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ORIGINAL ARTICLE

Comparison of drying characteristics of Thompson seedless grapes using combined microwave oven and hot air drying

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Abstract Comparison of drying characteristics of Thompson seedless grapes using combined microwave oven and hot air cabinet dryer was investigated. The drying rate curves indicated the absence of a constant-rate drying period in all drying methods. Within a certain microwave power range (75–900 W in the current study), increasing microwave power speeds up the drying process, thus shortening the drying time. No benefits were seen when increasing drying time from 30 to 120 min when grapes drying started in hot air cabinet dryer and finished in microwave oven for 1 min at any power level. The higher value of energy consumption during grapes drying belonged to hot air cabinet dryer alone as drying method with value of 564.5 $MJ/kg_{water\ evaporated}$. The average total soluble solids was 90.4° Brix when drying was achieved by microwave oven followed by hot air cabinet dryer, meanwhile, it was 90.2° Brix when drying was achieved by hot air cabinet dryer followed by microwave oven. The total soluble solid was 92° Brix when drying process started and finished in hot air cabinet dryer alone. The average drying ratio was 4.21 when drying was achieved by microwave oven followed by hot air cabinet dryer; meanwhile, it was 4.19 when drying

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was achieved by hot air cabinet dryer followed by microwave oven. The hot air cabinet drying method had higher drying constant 'k' compared to the other two methods. The microwave oven followed by hot air cabinet dryer as a drying method achieved 78% of the optimum selection percentage. However, the optimum drying method has a selection percentage of 100%.

1. Introduction

Drying process is one of the thermal processes that are time and energy consuming in the industry. That's why new methods are aimed to decrease drying time and energy consumption without reduction in quality. New methods included many mixed systems such as using microwave drying with solar drying to reduce drying time (Secmeler, 2003). Drying conditions or the drying equipments can be modified to increase overall efficiencies. Hybrid drying techniques can also be used, such as combining vacuum or convective drying with electro-technologies such as microwave, radio frequency, and infrared heating (Raghavan et al., 2005).

Over the past two decades, there has been an increasing interest in microwave drying to reduce drying time and increase the removal of water from agricultural products. Microwave drying has several advantages such as higher drying rate, shorter drying time, decrease energy consumption, and better quality of the dried products (Sanga et al., 2000). Improving drying processes by reducing energy consumption and providing high quality with minimal increase in economic input has become the goal of modern drying (Raghavan et al., 2005). Any single technique using this technology cannot by itself achieve this target. A combination of existing drying techniques should be considered. Based on the fast drying time of microwave heating, microwave-convective drying of fruit has shown success in obtaining high quality dried product with low specific energy consumption (Tulasidas et al., 1997; Raghavan and Silveira, 2001).

One of the primary advantages in using the microwave heating is that the temperature and moisture gradients are in the same direction, and hence aid each other as opposed to conventional heating where moisture must move out of the material against gradient of temperature (Murthy and Prasad, 2005).

Esmaiili et al. (2006) showed that the drying of grapes is a long time process and during the early stage of the process the temperature of the product rises until thermal equilibrium. The thin-layer drying of seedless grapes (*Vitis vinifera* L.) at temperatures of 40–70 °C and at air velocities of 0.5–1.5 m/s was investigated.

Doymaz (2006) examined the thin-layer drying behavior of black grapes in a laboratory dryer. Various pre-treatments were applied to black grapes, which were dried at 60 °C with an air velocity of 1.1 m/s. The shortest drying time (25 h) was obtained with black grapes dipped in ethyl oleate plus potassium carbonate solution.

Pahlavanzadeh et al. (2001) investigated the drying of Iranian seedless white grapes (sultana) in a batch operation in a laboratory dryer. Pre-treatment solutions contained different alkaline materials in different concentrations and air temperatures were used. Dipping grapes in an alkaline solution increased the drying rate substantially. Grapes dried in 450–900 min depending on pre-treatment and air temperature. The shortest drying time and best quality dried product were obtained with grapes dipped in a solution of potassium carbonate of 5% at 42 °C.

A laboratory-drying unit for sultana grapes was designed and constructed. Thin-layer model and Page's equation were used for modeling the drying of sultana grapes up to the water moisture content usually required to attain the shelf stability. The resulted curves were plotted in diagrams and graphically compared with experimental data. A good agreement was found between measurements and Page's equation prediction (Dionissios and Ghiaus, 2007).

