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ORIGINAL ARTICLE

Drying of chilli in a combined infrared and hot air rotary dryer

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Abstract The investigation of an economical and efficient drying method for chilli is beneficial because it could provide a means of overcoming the drawbacks of traditional drying methods: high operating power and long drying time, which result in a decrease in the quality of the chilli. This study involved the design and development of a combined infrared and hot air laboratory-scale rotary dryer, which consists of three operating modes: hot air, infrared, and combined infrared and hot air. Drying experiments were conducted at five different temperatures (50, 55, 60, 65, and 70 °C). The drying behavior produced with the three operating modes was evaluated. The best mode was determined based on the parameters for evaluating the quality of chilli, the power consumption, and the retention time. The results indicate that the optimal overall drying performance for chilli was achieved at 70, 65, 50 °C drying temperatures in hot air, combined, and IR mode, respectively. A positive correlation was observed between retention time and power consumption with the hot air and the combined modes, while a negative correlation was identified in the IR mode.

Keywords Chilli · Drying · Power consumption · Infrared · Hot air · Rotary dryer

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Introduction

Its use as a spice and condiment makes chilli is an essential food ingredient and cash crop in many parts of the world. The shelf life of freshly harvested chilli is limited to 2–3 days due to its initial high moisture content (300 d.b. to 400 d.b.) (Kaleemullah and Kailappan 2006). The initial moisture content of freshly harvested chilli can be reduced with the use of a variety of drying methods that extend its shelf life. Sun drying, hot air drying, and fluidized bed drying are the methods most commonly applied for drying chilli. Of the existing methods, sun drying is the one most widely employed in tropical areas, although this technique entails disadvantages such as loss of quality, product wastage, dependency on weather, and a substantial time requirement. Hot air drying is also not very suitable for chilli, since it requires relatively greater amounts of energy and time, especially during the falling rate drying period of the product (i.e., the period during which the moisture content of the drying product is reduced, decreasing the drying rate) (Maskan 2000, 2001). Although fluidized bed drying offers some advantages, such as efficient mixing and a faster drying rate due to the higher heat and mass transfer coefficient, its major drawback is the reduction in the size of the product particles (Goksu et al. 2005). This method also requires more power for the mixing of the particles (Mihindukulasuriya and Jayasuriya 2013).

In recent years, the use of electromagnetic radiation in drying, such as infrared (IR) and microwave, has become increasingly popular due to the wide range of potential applications and the advantages with respect to performance (Datta and Ni 2002; Goksu et al. 2005; Hebbar et al. 2004; Praveen Kumar et al. 2006). IR radiation heating has been used as a supplement to traditional heating methods because of its intrinsic advantages: the simplicity of the equipment required; convenient accommodation of IR heating requirements with convective, conductive, and microwave heating sources; a fast

transient response; and significant energy savings (Sandu 1986; Das et al. 2004, 2009). In spite of its higher drying rate, it is also characterized by a uniform temperature distribution, which produces a better quality product, saves space, and provides a clean environment. As a result of penetration throughout the product, the inner layers are heated, which increases the heat and mass transfer rates. Studies have shown that IR technology is well suited to the extraction of high-potency vitamins from herbal sources (Hebbar et al. 2004). The application of combined electromagnetic radiation methods such as IR and hot air heating is considered to be more efficient than radiation or hot air heating alone because of the synergistic effect (Umesh et al. 2004). In IR drying, the power density can be six to ten times greater than in convective drying with hot air (Abukhaiifeh et al. 2003). Although the literature contains a few reports related to the development of laboratory-scale combined IR dryers (Hebbar et al. 2004), none was found that evaluated the drying process in a combined IR and hot air rotary dryer with respect to drying performance characteristics such as retention time, power consumption, and the quality parameters of the product.

The objectives of this work were (i) to develop a laboratory-scale rotary dryer prototype that can operate in three different modes: hot air, IR, and combined IR and hot air, and (ii) to determine the optimal temperature and operating mode based on retention time, power consumption, and the capsaicin content and red color of the chilli.

Materials and method

The experiments were conducted with ripe chilli (pickino variety) that was purchased from a local supermarket in Bangkok, Thailand. Each batch was prepared with 100 g of fresh chilli sample. Grading, stem separation and washing were done prior to drying. Chillies were not treated with any chemical or sliced prior to the experiments.

Development of combined IR and hot air rotary dryer

A combined IR and hot air rotary dryer was designed and developed for drying fresh chillies. The schematic illustration of the dryer is shown in Fig. 1. The developed dryer consists of two chambers, inner and outer. The rotation of inner chamber was achieved by using an induction motor through a reduction gear box (Fig. 2). The gear box was used to reduce the motor speed. The rotation speed was further reduced by selecting a chain-sprocket drive up to a desired level. Three blades were connected to inner chamber in order to facilitate the product fluidization and the forward movement. The rotor was slanted with 5° angle in order to support the movement of the product from inlet to the outlet.

