Microwave assisted drying and extraction technique; kinetic modelling, energy consumption and influence on antioxidant compounds of fenugreek leaves

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Abstract
Fenugreek leaves contain bioactive compounds, which are helpful in maintaining human health. These compounds are adversely affected in conventional drying methods. Therefore, this study was carried out to retain maximum amount of these components through microwave-assisted drying and extraction techniques. The technique was optimized for simultaneous drying and extraction process for fenugreek leaves. The drying rate and drying time were influenced by the level of microwave power; time was reduced from 21 to 5 minutes, when microwave power was changed from 30 to 100 W. Unlike, the drying rate increased from 1.79 to 4.56 ± 0.05 g/(100 g.min) with the change in power (30 to 100 W). Moreover, moisture ratio analysis determined that two term model was the best to demonstrate the fitness with experimental values. The energy consumption was lowest for 100W compared to other powers. Furthermore, comparison between microwave-based extraction and methanol-extraction indicated that the antioxidant activity was better preserved compared to conventional ones even at higher microwave power levels.

Keywords: fenugreek; microwave; bioactive compounds; drying time; energy consumption.

Practical Application: Its application includes drying as well as pharmaceutical industry.

1 Introduction
Fenugreek (Trigonella foenum graecum L.) is famous as the seasonings and medicinal herb due to aromatic and functional compounds present in it. Its leaves are good source of minerals (iron, calcium, phosphorous), vitamins (vitamin C, riboflavin, niacin, thiamine, folic acid), carotene and flavonoids. These flavonoids are present as complex glycosides (C-glycosidic and O-glycosidic bonds) and among these major flavonoids are quercetin, vitexin, apigenin, etc (Nagulapalli Venkata et al., 2020; Aylanc et al., 2020; El Sohaimy et al., 2015).

Fenugreek leaves are usually dried for further use by various methods i.e. sun drying (Shrivastava & Kumar, 2016), Solar drying (Navale et al., 2014; Shrivastava & Kumar, 2016; Singh et al., 2004), hot air drying (Bishnoi et al., 2016; Kalaskar et al., 2012), freeze drying (Kushwaha & Mustafa, 2012), convective drying (Jawake et al., 2017), fluidized bed drying (Jawake et al., 2018) and microwave based drying (Borda-Yepes et al., 2019; Hihat et al., 2017; Khan et al., 2016; Martins et al., 2019; Monton et al., 2019b).

These techniques have high efficiency in drying, but the major concerns are loss of water-soluble bioactive compounds (BACs) and higher processing time & cost (Ferreira et al., 2018; Rocha & Melo, 2011; Thamkaew et al., 2020). Additionally, conventional drying techniques significantly reduce the quality of the product in terms of colour and textural properties (Duc-Pham et al., 2019). Therefore, an emerging drying technique with the purpose of making process of dehydration more sustainable is needed. Microwave based technique (Ali et al., 2020; Khan et al., 2016; Monton et al., 2019a) has exhibited its potential for drying i.e. reduced drying time and cost. Thus, microwave method of drying is energy efficient and easy to use compared to other drying methods (Alvi et al., 2019; Gamboa-Santos & Campaõne, 2019; Khan et al., 2016; Lv et al., 2019). However, loss of water-soluble bioactive compounds is still a major problem in microwave-based dehydration systems.

The superiority of microwave-based method urges to develop a novel method that may collect the vapours containing bioactive compounds as a superfluous improvement in addition to drying process. Therefore, present study focuses on the modification and optimization of microwave assisted drying and extraction (MADE) technique. In this regard, fenugreek leaves are used as model product for extraction and drying purposes. The extracted liquid obtained from microwave extraction method was compared with the one extracted with conventional method.

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2 Materials and methods

2.1 Procurement of raw materials

Fresh fenugreek leaves were procured from farms of University of Agriculture, Faisalabad-Pakistan. The impurities & dust particles were removed from fenugreek leaves through washing with running water. Afterwards, leaves were placed on tissue paper for the removal of excess water from their surface. These leaves were used for further experiments. Additionally, chemicals were procured from well-known company Sigma Aldrich (Germany).