Tulasidas et al. (1995) conducted drying of grapes using a single mode cavity applicator at 2450 MHz. Quality of raisins was assessed by several attributes, including color, damage, darkness, crystallized sugar, stickiness and non-uniformity. Microwave dried raisins were lighter in color and hence were superior to hot air dried samples. Convective drying was found to be highly energy intensive because of longer drying times as against shorter drying times and therefore lower specific energy consumption was achieved in microwave drying.

Margaris and Ghiaus (2007) presented results of experiments done in the case of hot air drying of sultana grapes. Thin-layer model and Page's equation were used for modeling the drying of sultana grapes up to the required water moisture content. They evaluated drying constants for sultana grapes and found the Page equation constant as $k = 4.7222 * 10^{-2}$ 1/h when the grapes dried at a mean temperature of 65 °C. However, the product constant 'n' was 1.1908.

Karathanos and Belessiotis (1999) dried grapes to 15% dry base and applied Page equation on their data and the drying temperature was 65 °C and the k constant was 0.00106 1/h and 'n' was 1.48.

Tulasidas et al. (1997) developed the semi-theoretical model of microwave drying of grapes based on mass, heat transfer, energy transfer and diffusivity of vapor. The numerical procedure predicted the behavior of microwave drying of grapes very well. However, they reported that the drying rate of the developed semi-theoretical model is very similar to the result from Page's model. That means Page's model is adequate to present the drying rate of microwave drying.

The main objective of this study is to investigate drying behavior of combined microwave oven/hot air cabinet drying methods compared to hot air drying method alone and their effects on drying characteristics and quality of grapes. The quality of grapes is specified by three criteria namely: rehydration ratio, total soluble solids and drying ratio.

2. Materials and methods

2.1. Grapes samples

Fresh Thompson seedless grapes were brought from local market during the summer season of 2006. The grapes clusters were cleaned with tape water, and then separated to single grapes (grains). For each drying experiment, about 3 kg of grapes were immersed in 3 l boiling solution (about 80 °C) of 0.2% sodium hydroxide for 30 s, and were immediately washed by immersing in cold water and washed with tape water to be free of alkali, then in 0.2% solution of citric acid. Grapes sulfuring was done by immersing the samples in 1000 ppm solution of potassium metabisulfite ($K_3S_2O_5$) for 4 h and this is sufficient to sulfur balanced samples. All pre-drying treatments were achieved at the evening preceding the drying experiment and the treated grapes were stored in plastic bags in a refrigerator at 7 °C until the next morning. The samples were removed from the refrigerator and kept in the room temperature for an hour before drying process started. More details are explained in Hamed (2008).

2.2. Instrumentations

An electric laboratory oven (Model mLw) was used for determining initial moisture content. A sample of 20 g was weighed and put into the Petri dish. The initial moisture content was determined by air-drying the samples of grapes at 70 °C for 24 h (AOAC, 1980). The initial moisture content was determined in three replicates. In this study, the average initial moisture content of the fresh pre-treated grapes was 354.64% d.b. (78% wb).

A microwave oven (Moulinex Model OPTiMO) operating at 2450 MHz was used in the drying experiments. The oven was equipped with knobs for setting different times and different power levels. The microwave oven was adjusted to different power levels from 75 to 900 W during microwave drying experiments.

A digital balance with 200 ± 0.01 g (METTLER AE0200, made in Germany) was used for determining the weight of the samples during the determination of initial moisture content of the grapes. Meanwhile, another digital balance was used during drying experiments (METTLER PM 30, made in Germany Digital Balance 3000 g).

A hot air cabinet dryer, locally manufactured having dimensions of 64 cm width, 44 cm height and 70 cm depth was used in drying experiments. The cabinet dryer had two