Four IR heaters (250 W) and one fin coil heater (1 kW) were fixed in the outer chamber as shown in Figs. 1 and 2. The air flow was set to pass the heaters by inlet blower fixed at the bottom of the outer chamber (Fig. 2). Convective heat was transferred in to the inner chamber that contains the chilli. Increase of operating temperature decreases the moisture content in air, thereby the partial pressure difference between the moisture in chilli and air is increased. As a result, the moisture in chilli is removed and flows out as a vapor with the dry heated air through the exhaust open fixed at the top of the chamber. Consequently, the moisture content of chilli is decreased with drying time.

The special feature in this design is that the combined effect of IR and hot air heat sources. In IR drying, the power density can be six to ten times higher than that in convection drying with hot air alone. IR allows a high rate of water evaporation without distorting of material's internal structure (Abukhaiifeh et al. 2003). In addition to combined IR and hot air mode, this developed dryer has a rotation facility that provides uniform drying of the product with fluidize bed effect. The temperature controller was used to control the temperature of the inner chamber. Thermocouple sensors were located in the inlet and the outlet opening to sense the temperature.

Component design and fabrication

The outer chamber

The total length of the outer chamber was 350 mm and the diameter was 250 mm. The outer chamber was made using 1.2 mm stainless steel sheet (Fig. 1). Four IR tubes (wave length of 2.4–3 μm) and one fin coil heater (1 kW) were fitted to the outer chamber along the longitudinal direction closer to the air inlet. Six bearings (2.54 cm outer diameter) were arranged to facilitate the frictionless rotation of the inner drum with respect to the outer. Aluminum foil with glass-wool layer was used as an insulation material to cover the outer drum in order to prevent the heat loss (Fig. 2). The inlet and outlet openings were made in the outer drum at appropriate locations and sizes in order to facilitate the smooth air flow movements as shown in Fig. 1.

The inner chamber

The total length of the inner chamber was 350 mm and the diameter was 150 mm. This size was selected in order to obtain optimum capacity to carry out laboratory experiments from 100 to 1,000 g of chilli. The inner chamber was made by using 0.58 mm thickness stainless steel sieve type (with 5 mm sieve size) sheet (304 SS). This sieve type material was used to maintain the required air flow into the inner chamber of the dryer. Three steel blades were connected to inner chamber in

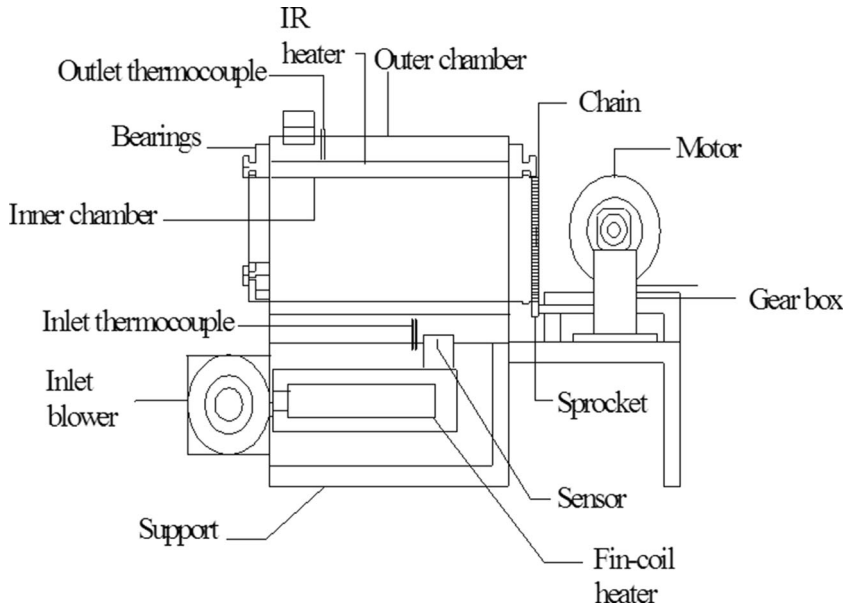

Fig. 1 Schematic illustration of the combined IR and hot air rotary dryer

order to facilitate the fluidize effect and forward movement of the product.

Power transmission system

The chain and sprocket drive were used to reduce the rotation speed of inner chamber. The inner chamber was rotated at relatively low rotation speed (5 rpm) in order to prevent the slippage during rotating. A 1/3 hp, 1,425 rpm, 220 v induction motor was used to drive the iner chamber. The rotational speed of 5 rpm was achieved by reducing the speed of motor using gear box with 1: 60 gear ratio and selecting 3.15 cm diameter sprokect (Fig. 2).

Blower installation at inlet

The inlet blower directed the heated air in to the inner chamber and maintained the airflow through the dryer. Since the dryer was laboratory scale, the air flow was maintained at 4.9×10^{-4} m^3/min (2A, 12 V, 1,450 rpm). This volume flow rate was controlled by using separate control switch.

