Drying Characteristics, Specific Energy Consumption, Qualitative Properties, Total Phenol Compounds, and Antioxidant Activity During Hybrid Hot Air-Microwave-Rotary Drum Drying of Green Pea

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ABSTRACT: *This study is aimed to investigate the effect of a Hybrid Hot air-Microwave- Rotary Drum (HMRD) dryer on the thermal properties, quality, and nutritional characteristics of green pea under different operational conditions. The experiments were conducted under different air temperatures (40, 55, and 70 °C), microwave power (90, 270, 450, and 630 W), and drum rotation speeds (5, 10, and 15 rpm). The thermal properties (e.g. drying time, effective moisture diffusion coefficient, activation energy, and specific energy consumption), quality features (color, shrinkage, and rehydration ratio), and nutritional properties (antioxidant activity and total phenol content) were determined. The results indicated that by increasing the microwave power, air temperature, and drum rotation speed, the drying time will decline. The highest diffusion coefficient and energy consumption were determined as 5.04×10^{-11} m^2/s and 109.91 MJ/kg, respectively. The lowest changes in color, shrinkage and rehydration were calculated as 41.34, 24.08%, and 1.57. The highest total phenol (14.02 mg GAE/g d.w) and antioxidant (85.86%) were obtained. Thus the newly designed dryer can be employed for drying the granular products and lead to satisfactory results.*

KEYWORDS: *Hybrid hot air-microwave- rotary drum dryer; Quality features; Specific energy consumption; Antioxidant activity; Green pea.*

INTRODUCTION

Green pea is an herbaceous, annual, and climbing plant with white, pink, and sometimes purple flowers [1]. Its compact pods are usually straight or shrunken with green or brownish-gray color. These pods vary in length and usually contain 4 to 9 seeds [2]. This plant is semi-vertical and tends to climb if has support. This plant adapted itself to the cold and moderate climate and is now cultivated all around the world [3]. Green pea includes carbohydrates, protein, and dietary fiber. Owing to its high protein content, it has been so far included as a part of the human diet [4- 6].

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1021-9986/2022/2/652-669 18/$/6.08

Drying is a common process in the food industry in which the controlled heat is employed to eliminate the main portion of water content through evaporation or sublimation. In this way, the aqueous activities will be reduced. Prevention from microbial and enzymic activities, decelerating the harmful chemical reactions (e.g. non-enzymic browning and auto-oxidation), volume and weight reduction to facilitate packaging, transportation, storage, and preservation of the foods in the over-productive seasons to be used in the under-productive seasons [7].

Drying, however, may cause some changes in the texture, fragrance, taste, nutritional value, and final color of the dried product; evaluation of these changes and attempts to minimize the harmful effects of the process are among the important issues in drying food products [8]. One of the important physical changes during drying is the reduction in the volume of the external shell and hence shrinkage [9]. Simultaneous mass and heat transfer during food drying may induce some stresses in their cellular structure leading to their deformation and shrinkage [10]. Color is another important quality feature of dried fruits which, along with taste and texture, can play a significant role in product popularity from the consumers' point of view. From the consumer's perspective, undesirable color is a sign of expiration [11].

Various methods have been developed to dry the food products each with its own advantages and disadvantages. Each of these methods can be employed for a specific type of product to reach the highest drying efficiency along with the maximum quality of the product [12]. One of these drying methods is hot air drying which is the oldest and most common method for drying food products. This method has significant drawbacks among which are reduction in energy efficiency, prolonged process, severe shrinkage, and degraded product quality (nutrients, color, texture) can be mentioned [9, 13]. On the other hand, during microwave drying, although the radiation energy penetrates into the product, the product is not evenly exposed to microwave radiation [14]. Despite their short drying time, the microwave-dried products won't be dried evenly and hence the product quality may be reduced [15]. Rotary driers are modern industrial products recognized as one of the most efficient and common permanent driers. These driers are used for the permanent drying of the granular substances with relatively free flow and average drying time [16]. Rotary driers include a rotating cylinder placed on proper bearings with a slight inclination relative to the horizontal direction.

The product is fed from one end of the cylinder (drum) and moves forward by the cylinder rotation, the final product will be then discharged from the other end of the cylinder [17].

Microwave drying is rarely employed alone for drying food products. It is rather used in combination with the other techniques to avoid over-heating the product and enhance its quality [18]. The application of microwave drying in combination with hot air drying and rotary driers is one of the modern hybrid techniques. Rotation and airflow in the microwave system can help in the continuous moisture elimination from the production environment and hence accelerate the drying process; moreover, the product temperature will be reduced as a result of evaporative cooling [19, 20]. In this study, the microwave method is employed in combination with a hot air dryer and a rotary drum dryer.

Firouzi et al. [21] experimentally investigated the quality and specific energy consumption of the rice drying process using industrial horizontal rotary dryers and a hot air dryer at different temperatures. Their results indicated that the use of hot air (compared to the rotary dryer) can decline the drying time. The specific energy consumption of the rotary dryer was higher than that of hot air dryers.

In another study, Behera and Sutar [22] compared three types of dryers: a hot air dryer at 50 °C, infrared-hot air (40 °C and 4.185 W/m), and a hybrid rotary-microwave dryer at the power of 0.37, 0.78 and 1.23 kW/kg to evaluate their impact on the physical properties and quality of the fried rice. Their results showed that the application of the rotary-microwave hybrid dryer induced lower changes in the physical properties and quality of the rice.

Drying features and quality of the garlic dried by a hybrid microwave-rotating drum dryer were investigated and it was observed that the color and time variations were declined by increasing microwave power [23].

To dry Chilli, *Kaensup et al.* [24] used a microwave-vacuum-rotary drum at different drum rotation speeds (10, 20, and 25 rpm) and vacuum pressures (60, 160, and 260 mmHg) but constant microwave power (800 W). They revealed that the increase in rotation speed and decrease in vacuum pressure can reduce the drying time.

Other researchers have also investigated the drying of agricultural crops using rotary drum dryer: *Qi et al.* [16]

for corncob, *Tarhan et al.* [25] for peppermint, *Silva et al.* [26] for acerola, *Galaz et al.* [27] for pomegranate peel, and Behera and Sutar [28] for paddy.

Through some experiments, *Chauhan* and *Srivastava* [29] evaluated the impact of microwave power and vacuum pressure on the time and efficiency of the drying process as well as shrinkage, color, and rehydration of green pea dried by a vacuum-microwave hybrid dryer. They clearly indicated the importance of microwave power and vacuum pressure in controlling the drying parameters and quality of the green pea. They also declared that an increase in the microwave power and vacuum pressure will decline the drying efficiency.

Doymaz and *Kocayigit* [5] studied the effects of three pre-treatments (citric acid, blanching, and alkali emulsion of ethyl oleate) and two temperature levels (55 and 65 °C) on different drying factors (e.g. drying time and rate, effective moisture diffusion coefficient and rehydration ratio) of the green pea. They indicated the significance of temperature in the drying rate as any increase in temperature resulted in a decline in the drying time. Blanching pretreatment also had the highest impact on the drying time, effective moisture diffusion coefficient, and rehydration).