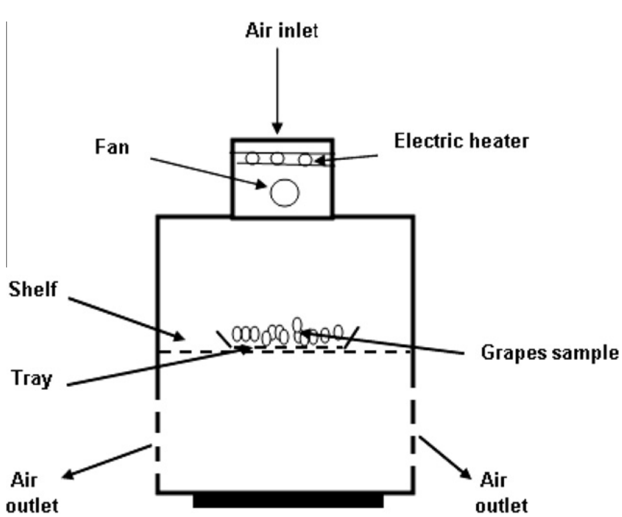

Figure 1 Schematic diagram of the hot air drying equipment (not to scale).

shelves to hold the drying trays. An electric motor [Alex mar b9 FMI mod A950 SPA] was connected to = electric fan for air circulating and four insulated heating coils were used to heat air before passing on grapes. Fig. 1 shows schematic diagram of the hot air cabinet dryer.

Total soluble solids in the grapes were measured by means of hand held pocket refractometer (TR Company, Italy). This refractometer has a measuring range of 0–32° Brix with accuracy of 0.2° Brix. For all measurements, 0.3 ml of the grapes extract sample was used. After drying grapes, the raisin had more total soluble solids values than the fresh. The raisin juice was diluted four times with water and the measured total soluble solids by the used refractometer were multiplied by 5 (El-Mahdy, 2007). The average total soluble solids of the fresh pre-treated grapes was 20.5° Brix.

2.3. Drying methods

The experiments were conducted in food processing engineering laboratory, agricultural engineering department, faculty of agriculture, Alexandria university, El Chatby, Alexandria, Egypt. Different drying methods were achieved in this study. These methods are composed of three groups as follows.

2.3.1. Group (I)

In this group, hot air cabinet dryer was used alone for drying and the drying method name is (hot air cabinet dryer alone). The dryer was adjusted at 70 °C. The grapes sample was about 300 g and put on metal tray. The metal tray had wire mesh at the bottom to hold the samples. The packing density of the drying tray was 3.1 kg/m^2. Constant temperature was held. Moisture loss was recorded by a digital balance at 60 min intervals during drying. The drying cycle was repeated to reach the case of no change in grapes weight.

2.3.2. Group (II)

In this group, a combination of two drying methods was used. Drying was started with hot air cabinet dryer then completed with microwave oven for 1 min at different microwave power levels, and the drying method name is (hot air cabinet dryer followed by microwave oven). Grapes grains sample was dried first in hot air cabinet dryer adjusted at 70 °C for 30 min then the drying and heating in microwave oven was completed for 1 min at specific microwave power level of 900 W and the experiment was repeated for other microwave power levels (700, 500, 400, 300, 250, 150 and 75 W). The drying method labels for this set are (A30M900, A30M700, A30M500, A30M400, A30M300, A30M250, A30M150, and A30M75). Also, the experiment was repeated as grapes grains sample was dried first in hot air cabinet dryer for 60 min then the drying in microwave oven for 1 min was completed at specific microwave power level of 900 W and the experiment was repeated for other microwave power levels (700, 500, 400, 300, 250, 150 and 75 W). The drying method labels for this set are (A60M900, A60M700, A60M500, A60M400, A60M300, A60M250, A60M150, and A60M75). Also, the experiment was repeated as grapes grains sample was dried first in hot air cabinet dryer for 120 min then the drying in microwave oven for 1 min was completed at specific microwave power level of 900 W and the experiment was repeated for other microwave power levels (700, 500, 400, 300, 250, 150 and 75 W). The drying method labels for this set are (A120M900, A120M700, A120M500, A120M400, A120M300, A120M250, A120M150, and A120M75). Moisture loss was measured by taking out and weighing the dish on the digital balance periodically. Each drying cycle was repeated to reach the case of no change in grapes weight. Attention was paid to ensure that the sample was not spoilage.