Installation of thermocouples, data acquisition systems, and temperature controller

Type J thermocouples with an accuracy of ±2 °C were used to measure the temperature data in the outlet as well as in the inlet. The product temperature was measured by connecting

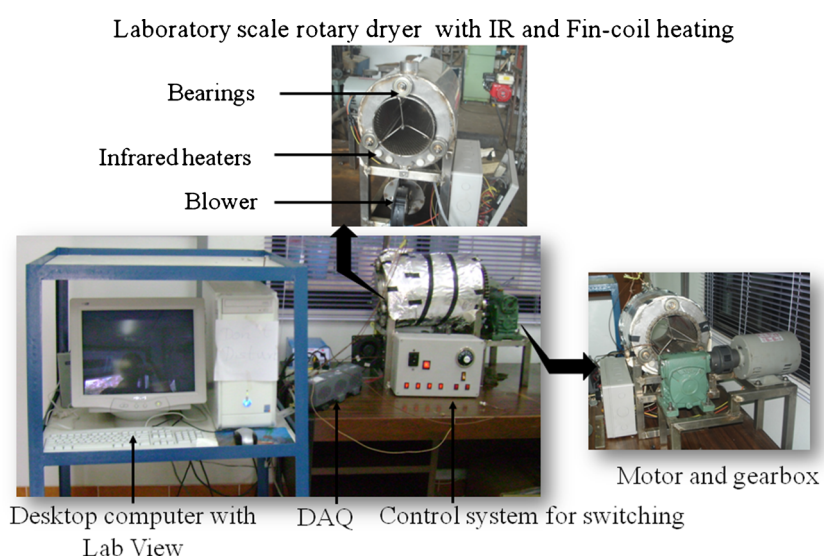

Fig. 2 Experimental setup of combined IR and hot air rotary dryer showing all parts: rotary dryer, motor and gear box, control system for switching, data acquisition system, and desktop computer with LabView software

one thermocouple with a chilli at the outlet. There were two positions for the thermocouple settings, two for outlet and other two for the inlet to measure the wet bulb and dry bulb temperatures at each point. An analog type temperature controller was used. It maintained the process temperature within ±1 °C of set point. The sensor which was connected to the regulator was located in the inlet. Separate switches were used to control the IR heaters, fin coil heater, and for the temperature controller. Therefore, inlet temperature was controlled throughout the experiment.

The temperature data were recorded with a high-speed LabView data acquisition (DAQ) system (National Instruments, Austin, TX) (Fig. 2). The data were collected by using NI Labview software (National Instruments, Austin, TX). Each power mode including IR, fin-coil, and combined IR and fin coil was manually controlled.

Experimental procedure

Chillies were dried from 280 % to nearly 9 % (d.b) moisture content in each experiment. The initial and final moisture content of the chilli samples were determined by drying duplicate samples in an hot air oven at 105 °C for 6 h. Chillies were dried at 50, 55, 60, 65 and 70 °C operating temperatures. Experiments were conducted at each operating temperature after achieving steady state conditions. The samples of 200 g were used for each experiment. Drying experiments with three replications were conducted at 50, 55, 60, 65, and 70 °C. Dry bulb and wet bulb temperatures in the drying air were recorded during the experiments. The power consumption of each mode (IR, hot air, and combined) was measured by using Fluke power meter (Bristol, PA, United States). The surface color of dried chilli was measured by using color flex hunter colorimeter (Color Flex of Hunter Associates Laboratory, Inc., Reston, Virginia, USA).

Measurement of capsaicin content in chilli

The capsaicin content of dried chilli was measured in each operating mode and temperature by using colorimetric method that was reported by Sadasivam and Manickam (1997). Dry chilli powder of 0.5 g was collected in a 100 ml volumetric flask. Dry acetone (10 ml) was added to volumetric flask and shaken in mechanical shaker for 3 h. The contents were centrifuged at 10,000 rpm for 10 min. One ml of clear supernatant was pipetted into a test tube and dried in a hot water bath. The resultant residue was dissolved in 5 ml of 0.4 % sodium hydroxide solution. Three milliliters of 3 % phosphomolybdic acid was added to the residue. After one hour, the filtered solution was transferred into centrifuge tubes and centrifuged at 5,000 rpm for 15 min. The supernatant color was measured in a spectrophotometer at 650 nm.

Measurement of color parameters

The color of the dried chilli was recorded at each temperature in each operation mode. The color was measured in L* (luminance), a* (red/green) and b* (yellow/blue) chromaticity coordinates using a colorimeter (Color Flex of Hunter Associates Laboratory, Inc., Reston, Virginia, USA). Although, all the values of L*, a* and b* were measured, the a* value was considered as a color parameter of chilli in the analysis, since a* value represents a measure of redness of chilli. The instrument was calibrated prior to each experiment with white and black ceramic plates. Each experiment was repeated three times and reported values were average of triplicates.

