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COMPARISON OF DRYING CHARACTERISTICS AND QUALITY OF PEPPERMINT LEAVES USING DIFFERENT DRYING METHODS

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ABSTRACT

In this study, we investigated the effects of hot air, infrared and combined hot air-infrared drying methods on the drying time, energy consumption, color, rehydration and oil content of peppermint leaves. Three different air temperatures (30, 40 and 50C) and air velocities (0.5, 1 and 1.5 m/s) were used in the hot air drying. Infrared drying process was implemented using three levels of radiation intensity (1500, 3000 and 4500 W/m^2), three distances between emitter and sample (10, 15 and 20 cm) and three air velocities (0.5, 1 and 1.5 m/s). The results showed that the optimum drying period and energy consumption were obtained when infrared- and hot air-drying were applied simultaneously. The results also showed that combined drying resulted in dried leaves of superior quality when compared to the leaves dried separately by either hot air alone or infrared, exhibiting lower total color change, greater rehydration ratio and higher extraction oil yield.

PRACTICAL APPLICATIONS

Peppermint leaves are highly valuable products with wide range of industrial uses but extremely perishable in normal surrounding temperature-humidity conditions too. This fact makes their preservation important. Drying is a common preservation method that is applied to foods and agricultural products. Hot air has been traditionally used for drying peppermint leaves; however, infrared radiation has been employed for this purpose recently. However, there is very little knowledge, if none, on the use of combination of hot air and infrared drying method on the drying performance as well as the quality of final dried leaves. We treated fresh peppermint leaves by hot air drying, infrared drying and combined hot air-infrared drying, and compared the quality of final products and energy consumption during drying, aiming to find out the optimum drying method and drying parameters; while are beneficial to related industry in drying this valuable product. Our research work confirmed that combined hot air-infrared drying is a good alternative instead of the use of hot air drying or infrared drying separately.

INTRODUCTION

Peppermint (*Mentha piperita* L.) is a plant with wide range of industrial uses, unique flavoring and pharmaceutical properties and therefore it is one of the most important aromatic plants and widely accepted by the public (Tarhan *et al.* 2010). The dried peppermint and/or its essential oil have been used extensively in dyeing, fragrances, cosmetics, beverages, confectionary, chewing gum and tobacco industries (Dai *et al.* 2010; Zheljazkov and Astatkie 2010; Golestan *et al.* 2016). Medicinal and aromatic plants, including peppermint, are usually dried by hot air drying, which is a common postharvest operation. Peppermints are dried to slow microbial growth and biodegradation and to reach a final product with an effectively increased shelf life (Tarhan *et al.* 2010). In fact, the main reason for drying food products is to reduce their moisture content to a level at which safe storage over an extended period is allowed (Doymaz 2014). In addition, dried products weigh less, require less packaging materials and, therefore, cost lower shipping charges (Doymaz and İsmail 2012).

During hot air drying, heat is transferred from the hot air to the product by convection; at the same time, evaporated water is transported to the air. However, long operation time, high energy consumption, and low quality are serious disadvantages for this drying method (Alibas 2006; Motevali *et al.* 2011; Qi *et al.* 2014; Roknul *et al.* 2014; Kantrong *et al.* 2014; El-Mesery and Mwithiga 2015; Bai-Ngew *et al.* 2015). Hot air drying has some other common problems such as non-enzymatic browning, shrinkage, poor rehydration characteristics and loss of nutrients (Kocabiyik *et al.* 2014). Hence, new drying methods and driers must be designed and studied to overcome these problems (Doymaz 2012, 2014). Alternatively, infrared drying has recently become popular drying method for agricultural products (Kantrong *et al.* 2014). When a material is exposed to infrared radiation, the radiation strikes on its surface and penetrates further down to the inner layers (Doymaz 2014). The material molecules vibrate as they absorb radiation. The vibration generates heat at surface and inner layers at the same time. The heating excites the movement of water molecules towards the surface (El-Mesery and Mwithiga 2015). Infrared radiation can be used to dry agricultural products quickly, efficiently energy-wise and uniformly temperature-wise, resulting in high quality final products (Doymaz 2012; Kantrong *et al.* 2014; Kocabiyik *et al.* 2014; Roknul *et al.* 2014; El-Mesery and Mwithiga 2015). From an industrial point of view, the application of combined electromagnetic radiation methods such as infrared and hot air heating is considered to be more efficient than the use of radiation or hot air heating separately because of the synergistic effect (Mihindukulasuriya and Jayasuriya 2015). In combined hot-air-infrared drying, a sample surface is heated by infrared rays and by the air that is already heated before it flows over the being-dried product while in drying using infrared radiation only the ambient air flows through over the product without being previously heated (Motevali *et al.* 2011).

Hot air drying technique has proved to be effective for a number of agricultural products such as chard leaves (Alibas 2006), lemon myrtle leaves (Buchaillot *et al.* 2009), tarragon leaves (Arabhosseini *et al.* 2011), pear slices (Doymaz and İsmail 2012), shiitake mushrooms (Qi *et al.* 2014), stem lettuce slices (Roknul *et al.* 2014) and chilli peppers (Mihindukulasuriya and Jayasuriya 2015). On the other hand, infrared and/or combined infrared-hot air dryers have been used to successfully dry other agricultural products such as carrot slices (Kocabiyik and Tezer 2009), sweet potato slices (Doymaz 2012), black mulberry (Adabi *et al.* 2013), peach slices (Doymaz 2014), shiitake mushrooms (Qi *et al.* 2014), stem lettuce slices (Roknul *et al.* 2014), chilli peppers (Mihindukulasuriya and Jayasuriya 2015) and green beans (Doymaz *et al.* 2015). However, there is very limited, if not at all, information and literature available on drying peppermint (Pääkkönen *et al.* 1999; Tarhan *et al.* 2010).

The objectives of this work, therefore, were (i) to evaluate the efficacy of hot air, infrared and combined hot air-infrared drying techniques for drying peppermint leaves; (ii) to examine the changes of color, essential oil and rehydration values in final dried products; and (iii) to determine the best method in drying peppermint leaves in terms of energy consumption, drying time and final product quality.

MATERIALS AND METHODS

Raw Materials

Fresh peppermint leaves were collected early morning daily after drying dew from the research farm of the Ferdowsi University of Mashhad, Iran. They were kept in cooled bags during transportation to the laboratory. The leaves were immediately cleaned with tissue papers to remove dirt and any soil particles. Three different leaf samples, each 30 g, were dried in an electric convection oven at 105C for 24 h to determine initial moisture content (Tarhan *et al.* 2010). The initial moisture content of fresh peppermint leaves was 82.17 $\pm$ 0.2% wet basis (w.b.).

Experimental Setup

In order to experiment the drying process of peppermint samples under different conditions, a prototype hot air-infrared dryer was developed. The schematic illustration of the drying apparatus is depicted in Fig. 1. The dryer basically consisted of heating control unit, a heater, airflow control unit, infrared heating unit, an air filter, an air duct, an electrical fan, and a drying chamber. The drying chamber of $0.5^{L} \times 0.5^{W} \times 0.4^{H}$ m was made out of 1 mm thick aluminum sheet. A door was embedded in one of the chamber's sides to facilitate placing and removing the sample tray. The external walls of the drying chamber were covered with glass-wool layer to minimize heat losses. Inside a duct, an electric heater (2 kW) was placed as part of the heating control unit. The ambient temperature of the chamber was measured using a k-type thermocouple. The air passed from the heater at the desired temperature and channeled to the drying chamber and then flowed horizontally through the samples. Air velocity was regulated by an axial flow fan and a fan speed control unit. The air velocity was measured using a hotwire anemometer (Testo 425, Germany) with accuracy of $\pm$ 0.03 m/s. Three 250 W infrared lamps (Philips, China) were installed in a row at the top of the drying chamber. Lamps were installed on the chamber in a way the allowed vertical movements. Infrared radiation intensity of the lamps could be varied by regulating the voltage by a variac. The infrared radiation intensities were

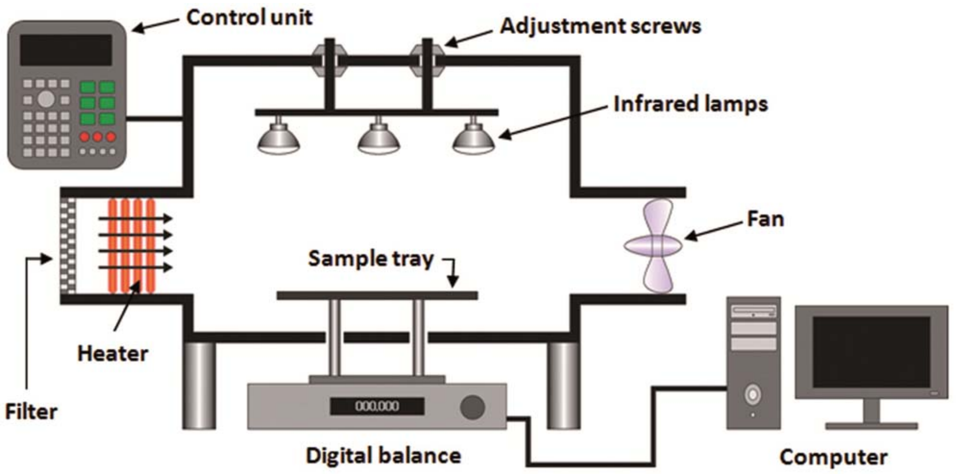

FIG. 1. SCHEMATIC DIAGRAM OF THE DRYING APPARATUS USED IN THE EXPERIMENTS

measured by a solarimeter (Casella 187010b-02, UK). Weight loss of samples were recorded by using a digital weighing scale (GF 6000, AND, Japan), which has 0–6000 g measurements range with reading accuracy of 0.01 g.