2.3.3. Group (III)

In this group, a combination of two drying methods was used. Heating was started in microwave oven for 1 min at different microwave power levels then completed drying in hot air cabinet for different times, and the drying method name is (microwave oven followed by hot air cabinet dryer). Also, the experiment was repeated as grapes grains sample was put first in microwave oven for 1 min at specific microwave power level of 900 W, then finishing drying in hot air cabinet dryer 70 °C through 30 min, and the experiment was repeated for other microwave power levels (700, 500, 400, 300, 250, 150 and 75 W). The drying method labels for this set are (M900A30, M700A30, M500A30, M400A30, M300A30, M250A30, M150A30, and M75A30). Also, the experiment was repeated as grapes grains sample was put first in microwave oven for 1 min at specific microwave power level of 900 W, = and then finishing drying in hot air cabinet dryer through 60 min, and the experiments were repeated for other microwave power levels (700, 500, 400, 300, 250, 150 and 75 W). The drying method labels for this set are (M900A60, M700A60, M500A60, M400A60, M300A60, M250A60, M150A60, and M75A60). Also, grapes grains sample was put first in microwave oven for 1 min at specific microwave power level of 900 W, then finishing drying in hot air cabinet dryer through 120 min, and the experiment was repeated for other microwave power levels (700, 500, 400, 300, 250, 150 and 75 W). The drying method labels for this set are (M900A120, M700A120, M500A120, M400A120, M300A120, M250A120, M150A120, and M75A120). Moisture loss was measured by taking out and weighing the dish on the digital balance periodically. Each drying cycle was repeated to reach the case of no change in grapes weight. Attention was paid to ensure that the sample was not spoilage.

2.4. Data analysis

Specific energy consumption (SEC) of the drying process was expressed in $MJ/kg_{water\ evaporated}$. Therefore, the SEC could be determined as follows (Varith et al., 2007):

$$SEC = \frac{(E_{microwave} + E_{oven}) \times 3.6}{(M_i - M_f) \times m_s} \quad (1)$$

The energy consumption of microwave could be calculated as follows (Changrue, 2006):

$$E_{microwave} = P \times t_{on} \quad (2)$$

where $E_{microwave}$ and E_{oven} are electrical power consumption from microwave oven and hot air cabinet dryer, respectively (kW h), M_i and M_f refer to the initial and final moisture content (decimal, d.b.), m_s is the mass of dry solid (kg), P is the microwave power input (kW) and t_{on} is the total time of microwave power-on (h). Efficiency of 100% was assumed for microwave oven and hot air cabinet dryer in converting line power.

2.5. Raisin quality

Three criteria were used as indictors of the drying process of grapes to produce raisins. They are rehydration ratio, total soluble solids (°Brix) and drying ratio. Procedures and calculations are shown in Hamed (2008).

2.6. Modeling of drying process

Moisture ratio was calculated using the following equation:

$$MR = \frac{M}{M_i} \quad (3)$$

where MR is the moisture ratio (dimensionless), M is the moisture content at drying time t (% d.b.) and M_i is the initial moisture content (% d.b.). However, the values of the equilibrium moisture content of grapes in the drying models are relatively small compared to M or M_i (Diamante and Munro, 1993). So, in the current study, the equilibrium moisture content of grapes was considered as zero. So, the Page's model (Page, 1949) was used in this study as follows:

$$MR = \exp(-kt^n) \quad (4)$$

where k (min^{-1}) and n (dimensionless) are drying constants, respectively, and t is drying time (min). The regression was performed by a statistical computer program (SPSS, 2005). The observed values of moisture ratio and those predicted by the model can be compared by coefficient of determination (R^2).

2.7. Selection of the best drying method

To select the best drying method, the following equation was developed in the current study for the calculation of the selection percentage:

$$SP = \frac{\sum_{i=1}^{m} R_i}{m \times N} \times 100 \quad (5)$$

where SP is selection percentage (%), m is number of criteria which be used in the selecting the best drying method ($m = 6$). N is number of drying methods ($N = 3$) and R_i is the rank of each selection criteria. In this study, the rank takes 3 for best drying method and takes 1 for bad drying method or takes 2 if less than 3 according to selection criteria. In the case of number of drying methods is 4, the rank takes 4 for best drying method and takes 1 for bad drying method or takes 3 if less than 4 or takes 2 if less than 3 according to selection criteria, etc. In this study, the selection criteria were rehydration ratio, total soluble solids, drying ratio, final drying time, final moisture content, and specific energy consumption.