Zielinska et al. [30] examined the effect of different dryers (hot air, microwave, vacuum, and hybrid fluid substrate heat pump-microwave-vacuum) on the drying time and rate, effective moisture diffusion coefficient, shrinkage, and color of the green pea. They showed that the longest drying time and highest shrinkage can be recorded in the products dried by the hot air dryer. The highest color changes were observed in the microwave and vacuum dryer.

Chahbani et al. [4] assessed the effect of microwave power on the drying properties (drying time and rate and effective humidity diffusion coefficient) and physical characteristics (color) and antioxidant features of the green pea. They realized that the lowest microwave power resulted in the longest drying time and highest color variations as well as the lowest antioxidant content.

Other researchers have also addressed different properties of green pea dried by various dryers: *Gao et al.* [31] in fluidized bed dryer, *Jadhav et al.* [32] in solar cabinet dryer, *Momenzadeh et al.* [33] in microwave-fluidized bed dryer, *Honarvar et al.* [34] in hybrid fluidized bed-infrared drier with vibrating substrate and *Shete et al.* [2] in hot air dryer with different pre-treatments.

Regarding what mentioned above and the significance of this topic, investigation of the effectiveness of different factors on the quality of the dried green pea sounds essential. To this end, a hybrid HMRD dryer was designed and fabricated to examine the drying behavior of the green pea under different conditions in terms of microwave power, temperature, and rotary drum speed. In this regard, the aim of this study is to investigate the effect of inlet air temperature, microwave power, and drum rotation speed on the thermal parameters (drying time, effective moisture diffusion coefficient, activation energy, energy consumption), quality (color, shrinkage, and rehydration) and nutritional (Total Phenolic Content (TPC) and antioxidant capacity) properties of the green pea dried by this novel hybrid dryer. Determination of the best thin-layer model for describing the green pea leaf drying process is among the other objectives of this research.

EXPERIMENTAL SECTION

In this study, the fresh green pea was prepared from the farms in Sardasht town in West-Azerbaijan province. All the samples were kept in the refrigerator (4°C) to decline the rate of respiration and physiological-chemical changes. For equilibration with the ambient temperature, the samples were taken out of the refrigerator and transferred to the lab 1 hour prior to the experiments. The initial humidity of the samples was measured by placing them in an oven (Memmert, UFB500, Germany) at 105 °C for 24 hours until reaching a constant weight [30, 34]. The initial humidity of the green pea samples was obtained 73.23 ± 0.5 (%w.b.). The samples were dried to 20.05 ± 0.5 (%w.b.).

Design and fabrication of the dryer

For the experiments, a hybrid Hot air-Microwave-Rotary Drum (HMRD) dryer (Fig. 1) was designed and fabricated in the laboratory of the biosystem engineering department, Mohaghegh Ardebili University. This dryer is composed of 3 SECtions: 1) the hot air SECtion including a centrifuge fan (1 hp/3000 rpm) to create a hot airstream, an inverter (LS, Korea) to control the airstream speed, 3 elements (model) with the overall power of 4.8 kW to heat the air inlet to the dryer chamber; 2) rotary drum section encompassing a drum with respective diameter and length

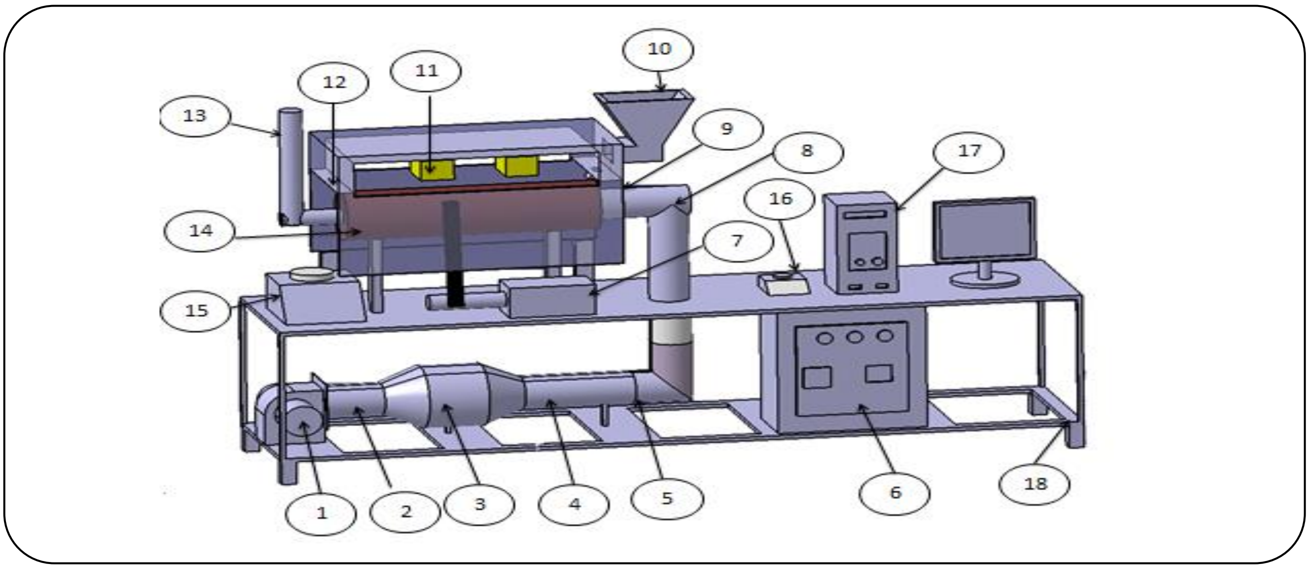


Fig. 1: Schematic diagram of the microwave-convective- rotary drum drying system. 1. Air blow system (1 hp/3000 rpm), 2. Airflow control system, 3. Air heating chamber. 4. Outlet temperature sensor (k- type thermocouple), 5. Air flow transfer tube, 6. Control panel, 7. Motor for rotating the drum, 8. Anemometer for air velocity measurement, 9. Drying chamber, 10. Feed hopper, 11. Microwave magnetrons, 12. Exhaust fan, 13. Air exit opening, 14. Rotary drum, 15. Digital balance, 16. Thermometer, 17. Computer and 18. Chassis.

of 36 and 90 cm. this SECtion includes two rollers at the beginning and the end of the chamber rotating through a gearbox (VF 861/100). The gearbox speed could be regulated by an inverter (LS. Korea); and 3) a microwave SECtion to create microwave radiation from 2 magnetrons (LG2M246, China) with a maximum output power of 900 W installed along with the dryer chamber. For a more uniform distribution of the waves within the microwave chamber, 2 magnetrons were used along the length of the instrument. The magnetrons' feeding circuit included 2 transformers, 1 self-capacitor circuit, 1 magnetron cooling system (2 fans, P/N 2123XSL, China). The rotary and microwave SECtions were placed inside a steel chamber with a dimension of $130 \times 10 \times 120$ cm^3. To measure the air temperature, two temperature sensors (K type) were employed one at the beginning of the dryer chamber and the other inside the chamber. Two thermostats were also utilized to control the air temperature inside the circuit. To avoid heat waste, the system was totally insulated by glass wool. The airstream velocity was measured by a velocimeter (Lutron AM-4216, Taiwan); in which the velocimeter support was placed at different points of the air inlet channels to read the velocity values. To equilibrate the system all the tests were commenced 30 min after the dryer switched on. For the main test, the air temperature was set at three different levels (40, 55, and 70 °C); the inlet air stream was set at 1 m/s while the drum rotation speed was considered at three levels (5, 10, 15 rpm). The microwave power was considered in 4 levels (90, 270, 450, and 630 W). The sample weight was measured by a balance (GF-600, Japan) with an accuracy of $\pm$ 0.001 g.

