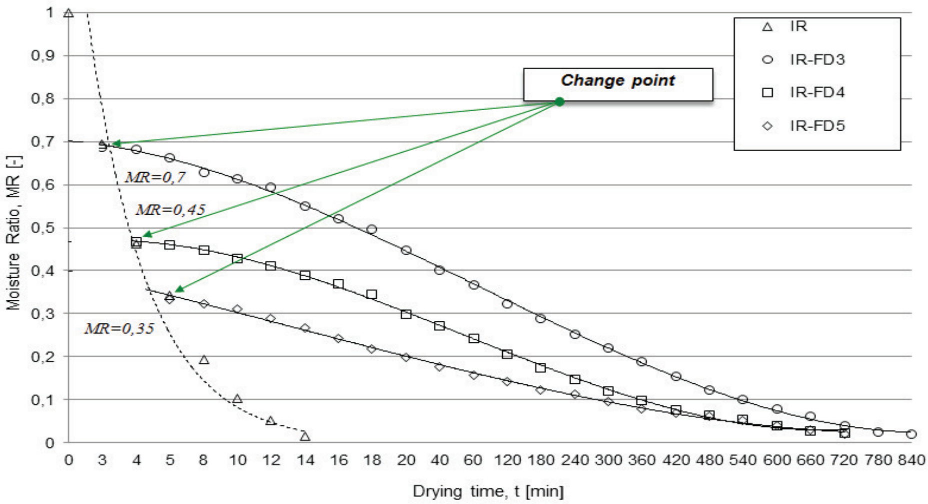

Figure 2. Variation of experimental and predicted moisture ratio with drying time at IR-FD.

Electricity energy consumption of drying processes

The energy uptake for drying was estimated based on the power input. The results are given in Fig. 3. The energy consumption values for IR-FD4-5 drying mode were slightly lower (6.52 and 6.53 kWh) as compared to HAD-FD2 drying (6.7 kWh) in apple. The IR-FD3-5 and HAD-FD1-2 hybrid drying also gave significantly lower energy uptake values (7.78, 6.7 and 7.58, 6.52, 6.53 kWh) than FD drying (11.88 kWh). This might be due primarily to the higher drying rate and lower energy uptake of IR. This is because infrared waves can penetrate into the interior of the apple, where it is converted to thermal energy, providing a rapid heating mechanism

The energy consumption obtained in the drying process using FD was almost two fold higher than IR-FD4-5 and HAD-FD2. This trend was also observed by other researchers (Xu et al., 2005). In addition, the change points in drying curve decreases, as well as the consume energy decreases significantly, except of IR-FD5.

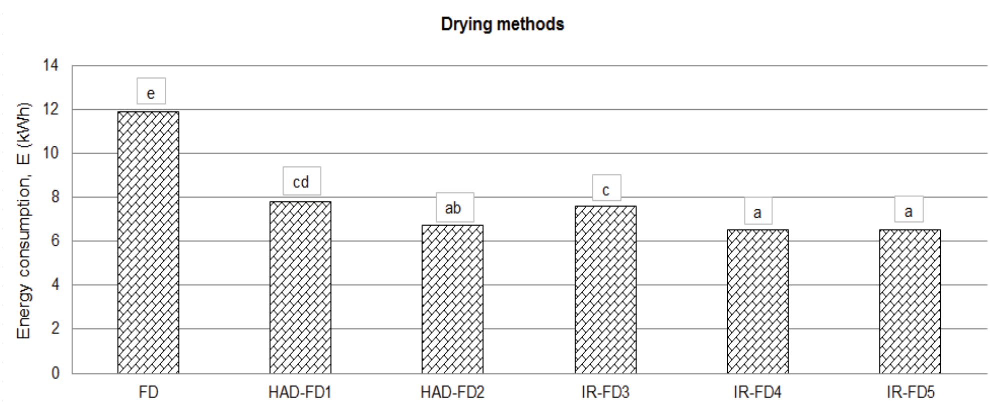

Figure 3. Energy consumption during FD, HAD-FD and IR-FD of *Idared* apple. Means with different letters indicate a significant difference ($P < 0.05$) in a column.

Evaluation of quality

Table 5 illustrates the colour changes of *Idared* apple samples undergoing various drying methods. The colour values measured using colour measurement system (Hunter Lab, USA) as total colour change (ΔE) indicated less variation with infrared-assisted freeze dried (IR-FD) samples compared to FD. Zhu & Pan (2009) stated that the surface colour did not change very significantly during short processing time. In addition, in case of relatively high radiation intensity treatment (5 kW m^{-2}) occurred unacceptable colour change after 6 min drying time.