3. Results and discussion

3.1. Grapes drying behavior

For hot air cabinet dryer followed by microwave oven drying method, moisture ratio-time diagram of grapes along the drying period is shown in Fig. 2 when grapes dried achieved by starting drying in hot air cabinet dryer for 30 min, 60 min and 120 min and finishing drying in microwave oven for 1 min at different power levels. As seen in Fig. 2, an increase

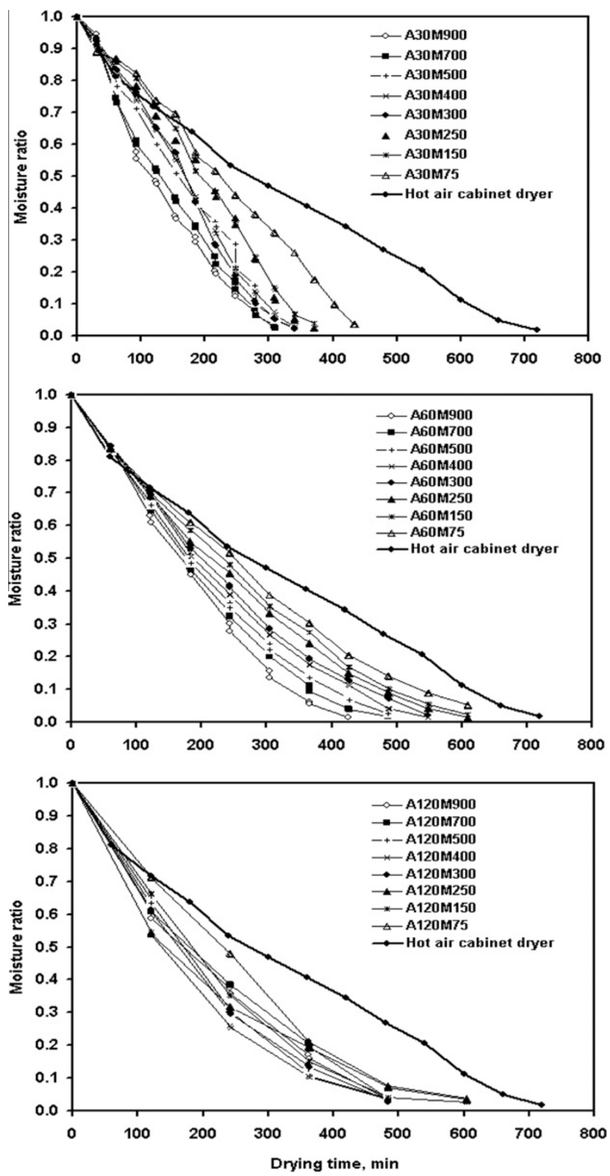

Figure 2 Thin layer drying curves of Thompson grapes dried by hot air cabinet dryer followed by microwave oven as compared to hot air cabinet dryer alone.