In most of the research, the drying process was reported based on the Moisture Ratio (*MR*) which can be due to less data dispersion. In the present study, the Eq. (1) was used to calculate the *MR* of green peas during the drying process [5]:

$$MR = \frac{M_t - M_e}{M_b - M_e} \tag{1}$$

Effective moisture diffusivity coefficient and activation energy

The effective moisture diffusion coefficient (D_{eff}) is one of the important transport properties used to determine and model the food product drying and calculate the moisture absorption and repulsion during storage and rehydration [35]. Assuming that moisture transport is only through diffusion along the radial direction, and the drying process was conducted for a relatively long time, the analytical solution of the Fick SECond low in unstable diffusion for spherical materials can describe the moisture displacement during the drying process as shown in Eq. (5) [28]:

$$MR = \frac{M_t - M_e}{M_b - M_e} = \frac{6}{\pi^2}\sum_{n=1}^{\infty}\frac{1}{2n^2}\exp\left(-n^2\pi^2\frac{D_{eff}t}{r_e^2}\right) \quad (2)$$

For long-time drying, Eq. (2) can be simplified to Eq. (3):

$$MR = \left(\frac{6}{\pi^2}\right)\exp\left(-\frac{\pi^2 D_{eff}t}{r_e^2}\right) \quad (3)$$

K_1 could be calculated by plotting ln(D_{eff}) vs. time as shown in Eq. (4). Thus, D_{eff} can be determined by:

$$K_1 = \left(\frac{D_{eff}\pi^2}{r_e^2}\right) \quad (4)$$

The relationship between temperature and D_{eff} is shown in Eq. (5):

$$D_{eff} = D_0 \exp\left(\frac{E_a}{R_g T_a}\right) \quad (5)$$

The activation energy can be determined by ln(D_{eff}) as a function of ($1/T_a$).

$$K_2 = \frac{E_a}{R_g} \quad (6)$$

Specific energy consumption

The drying process consumes a huge deal of energy. Regarding the energy crisis, innovations in drying systems and the development of methods with higher energy efficiency are among the research priorities in the engineering field. Regarding the high cost of energy (e.g. natural gas, electricity), the lower the energy consumption of an instrument, the higher its cost-effectiveness will be [36].

The *SEC* of each drying condition can be expressed considering the drying time and the energy applied by different components of the hybrid HMRD dryer. In other words, the *SEC* of a hybrid HMRD dryer can be defined as the energy required for evaporating one unit mass of moisture which includes the thermal energy, blower, engine, and magnetron. It can be estimated by the following Eqs. [19, 22]:

$$SEC = \frac{\text{Total energy supplied in drying process}}{\text{Amount of water removed during drying}} \quad (7)$$

$$SEC = \frac{E_1 + E_2 + E_3 + E_4}{M_w} \quad (8)$$

Color

To investigate the color indices, color space was used. L^* color index indicates the brightness of the sample whose range varies from zero (absolute black) to 100 (absolute white). a* index ranges from -120 to +120 and positive values are corresponding to the red color while the negative ones are associated with the green color. Similar to a*, b* also ranges from -120 to +120 in which the positive and negative values are indicative of blue and yellow color, respectively [37]. The color indices were evaluated by an HP scanner (G3110, China). The values of the indicators (L*, a*, and b*) are obtained from the following Equation.

$$L^* = \frac{L}{255}\times 100 \quad (9)$$

$$a^* = \frac{240a}{255} - 120 \quad (10)$$

$$b^* = \frac{240b}{255} - 120 \quad (11)$$

Total color difference (ΔE) was considered for the overall evaluation of the color in fresh and dried green pea as written in Eq. (12) [38].

$$\Delta E = \sqrt{(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2} \quad (12)$$

Shrinkage

To measure the shrinkage in the green peas, the volume variation of the samples was assessed by the fluid displacement method through the use of toluene. Among the superiorities of toluene over the other liquids, low surface tensile and density, as well as no chemical structure alternation upon air exposure, can be mentioned. Shrinkage percentage (S_b) was calculated by the determination of the initial (φ_i) and final (φ_f) volumes through Eq. (13) [39].

$$S_b = \frac{(\phi_i - \phi_f)}{\phi_i}\times 100 \quad (13)$$

Rehydration capacity

To assess the Rehydration Capacity (RC) of the samples, green peas were immersed in water at 25 °C after drying in the dryer and weight measurement (W_d). After 20 min, samples were removed from the water and their surface water was dried. samples were then weighed again (W_r) The rehydration capacity was estimated through the following Equation [5]:

$$RC = \frac{W_r}{W_d} \tag{14}$$

Measurement of the antioxidant activities

To measure the content of phenolic and antioxidant compounds, the extraction was first performed. The 10% methanolic extract was prepared by soaking and ultrasonic waves and the extract was used after the centrifugation in the later stages. The antioxidant capacity of the dried green peas was assessed at Mohaghegh Ardebili University. For this purpose, DPPH was used, to determine the green pea essence's ability to trap the free radicals of DPPH, 15 μL of the essence was mixed with 2 mL methanolic solution of DPPH (0.01 M). The optical absorbance was then read at 517 nm using a spectrophotometer. DPPH solution (0.01 M) was used as the control [40, 41]. Total antioxidant activity can be expressed as the DPPH radical scavenging ability (in percentage) through the following Equation [42, 43]:

$$I = \frac{(A_i - A_t)}{A_t} \times 100 \tag{15}$$

Total phenol content

The total phenolic compound of the extracts was evaluated by Folin & Ciocalteu method as described in *Vega-Gálvez et al.* [44]. Green pea extracts were prepared at a concentration of 0.01 g/L. 100 μL of the extract was transferred to the vial and 0.75 mL Folin & Ciocalteu reagent (which had been diluted by deionized water, 1:10) was added. The mixture was kept at room temperature for 5 min. Then 4 mL sodium carbonate (7.5% wt/Vol) was added to the mixture and stirred slowly. The optical absorbance was determined after 1 hour of storage at room temperature at the wavelength of 765 nm [40].

Statistical analysis

SAS 9.1 software was used for statistical analysis of the data. Duncan's multifactorial test was also employed for comparing the mean of main effect levels and the interaction between the variables.