Drying Processes

Experiments were conducted on peppermint leaves in the hot air dryer at three levels of temperature (30, 40 and 50C) and three levels of air velocity (0.5, 1 and 1.5 m/s), in the infrared dryer at three radiation intensity levels of 1,500, 3,000 and 4,500 W/m^2, three distances between emitter and surface sample (10, 15 and 20 cm) and three levels of air velocity (0.5, 1 and 1.5 m/s). Additional experiments were also performed in a combined hot air-infrared dryer at three levels of radiation intensity (1,500, 3,000 and 4,500 W/m^2), three distances between emitter and surface sample (10, 15 and 20 cm), three air temperatures of 30, 40 and 50C, and three levels of air velocity (0.5, 1 and 1.5 m/s). Prior to each experiment, the dryer system was allowed to run for about 30 min until it reached the desired steady-state drying conditions (Doymaz and İsmail 2012). After reaching the stable conditions, the 200 ± 1 g of peppermint leaves was distributed uniformly into a thin layer on the aluminum perforated tray of size 40×40 cm. Moisture loss was recorded at regular time intervals (1 min). Drying process was stopped when the moisture content of the dried product was about 10% (w.b.). The dried product was cooled under laboratory conditions and packed in low-density polyethylene bags that were heat sealed and then kept in a desiccator for further quality evaluations. Each experimental treatment was performed three times.

Specific Energy Consumption in Drying Process

One of the important considerations for the suitable drying conditions is the cost of energy inputs (Kantrong *et al.* 2014). Total energy was defined as the sum of the energy consumed by all devices during the whole drying process and measured by a digital electricity meter (Kocabiyik *et al.* 2015). The specific energy consumption during dehydration was calculated according to Kantrong *et al.* (2014) as follows:

$$E_s = \frac{E_t}{W_r} \tag{1}$$

where E_s is the specific energy consumption (MJ/kg), E_t is the total electrical power supplied to the dryer (MJ) and W_r is the amount of water removed by drying (kg).

Drying Time and Rehydration

Drying time was defined as the time required to decrease the moisture content of the product to 10% (w.b.). Dried peppermint leaves were rehydrated in distilled water at 25 ± 1C. About 5 g of the dried products were added to 500 mL of distilled water, in a 750 mL beaker. Weight of the sample was measured after 12 h. Before weighing, the sample was drained and blotted with tissue paper to eliminate excess water on the surface of the sample. All measurements were performed in triplicate and the rehydration ratio was calculated using the following equation (Doymaz *et al.* 2015):

$$R_r = \frac{W_r - W_d}{W_d} \tag{2}$$

where R_r is the rehydration ratio (kg water/kg dry matter (DM)), W_r is the weight of rehydrated sample (kg) and W_d is the weight of the dried sample (kg).

Essential Oil Extraction

A Clevenger hydro-distillation apparatus was used to extract essential oil from the leaves. For this purpose, 30 g of dried peppermint leaves were soaked in 250 mL distilled water, followed by boiling it on hot plates up for about 3 h. The extracted peppermint oil was separated from water and collected at the end each distillation, it was then weighed, and its oil content was calculated as the weight (g) of the collected oil divided by 30 g of original dried leaves (Zheljazkov and Astatkie 2010). Each test was repeated three times and average values were reported.

Color Measurement

Color is an important qualitative factor in agriculture and food industry as it is often the first feature that attracts buyers' attention while making purchasing decisions (Arabhosseini *et al.* 2011). The colors of both fresh and dried peppermint leaves were quantified by using a CR-400 chroma meter (Konica Minolta, Japan). The instrument was calibrated prior to each experiment using standard white tile. Lightness/darkness (L^*), redness/greenness (a^*) and yellowness/blueness (b^*) color values of 10 fresh and 10 dried peppermint leaves were measured in each experiment. The data were reported as mean values of these measurements. Color difference was used to describe the peppermint leave's color change occurred during the drying. It is calculated from following formula (Roknul *et al.* 2014):

$$\Delta E = \sqrt{\Delta L^{*2} + \Delta a^{*2} + \Delta b^{*2}} \tag{3}$$

where ΔE is the color change and ΔL^*, Δa^* and Δb^* refer to the difference between color values L^*, a^* and b^* of fresh peppermint leaves and those values of leaves after drying.

Statistical Analysis

Analysis of variance (ANOVA) was used to analyze the collected data using SPSS version 16 software (IBM, Chicago, IL). Multiple mean comparisons were performed using Duncan's test to determine differences between means at a 95% confidence level ($P < 0.05$).

RESULTS AND DISCUSSION

Drying Time

Figure 2 shows the drying time required for hot air drying method at various conditions. Analysis of effects of drying air temperature on drying time at various air velocities showed a decrease in the drying time with increasing the drying air temperature (Fig. 2). As air temperature increased, drying time decreased because the material's thermal gradient increased and this, consequently, increased the moisture evaporation rate (Motevali *et al.* 2011). Results were in line with those reported by different authors on drying of various agricultural products (Alibas 2006, 2007; Buchaillot *et al.* 2009; Motevali *et al.* 2011; Doymaz and İsmail 2012; Moon *et al.* 2015; Bai-Ngew *et al.* 2015; Horuz and Maskan 2015). Also, drying time showed a decreasing trend with increasing drying air velocity at all the examined drying air temperatures (Fig. 2). This could be due to the reduction in vapor pressure with increasing air flow rate, which in turn reduces the resistance to moisture evaporation (Motevali *et al.* 2011). A similar effect of air velocity on drying time has already been found in the studies on mushroom slices (Motevali *et al.* 2011) and black mulberry (Adabi *et al.* 2013). Minimum drying time (928 min) was achieved at air temperature of 50C and air velocity of 1.5 m/s. Maximum drying time (1,283 min) was related to 30C and 0.5 m/s.

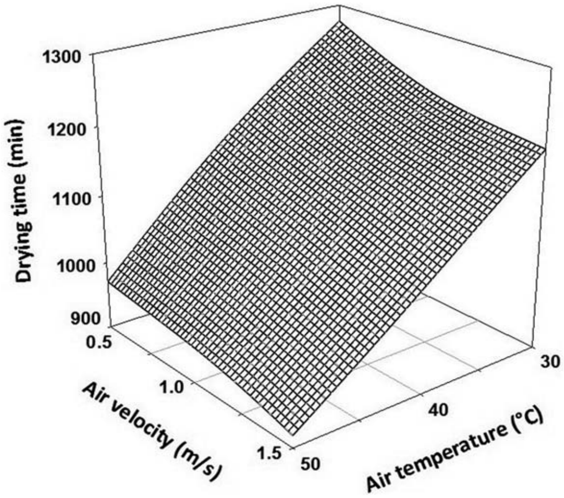

FIG. 2. INTERACTION EFFECT OF AIR VELOCITY AND TEMPERATURE ON THE DRYING TIME FOR HOT AIR DRYING OF PEPPERMINT LEAVES

The drying time values during infrared drying of peppermint leaves are given in Fig. 3. As can be seen, the drying time was shortened with increasing infrared radiation intensity at constant air velocity and distance between emitter and sample. This behavior can be explained as follows: At higher infrared intensity levels, with higher heat absorption, the product temperature and mass transfer driving force were higher, and the drying was accelerated reducing the drying time (Motevali *et al.* 2011; Doymaz 2014). This finding was in agreement with those found in earlier studies reported by Motevali *et al.* (2011) on mushroom slices, Doymaz *et al.* (2015) on green beans and Kocabiyik *et al.* (2015) on tomatoes. It is also clear from the same figure that, the drying time decreased with decreasing distance between emitter and sample at constant infrared radiation intensity and air velocity. The reason for this is that, with decreasing distance between emitter and sample, due to the increase in sample surface temperature and moisture evaporation rate,

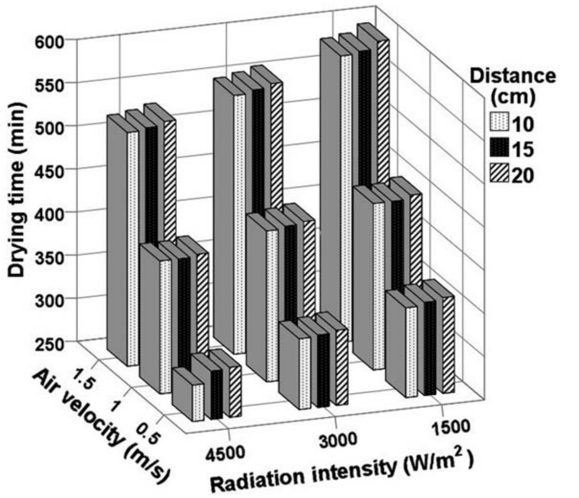

FIG. 3. VARIATIONS OF DRYING TIME FROM THE EFFECTS OF INFRARED RADIATION INTENSITY, DISTANCE BETWEEN EMITTER AND SAMPLE AND AIR VELOCITY

the drying period decreases. The results showed that drying time increased with an increase in air velocity under constant infrared radiation intensity and distance between emitter and sample (Fig. 3). This can be caused by cooling of the sample's surface with the air passing through the chamber. Accordingly, any increase in the air velocity increases the air cooling process. As a result, evaporation decreases and the drying time increases (Motevali *et al.* 2011). This increase in drying time with an increase in the air velocity level was also reported by Kocabiyik and Tezer (2009) for carrot slices and Motevali *et al.* (2011) for mushroom slices. Accordingly, the shortest drying time in infrared experiments was obtained to be 291 min which was associated with the combination of 4,500 W/m^2 infrared radiation intensity, 0.5 m/s air velocity and 10 cm distance between emitter and sample, whereas the longest drying process, 597 min, resulted from the combination of 1,500 W/m^2 infrared radiation intensity, 1.5 m/s air velocity and 20 cm distance between emitter and sample. The finding that hot air drying method required longer time to dry materials than infrared drying can be described by case hardening effect. The hardened surface layer, caused in hot air drying, creates a barrier for inner moisture to reach to the surface and, therefore, slows down the dehydration rate (Bai-Ngew *et al.* 2015).