Selection of optimum temperature in each drying mode

The drying air temperature of chilli was optimized based on the retention time, power consumption, color, and capsaicin content. Nine point self scaling method was used to evaluate and optimize the mode of dryer as well as the operating temperature (Drewnowski et al. 1999). Scaling of each parameter was done based on maximum and minimum of parameters which were consequence of descriptive statistical analysis. The scaling procedure for power consumption, color chromaticity coordinate (a*), retention time, and capsaicin content was shown in Table 1. The applied point scale ranged from 1 to 9. Since, the power consumption and retention time were inversely correlated with the drying efficiency, the operating mode exhibited lowest power consumption and retention time with higher color coordinate a* and capsaicin content was selected as the best operating mode. Therefore, the highest point in the scale, '9' was applied to the highest color coordinate and capsaicin content. Since, the retention time and power consumption are inversely correlated with the effectiveness of drying, the lower scaling values were assigned to the higher retention time and power consumption values. The scaling process was conducted by assuming each attribute is equally important, since the weight of each attributes will be depended on various factors such as sensory attributes, perception on quality parameters of people in different geological context, and cost of production, availability of energy, and etc. Total score was calculated based on this scaling method for each mode at each temperatures. The optimum temperature and the best mode were qualitatively analyzed based on the total score.

Table 1 Scoring procedure for dried chilli based on color chromaticity coordinate (a*)

Color (a*)	Capsaicin content (mg/ml)	Retention time (h)	Power consumption (kWh)	Points
15.27–16.64	0.39–041	17.12–19.00	3.69–4.08	1
16.65–18.02	0.42–0.44	15.23–17.11	3.32–3.68	2
18.03–19.40	0.45–0.47	13.34–15.22	2.95–3.31	3
19.41–20.78	0.48–0.50	11.45–13.33	2.58–2.94	4
20.79–22.16	0.51–0.53	9.56–11.44	2.21–2.57	5
22.17–23.54	0.54–0.56	07.67–9.55	1.84–2.20	6
23.55–24.92	0.57–0.59	05.78–7.66	1.47–1.83	7
24.93–26.30	0.60–0.62	03.89–5.77	1.10–1.46	8
26.31–27.68	0.63–0.66	02.00–3.88	0.73–1.09	9

Results and discussion

Drying characteristics of chilli

Figure 3 shows the moisture ratio verses time profile of chilli at each temperature in combined IR and hot air mode. It is apparent from Fig. 3 that the absence of constant rate drying period during the drying of chilli for the temperatures tested. Similar results were reported by Akpinar et al. (2003) for red pepper, Kaleemullah and Kailappan (2005) for red chilli, Ibrahim (2006) for mint, Togrul and Dursun (2003) for apricot, Garau et al. (2006) for orange skin, Senadeera et al. (2003) for potato and green bean, Sogi et al. (2003) for tomato seeds, and Krokida et al. (2003) for vegetables. However, Akintunde et al. (2005) found that the drying of bell-pepper was in two drying rate periods, mainly the constant rate drying period and the falling rate drying period. The falling rate drying period was observed due to the rapid heat and mass transfer across the skin (i.e. pericarp) of the fruit. The thickness of pericarp and thermophysical properties of the fruit can directly affect for the heat and mass transfer during drying. The fruits exhibit constant rate drying period may comprise specific thermophysical properties that decrease the heat and mass transfer rate during drying. Generally, constant rate drying period is observed for hygroscopic products. The surface diffusion is the dominant mechanism during constant rate drying period (Erbay and Icier 2010).

The time required to reduce the moisture ratio of chilli from 1 to 0.001 was 2 h at 70 °C in combined hot air and IR mode, while hot air oven alone required more than 5 h. At 50 °C, it required more than 18 h in hot air alone mode and nearly 4 h in the IR mode alone. The combined mode with IR and hot air together required only 13 h. This indicated that IR mode alone required lower retention time to dry chilli. This fast drying may be attributed to the more efficient energy transfer from heat source to the heating element. In an IR drying, the energy is transferred from source to the target without leaking to air (Togrul and Dursun 2003). Indeed, it is apparent from the data that drying efficiency in terms of retention time was higher in IR alone mode compared with either combined mode or hot air mode alone. A significant reduction ($P<0.05$) of retention time was observed when increasing drying temperature from 50 to 55 °C in all operating modes. The observed differences in retention time with increasing drying temperature from 50