RESULTS AND DISCUSSION

Drying kinetics

To investigate the kinetics of the green pea drying process by a hybrid HMRD dryer, combination tests were conducted at three temperature levels (40, 55, and 70 °C), four microwave powers (90, 270, 450, and 630 W), and three drum rotation rates (5, 10, and 15 rpm). The moisture ratio of the green pea is plotted as a function of time for different temperature, microwave power, and rotation rate levels in Fig. 2. As can be seen, by elevating the microwave power from 90 to 630 W, the slope of the moisture content increased and the processing time was shortened for all three drum rotation speeds and inlet air temperature. This can be attributed to the increase in the internal temperature of the product which resulted in the elevation of the internal pressure and hence accelerating the mass transfer rate. Thus the product will lose its moisture faster and the slope of the diagram will be increased [18, 45]. Similar results were obtained in the case of apricot, garlic puree, and *Salvia officinalis* L. by *Horuz et al.* [18], *Ilter et al.* [45], and *Jebri et al.* [46], respectively.

Concerning the inlet air temperature, it was observed that by raising the temperature, the moisture loss rate was accelerated giving rise to the steeper slope and shorter drying time. By augmenting the temperature, the temperature gradient inside the product was increased leading to faster evaporation [47]. *Torki Harchegan et al.* [35]; *Suna* [48]; and *Kaveh et al.* [49] reported similar results for Whole Lemons, medlar fruit leather, mint leaf, and green pea, respectively.

Results indicated that in green pea drying by the hybrid HMRD dryer, an increase in the drum rotation resulted in a decline in drying time. This could be due to the uniform distribution of the moisture throughout the grains which decreased the vapor pressure of the environment; hence the product moisture would face lower resistance in exiting the surface which might lead to a shorter drying time [50]. These findings were in line with the results of *Kaensup et al.* [24] on Chilli drying.

Malekjani et al. [51] in drying hazelnuts with a microwave dryer showed that with increasing microwave power, green pea samples lose their moisture faster, and drying time decreases. In another study, *Zahoor* and *Khan* [42] in bitter gourd drying by combined microwave-hot air method showed that by increasing the inlet microwave

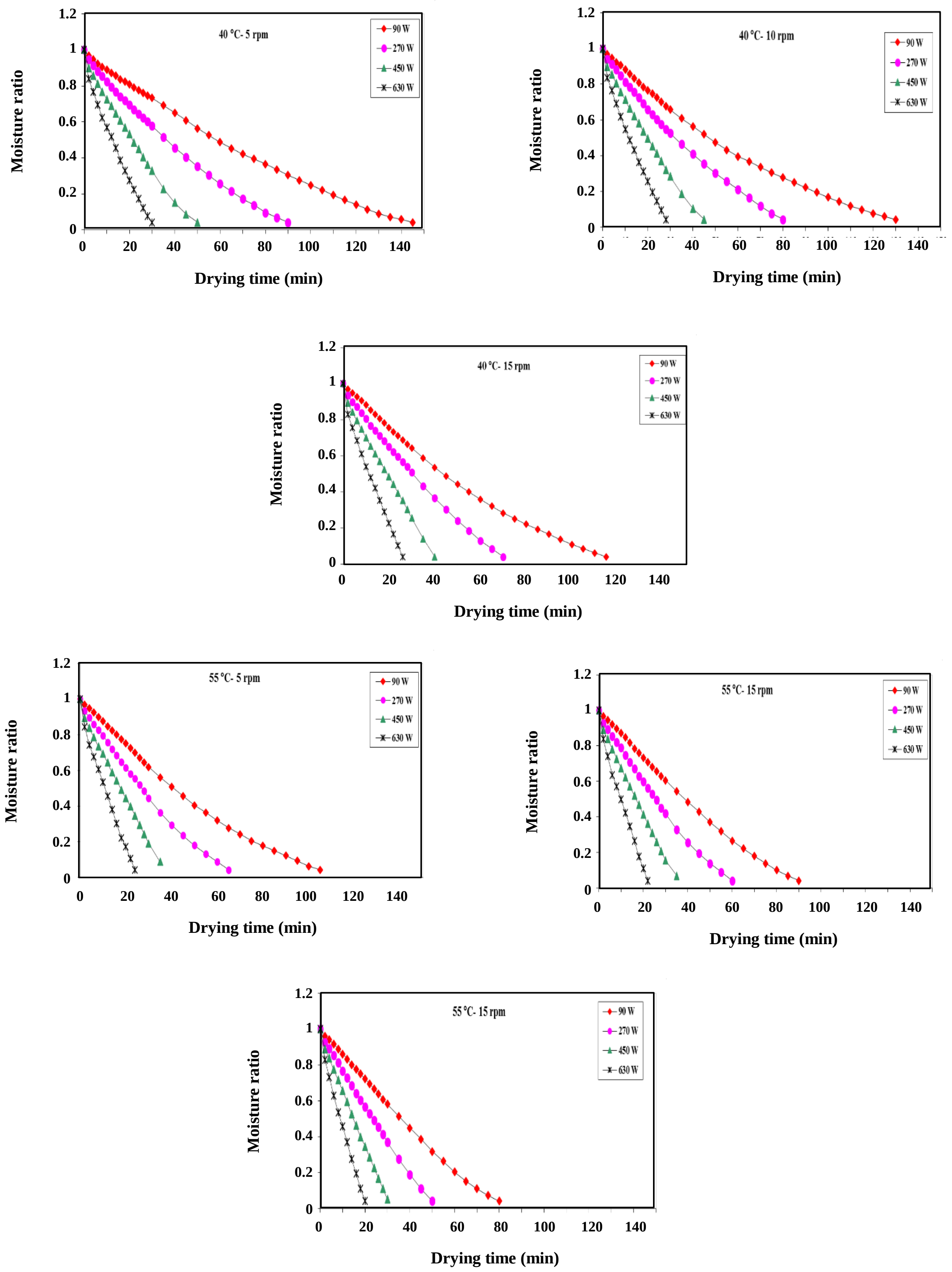
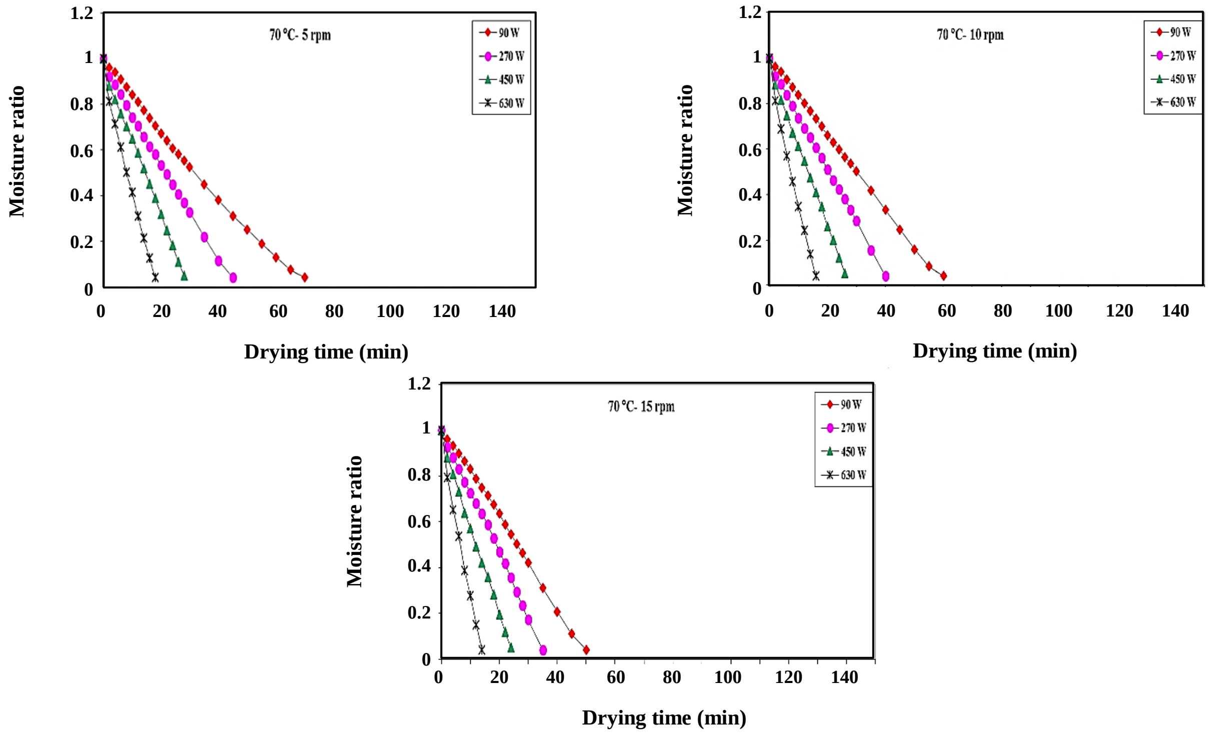