The HAD pre-dried product had a greater colour change (ΔE) than IR pre-dried apple. Compared to fresh apple cubes, the ΔE in the FD samples were increased by 5.01. For the examined fresh apple, the parameter a* is negative indicating the green colour of the apple samples. It was found that lightness (L) of HAD-FD apple decreased and ΔE of HAD-FD apple increased significantly with increasing hot air temperature (from 60°C to 80°C), while redness (a) increased with increasing hot air temperature due to browning reaction occurring during dehydration process. The low L*parameter indicated that HAD pre-dried product colour shift towards the darker region.

As shown in Table 5, the FD and IR-FD dried apple gives slightly higher values of lightness (L), redness (a) and yellowness (b). The values of L* parameter of the FD and IR-FD dried apple cubes increases if compared with those measured on fresh sample, thus the luminance of the treated apple is improved by FD and IR-FD drying. The freezing rate has a marked effect in the lightness of the freeze dried samples: frozen apple slices maintained a whiter colour (Ceballos et al., 2012). Similarly to our results, Boudhrioua et al. (2009) established that value of L* parameter of the IR dried olive leaves increases compared to lightness of fresh olive leaves samples. According to Pan et al. (2008), the IR pre-drying resulted in significantly higher values of lightness (L) and yellowness (b) of banana slices than the fresh and FD samples. The hybrid drying induces deterioration of the greenness parameters (a). In fact, a* colour parameter become positive. It was found that lightness (L) of IR-FD apple decreased and redness (a) and yellowness (b) of IR-FD apple increased with decreasing the change point in the drying curve.

Table 5. Colour parameters of *Idared* apple dices

Drying method (Symbol)	Colour parameters					
	L	a	b	C	h	ΔE
Raw mat.	75.92	-1.68	18.35	18.43	95.24°	–
FD	79.63	1.70	18.38	18.43	84.70°	5.01^{a}
HAD-FD1	71.56	3.67	11.71	12.27	72.59°	9.57^{d}
HAD-FD2	69.88	4.02	10.33	11.08	68.73°	11.55^{e}
IR-FD3	80.75	0.86	21.80	21.82	87.73°	6.45^{bc}
IR-FD4	79.22	1.78	22.15	22.23	85.41°	6.1^{b}
IR-FD5	78.94	2.57	22.22	22.37	83.40°	6.49^{bc}

Means with different letters in the same column were significantly different at the level $P < 0.05$.

The FD samples had higher hue angle (h) values than HAD-FD samples, but lower than IR-FD products, except of IR-FD5. The hue angle of fresh apple is yellow-green colour (hue of 95.24°). The hue angle value of FD and IR-FD product remained range of 87.73°–83.4°, which is yellow colour. The elapsed time increased at IR-FD (change point), the hue angles were decreased from 87.73° to 83.4°. This meant that there was decreased in yellow colour when the change point was varied from MR = 0.7 to 0.35. Due to heat damage of HAD pre-dried sample, the hue angle value changed drastically from 95.24° to 72.6°–68.7° (orange colour). The hue values of HAD-FD decreased when the air temperature changed from 60°C to 80°C. The chroma (C) of all dried samples was found in range of dullness (11.08–22.37). The HAD-FD1-2 products had significantly lower chroma (C) values than the others.

The water activity of dried apple cubes in all cases is below 0.6, hence the samples can be deemed to be safe from common microbial damage. The dried apple cubes retained low water activity value, range from 0.180 to 0.249 (Table 6). Our results reveal that IR-FD drying process could give steady a_w values for long term storage.

The hardness values for apple dices dried by combination drying and FD methods are shown in Table 7. From Table 7, the FD process was not significant effect to hardness of fresh apple cubes. The textural superiority of the apple samples dried with FD was observed when compared to the textures of the apple dried by combination dried.

Table 6. Water activity (a_w) of *Idared* apple cubes

Symbol	Fresh	FD	HAD-FD1	HAD-FD2	IR-FD3	IR-FD4	IR-FD5
a_w (–)	0.961^{d}	0.186^{a}	0.249^{c}	0.220^{b}	0.180^{a}	0.186^{a}	0.181^{a}

Values in the same line not sharing the same superscript are significantly different ($P < 0.05$).

This phenomenon due to fine-pored structure and smooth cell walls of FD dried samples (Rother et al., 2011). As a result, the increase of air temperature at HAD-FD resulted significant increasing of firmness value (from 19.67 to 22.33). In the case of HAD pre-drying the relatively high air temperature leads to solid surface, collapsed cellular tissues, changes in cell size and cell size distribution of sample (Lewicki & Jukubczyk, 2004; Shih et al., 2008). It is observed that firmness value in samples dried by IR-FD increased significantly as compared to FD method. On the whole, for the surface hardness values in dried samples, FD and IR-FD methods are significantly better than the HAD-FD method, except of IR-FD4.