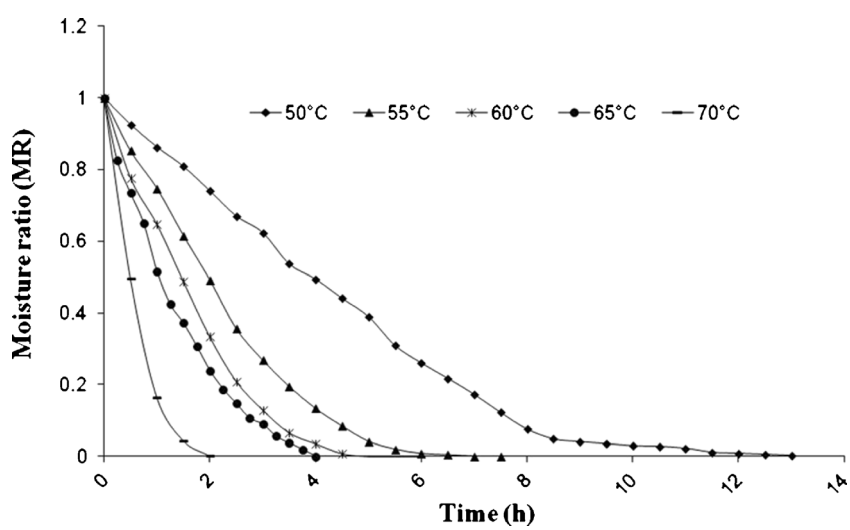

Fig. 3 Variation of moisture ratio with time during the drying of chilli at 50, 55, 60, 65, and 70 °C in the combined IR and hot air rotary mode

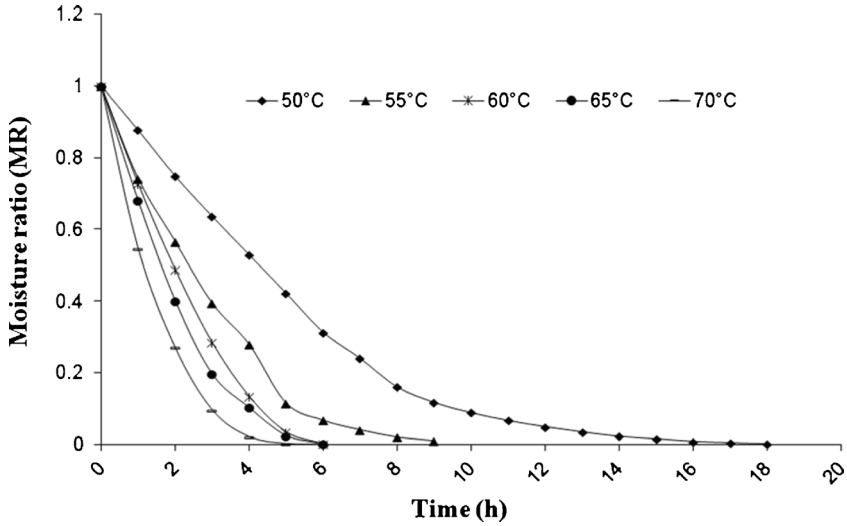

Fig. 4 Variation of moisture ratio with time of dried chilli at 50, 55, 60, 65, and 70 °C in the hot air rotary mode

to 55 °C were 9 (Fig. 3), 5.5 (Fig. 4), and 1 h (Fig. 5) in hot air, combined, and IR mode, respectively.

Variation of color

Figure 6 reveals the changes of red color chromaticity coordinate a* at five different temperatures in three different operating modes. As can be seen in Fig. 6, the operating temperature and color were inversely related. With the increase of drying temperature from 50 to 70 °C, the color reduction of chilli was significant ($P<0.05$). Similar results were observed by Kim et al. (1982) and Kaleemullah and Kailappan (2005) for red pepper and chilli.

The lowest color coordinate (a*) was observed in an IR mode whereas the highest was observed in the hot air mode. Therefore, the quality with respect to color of chilli was comparably good in hot air mode. Although the retention time of chilli was longer in hot air mode as mentioned in section 3.1, the color coordinate (a*) was varied between 25 and 30 in the range of temperatures from 50 to 55 °C. At higher temperatures ranging from 60 to 70 °C, the color coordinate (a*) was varied between 20 and 25 in hot air mode. It indicated that maximum change of color was 44 % in the hot air mode within the temperature range of 50–70 °C. The color coordinate (a*) varied between 10 and 15 at 70 °C in IR mode and it reduced almost 60 % of the color compared with fresh value of the product. The operation of dryer in IR mode alone can increase the heat penetration directly into the product within short time period. Consequently, higher color change was observed in IR mode at higher temperatures. However, the color of chilli was almost similar in hot air and combined modes at 70 °C. It can be attributed to the synergistic effect emanates from both IR and hot air sources leading to efficient heat and mass transfer during drying of the product in a combined hot air and IR mode.

The color reduction was 27 % compared with fresh sample in hot air mode whereas it was 36.9 % and 43.8 % in combined mode and IR mode respectively at 50 °C. Within the