Fig. 2: Drying kinetics of green pea under different drying conditions (microwave power, air temperature and rotating speed of the drum)



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power and air temperature due to the increase in evaporation rate, the product loses its moisture faster and the process takes less time. *Yildiz* and *Izli* [52] dried pomelo and *Hazervazifeh et al.* [53] dried the apple slices, both research groups showed that an increase in the microwave power and inlet air temperature will result in a faster drying process as the product lost its moisture in a shorter duration of time.

Analysis of variance results

The results of the analysis of variance (ANOVA) obtained by the Duncan test (using SAS software. 9.1) are presented in Table 1 for thermal properties, quality and nutritional features of the green pea dried by the proposed hybrid dryer.

Moisture diffusion coefficient

Effective moisture diffusion coefficients were calculated according to the SECond law of Fick using Eq. (7). The obtained results are listed in Fig. 3, for the hybrid HMRD drier. This coefficient ranges from 4.66×10^{-12} to 5.04×10^{-11} m^2/s. *Chahbani et al.* [4] dried the green pea in a microwave dryer and reported this coefficient in the range from 1.69×10^{-9} to 5.36×10^{-9} m^2/s. Moreover, *Doymaz* & *Kocayigit* [5] employed hot-air dryers on the green pea with different pre-treatments and reported the D_{eff} in the range from 1.973×10^{-11} to 5.059×10^{-10} m^2/s. Based on *Kaveh et al*. [54], the D_{eff} of the agricultural and food products ranged from 10^{-7} to 10^{-12} m^2/s. The calculated values of this research lay in the mentioned range.

The ANOVA results of the effect of microwave power, inlet air temperature, and drum rotation speed on the D_{eff} of the green pea dried by the proposed hybrid dryer are listed in Table 1. According to this Table, the impact of the microwave power, air temperature, and drum rotation speed, as well as their interactive effects, on the D_{eff} are significant at the level of 1%.

According to Fig. 3, the highest D_{eff} (5.04×10^{-11} m^2/s) was recorded under microwave power of 630 W, air temperature of 70 °C, and drum rotation speed of 15 rpm; while the lowest diffusion coefficient (4.66×10^{-12} m^2/s) was observed for the samples dried at microwave power, air temperature and drum rotation speed of 90 W, 40 °C, and 5 rpm, respectively.

Table 1: Variance analyses for the means of variables and their interaction for green pea drying in HMRD dryer.

S.O.V	DF	D_{eff}	SEC	S_b	RC	L	a	b	ΔE	TPC	AC
T	2	1.034**	791.95**	822.88**	0.592**	27.78**	7.07**	21.63**	51.52**	88.59**	341.86**
S	2	1.35**	1632.06**	101.28**	0.108**	4.35**	1.08**	3.38**	8.02**	10.98**	76.19**
P	3	3.25**	11363.47**	3551.37**	1.94**	85.28**	23.17**	50.52**	146.42**	244.59**	821.63**
T*S	4	1.24*	36.18 ns	3.61 **	0.00ns	0.08 *	0.07 ns	0.078 ns	0.096 ns	0.062 ns	6.38*
T*P	6	1.03**	78.46 ns	11.73 **	0.002ns	0.13 *	0.134 ns	0.17 ns	0.234 ns	0.073 ns	3.06ns
P*S	6	9.66**	42.84ns	6.29 **	0.012ns	0.445 *	0.216 ns	3.90 **	2.17 *	0.641 ns	7.19 *
T*S*P	12	4.13**	10.41ns	4.14 ns	0.001ns	0.041 ns	0.102 ns	0.33 ns	0.175 ns	0.098 ns	4.28ns

***Significant at 1% probability level.*
**Significant at 5% probability level.*
^{ns} *not significant*

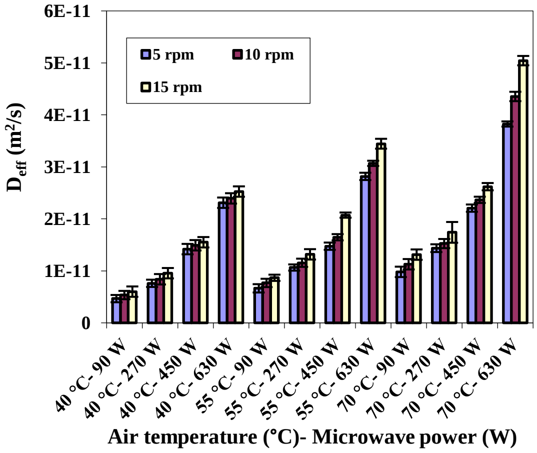

***Fig. 3: Different drying conditions on moisture effective diffusion coefficients of the green pea*.**

As suggested in Fig. 3, the moisture diffusion coefficient is significantly increased by microwave power enhancement for all temperatures and drum rotation speeds; since the elevation of the microwave power can augment the moisture vapor pressure and the internal temperature of the product and finally lead to an acceleration of the moisture transfer. For high temperatures, it can create the highest vapor gradient on the surface of the product which can, in turn, result in faster moisture evaporation in the air-food interface [55].