In the case of combined hot air-infrared drying at constant air velocity, air temperature and distance between lamps and sample drying time decreased with increasing infrared radiation intensity, as expected. The same trends were also observed for other drying conditions, except for two cases where drying time increased with increasing air velocity and increasing distance between lamps and sample (Table 1). This is due to the fact that with increasing infrared intensity, sample surface temperature increases and moisture evaporation occurs at faster pace (Motevali *et al.* 2011). The results were generally in agreement with the some of the literature on the drying of various food products (Motevali *et al.* 2011; Kocabiyik *et al.* 2014). Comparison of the required drying time, at all drying conditions, indicates that the lowest drying time occurring at 50C air temperature, 0.5 m/s air velocity, 4,500 W/m^2 infrared radiation intensity, and 10 cm distance between lamps and sample, was 143 min and the highest value of drying time, occurring at 30C air temperature, 1.5 m/s air velocity, 1,500 W/m^2 infrared radiation intensity, and 20 cm distance between lamps and sample, was 502 min showing a nearly 3.5-fold increase. Among the three studied drying methods, the longest drying time was observed in hot air mode alone and also the infrared mode alone followed a pattern between hot air and hot air-infrared combined drying in terms of drying time. El-Mesery and Mwithiga (2015) obtained similar findings while investigating the effects of combined infrared and hot air drying of apple slices. Their performance evaluation studies indicated that the combined mode drying shortened the drying time nearly to 57.5% of the corresponding time assigned for hot air drying and 39.1% of that for infrared drying.

Specific Energy Consumption

The specific energy consumption values obtained during hot air drying of peppermint leaves are given in Fig. 4. As can be seen, energy consumption decreased with increasing temperature at all air velocities. Similar observations have been reported for the drying of nettle leaves (Alibas 2007) and chard leaves (Alibas 2006). Also, energy consumption reduced with increasing air velocity at all air temperatures. A similar finding was published by Motevali *et al.* (2011) for mushroom slices. This can be due to the fact that drying undergoing higher air temperature and air velocity resulting in the shorter drying time that consequently decreases the specific energy consumption. The minimum and maximum values of specific energy consumption for drying peppermint leaves were found to be 10.09 and 32.63 MJ/kg, at 50C and 1.5 m/s, and 30C and 0.5 m/s, respectively.

The specific energy consumption during infrared drying is given in Fig. 5. The results showed that in the infrared radiation method, unlike the hot air technique, energy consumption increased with increasing air velocity. This can be due to the air flow-induced temperature drop on the product surface; therefore, at higher air flow rates, the product surface becomes cooler decreasing the thermal gradient inside the product. This, in turn, leads to longer drying time and higher energy consumption of the infrared dryer (Motevali *et al.* 2011). Similar results were reported by

TABLE 1. EFFECT OF OPERATING PARAMETERS ON DRYING TIME (D_r), SPECIFIC ENERGY CONSUMPTION (E_s), COLOR CHANGE (ΔE), OIL YIELD (E_c) AND REHYDRATION RATIO (R_r) FOR DRYING OF PEPPERMINT LEAVES BY HOT AIR-INFRARED COMBINATION DRYER