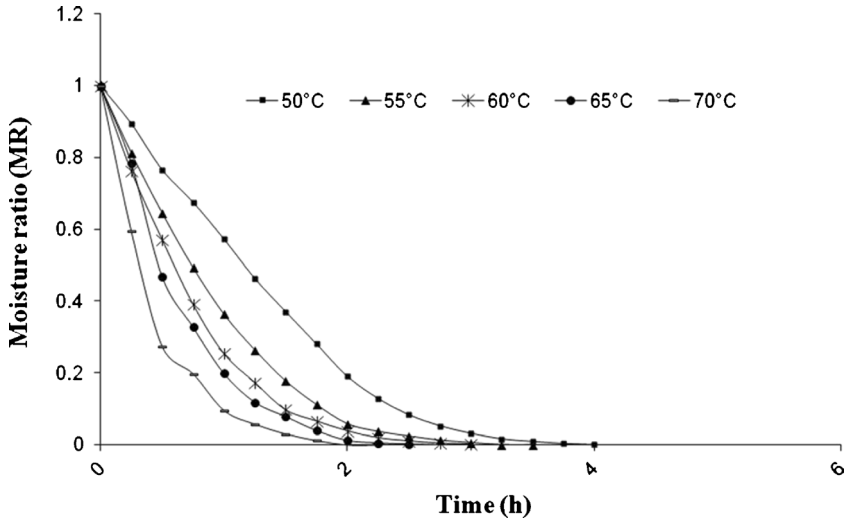

Fig. 5 Variation of moisture ratio with time of dried chilli at 50, 55, 60, 65, and 70 °C in the IR rotary mode

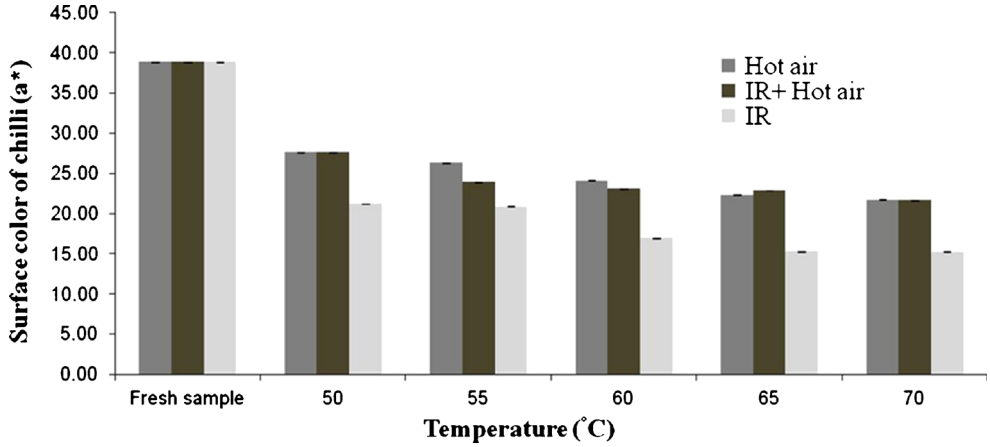

Fig. 6 Comparison of color between fresh and dried chilli at 50, 55, 60, 65, and 70 °C in hot air, IR, and combined IR and hot air rotary modes

temperature range of 50–70 °C, the observed color changes were 21, 21.5, and 28 % in hot air, combined, and IR mode respectively. There was no significant ($P<0.05$) difference in color change in the range of temperature of 50–70 °C in hot air mode and combined mode. Thus, quality loss can be reduced by using combined IR and hot air mode as it provides the synergistic effect. Overall results indicated that the chilli color was depended on the operation mode used during drying and the color was negatively correlated with the drying temperature.

Variation of capsaicin content

Capsaicin content was measured in each chilli sample in three different modes of the rotary dryer. Figure 7 shows the variation of capsaicin content with different temperatures in each operating mode. It is apparent from the data that the capsaicin content and the operating temperature were negatively correlated with each other. Similar results were observed by Kaleemullah and Kailappan (2005) for red chilli. As can be seen in Fig. 7, the highest capsaicin reduction was observed in IR mode while the lowest reduction was observed in hot air mode. The capsaicin content of chilli dried in IR mode was reduced nearly by 22 % over combined mode as the drying temperature increased from 50 to 70 °C while it was reduced by 25 % over hot air mode.

The linear relationship was observed between the capsaicin content and the drying temperature in each mode under the tested temperature range of 50–70 °C (Fig. 7).

The developed relationship for the capsaicin content and operating temperature in hot air mode was,

$$C_1 = -0.0067(\theta) + 0.9854 \quad (1)$$

where, C_1=capsaicin content in hot air mode and θ=drying temperature.

The calculated RMSE and R^2 values for the developed model were 0.01068932 and 0.9521 respectively.