Activation energy

The activation energy (E_a) is defined as the lowest energy required for eliminating moisture from the product body which can be calculated by Eq. (9). Table 2 lists the E_a was obtained for the green pea in this study. The highest and lowest E_a were 23.41 and 31.42 kJ/mol, respectively which lay in an acceptable range. *Doymaz* & *Kocayigit* [5] and *Pandey et al.* [56] reported E_a of 22.01 to 30.31 and 19.54 to 26.71 kJ/mol for green pea, respectively.

Specific energy consumption

Table 1 shows the ANOVA results about the effect of microwave power, air temperature, and drum rotation speed on the SEC green peas dried by the proposed hybrid HMRD dryer. According to this Table, microwave power, air temperature and drum rotation speed significantly affected the SEC at the level of 1%.

As suggested in Fig. 4, the lowest SEC (27.01 MJ/kg) was obtained under microwave power of 630 W, drum rotation of 15 rpm, and air temperature of 70 °C. Furthermore, the highest SEC (109.91 MJ/kg) was recorded at the lowest microwave power, air temperature, and drum rotation speed. By increasing the microwave power, the SEC of the magnetron lamps will be elevated at the unit of time. The moisture content of the product can absorb high-power radiation, the processing time will be declined. Thus, the increase in microwave power can reduce SEC [37]. The reason for such a phenomenon can be described in the thermal gradient of the green pea grains at high microwave powers which can decline the drying time and intensify the slope of the moisture content variation by microwave power [57]. In their study on drying paddy by microwave-rotary drum dyer, *Behera* & *Sutar* [28] reported the SEC of 100.23- 268.65 kJ/kg. the SEC of paddy drying by IR, hot air, and microwave-rotary drum dryers were obtained 103.55, 101.58, and 11.22 kJ/kg,

Table 2: Activation energy values and related correlation coefficient for rotating speed of the drum and microwave power of green pea.

Rotating speed of the drum (rpm)	Microwave power (W)	Activation energy (E_a) (kJ/mol)	Coefficient of determination (R^2)
5	90	24.16	0.9975
5	270	23.41	0.9968
5	450	27.59	0.9989
5	630	28.58	0.9991
10	90	24.56	0.9958
10	270	25.95	0.9984
10	450	27.22	0.9990
10	630	28.54	0.9975
15	90	29.64	0.9982
15	270	30.48	0.9959
15	450	30.95	0.9974
15	630	31.42	0.9988

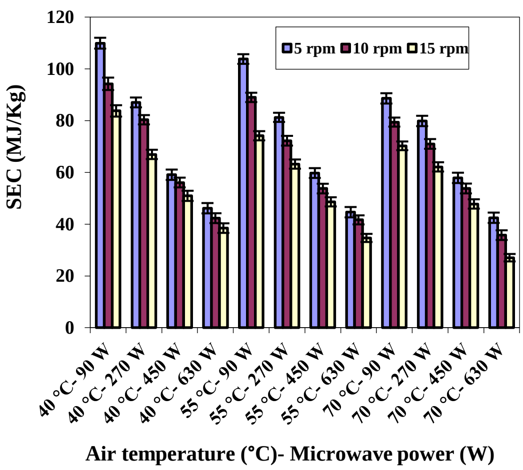

Fig. 4: Specific Energy consumption of different drying condition.

respectively [22]. *Hazervazifeh et al.* [53] obtained the SEC of 15.33 to 23.69 MJ/kg for apples. These researchers indicated that the increase in microwave power can decline SEC. Investigation of the impact of temperature on the SEC revealed that an enhancement in the inlet air temperature will increase the thermal gradient and accelerate the moisture evaporation; hence declining the drying time. By increasing air temperature, the operation time of the heaters will also increase; but as the process duration is decreased, the SEC will be declined. According to *Beigi* [58] and *Dehghannya et al.* [39] reports, the elevation of the air temperature could decrease the drying time. Furthermore, by increasing the drum rotation speed, the vapor pressure of the chamber will be decreased which may finally reduce the SEC.

Color

Table 1 provides a comparison of the color parameters (L*, a*, and b*). As can be seen, the lowest brightness index (L*=42.98) was obtained at the microwave power of 630 W, inlet air temperature of 70 °C, and drum rotation of 15 rpm. By enhancing the temperature and microwave power and drum rotation speed, the brightness of the sample declined (from 36.28 to 42.98 for all the experiments); i.e. the color of the sample was darkened (Table 3). Concerning the index of a*, the color of the green pea (their green color) increased by elevation of temperature, power, and rotation speed (mean variation of -8.97 to -5.33 for all the tests); this implies that the samples' green color was decreased (Table 3). In terms of the index of b*, the elevation of the microwave power, inlet air temperature, and drum rotation speed the yellow color of the samples was decreased (mean variation from 19.09 to 24.23 for all the tests) and their color approached gray (Table 3). Variation of ΔE shows that by increasing microwave power, temperature, and drum rotation speed, the color variation of the samples declined in comparison with the initial samples (mean variation from 41.34 to

50.14 for all the tests). The lowest color variation (relative to the initial sample) (41.34) was observed in the samples dried at the microwave power of 630 W, the temperature of 70 °C, and drum rotation speed of 15 rpm (Table 3).

Zielinska et al. [30] investigated the quality indices of green peas dried by different methods and concluded that as the drying time by a hot air dryer is very long, chlorophyll may be degraded to undesirable gray compounds such as pheophorbide or pheophytin and tend to convert to colorless compounds. In a study by *Zahoor* and *Khan* [42] on the color of bitter gourd dried by a hybrid hot air-microwave dryer, the color variation of the samples decreased with the increase of the microwave power and decreased the inlet air temperature. *Horuz* and *Maskan* [59] examined the color variation of pomegranate dried with hot air and microwave dryers, they showed that the color variation will be declined by increasing the microwave power and temperature.

Shrinkage

Table 1 reveals the ANOVA results about the impact of microwave power, inlet air temperature, and drum rotation on the shrinkage (S_b) level in the dried green peas. According to this Table, the effects of microwave power, air temperature, and drum rotation speed, as well as their interaction impact on the moisture diffusion coefficient were significant at the level of 1%. According to Table 3, the highest S_b (47.54%) was recorded at a microwave power of 90 W, inlet air temperature of (40 °C) and drum rotation speed of 5 rpm; while the lowest S_b (24.08%) was observed at microwave power, air temperature and drum rotations peed of 630 W, 70 °C, and 15 rpm, respectively.

Table 3 shows the S_b for the green peas dried by the proposed hybrid HMRD dryer. As the results suggest, the S_b was decreased at higher temperatures and microwave powers. Green pea has high initial moisture, during the drying process, significant S_b can alter its initial structure. Green pea texture has turor pressure (i.e. the liquid content imposes pressure on the cell wall and the liquid inside the cell is under pressure) [60]. During the drying process, water elimination from the cell will decline the stress imposed by the liquid on the cell wall which in turn, may create S_b on the product texture. High microwave power and temperature, however, will accelerate the water evaporation leaving no time for deformation [61, 62].