Drying conditions	D_r (min)	E_s (MJ/kg)	ΔE	E_c (%)	R_r (kg water/kg DM)
1,500 W/m^2, 10 cm, 30C, 0.5 m/s	440 ± 16	11.51 ± 0.86	15.12 ± 0.63	0.801 ± 0.018	0.800 ± 0.020
1,500 W/m^2, 15 cm, 30C, 0.5 m/s	449 ± 12	11.75 ± 0.79	15.05 ± 0.36	0.776 ± 0.025	0.801 ± 0.014
1,500 W/m^2, 20 cm, 30C, 0.5 m/s	455 ± 26	11.95 ± 0.60	14.95 ± 0.71	0.761 ± 0.011	0.802 ± 0.019
3,000 W/m^2, 10 cm, 30C, 0.5 m/s	402 ± 11	10.64 ± 0.88	16.24 ± 0.25	0.865 ± 0.012	0.795 ± 0.003
3,000 W/m^2, 15 cm, 30C, 0.5 m/s	403 ± 18	10.82 ± 0.57	16.16 ± 0.79	0.856 ± 0.009	0.796 ± 0.012
3,000 W/m^2, 20 cm, 30C, 0.5 m/s	406 ± 27	10.99 ± 0.71	16.01 ± 0.51	0.832 ± 0.020	0.798 ± 0.005
4,500 W/m^2, 10 cm, 30C, 0.5 m/s	350 ± 11	9.91 ± 0.73	17.26 ± 0.32	0.965 ± 0.021	0.790 ± 0.008
4,500 W/m^2, 15 cm, 30C, 0.5 m/s	353 ± 10	10.23 ± 0.67	17.18 ± 0.33	0.954 ± 0.010	0.792 ± 0.012
4,500 W/m^2, 20 cm, 30C, 0.5 m/s	356 ± 14	10.37 ± 0.75	17.05 ± 0.67	0.940 ± 0.008	0.793 ± 0.009
1,500 W/m^2, 10 cm, 30C, 1 m/s	465 ± 20	16.61 ± 0.86	15.03 ± 0.40	0.784 ± 0.015	0.803 ± 0.017
1,500 W/m^2, 15 cm, 30C, 1 m/s	472 ± 15	16.77 ± 0.52	14.93 ± 0.75	0.774 ± 0.013	0.804 ± 0.017
1,500 W/m^2, 20 cm, 30C, 1 m/s	478 ± 20	16.92 ± 0.20	14.80 ± 0.51	0.745 ± 0.006	0.804 ± 0.010
3,000 W/m^2, 10 cm, 30C, 1 m/s	419 ± 19	15.58 ± 0.58	16.00 ± 0.44	0.842 ± 0.012	0.797 ± 0.011
3,000 W/m^2, 15 cm, 30C, 1 m/s	423 ± 28	15.85 ± 0.99	15.87 ± 0.52	0.830 ± 0.004	0.799 ± 0.015
3,000 W/m^2, 20 cm, 30C, 1 m/s	427 ± 23	16.07 ± 0.55	15.75 ± 0.77	0.824 ± 0.016	0.799 ± 0.008
4,500 W/m^2, 10 cm, 30C, 1 m/s	369 ± 18	14.97 ± 0.94	17.15 ± 0.42	0.963 ± 0.024	0.792 ± 0.005
4,500 W/m^2, 15 cm, 30C, 1 m/s	374 ± 18	15.19 ± 0.89	17.10 ± 0.56	0.935 ± 0.013	0.793 ± 0.006
4,500 W/m^2, 20 cm, 30C, 1 m/s	378 ± 15	15.38 ± 0.70	16.93 ± 0.84	0.913 ± 0.019	0.794 ± 0.018
1,500 W/m^2, 10 cm, 30C, 1.5 m/s	489 ± 16	21.34 ± 0.58	14.68 ± 0.76	0.762 ± 0.011	0.806 ± 0.008
1,500 W/m^2, 15 cm, 30C, 1.5 m/s	495 ± 22	21.86 ± 0.62	14.60 ± 0.55	0.755 ± 0.007	0.807 ± 0.021
1,500 W/m^2, 20 cm, 30C, 1.5 m/s	502 ± 24	22.27 ± 0.85	14.38 ± 0.53	0.724 ± 0.012	0.811 ± 0.011
3,000 W/m^2, 10 cm, 30C, 1.5 m/s	434 ± 13	20.80 ± 0.55	15.80 ± 0.70	0.832 ± 0.010	0.799 ± 0.003
3,000 W/m^2, 15 cm, 30C, 1.5 m/s	438 ± 19	20.99 ± 0.92	15.69 ± 0.52	0.823 ± 0.015	0.801 ± 0.013
3,000 W/m^2, 20 cm, 30C, 1.5 m/s	441 ± 15	21.11 ± 0.82	15.65 ± 0.39	0.807 ± 0.015	0.802 ± 0.020
4,500 W/m^2, 10 cm, 30C, 1.5 m/s	390 ± 17	18.87 ± 0.91	16.89 ± 0.48	0.924 ± 0.008	0.795 ± 0.004
4,500 W/m^2, 15 cm, 30C, 1.5 m/s	393 ± 22	19.24 ± 0.58	16.80 ± 0.22	0.914 ± 0.007	0.796 ± 0.007
4,500 W/m^2, 20 cm, 30C, 1.5 m/s	399 ± 24	19.37 ± 0.30	16.74 ± 0.57	0.891 ± 0.014	0.798 ± 0.015
1,500 W/m^2, 10 cm, 40C, 0.5 m/s	347 ± 13	9.27 ± 0.69	16.50 ± 0.69	0.900 ± 0.013	0.785 ± 0.012
1,500 W/m^2, 15 cm, 40C, 0.5 m/s	350 ± 18	9.40 ± 0.89	16.42 ± 0.65	0.883 ± 0.009	0.786 ± 0.013
1,500 W/m^2, 20 cm, 40C, 0.5 m/s	352 ± 15	9.63 ± 0.44	16.31 ± 0.27	0.870 ± 0.018	0.787 ± 0.004
3,000 W/m^2, 10 cm, 40C, 0.5 m/s	302 ± 23	8.50 ± 0.50	17.32 ± 0.46	1.072 ± 0.016	0.780 ± 0.016
3,000 W/m^2, 15 cm, 40C, 0.5 m/s	303 ± 13	8.74 ± 0.74	17.21 ± 0.78	0.990 ± 0.007	0.781 ± 0.019
3,000 W/m^2, 20 cm, 40C, 0.5 m/s	307 ± 11	8.97 ± 0.65	17.10 ± 0.81	0.984 ± 0.016	0.782 ± 0.014
4,500 W/m^2, 10 cm, 40C, 0.5 m/s	252 ± 09	7.89 ± 0.38	18.56 ± 0.56	1.235 ± 0.024	0.775 ± 0.009
4,500 W/m^2, 15 cm, 40C, 0.5 m/s	253 ± 12	8.13 ± 0.73	18.37 ± 0.47	1.195 ± 0.033	0.776 ± 0.017
4,500 W/m^2, 20 cm, 40C, 0.5 m/s	256 ± 13	8.37 ± 0.91	18.31 ± 0.63	1.177 ± 0.013	0.777 ± 0.022
1,500 W/m^2, 10 cm, 40C, 1 m/s	367 ± 17	14.31 ± 0.48	16.32 ± 0.51	0.871 ± 0.025	0.787 ± 0.006
1,500 W/m^2, 15 cm, 40C, 1 m/s	371 ± 21	14.52 ± 0.73	16.27 ± 0.22	0.864 ± 0.027	0.788 ± 0.002
1,500 W/m^2, 20 cm, 40C, 1 m/s	373 ± 14	14.85 ± 0.88	16.13 ± 0.58	0.846 ± 0.012	0.789 ± 0.010
3,000 W/m^2, 10 cm, 40C, 1 m/s	321 ± 13	13.61 ± 0.82	17.13 ± 0.44	0.970 ± 0.007	0.782 ± 0.012
3,000 W/m^2, 15 cm, 40C, 1 m/s	323 ± 18	13.70 ± 0.95	17.05 ± 0.48	0.966 ± 0.010	0.783 ± 0.016
3,000 W/m^2, 20 cm, 40C, 1 m/s	327 ± 25	13.98 ± 0.66	16.93 ± 0.72	0.952 ± 0.020	0.784 ± 0.008
4,500 W/m^2, 10 cm, 40C, 1 m/s	271 ± 15	12.92 ± 0.73	18.30 ± 0.60	1.173 ± 0.019	0.777 ± 0.013
4,500 W/m^2, 15 cm, 40C, 1 m/s	272 ± 10	13.12 ± 0.73	18.26 ± 0.19	1.162 ± 0.024	0.778 ± 0.012
4,500 W/m^2, 20 cm, 40C, 1 m/s	276 ± 12	13.35 ± 0.95	18.08 ± 0.44	1.147 ± 0.009	0.779 ± 0.028
1,500 W/m^2, 10 cm, 40C, 1.5 m/s	385 ± 16	17.37 ± 0.98	16.23 ± 0.73	0.843 ± 0.019	0.790 ± 0.016
1,500 W/m^2, 15 cm, 40C, 1.5 m/s	390 ± 20	17.55 ± 0.48	16.10 ± 0.59	0.830 ± 0.013	0.791 ± 0.024
1,500 W/m^2, 20 cm, 40C, 1.5 m/s	394 ± 19	17.84 ± 0.38	16.00 ± 0.28	0.825 ± 0.016	0.792 ± 0.017
3,000 W/m^2, 10 cm, 40C, 1.5 m/s	335 ± 17	16.67 ± 0.89	16.95 ± 0.60	0.950 ± 0.029	0.785 ± 0.010
3,000 W/m^2, 15 cm, 40C, 1.5 m/s	336 ± 16	16.85 ± 0.73	16.84 ± 0.74	0.942 ± 0.028	0.786 ± 0.019
3,000 W/m^2, 20 cm, 40C, 1.5 m/s	341 ± 15	17.03 ± 0.55	16.70 ± 0.35	0.930 ± 0.012	0.787 ± 0.018
4,500 W/m^2, 10 cm, 40C, 1.5 m/s	292 ± 26	15.94 ± 0.93	18.10 ± 0.30	1.148 ± 0.020	0.779 ± 0.011
4,500 W/m^2, 15 cm, 40C, 1.5 m/s	293 ± 07	16.15 ± 0.86	17.97 ± 0.69	1.130 ± 0.021	0.780 ± 0.009
4,500 W/m^2, 20 cm, 40C, 1.5 m/s	298 ± 12	16.38 ± 0.90	17.83 ± 0.34	1.111 ± 0.007	0.781 ± 0.004
1,500 W/m^2, 10 cm, 50C, 0.5 m/s	240 ± 11	7.09 ± 0.61	18.20 ± 0.25	0.850 ± 0.004	0.770 ± 0.015

TABLE 1. *CONTINUED*

Drying conditions	D_r (min)	E_s (MJ/kg)	ΔE	E_c (%)	R_r (kg water/kg DM)
1,500 W/m^2, 15 cm, 50C, 0.5 m/s	243 ± 10	7.32 ± 0.40	18.10 ± 0.60	0.833 ± 0.014	0.771 ± 0.012
1,500 W/m^2, 20 cm, 50C, 0.5 m/s	245 ± 15	7.55 ± 0.54	18.00 ± 0.27	0.820 ± 0.013	0.772 ± 0.013
3,000 W/m^2, 10 cm, 50C, 0.5 m/s	200 ± 21	6.31 ± 0.70	19.00 ± 0.54	0.925 ± 0.024	0.764 ± 0.019
3,000 W/m^2, 15 cm, 50C, 0.5 m/s	203 ± 13	6.58 ± 0.48	18.86 ± 0.45	0.900 ± 0.017	0.765 ± 0.027
3,000 W/m^2, 20 cm, 50C, 0.5 m/s	206 ± 11	6.82 ± 0.57	18.76 ± 0.20	0.895 ± 0.025	0.766 ± 0.022
4,500 W/m^2, 10 cm, 50C, 0.5 m/s	143 ± 09	5.62 ± 0.62	20.23 ± 0.88	0.980 ± 0.016	0.755 ± 0.009
4,500 W/m^2, 15 cm, 50C, 0.5 m/s	149 ± 26	5.95 ± 0.51	20.06 ± 0.54	0.975 ± 0.008	0.759 ± 0.015
4,500 W/m^2, 20 cm, 50C, 0.5 m/s	157 ± 10	6.17 ± 0.48	19.88 ± 0.36	0.960 ± 0.010	0.760 ± 0.018
1,500 W/m^2, 10 cm, 50C, 1 m/s	266 ± 22	12.18 ± 0.74	17.77 ± 0.55	0.805 ± 0.014	0.773 ± 0.006
1,500 W/m^2, 15 cm, 50C, 1 m/s	271 ± 17	12.30 ± 0.58	17.66 ± 0.76	0.790 ± 0.012	0.774 ± 0.007
1,500 W/m^2, 20 cm, 50C, 1 m/s	272 ± 19	12.69 ± 0.60	17.53 ± 0.31	0.785 ± 0.018	0.775 ± 0.011
3,000 W/m^2, 10 cm, 50C, 1 m/s	221 ± 14	11.50 ± 0.83	18.80 ± 0.51	0.880 ± 0.018	0.767 ± 0.019
3,000 W/m^2, 15 cm, 50C, 1 m/s	223 ± 11	11.74 ± 0.77	18.70 ± 0.45	0.865 ± 0.029	0.768 ± 0.024
3,000 W/m^2, 20 cm, 50C, 1 m/s	226 ± 16	11.88 ± 0.83	18.56 ± 0.40	0.850 ± 0.016	0.769 ± 0.005
4,500 W/m^2, 10 cm, 50C, 1 m/s	168 ± 28	10.77 ± 0.55	19.79 ± 0.65	0.972 ± 0.011	0.761 ± 0.013
4,500 W/m^2, 15 cm, 50C, 1 m/s	173 ± 23	10.98 ± 0.81	19.74 ± 0.54	0.939 ± 0.016	0.763 ± 0.008
4,500 W/m^2, 20 cm, 50C, 1 m/s	182 ± 10	11.15 ± 0.85	19.61 ± 0.71	0.922 ± 0.019	0.764 ± 0.060
1,500 W/m^2, 10 cm, 50C, 1.5 m/s	287 ± 12	15.26 ± 0.42	17.50 ± 0.50	0.779 ± 0.029	0.776 ± 0.025
1,500 W/m^2, 15 cm, 50C, 1.5 m/s	290 ± 15	15.40 ± 0.33	17.39 ± 0.74	0.760 ± 0.022	0.777 ± 0.017
1,500 W/m^2, 20 cm, 50C, 1.5 m/s	293 ± 24	15.60 ± 0.79	17.28 ± 0.52	0.753 ± 0.011	0.778 ± 0.013
3,000 W/m^2, 10 cm, 50C, 1.5 m/s	235 ± 19	14.57 ± 0.61	18.60 ± 0.74	0.835 ± 0.013	0.770 ± 0.008
3,000 W/m^2, 15 cm, 50C, 1.5 m/s	238 ± 31	14.75 ± 0.93	18.50 ± 0.31	0.828 ± 0.020	0.771 ± 0.016
3,000 W/m^2, 20 cm, 50C, 1.5 m/s	241 ± 13	14.92 ± 0.86	18.27 ± 0.64	0.813 ± 0.011	0.772 ± 0.019
4,500 W/m^2, 10 cm, 50C, 1.5 m/s	189 ± 10	13.90 ± 0.90	19.53 ± 0.36	0.933 ± 0.012	0.764 ± 0.005
4,500 W/m^2, 15 cm, 50C, 1.5 m/s	193 ± 21	14.25 ± 0.52	19.41 ± 0.72	0.920 ± 0.009	0.766 ± 0.017
4,500 W/m^2, 20 cm, 50C, 1.5 m/s	198 ± 17	14.44 ± 0.63	19.25 ± 0.64	0.910 ± 0.019	0.767 ± 0.018