Table 7. Texture of *Idared* dried apples associated with different drying method

Symbol	Fresh	FD	HAD-FD1	HAD-FD2	IR-FD3	IR-FD4	IR-FD5
F (N)	4.70^{ab}	4.13^{a}	19.67^{e}	22.33^{g}	14.14^{c}	19.81^{ef}	17.51^{d}

Values in the same line not sharing the same superscript are significantly different ($P < 0.05$).

The rehydration ratio of dried *Idared* apple dices dehydrated by two combinations and FD is presented in Fig. 4. The water uptake of dried apple cubes is dependent on the extent of the structural failure to the apple samples during drying. The higher rehydration ratios (RR) with IR-FD3-5 (30 min: 24.5%, 28.6%, 28.6%; 60 min: 18.1%, 21.3%, 30.4%) dried apple indicated an improved product structure as compared to FD dried samples.

The rapid heating with IR and quicker diffusion of water vapour within the sample might be facilitating the material to retain its porous structure, thereby increasing its ability to absorb higher amount of water during rehydration (Vishwanathan et al., 2010).

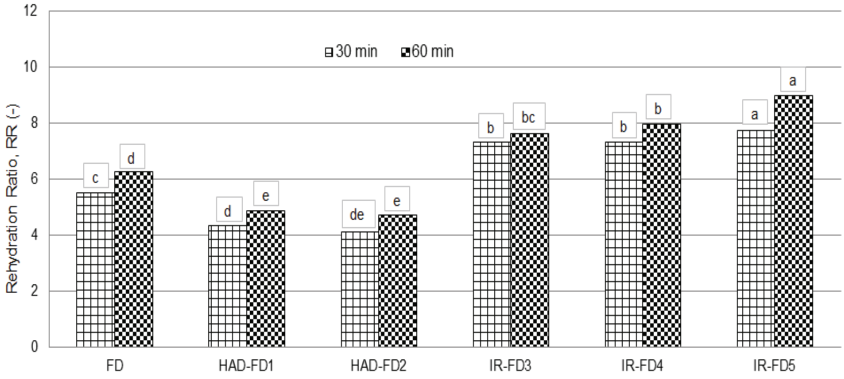

Figure 4. Effect of FD and combination drying on rehydration ratio of *Idared* apple cubes. Means within columns with different letters are significantly different ($P < 0.05$).

As revealed in the graph, the rehydration ratio of HAD pre-dried sample was a significantly lower than FD and IR pre-dried ones. The long period of HAD drying and the high temperature may contribute to a decrease in water uptake. Similarly to our result, Shih et al. (2008) stated that rehydration ratio of HAD-FD product was significantly lower than samples dried by IR-FD. According to Sharma et al. (2005), the onion slices dried under IR-HAD conditions had better rehydration ratio as compared to conventionally dried sample.

In addition, when the soaking time was increased from 30 min to 60 min, the RR of samples was increased slightly. It was observed, when change point of IR and FD drying modes is decreased (from MR = 0.7 to 0.35), the values of rehydration ratio increased slightly.

It can be seen from above results that under IR-assisted drying have a pronounced influence on RR of apple cubes. This conclusion is in accord with that of other authors (Lin et al., 2007).

CONCLUSIONS

Apple cubes drying using freeze drying (FD), hot air-assisted freeze drying (HAD-FD) and infrared-assisted freeze drying (IR-FD) were studied. The effect of drying processes on the energy consumption, colour, water activity, firmness and rehydration ratio was examined.

When processed the samples under hybrid drying (HAD-FD and IR-FD) resulted a higher drying rate. A decrease in processing time for all changes points in comparison to single-stage FD drying was observed. The HAD-FD and IR-FD drying reduced the processing time dramatically (27.3–45.5%) and consumed significantly less electricity energy (34.5–45.1%) compared to FD. Drying with application of IR is much faster than HAD and IR pre-treated product had significantly better quality (colour, water activity, hardness and rehydration ratio).

Based our experimental study, the IR-FD3-5 methods are better when drying time, energy consumption, rehydration ratio were compared to FD. The IR pre-drying produced significantly firmer texture product compared to FD drying. The FD drying is demonstrated to preserve the colour of *Idared* apple samples. However, the total colour changes are significantly affected by hybrid drying methods compared to FD. Between the total colour difference of FD and IR pre-dried products was little difference. Increasing the temperature from 60°C to 80°C, showed reduction in drying time caused significant negative effect on the quality of HAD-FD products.

The applied mathematical models – Henderson-Pabis and third-degree polynomial – performed well for describing the drying behaviour of the process on the basis of statistical parameters such as coefficient of determination and root mean square error.

The drying process combining infrared (treatment time: 5 min) and lyophilisation provides a potential alternative to the freeze drying of apple. Further research is required to determine the adequate change point in drying curve and chemical component of final product.

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