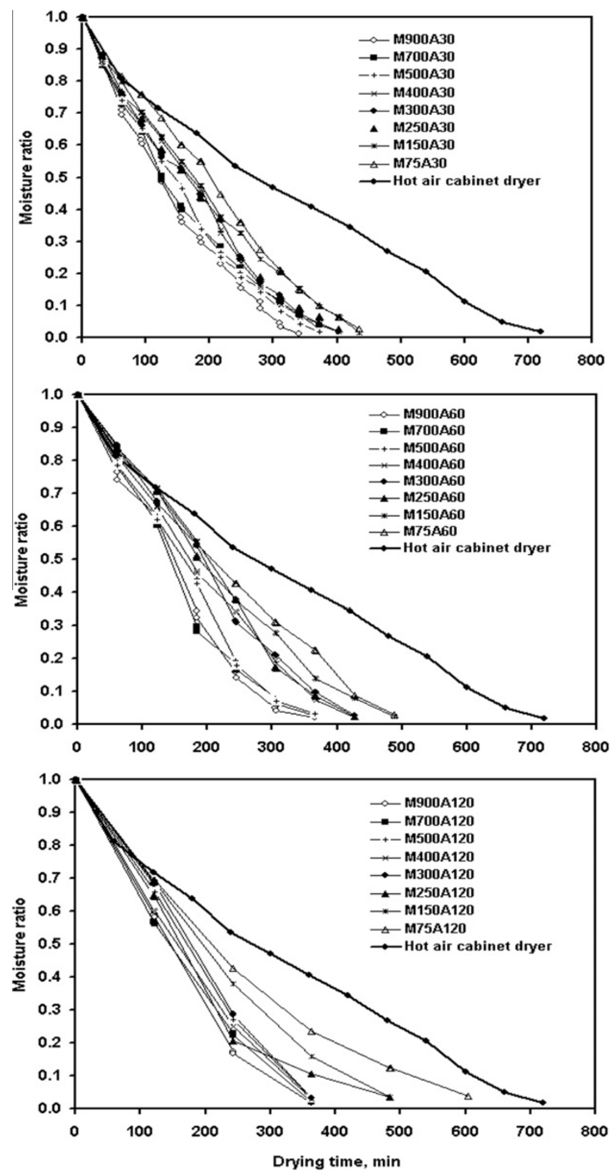

Figure 3 Thin layer drying curves of Thompson grapes dried by microwave oven followed by hot air cabinet dryer as compared to hot air cabinet dryer alone.

in drying time occurred with the increasing drying time in the hot air cabinet dryer from 30 to 120 min at any microwave power level. The drying rate curves indicated the absence of a constant-rate drying period. After reaching its maximum value the drying rate initially dropped rapidly, signifying a falling-rate period. The drying behavior when the grapes dried by starting drying in hot air cabinet dryer for 30 min and finishing by microwave oven for 1 min at different power levels were not different. Within a certain microwave power level range (75–900 W in this study), increasing microwave power speeds up the drying process, thus shortening the drying time. Also, when grapes drying started in hot air cabinet dryer, increasing drying time from 30 to 120 min until the moisture ratio was near to 0.02, the drying time increased.

For microwave oven followed by hot air cabinet drying method, moisture ratio-time diagram of grapes along the drying period when grapes dried by starting drying in microwave oven for 1 min at different power levels and finishing drying in hot air cabinet dryer for 30 min, 60 min and 120 min is shown in Fig. 3. A decline in drying time occurred with the increasing microwave power levels. The drying period of grapes had big difference when the grapes were dried by starting drying in microwave oven for 1 min at 900 W power level compared to other microwave power level of 75 W and finishing drying in hot air cabinet dryer for 120 min. Within a certain microwave power level range (75–900 W in this study), increasing microwave power speeds up the drying process, thus shortening the drying time. Also, increasing drying time from 30 to 120 min when grapes drying finished in hot air cabinet dryer until the moisture ratio was near to 0.02, the drying time increased. So, no benefits in drying time were seen when increasing drying time from 30 to 120 min when grapes drying started in microwave oven for 1 min at any power level and finished in hot air cabinet dryer.

Table 1 Some statistical criteria of final moisture content, rehydration ratio, total soluble solids drying ratio, and final drying time related to drying methods.

Statistical criteria	Microwave oven followed by hot air cabinet dryer	Hot air cabinet dryer followed by microwave oven	Hot air cabinet dryer alone
Final moisture content (% d.b.)			
Average	8.99	9.07	6.69
Minimum	4.57	5.68	–
Maximum	13.66	18.36	–
Rehydration ratio (–)			
Average	1.65	1.77	1.57
Minimum	1.38	1.57	–
Maximum	1.83	1.94	–
Total soluble solids (°Brix)			
Average	90.4	90.2	92.00
Minimum	87.3	86.5	–
Maximum	93.7	93.2	–
Drying ratio (–)			
Average	4.21	4.19	4.32
Minimum	4.06	4.02	–
Maximum	4.34	4.35	–
Final drying time (min)			
Average	413	474	720
Minimum	341	309	–
Maximum	605	610	–

Table 2 Averages of drying constants and coefficients of determination (R^2) for different drying methods.

Drying method	k (min^{-1})	n	R^2
Hot air cabinet dryer followed by microwave oven	0.000745	1.446	0.9913
Hot air cabinet dryer alone	0.00093	1.189	0.9753
Microwave oven followed by hot air cabinet dryer	0.000453	1.513	0.9927

Table 3 Average, minimum and maximum values of specific energy consumption for different drying methods.

Drying method	Specific energy consumption (MJ/$kg_{water\ evaporated}$)		
	Average	Minimum	Maximum
Microwave oven followed by hot air cabinet dryer	320.6	259.7	480.1
Hot air cabinet dryer followed by microwave oven	371.0	238.5	535.58
Hot air cabinet dryer alone	564.5	–	–

3.2. Effect of drying methods on raisin quality related to both final moisture content and drying time

Table 1 shows some statistical criteria of rehydration ratio, total soluble solids, and drying ratio related to both final moisture content and drying time. It is obvious that the average final moisture content changes according to the drying method and it was 8.99% d.b. when the drying was achieved by microwave oven followed by hot air cabinet dryer, meanwhile, it was 9.07% d.b. when the drying was achieved by hot air cabinet dryer followed by microwave oven. The lowest final moisture content was 6.69% d.b. when the drying process was started and finished in hot air cabinet dryer alone.