Note: Values are expressed as mean ± standard deviation.

Kocabiyik and Tezer (2009) for carrot slices and Motevali *et al.* (2011) for mushroom slices. At constant air velocity, energy consumption decreased with increasing infrared intensity and also decreasing distance between lamps and sample, due to the increase in sample temperature and evaporation rate and the decrease in drying time (Motevali *et al.* 2011; Kantrong *et al.* 2014). This finding is in line with the results of the study conducted by Motevali *et al.* (2011). The minimum specific energy consumption (9.07 MJ/kg) was obtained at air velocity of 0.5 m/s, radiation intensity of 4,500 W/m^2 and distance between emitter and sample of 10 cm, while the maximum specific energy was 15.51 MJ/kg observed at 1.5 m/s air velocity, 1,500 W/m^2 illumination intensity and 20 cm distance between emitter and sample.

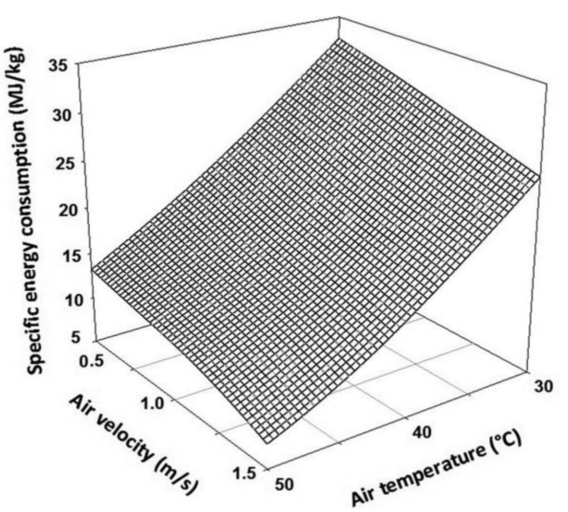

FIG. 4. INTERACTION EFFECT OF AIR VELOCITY AND TEMPERATURE ON THE SPECIFIC ENERGY CONSUMPTION FOR HOT AIR DRYING OF PEPPERMINT LEAVES

Table 1 shows the required specific energy for drying peppermint leaves in a hot air flow-infrared dryer. The specific energy consumption decreased at all air velocities, all examined distances between lamps and sample and infrared radiation intensity levels with increase in air temperature. The same trends were also observed for other drying conditions, except for two cases where energy consumption increased with increasing air velocity and increasing distance between lamps and sample. In combined drying, increasing air temperature had more profound effect on energy consumption than the increase in infrared intensity. In general, when the three methods were compared in terms of energy consumption, the combined drying method had the lowest value, followed by infrared and convective drying methods, respectively. Other researchers also observed a reduction in specific energy consumption when drying products under a

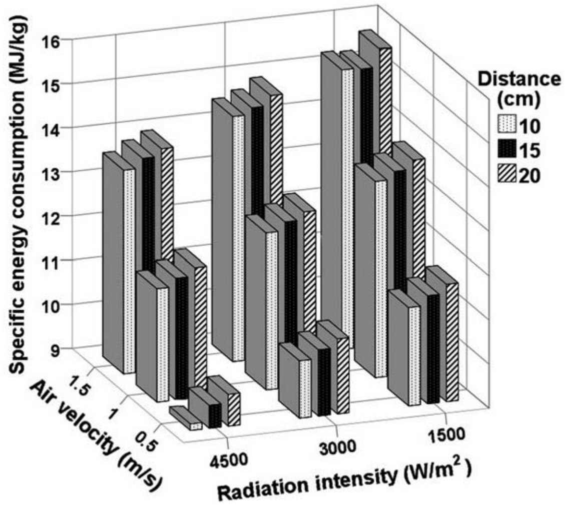

FIG. 5. VARIATIONS OF SPECIFIC ENERGY CONSUMPTION FROM THE EFFECTS OF INFRARED RADIATION INTENSITY, DISTANCE BETWEEN EMITTER AND SAMPLE AND AIR VELOCITY

combined mode of heating (Motevali *et al.* 2011; El-Mesery and Mwithiga 2015).

Rehydration Characteristics

Rehydration is an important quality characteristic for dried food materials. Rehydration can also be used to quantify the injury caused by drying or pre-drying treatments (Doymaz *et al.* 2015). The rehydration ratios estimated for peppermint leaves dried under hot air mode are presented in Fig. 6. As seen in this figure, the amount of absorbed water decreased slowly due to increasing air velocity at constant air temperature. Similar finding was reported by Vega-Gálvez *et al.* (2012) for apple slices. Also, from the rehydration curve in Fig. 6, the influence of drying air temperature on rehydration ratio is almost negligible. At constant air-drying velocity, rehydration ratio decreased slightly as drying temperature increased. Similar findings were reported by Vega-Gálvez *et al.* (2012) for apple slices and Horuz and Maskan (2015) for pomegranate arils. This was probably a result of the severe shrinkage and tissue collapse produced by higher air temperatures, which finally results in decreasing rehydration capacity (Horuz and Maskan 2015). It can be concluded that the tissue was imposed irreversible structural damages during drying, with loss of rehydration ability as a result (Vega-Gálvez *et al.* 2012). Therefore, samples dried at 0.5 m/s air velocity and 30C showed the highest value of rehydration ratio (0.781 kg water/kg DM), whereas the samples being dried at 1.5 m/s air velocity and 50C gave the lowest rehydration ratio value (0.743 kg water/kg DM).

The rehydration ratio for dried products under infrared drying conditions is shown in Fig. 7. A decline in rehydration ratio occurred as the infrared intensity levels increase at constant air velocity and constant distance between emitter and sample. This may be indicative of a change in the product induced by radiation intensity level and perhaps a loss of solids during rehydration (Doymaz 2014). Figure 7 also indicates that rehydration ratio increased with an increase in distance between emitter and sample under constant air velocity and infrared intensity. At constant infrared intensity and distance between emitter and sample, increasing air velocity increases rehydration ratio. Similar effect of infrared intensity was reported by Doymaz (2012). As a result, the minimum rehydration ratio (0.750 kg water/kg DM) was obtained at air velocity of 0.5 m/s, radiation intensity of 4,500

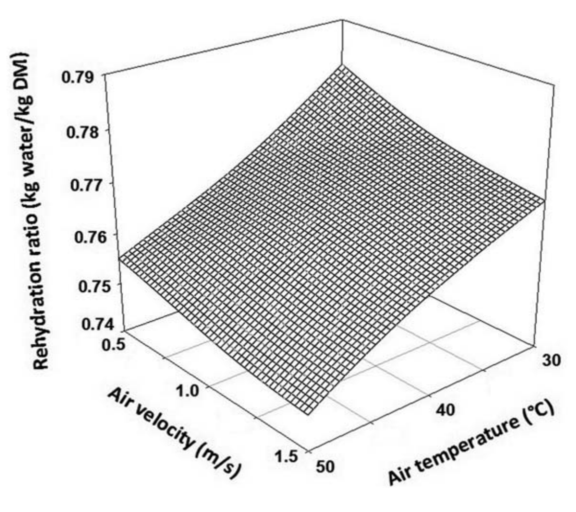

FIG. 6. INTERACTION EFFECT OF AIR VELOCITY AND TEMPERATURE ON THE REHYDRATION RATIO FOR HOT AIR DRYING OF PEPPERMINT LEAVES