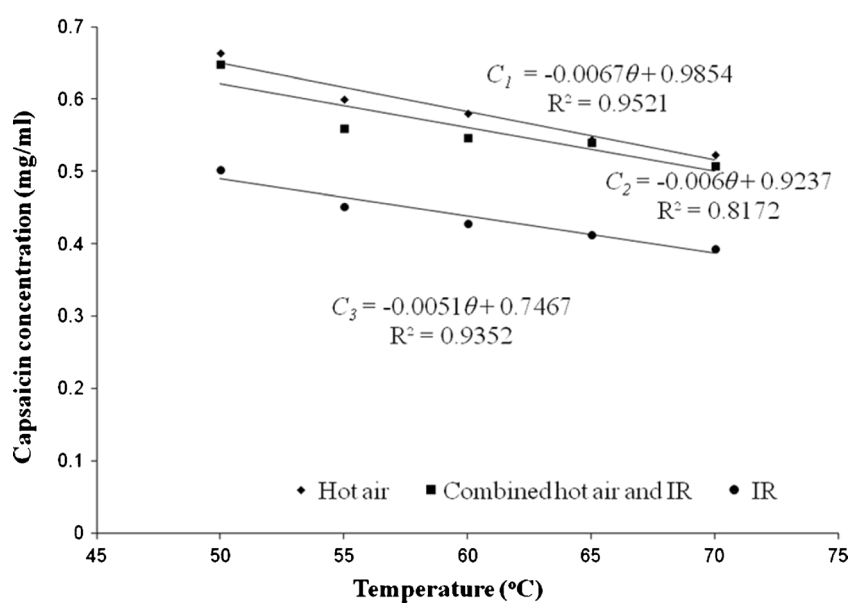

Fig. 7 Variation of capsaicin content during the drying of chilli in hot air, IR, and combined IR and hot air rotary modes

Table 2 The calculated total power consumption in hot air rotary mode at 50, 55, 60, 65, 70 °C

Temperature (°C)	Retention time (h)	Time-on (s)	Time-off (s)	Time duration for heater on system (h)	Total on period (h)	Power consumption (kW)	Total power consumption (kWh)
50	19.00	90	210	0.30	5.70	0.715	4.08
55	11.00	158	165	0.49	5.38	0.715	3.85
60	08.00	217	118	0.65	5.18	0.715	3.71
65	06.25	280	98	0.74	4.63	0.715	3.31
70	04.00	413	80	0.84	3.35	0.715	2.40

The developed empirical relationship for the combined mode was,

$$C_2 = -0.0060(\theta) + 0.9237 \quad (2)$$

where, C_2=capsaicin content in combined mode and θ= drying temperature.

The calculated RMSE and R^2 values were 0.02032994 and 0.8172 respectively for the capsaicin content in combined mode.

The developed empirical model to calculate the capsaicin content in IR mode was

$$C_3 = -0.0051(\theta) + 0.7467 \quad (3)$$

where, C_3=capsaicin content in IR mode and θ=drying temperature.

The calculated RMSE and R^2 values were 0.00995508 and 0.9352 respectively for the capsaicin content in IR mode during drying. The developed empirical models can be used to calculate the capsaicin content at any temperature in each mode, since the calculated RMSE and R^2 values were within the acceptable limits.

Power consumption

The consumed power was measured individually in three different modes at each temperature during drying. Since the temperature was controlled by using ON-OFF system, the time duration was measured separately. The total time duration required for the switch on system was calculated and it was used to calculate the consumed power at five different temperatures. The retention time of chilli, the time duration for heater on system, and the total power consumption in each mode at each temperature are tabulated in Tables 2, 3, 4. According to the calculated values, the highest power consumption of 4.08 kWh was observed in hot air mode while IR mode consumed 0.73 kWh at 50 °C.

A negative correlation was observed between operating temperature and power consumption with the hot air and the combined modes, while a positive correlation was identified in the IR mode. On the other hand, the retention time and power consumption correlated positively in hot air and combined mode, while a negative correlation was observed in IR mode. It indicates that power consumption was mainly depended on the operating temperature in IR mode.

The observed maximum retention time variation for the temperature range of 50–70 °C was 2 h in IR mode, which was the minimum time variation observed in all these three different rotary modes, thereby effect of retention time on the consumed power was not significant in IR mode. The IR mode showed the highest power consumption at 70 °C of approximately 0.95 kWh and lowest at 50 °C of 0.73 kWh. Thus, IR mode takes longer time duration at higher temperatures for heater on system increasing power consumption. The combined mode consumed fairly lower power compared to hot air mode due to the lower retention time. The hot air mode consumed 60.4 % more power than the IR mode as well as 33.5 % more power than the combined mode at 70 °C. It can be attributed to the different heating sources used in different

Table 3 The calculated total power consumption in combined IR and hot air rotary mode at 50, 55, 60, 65, 70 °C

Temperature (°C)	Retention time (h)	Time-on (s)	Time-off (s)	Time duration for heater on system (h)	Total on period (h)	Power consumption (kW)	Total power consumption (kWh)
50	13.50	90	240	0.27	3.68	1.08	3.98
55	08.00	120	180	0.40	3.20	1.08	3.46
60	05.00	150	150	0.50	2.50	1.08	2.70
65	04.00	180	133	0.58	2.30	1.08	2.48
70	02.00	240	90	0.73	1.45	1.08	1.57

Table 4 The calculated total power consumption in IR rotary mode at 50, 55, 60, 65, 70 °C

Temperature (°C)	Retention time (h)	Time-on (s)	Time-off (s)	Time duration for heater on system (h)	Total on period (h)	Power consumption (kW)	Total power consumption (kWh)
50	4.25	475	1,140	0.29	1.25	0.58	0.73
55	3.25	564	809	0.41	1.34	0.58	0.77
60	2.75	634	565	0.53	1.45	0.58	0.84
65	2.25	660	450	0.59	1.34	0.58	0.78
70	2.00	819	180	0.82	1.64	0.58	0.95

modes, since fin coil heaters required higher power in a hot air mode when compared to IR heaters. In addition, hot air mode consumed further power for blower operation due to the air flow characteristics.