The average rehydration ratio changes according to drying method. It was 1.65 when the drying was achieved by microwave oven followed by hot air cabinet dryer. Meanwhile, it was 1.77 when the drying was achieved by hot air cabinet dryer followed by microwave oven as listed in Table 1. The rehydration ratio was 1.57 when the drying process was started and finished in hot air cabinet dryer alone.

The average total soluble solids was 90.4° Brix when the drying was achieved by microwave oven followed by hot air cabinet dryer. Meanwhile, it was 90.2° Brix when the drying was achieved by hot air cabinet dryer followed by microwave oven. The total soluble solid was 92° Brix when the drying process was started and finished in hot air cabinet dryer alone as listed in Table 1.

The average drying ratio was 4.21 when the drying was achieved by microwave oven followed by hot air cabinet dryer. Meanwhile, it was 4.19 when drying was achieved by hot air cabinet dryer followed by microwave oven as listed in Table 1.

Table 4 Ranks of selection criteria for selecting the best drying method.

Selection criteria	Drying method		
	Microwave oven followed by hot air cabinet dryer	Hot air cabinet dryer followed by microwave oven	Hot air cabinet dryer alone
Rehydration ratio	2	3	1
Total soluble solids	2	1	3
Drying ratio	2	1	3
Final drying time	3	2	1
Final moisture content	2	3	1
Specific energy consumption	3	2	1
Summation rank	14	12	10
Selection percentage (SP, %)	14/18 = 78	12/18 = 67	10/18 = 56

3.3. Drying model

Table 2 shows averages of drying constants k and n of Page's equation and coefficients of determination (R^2) for different drying methods. As could be expected, the rate constant term k increased resulting in higher drying rate. It is clear that, the hot air cabinet drying method had higher 'k'.

3.4. Drying energy

Table 3 shows average, minimum and maximum values of specific energy consumption related to drying methods. The lower energy was observed when grapes were dried by microwave oven followed by hot air cabinet dryer. The higher value of energy consumption during grapes drying belonged to hot air cabinet dryer alone as drying method with value of 564.5 $MJ/kg_{water\ evaporated}$. These results gave benefits of drying grapes in combination of microwave oven with hot air drying method. It should be noted that the specific energy consumption was calculated for comparing different methods in this study. Since the apparatus used was a laboratory-scaled device and not purpose for energy optimization, the results will hold good for a relative assessment for this study.

3.5. Best drying method

Because in this study, three drying methods were investigated and based on average values, the highest value of rehydration ratio takes three and the lowest value takes one as listed in Table 3. The highest value of drying ratio takes three and the lowest takes one as listed in Table 3. The highest total soluble solids takes three and the lowest total soluble solids takes one as listed in Table 3. For the final drying time, the lowest value takes three and the highest takes one as listed in Table 3. For the final moisture content, the highest value takes three and the lowest value takes one as listed in Table 1. For the specific energy consumption, the highest average value takes one and the lowest average value takes three as listed in Table 3. To select the best drying method, which has the highest selection percentage, the all ranks are summed in vertical axes, then divided by 18. The results in Table 4 shows that the microwave oven followed by hot air cabinet dryer as a drying method achieved 78% of the optimum selection percentage. However, the optimum drying method in the current study gave selection percentage of 100%.

4. Conclusion

The moisture ratio of grapes was affected by drying methods. The hot air cabinet alone as a drying method required more time to dry grapes. The drying rate curves indicated the absence of a constant-rate drying period in all drying methods. No benefits were seen when increasing drying time from 30 to 120 min when grapes drying started in hot air cabinet dryer and finished in microwave oven for 1 min at any power level. The hot air cabinet alone as a drying method had higher drying constant 'k' compared to other two methods. The microwave oven followed by hot air cabinet dryer as a drying method achieved 78% of the optimum selection percentage. However, the optimum drying method in the current study has a selection percentage of 100%.

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