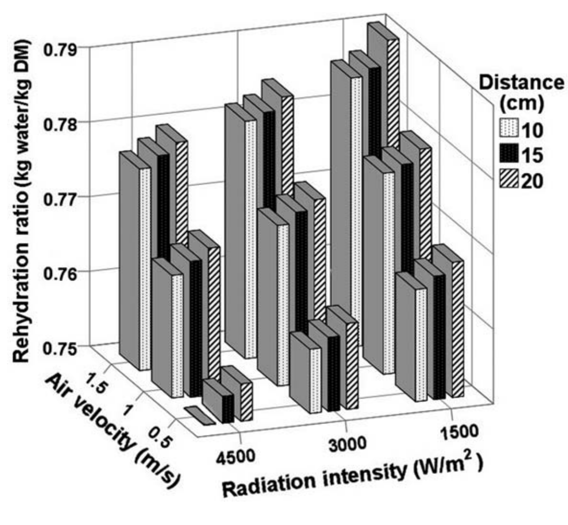

FIG. 7. REHYDRATION RATIO OF PEPPERMINT LEAVES AT DIFFERENT INFRARED RADIATION INTENSITIES, DISTANCES BETWEEN EMITTER AND SAMPLE AND AIR VELOCITIES

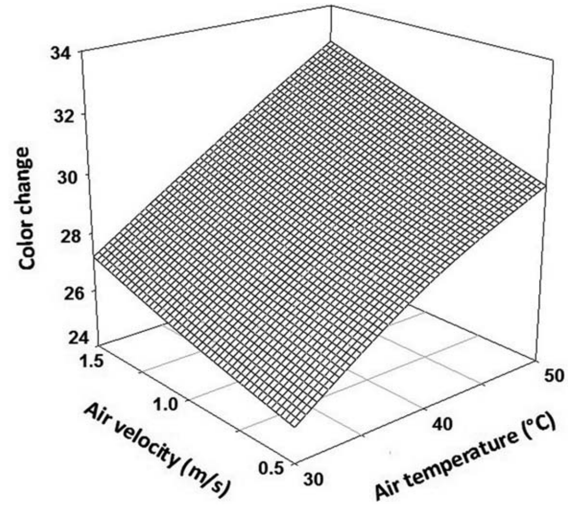

FIG. 8. INTERACTION EFFECT OF AIR VELOCITY AND TEMPERATURE ON THE COLOR CHANGE FOR HOT AIR DRYING OF PEPPERMINT LEAVES

W/m^2 and when emitter is 10 cm away from sample, while the maximum rehydration ratio was 0.791 kg water/kg DM observed at 1.5 m/s air velocity, 1,500 W/m^2 illumination intensity and 20 cm distance between emitter and sample.

The rehydration ratios for dried products under infrared-assisted hot air drying conditions are given in Table 1. In the combined infrared-hot air method, the rehydration ratio was increased with increasing air velocity while it increased with decreasing air temperature. Also, rehydration ratio increased with increasing distance between lamps and sample and decreasing infrared intensity. The minimum rehydration ratio (0.755 kg water/kg DM) was obtained at air velocity of 0.5 m/s, air temperature of 50C, radiation intensity of 4,500 W/m^2 and distance between emitter and sample of 10 cm, while the maximum rehydration ratio was 0.811 kg water/kg DM observed at 1.5 m/s air velocity, 30C air temperature, 1,500 W/m^2 illumination intensity and 20 cm distance between emitter and sample. As a result, we can see that there is a negligible difference between the rehydration ratios from hot air drying and infrared drying. Also, the highest rehydration ratio, which was obtained from infrared-assisted hot air drying, was probably due to fewer physical and chemical changes occurred in shorter drying time and uniform heating in the process of this drying method compared to hot air and infrared drying (Vishwanathan *et al.* 2010).

Color Difference

Color difference (ΔE) shows the degree of overall color change in dried samples with respect to the color of fresh peppermint. A good quality dehydrated products should have a minimum ΔE value (Kantrong *et al.* 2014). The changes in ΔE values of hot air dried peppermint leaves are presented in Fig. 8. The ΔE ranged from 24.86 to 32.53. At constant air-drying velocity, ΔE increased with air-drying temperatures. The natural green color of leaves is created by the mixture of two compounds, chlorophyll a and chlorophyll b, which are directly linked to magnesium (Sandra Sagrin and Chong 2013). High temperature helps to substitute magnesium with hydrogen in chlorophyll which is altered to pheophytins in this condition (Therdthai and Zhou 2009). The similar results were also reported by Alibas (2006), Ahmadi Chenarbon *et al.* (2012) and Moon *et al.* (2015), where high values of ΔE were associated with high drying temperatures. The ΔE value for all air temperatures increased with an increase in air velocity. The same behavior was observed by Ahmadi Chenarbon *et al.* (2012) during drying of St. John's wort leaves. The results indicate that in the case of hot air drying, less color difference could be found when lower air temperature and air velocity were applied.

The ΔE values of peppermint leaves undergone infrared drying are shown in Fig. 9. Similar to the finding of Nasiroglu and Kocabiyik (2009) for red pepper slices, applying high radiation intensities to the product resulted in an increase in discoloration of the peppermint leaves. As well, from Fig. 9 it was found that with increase in air velocity, ΔE decreased and with the decrease in distance between emitter and sample, ΔE increased. Small color changes with increasing air velocities were also reported by Ning *et al.* (2013) for *Ligularia fischeri* leaves. As a result, ΔE values of the hot air dried samples were higher than those dried by infrared. Due to the short drying time, the pigments might be less destroyed and color was more preserved (Kantrong *et al.* 2014). Similarly, Roknul

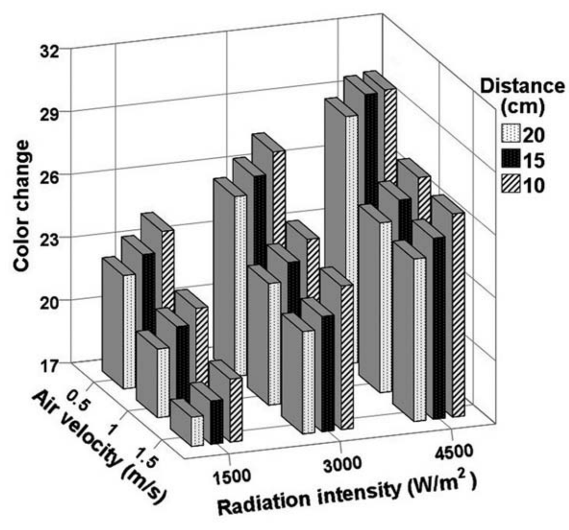

FIG. 9. COLOR CHANGE IN PEPPERMINT LEAVES AT DIFFERENT INFRARED RADIATION INTENSITIES, DISTANCES BETWEEN EMITTER AND SAMPLE AND AIR VELOCITIES

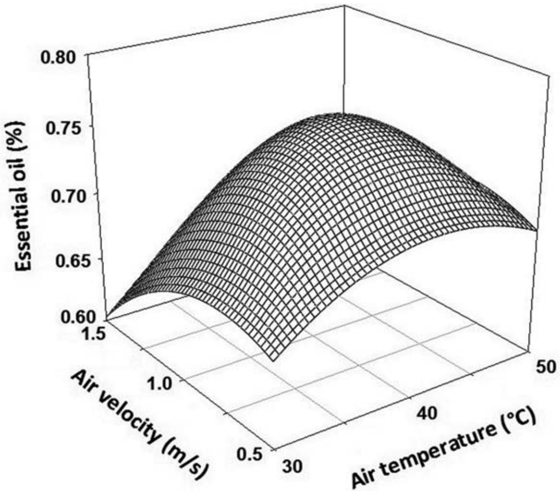

FIG. 10. INTERACTION EFFECT OF AIR VELOCITY AND TEMPERATURE ON THE OIL CONTENT FOR HOT AIR DRYING OF PEPPERMINT LEAVES

et al. (2014) and Qi *et al.* (2014) suggested that the pigment degradation rate was lower when infrared was applied. Comparing to the infrared drying, the hot air drying yielded dried peppermint leaves being darker, less green and more yellow. Minimum ΔE (18.48) was related to air velocity of 1.5 m/s, distance between emitter and sample of 20 cm and infrared intensity of 1,500 W/m^2. Maximum ΔE (29.89) was computed at air velocity of 0.5 m/s, distance between emitter and sample of 10 cm and infrared intensity of 4,500 W/m^2.

The values of ΔE obtained from the experimental data during combined hot air-infrared drying method are given in Table 1. In combined hot air-infrared drying method, an increase in air velocity had an adverse effect on the ΔE value, which decreased with increasing air velocity. The results (Table 1) show that less color differences in samples with respect to their original undried color was observed when lower air temperature, higher distance between emitter and sample and lower infrared intensity were applied. The results presented in this work suggest that the changes in ΔE of combined hot air and infrared mode were smaller as compared to hot air and infrared modes (El-Mesery and Mwithiga 2015). It can be attributed to the synergistic effect emanates from both infrared and hot air sources leading to efficient heat and mass transfer during drying of the product in a combined hot air and infrared mode (Mihindukulasuriya and Jayasuriya 2015). Therefore, quality loss can be reduced by using combined hot air and infrared mode.