Optimum temperature in each drying mode

Table 5 shows the total score for the hot air rotary mode. It is apparent from the data that the highest score was observed at 70 °C in hot air mode. It is mainly due to the less power consumption and retention time. Although the chillies dried at 50 °C received good score for the quality parameters of '9' out of '9', it received a poor score for both retention time and power consumption. In terms of quality parameters, the best temperature was 50 °C in hot air mode. However, the difference between minimum and maximum score was 3 (8–5) at 70 °C, whereas it was 8 (9–1) at 50 °C. Moreover, the minimum score observed at 70 °C was 5, whereas it was≤3 for all other drying temperatures. It indicated that variation between all the attributes at 70 °C drying temperature was minimum. Additionally, it was able to maintain relatively higher minimum score (≥5) for each attribute, confirming that the 70 °C drying temperature was more suitable for drying of chilli in hot air mode.

Table 6 shows the total score recorded in each temperature in combined hot air and IR mode. It is clear from the data that the highest score was observed at 70 °C. However, the difference between minimum and maximum score was 3 (8–5) at 65 °C, whereas it was≥ 4 in all other temperatures. At 65 °C temperature, the observed minimum score was 5. It indicates that at 65 °C, it maintains considerably higher score for all the attributes with minimum variation. It further confirms that drying of chilli at 65 °C was more suitable compared with other temperatures in combine mode. However, chillies were dried at 50 °C received a good score for the color and capsaicin content of '9', out of '9', it received a poor score of '1' for power consumption. Therefore, with respect to quality parameters, the most suitable temperature was 50 °C in the combined mode.

Table 7 reveals the total scores recorded at each temperature in IR mode. As can be seen in Table 7, the highest score was observed at 50 and 55 °C with total of 26 points. The difference between minimum and maximum scores applied at 50 °C was 5 (9–4). Moreover, the minimum score was 4 that was observed for capsaicin content. The considerable quality loss was observed at 65–70 °C, thereby 65–70 °C temperature range was not suitable for chilli drying in IR mode when considering quality parameters. However, when considering quality parameters and the minimum variation between the scores of each parameters, the drying at 50 °C temperature in IR mode was more suitable for chilli.

Table 5 Scoring procedure applied for dried chilli based on retention time, capsaicin content, power consumption, and color in hot air rotary mode

Temperature (°C)	Score				Total score
	Power consumption (kWh)	Retention time (h)	Capsaicin content (mg/ml)	Color (a*)	
50	1	1	9	9	20
55	1	5	7	9	22
60	1	6	7	7	21
65	3	7	6	6	22
70	5	8	5	5	23

Table 6 Scoring procedure applied for dried chilli based on retention time, capsaicin content, power consumption, and color in combined IR and hot air rotary mode

Temperature (°C)	Score				Total score
	Power consumption (kWh)	Retention time (h)	Capsaicin content (mg/ml)	Color (a*)	
50	1	3	9	9	22
55	2	6	6	7	21
60	4	8	6	6	24
65	5	8	6	5	24
70	7	9	4	6	26

Table 7 Scoring procedure applied for dried chilli based on retention time, capsaicin content, power consumption, and color in IR rotary mode

Temperature (°C)	Score				Total score
	Power consumption (kWh)	Retention time (h)	Capsaicin content (mg/ml)	Color (a*)	
50	9	8	4	5	26
55	9	9	3	5	26
60	9	9	2	2	22
65	9	9	1	1	20
70	9	9	1	1	20

Conclusion

In each mode, including hot air, IR, and combined IR and hot air, during the drying of the chilli, moisture removal occurred during the falling rate period and was not exhibited the constant rate drying period. In each drying mode, a negative correlation was observed between the chilli color and the operating temperature, leading to adverse color changes at higher operating temperatures. Considerable loss of quality was observed with the IR drying mode, although, at 70 °C, 60 % less power was consumed than with the hot air mode. At 70 °C, the redness of the chilli was decreased by 30 % in the IR mode compared to the hot air and combined modes. In the IR mode, at 70 °C, the loss in capsaicin content was 25 % and 22 % greater than with the hot air or the combined mode, respectively. The quality characteristics in terms of capsaicin content and color were similar with the combined mode and the hot air mode for temperatures ranging from 65 to 70 °C. A positive correlation was observed between retention time and power consumption with the hot air and the combined modes, while a negative correlation was identified in the IR mode.

Under the experimental conditions and with the evaluation method employed, the optimal temperature for drying chilli with either the hot air mode or the combined mode was determined to be 50 °C when considered only quality attributes, whereas with the IR mode, it was 50 °C to 55 °C. Based on color, capsaicin content, power consumption, and retention time in each mode, the best overall performance with respect to drying chilli was obtained at 70 °C, 65 °C, and 50 °C in hot air, combined, and IR mode, respectively.

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