During food product drying, moisture will be eliminated from the product which will empty its inter-textual space. This will impose stress on the sample. As shown in Table 3. An increase in the air temperature declined the green peas S_b. Temperature can decrease the mentioned pressure difference and hence its consequent stress which will finally decrease the S_b.

These findings are in line with the study by *Dehghannya et al.* [61] who investigated the effect of microwave power and inlet air temperature on the S_b of potato dried by hot air dryer with different ultrasound and microwave pretreatments. Their results indicated that an increase in the microwave power and inlet air temperature will decrease the shrinkage. Furthermore, *Aydogdu et al.* [63], *Dai et al.* [15], *Dehghannya et al.* [64], *Kaveh* and *Abbaspour-Gilandeh* [65] reported similar results for drying eggplant, apple, apple, and green pea respectively.

Rehydration

According to Table 1, ANOVA results of *RC* at different microwave powers, temperatures, and drum rotation speeds show that these parameters were significantly effective on the *RC* at 1%.

As shown in Table 3, the *RC* will be increased by the increase of the microwave power, air temperature, and drum rotation speed. The reason could be attributed to the destruction of the cell tissue by higher microwave powers and temperatures which can enhance the *RC* and hence entrapment of the water in the spaces created by the damaged cells [44]. This can be explained by the expansion and puffing of the food by high internal pressure, which is caused by microwave power and air temperature. Depending on the reduction in structure density and the increment in intercellular gaps by this mechanism, the capacity of water absorption increases.

According to the results obtained by *Aydogdu et al.* [63] and *Dehghannya et al.* [64] The elevation of the microwave power and drying temperature will enhance the *RC* which could be due to accelerated moisture evaporation and hence decline of samples shrinkage. It seems that due to faster drying and accelerated moisture departure from the structure, some porosities and channels can be created which can promote fast water absorption and increase the *RC* [66].

Table 3: The quality attributes of dried green pea.

Temperature (°C)	Rotating speed of the drum (rpm)	Microwave Power (W)	ΔL^*	Δa^*	Δb^*	ΔE	RC	S_b
40	5	90	42.98	-8.97	24.23	50.14±0.9	1.57±0.07	47.54±1.2
40	5	270	41.59	-8.19	23.69	48.55±1.2	1.74±0.05	42.08±1.0
40	5	450	39.65	-7.59	20.98	45.49±1.0	2.04±0.06	33.24±0.9
40	5	630	38.17	-6.88	20.77	43.99±0.8	2.28±0.03	29.08±1.3
40	10	90	42.21	-8.58	24.02	49.31±1.1	1.64±0.02	46.29±0.8
40	10	270	41.28	-8.4	23.32	48.14±0.8	1.81±0.03	40.29±1.1
40	10	450	39.2	-7.32	20.51	44.84 ± 1.1	2.10±0.05	31.58±0.7
40	10	630	38	-6.72	20.68	43.78 ± 0.9	2.30±0.04	27.67±1.1
40	15	90	41.88	-8.29	23.97	48.96 ± 1.2	1.68±0.03	44.29±1.0
40	15	270	40.77	-8.13	22.74	47.38 ± 0.9	1.92±0.04	38.11±0.9
40	15	450	38.95	-7.11	20.27	44.48 ± 1.0	2.13±0.03	31.05±0.8
40	15	630	37.72	-6.45	20.42	43.37 ± 1.0	2.34±0.02	26.84±0.9
55	5	90	41.72	-8.23	23.93	48.79 ± 0.9	1.70±0.04	42.98±0.8
55	5	270	40.35	-7.89	21.77	46.52 ± 1.0	1.94±0.06	36.25±1.1
55	5	450	38.82	-7.77	21.69	45.14 ± 1.1	2.08 ± 0.02	30.78±1.0
55	5	630	37.52	-6.3	20.2	43.07 ± 1.1	2.40 ± 0.04	26.05±1.2
55	10	90	41.54	-8.55	23.6	48.53 ± 1.1	1.77 ± 0.03	41.77±0.7
55	10	270	39.97	-7.67	21.27	45.92 ± 1.2	1.99 ± 0.02	35.15±1.0
55	10	450	38.68	-7.69	21.19	44.76 ± 0.9	2.16 ± 0.03	30.28±1.1
55	10	630	37.33	-6.14	19.99	42.78 ± 1.0	2.43 ± 0.03	25.77±0.9
55	15	90	41.18	-8.33	23.19	47.98 ± 1.0	1.85 ± 0.04	39.20 ± 1.0
55	15	270	39.71	-7.62	21.04	45.58 ± 1.0	2.03 ± 0.02	33.93 ± 1.0
55	15	450	38.29	-6.94	20.88	44.16 ± 0.9	2.22 ± 0.01	28.63 ± 1.0
55	15	630	37.17	-6.03	19.85	42.56 ± 0.9	2.44 ± 0.03	25.29 ± 1.3
70	5	90	41.05	-8.2	22.9	47.71 ± 1.0	1.88 ± 0.06	37.37 ± 0.7
70	5	270	39.42	-7.42	20.67	45.12 ± 0.8	2.07 ± 0.02	32.33 ± 1.1
70	5	450	38.11	-6.85	20.57	43.84 ± 0.9	2.24 ± 0.03	28.02 ± 1.5
70	5	630	36.88	-5.79	19.55	42.14 ± 1.0	2.47 ± 0.02	24.99 ± 1.3
70	10	90	40.11	-7.77	21.5	46.16 ± 1.0	1.97 ± 0.02	35.95 ± 1.0
70	10	270	39.05	-7.21	20.38	44.63 ± 1.2	2.11 ± 0.02	31.65 ± 1.2
70	10	450	37.87	-6.55	20.5	43.55 ± 1.1	2.27 ± 0.03	27.01 ± 0.8
70	10	630	36.58	-5.59	19.33	41.74 ± 1.0	2.50 ± 0.02	24.66 ± 1.1
70	15	90	39.75	-7.5	21.11	45.62 ± 1.0	2.02 ± 0.03	34.57 ± 1.1
70	15	270	38.59	-7.6	20.09	44.16 ± 0.9	2.19 ± 0.02	29.88 ± 1.4
70	15	450	37.63	-6.37	20.28	43.21 ± 1.0	2.36 ± 0.02	26.42 ± 1.2
70	15	630	36.28	-5.33	19.09	41.34 ± 0.9	2.55 ± 0.01	24.08 ± 0.9

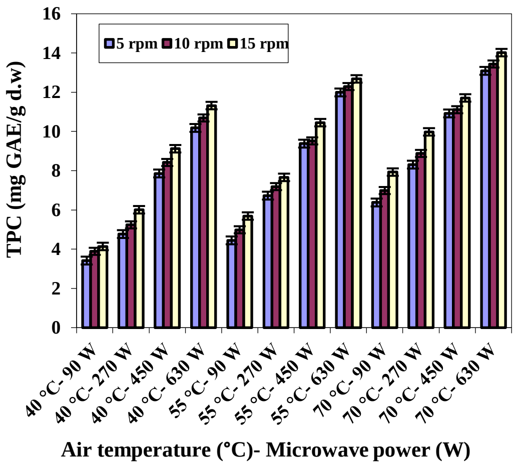

Fig. 5: Total phenolic content (mg GAE/g d.w) of a green pea at different drying conditions.