Essential Oil Content

The yields of the essential oil extracted from the hot air dried samples are shown in Fig. 10. As seen in this figure, a reduction in essential oil content occurred as air velocity increased. The explanation for this behavior may be related to the fact that, during convective drying, the air stream that flows through the herb sample allows volatile particles to easily evaporate out of the dryer or could cause intensive oxidation (Shahhoseini *et al.* 2013). The effect of air velocity on essential oil content was similar with the findings of a study undertaken on lemon grass (Rocha *et al.* 2012). The results (Fig. 10) showed that the essential oil contents of dried peppermint leaves at 40C were higher than those of dried ones at other temperatures. In fact, high drying temperature (i.e., 50C) might have caused rupturing the oil glands leading to rapid evaporation of oil from the leaves (Argyropoulos and Müller 2014), while at low drying temperature (i.e., 30C) longer drying time might lead to more enzymatic activity and destroying oil glands in the leaves (Rocha *et al.* 2011). However, the amount of essential oil extracted from the leaves dried at 50C was more than those dried at 30C. Increasing temperature to above 40C had an adverse effect on the essential oil yield. These results are in agreement with those reported by Rocha *et al.* (2011) for guaco leaves and Shahhoseini *et al.* (2013) for lemon verbena. In contrast with their results, however, some other researchers showed that decreasing drying temperature could induce an increase in the essential oil yield of many aromatic plants such as lemon balm (Argyropoulos and Müller 2014) and *Laurus nobilis* L. leaves (Sellami *et al.* 2011). According to Sellami *et al.* (2011), these contradictory results may be due to physiological differences in plant species, secretory structures and their localization in the plant and chemical composition of essential oil. In our research, leaves dried at 40C at an air flow rate of 0.5 m/s

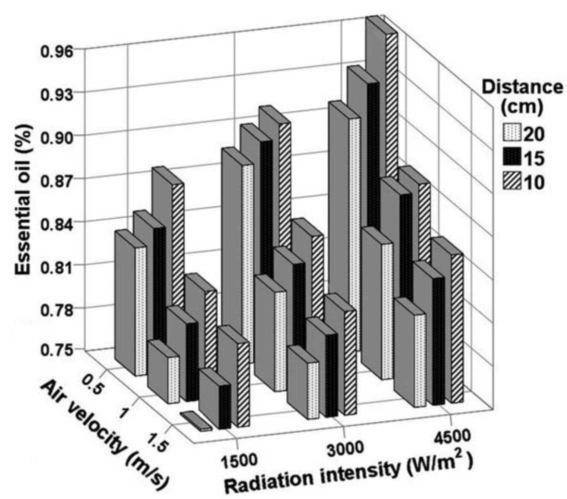

FIG. 11. EXTRACTED OIL CONTENT OF PEPPERMINT LEAVES AT DIFFERENT INFRARED RADIATION INTENSITIES, DISTANCES BETWEEN EMITTER AND SAMPLE AND AIR VELOCITIES

TABLE 2. RESULTS OF THE VARIANCE ANALYSIS FOR DRYING TIME (D_r), SPECIFIC ENERGY CONSUMPTION (E_s), COLOR CHANGE (ΔE), OIL YIELD (E_c) AND REHYDRATION RATIO (R_r) OF PEPPERMINT LEAVES

Variables	Degree of freedom	D_r	E_s	ΔE	E_c	R_r
Hot air drying						
T	2	4404.664**	5982.479**	8620.163**	2285.961**	1016.348**
V	2	292.952**	553.018**	1617.848**	299.938**	102.652**
T×V	4	21.272**	24.323**	1.897^{ns}	3.490*	0.848^{ns}
Error	18					
Total	27					
Infrared drying						
V	2	250289.505**	93976.572**	674.483**	4511.314**	1985.760**
IR	2	13069.239**	17788.295**	1495.342**	2228.109**	468.521**
D	2	209.642**	840.595**	190.116**	808.910**	34.877**
V×IR	4	194.862**	40.570**	2.473^{ns}	39.991**	6.243**
V×D	4	4.665**	2.079^{ns}	1.198^{ns}	3.922**	0.685^{ns}
IR×D	4	0.289^{ns}	2.201^{ns}	0.370^{ns}	2.484^{ns}	0.962^{ns}
V×IR×D	8	1.651^{ns}	0.906^{ns}	1.365^{ns}	1.937^{ns}	0.890^{ns}
Error	54					
Total	81					
Combined hot air-infrared drying						
T	2	579600.165**	60700.402**	4.727*	28665.157**	173406.889**
V	2	23123.922**	199058.547**	4.091*	3315.521**	5223.817**
IR	2	132183.182**	6388.026**	3.448*	45229.118**	22116.929**
D	2	832.899**	530.707**	3.086*	4.050*	938.001**
T×V	4	30.269**	1034.097**	2.529*	123.678**	67.038**
T×IR	4	22.379**	98.713**	1.494^{ns}	2649.507**	49.392**
T×D	4	2.847*	1.808^{ns}	2.514*	2.633*	2.359^{ns}
V×IR	4	145.127**	46.037**	2.516^{ns}	16.382**	9.413**
V×D	4	2.150^{ns}	1.116^{ns}	1.516^{ns}	21.669**	1.817^{ns}
IR×D	4	18.516**	3.253*	2.520^{ns}	4.375**	2.397^{ns}
T×V×IR	8	2.264*	2.175*	1.094^{ns}	2.484*	2.150*
T×V×D	8	1.496^{ns}	1.563^{ns}	1.882^{ns}	1.935^{ns}	1.331^{ns}
T×IR×D	8	20.313**	0.799^{ns}	1.335^{ns}	0.463^{ns}	2.068*
V×IR×D	8	1.441^{ns}	1.619^{ns}	1.518^{ns}	1.206^{ns}	2.840**
T×V×IR×D	16	1.296^{ns}	1.318^{ns}	0.905^{ns}	1.093^{ns}	1.788*
Error	162					
Total	243					

Note: *F* values are shown. T, V, IR and D are air temperature, air velocity, infrared radiation intensity and distance between emitter and sample, respectively. **, *, ns show significant differences at $P < 0.01$ and 0.05, and non-significance, respectively.

had the highest essential oil content (0.797%), and leaves dried at 30C at an air flow rate of 1.5 m/s had the lowest essential oil content (0.603%).

The yields of the essential oil extracted from the infrared dried sample are shown in Fig. 11. According to Fig. 11, the amount of essential oil increased with the increasing of infrared intensity levels at each one of the constant distance between emitter and samples and air velocity values. An increase in essential oil content with higher infrared intensities has been reported by Pääkkönen *et al.* (1999). Also, the essential oil yield increased with a decrease in distance between emitter and samples under constant infrared intensity and air velocity. These increases in the essential oil yield seems to be strongly related to the drying time, as a decrease in drying time helps to minimize the time for the volatiles to be lost (Buchaillot *et al.* 2009). The obtained results showed that increasing air velocity resulted in decreasing essential oil content. Importantly, in our study, the values of essential oil yield were higher for infrared dried samples compared to hot air dried leaves. This could be associated with the time of drying which is longer in the case of hot air drying (Sellami *et al.* 2011). In the case of infrared drying, the lowest amount of essential oil (0.748%) was obtained from samples dried at 1,500 W/m^2 infrared radiation intensity, 1.5 m/s air velocity and 20 cm distance between emitter and sample while the highest amount (0.981%) was obtained at 4,500 W/m^2 infrared radiation intensity, 0.5 m/s air velocity and 10 cm distance between emitter and sample.

The impact of combined infrared-hot air drying system on the yield of essential oil from peppermint leaves is shown in Table 1. It is evident from this table that, the essential oil content decreased with the increase in both emitter-to-sample distance and air drying velocity. Similarly, in combined drying method, the yield of essential oil from the leaves dried at 40C was higher than the yield of those dried at 30 and 50C. The yield of essential oil was higher from the leaves dried by the combined infrared-hot air drying method than those dried by either infrared drying or hot air drying method. In combined infrared and hot air drying system, minimum yield of essential oil (0.724%) belonged to air velocity of 1.5 m/s, distance between emitter and sample of 20 cm, infrared intensity of 1,500 W/m^2 with air temperature of 30C and maximum value (1.235%) belonged to air velocity of 0.5 m/s, distance between emitter and sample of 10 cm, infrared intensity of 4,500 W/m^2 with air temperature of 40C. Results of the variance analysis for the effect of different drying factors on drying time, specific energy consumption, color change, oil yield and rehydration ratio are presented in Table 2.

CONCLUSIONS

Based on the experimental tests reported in this work, it is observed that the drying method significantly affects the drying characteristics and quality attributes of dried peppermint leaves. The results demonstrated that the application of combined hot air and infrared drying for peppermint leaves decreased specific energy consumption, drying time and increased the quality of dried product in terms of overall color change, rehydration ratio and essential oil content when compared to drying under infrared heating with cold air convection or convective hot air heating alone. Considering both quality and energy parameters, the optimum drying condition was obtained to have drying air temperature of 40C, air velocity of 0.5 m/s, infrared radiation of 4,500 W/m^2 and distance between emitter and sample of 15 cm. Future research works are required for further understanding the characteristics of chemical compositions in addition to the structural properties of dried samples.

REFERENCES

ADABI, M.E., MOTEVALI, A., NIKBAKHT, A.M. and KHOSHTAGHAZA, M.H. 2013. Investigation of some pretreatments on energy and specific energy consumption drying of black mulberry. Chem. Ind. Chem. Eng. Q. *19*, 89–105.

AHMADI CHENARBON, H., MINAEI, S., BASSIRI, A.R., ALMASSI, M., ARABHOSSEINI, A. and MOTEVALI, A. 2012. Effect of drying on the color of St. John's wort (*Hypericum perforatum* L.) leaves. Int. J. Food Eng. *8*. doi: 10.1515/1556-3758.2545.

ALIBAS, I. 2006. Characteristics of chard leaves during microwave, convective, and combined microwave-convective drying. Drying Technol. *24*, 1425–1435.

ALIBAS, I. 2007. Energy consumption and colour characteristics of nettle leaves during microwave, vacuum and convective drying. Biosyst. Eng. *96*, 495–502.

ARABHOSSEINI, A., PADHYE, S., HUISMAN, W., BOXTEL, A.V. and MÜLLER, J. 2011. Effect of drying on the color of tarragon (*Artemisia dracunculus* L.) leaves. Food Bioprocess Technol. *4*, 1281–1287.

ARGYROPOULOS, D. and MÜLLER, J. 2014. Changes of essential oil content and composition during convective drying of lemon balm (*Melissa officinalis* L.). Ind. Crops Prod. *52*, 118–124.

BAI-NGEW, S., THERDTHAI, N., DHAMVITHEE, P. and ZHOU, W. 2015. Effect of microwave vacuum drying and hot air drying on the physicochemical properties of durian flour. Int. J. Food Sci. Technol. *50*, 305–312.

BUCHAILLOT, A., CAFFIN, N. and BHANDARI, B. 2009. Drying of lemon myrtle (*Backhousia citriodora*) leaves: retention of volatiles and color. Drying Technol. *27*, 445–450.

DAI, J., ORSAT, V., VIJAYA RAGHAVAN, G.S. and YAYLAYAN, V. 2010. Investigation of various factors for the extraction of peppermint (*Mentha piperita* L.) leaves. J. Food Eng. *96*, 540–543.

DOYMAZ, İ. 2012. Infrared drying of sweet potato (*Ipomoea batatas* L.) slices. J. Food Sci. Technol. *49*, 760–766.

DOYMAZ, I. 2014. Suitability of thin-layer drying models for infrared drying of peach slices. J. Food Process. Preserv. *38*, 2232–2239.

DOYMAZ, İ. and İSMAIL, O. 2012. Experimental characterization and modelling of drying of pear slices. Food Sci. Biotechnol. *21*, 1377–1381.

DOYMAZ, I., KIPCAK, A.S. and PISKIN, S. 2015. Characteristics of thin-layer infrared drying of green bean. Czech J. Food Sci. *33*, 83–90.

EL-MESERY, H. and MWITHIGA, G. 2015. Performance of a convective, infrared and combined infrared-convective heated conveyor-belt dryer. J. Food Sci. Technol. *52*, 2721–2730.

GOLESTAN, L., SEYEDYOUSEFI, L., KABOOSI, H. and SAFARI, H. 2016. Effect of *Mentha spicata* L. and *Mentha aquatica* L. essential oils on the microbiological properties of fermented dairy product, kashk. Int. J. Food Sci. Technol., doi: 10.1111/ijfs.13014.

HORUZ, E. and MASKAN, M. 2015. Hot air and microwave drying of pomegranate (*Punica granatum* L.) arils. J. Food Sci. Technol. *52*, 285–293.

KANTRONG, H., TANSAKUL, A. and MITTAL, G.S. 2014. Drying characteristics and quality of shiitake mushroom undergoing microwave-vacuum drying and microwave-vacuum combined with infrared drying. J. Food Sci. Technol. *51*, 3594–3608.

KOCABIYIK, H. and TEZER, D. 2009. Drying of carrot slices using infrared radiation. Int. J. Food Sci. Technol. *44*, 953–959.

KOCABIYIK, H., YILMAZ, N., BARIS TUNCEL, N., SUMER, S.K. and BURAK BUYUKCAN, M. 2014. The effects of middle infrared radiation intensity on the quality of dried tomato products. Int. J. Food Sci. Technol. *49*, 703–710.

KOCABIYIK, H., YILMAZ, N., TUNCEL, N.B., SUMER, S.K. and BUYUKCAN, M.B. 2015. Drying, energy, and some physical and nutritional quality properties of tomatoes dried with short-infrared radiation. Food Bioprocess Technol. *8*, 516–525.

MIHINDUKULASURIYA, S.D.F. and JAYASURIYA, H.P.W. 2015. Drying of chilli in a combined infrared and hot air rotary dryer. J. Food Sci. Technol. *52*, 4895–4904.

MOON, J.H., PAN, C.H. and YOON, W.B. 2015. Drying characteristics and thermal degradation kinetics of hardness, anthocyanin content and colour in purple-and red-fleshed potato (*Solanum tuberosum* L.) during hot air drying. Int. J. Food Sci. Technol. *50*, 1255–1267.

MOTEVALI, A., MINAEI, S., KHOSHTAGHAZA, M.H. and AMIRNEJAT, H. 2011. Comparison of energy consumption and specific energy requirements of different methods for drying mushroom slices. Energy *36*, 6433–6441.

NASIROGLU, S. and KOCABIYIK, H. 2009. Thin-layer infrared radiation drying of red pepper slices. J. Food Process Eng. *32*, 1–16.

NING, X., HAN, C., CHO, S., LEE, J. and YOON, S. 2013. Far-infrared drying characteristics and quality assessment of *Ligularia fischeri.* Food Sci. Biotechnol. *22*, 281–288.

PÄÄKKÖNEN, K., HAVENTO, J., GALAMBOSI, B. and PYYKKÖNEN, M. 1999. Infrared drying of herbs. Agric. Food Sci. Finl. *8*, 19–27.

QI, L.L., ZHANG, M., MUJUMDAR, A.S., MENG, X.Y. and CHEN, H.Z. 2014. Comparison of drying characteristics and quality of shiitake mushrooms (*Lentinus edodes*) using different drying methods. Drying Technol. *32*, 1751–1761.

ROCHA, R.P., MELO, E.C. and RADÜNZ, L.L. 2011. Influence of drying process on the quality of medicinal plants. J. Med. Plants Res. *5*, 7076–7084.

ROCHA, R.P., MELO, E.C., DEMUNER, A.J., RADÜNZ, L.L. and BRAUN, H. 2012. Effect of drying air velocity on the quality of essential oil from lemon grass. Global Sci. Technol. *5*, 23–31.

ROKNUL, A.S.M., ZHANG, M., MUJUMDAR, A.S. and WANG, Y. 2014. A comparative study of four drying methods on drying time and quality characteristics of stem lettuce slices (*Lactuca sativa* L.). Drying Technol. *32*, 657–666.

SANDRA SAGRIN, M. and CHONG, G.H. 2013. Effects of drying temperature on the chemical and physical properties of *Musa acuminate* Colla (AAA Group) leaves. Ind. Crops Prod. *45*, 430–434.

SELLAMI, I.H., WANNES, W.A., BETTAIEB, I., BERRIMA, S., CHAHED, T., Marzouk, B. and LIMAM, F. 2011. Qualitative and quantitative changes in the essential oil of *Laurus nobilis* L. leaves as affected by different drying methods. Food Chem. *126*, 691–697.

SHAHHOSEINI, R., GHORBANI, H., KARIMI, S.R., ESTAJI, A. and MOGHADDAM, M. 2013. Qualitative and quantitative changes in the essential oil of lemon verbena (*Lippia citriodora*) as affected by drying condition. Drying Technol. *31*, 1020–1028.

TARHAN, S., TELCI, İ., TUNCAY, M.T. and POLATCI, H. 2010. Product quality and energy consumption when drying peppermint by rotary drum dryer. Ind. Crops Prod. *32*, 420–427.

THERDTHAI, N. and ZHOU, W. 2009. Characterization of microwave vacuum drying and hot air drying of mint leaves (*Mentha cordifolia* Opiz ex Fresen). J. Food Eng. *91*, 482–489.

VEGA-GÁLVEZ, A., AH-HEN, K., CHACANA, M., VERGARA, J., MARTÍNEZ-MONZÓ, J., GARCÍA-SEGOVIA, P., LEMUS-MONDACA, R. and DI SCALA, K. 2012. Effect of temperature and air velocity on drying kinetics, antioxidant capacity, total phenolic content, colour, texture and microstructure of apple (var. *Granny Smith*) slices. Food Chem. *132*, 51–59.

VISHWANATHAN, K.H., HEBBAR, H.U. and RAGHAVARAO, K.S.M.S. 2010. Hot air assisted infrared drying of vegetables and its quality. Food Sci. Technol. Res. *16*, 381–388.

ZHELJAZKOV, V.D. and ASTATKIE, T. 2010. Distillation waste water can modify peppermint (*Mentha* × *piperita* L.) oil composition. Ind. Crops Prod. *36*, 420–426.