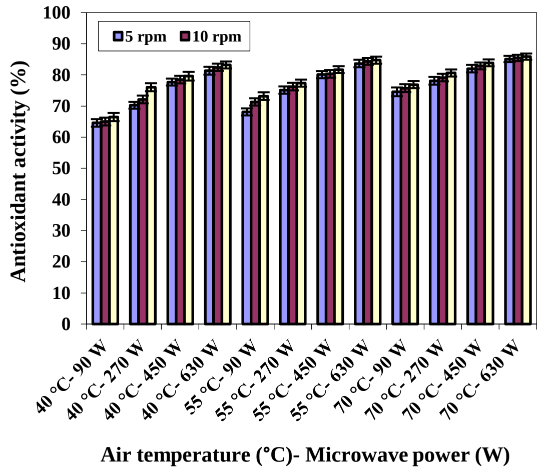

Fig. 6: Antioxidant activity (%) of a green pea at different drying conditions.

Total phenolic compounds

Concerning the TPC, Table 1 suggests the significant impact of microwave power, inlet air temperature, and drum rotation speed on the TPC compound of the samples. According to Fig. 5, the lowest TPC (3.42 mg GAE/g d.w) was observed in the samples dried under microwave power, air temperature, and drum rotation speed of 90 W, 40 °C, and 5 rpm, respectively. The highest TPC (14.02 mg GAE/g d.w) was extracted from the samples dried at the microwave power of 630 W, inlet air temperature of 70 °C, and drum rotation speed of 15 rpm. As can be seen, in the proposed hybrid HMRD dryer, an increase in the air temperature, microwave power, and drum rotation speed augmented the TPC as well. It can be attributed to the effect of temperature on the TPC; as these compounds are highly temperature-dependent.

The other probable reason could be the release of the TPC as the result of cellular compounds degradation thigh microwave powers and temperatures. Sample exposure to the high temperature as well as short drying time by microwave can inactivate the enzymes and preserve the TPC against further degradation [42]. Numerous researchers have shown the increase of TPC by elevation of the temperature and microwave power: *Zahoor* and *Khan* [42] for bitter gourd, *Suna* [48] for medlar fruit leather.

Antioxidant activity evaluation

The antioxidant activity of the fresh and dried samples was analyzed at completely randomized temperature, microwave power, and drum rotation speeds to determine their impact on the antioxidant properties; the results are shown in Table 1. As can be seen, different parameters were significantly effective in the antioxidant activity at 1%. The inhibition behavior of green pea extracts toward DPPH radical varied from 58.58 to 86.86% for different methods (Fig. 6).

The highest antioxidant activity was observed in the samples dried at a microwave power of 630 W, temperature of 70 °C, and drum rotation speed of 15 rpm; while the lowest antioxidant activity was detected in the samples dried at microwave power, temperature, and drum rotation speed of 90 W, 40 °C, and 5 rpm, respectively. Drying processes, in particular, long-term drying, are principally conducted at low temperatures which can stimulate the reduction in the antioxidant capacity [66, 67]. In other words, the antioxidant percentage of the extracts obtained from the samples dried at higher microwave powers, air temperatures, and drum rotation speeds were nearer to the control samples and lower variations were observed in their antioxidant activity. Antioxidant activity increased with increasing microwave power, air temperature, and drum rotation speeds.

In a part of their research, *Jebri et al.* [46] investigated the effect of microwave power and air temperature on the antioxidant properties of Salvia officinalis L. they reported the highest and lowest antioxidant activity at the highest microwave power and air temperature, respectively.

Furthermore, *Turkiewicz et al.* [68] studied the impact of different drying methods on the antioxidant properties of Japanese quince fruit. They employed a hot air dryer and microwave-vacuum hybrid dryer with microwave-vacuum and freezing pretreatments at various microwave powers and air temperatures. Their results indicated that for all the microwave-vacuum samples, higher thermal processes effectively preserved the phenolic compounds; hence the samples dried by this technique possessed higher antioxidant activities. Moreover, by increasing the microwave power and inlet air temperature, the antioxidant properties were enhanced as well.

CONCLUSIONS

In this study, a novel hybrid hot air-microwave- rotary drum dryer was designed and fabricated for drying green peas. This dryer was composed of three Sections: a microwave, hot air, and a rotating drum. Green peas were dried at various microwave powers (90, 270, 450, and 630 W), inlet air temperatures (40, 55, and 70 °C), and drum rotation speeds (5, 10, and 15 rpm). The results showed that by increasing the microwave power, air temperature, and drum rotation speed, the drying time will be declined. The effective moisture diffusivity varied in the range of 4.66×10^{-12} to 5.04×10^{-11} m^2/s. Specific energy consumption declined by elevation of the microwave power, air temperature, and drum rotations speed. The lowest specific energy consumption was obtained by microwave power of 630 W, temperature of 70 °C, and drum rotation speed of 15 rpm. The highest color, shrinkage, and rehydration capacity variations were 50.14, 47.54%, and 2.55, respectively. The highest and the lowest antioxidant content were 85.86% and 64.58%, respectively. The Total phenolic compounds varied in the range of 3.42 to 14.02 mg GAE/g d.w.

Nomenclature

A_i	Sample absorbance
A_t	Control absorbance
D_0	Pre-exponential factor, m^2/s
D_{eff}	Effective moisture diffusion coefficient, m^2/s
E_1	Energy values required for heating, MJ
E_2	Energy values required for the blower, MJ
E_3	Energy values required for drum rotating engine, MJ
E_4	Energy values required for magnetron, MJ
E_a	Activation energy, kJ/mol
M_b	Initial moisture content, kg_{water} / $kg_{dry\ matter}$
M_e	Equilibrium moisture content, kg_{water} / $kg_{dry\ matter}$
M_t	Moisture content at any time, kg_{water} / $kg_{dry\ matter}$
M_w	Mass of removal water, kg
MR	Moisture ratio
I	DPPH radical entrapping
p	Microwave power, W
R_g	Universal gas constant, 8.3143 kJ/mol K
RC	Rehydration capacity
r_e	Diameter, m
S	Drum rotation speed, rpm
S_b	Shrinkage, %
SEC	Specific energy consumption, MJ/kg
T	Air temperature, °C
T_a	Air temperature inside the drying chamber, K
W_r	Weight after rehydration
W_d	Initial weight of the dry sample
ΔL^*, Δb^*, Δa^*	Differences between the color of the fresh and dried sample
ΔE	Total color change
φ_f	Final volume, cm^2
φ_i	Initial volume, cm^2

Received : Jul. 5, 2020 ; Accepted : Nov. 16, 2022

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