2.2 Drying and extraction process

Drying of fenugreek leaves was done through microwave assisted extraction and drying technique. In this regard, an experimental setup was built in lab facility which consist of a modified microwave oven HDG 236S (Homage, Korea) as shown in Figure 1. The samples of leaves (50 g) were placed in glass reactor for drying purpose to extract the bioactive compounds from these leaves. The oven was operated at different powers (30, 50, 80 and 100 W). The loss in moisture was investigated by measuring the weight of the samples at different time intervals (1, 2, 3, 4, ……22 minutes) with the help of weighing balance (Shimadzu, Japan). The water vapors containing bioactive compounds were liquified with the help of condenser (Figure 1) in glass bottles and preserved at 4˚C for further analysis. Additionally, methanol-based extraction was performed for the comparison point of view. For this purpose, sample (5 g) homogenized in methanol solution (80%) for 45 minutes at 8000 rpm. The supernatant layer was removed from the rest of the sample and utilized for the TFC, TPC and DPPH analysis (Justine et al., 2019).

2.3 Drying rate

The values of drying rate for fenugreek leaves were calculated by using Equation 1 and expressed as g water/100 g.min.

\[
\text{Drying rate} = \frac{V_t - V_{t+dt}}{dt}
\]

where, \( t \) is drying time in minutes, \( V_t \) represents the moisture contents at time \( t \), while \( V_{t+dt} \) are the moisture contents at \( t + dt \) interval (Alvi et al., 2019; Yılmaz & Alibas, 2017).

2.4 Moisture ratio

The moisture ratio of a product demonstrates the relative removal of water contents and calculated as below (Equation 2).

\[
\text{Moisture ratio} (MR) = \frac{M_i - M_e}{M_o - M_e}
\]

where, \( M_t, M_i, \) and \( M_e \) represents moisture levels in leaves at time interval of \( t \), initial and equilibrium, respectively. This equation for moisture ratio was further modified to \( M_t/M_o \) by some researchers for ease in calculations as described in the literature (Al-Harahsheh et al., 2009; Doyraz, 2005; Karacadag, 2016). Besides, the most important aspect of drying process is mathematical modelling that may help to design drying equipment with optimum drying of desired product. The modelling was based on mathematical equations that can portray the system of drying (Sunil et al., 2014). Therefore, different models were selected from the literature and compared with experimental data to observe which model is best fit (Agbede et al., 2020).

Figure 1. Experimental setup for Microwave based drying of fenugreek leaves.
Midilli Model  \[ \text{Moisture Ratio} = \alpha \cdot e^{-kt} + \beta \]  

Two term Model  \[ \text{Moisture Ratio} = \alpha \cdot e^{-kt} + \beta \cdot e^{-kt} \]  

Page Model  \[ \text{Moisture Ratio} = e^{-kt} \]  

Two term exponential Model  \[ \text{Moisture Ratio} = \alpha \cdot e^{-kt} + (1 - \alpha) \cdot e^{-kt} \]  

Diffusion approximation Model  \[ \text{Moisture Ratio} = \alpha \cdot e^{-kt} + (1 - \alpha) \cdot e^{-kt} \]  

Verma Model  \[ \text{Moisture Ratio} = \alpha \cdot e^{-kt} + (1 - \alpha) \cdot e^{-kt} \]  

Moreover, diffusion coefficient was determined by using Fick’s law (Mahjoorian et al., 2016). For microwave based drying process, Fick’s law can be transcribed as below:

\[
\frac{M_{1} - M_{f}}{M_{0} - M_{e}} = \frac{8}{\pi^2} \exp \left(\frac{-\pi^2 D}{4L^2}\right) \tag{9}
\]

where, \(D\) is the diffusion coefficient (m²/s) in the sample having thickness \(L\) in meters. Here, the value of \(D\) was obtained by slope of a graph which was plotted between the values of ln MR and time (minutes). The slope of this graph (\(a\)) is described as:

\[
\alpha = \frac{\pi^2 D}{4E^2} \tag{10}
\]

Furthermore, influence of various variables (time, power and moisture content) on the values of drying rate and moisture ratio were determined by applying box–Behnken design. The box–Behnken design was elaborated by quadratic equation by using JMP software (SAS Institute, USA).

### 2.5 Specific energy of MADE

Specific energy consumption of MADE process of fenugreek leaves at various powers can be determined by the following equation (Darvishi et al., 2013; Jahanbakhshi et al., 2020) and expressed in MJ/kg (Equation 11):

\[
E_{\text{Specific}} = \frac{3.6 \times E_{\text{Microwave}}}{(M_{i} - M_{f}) \times M_{e}} \tag{11}
\]

where, \(M_{i}\) and \(M_{f}\) are initial and final moisture contents of fenugreek leaves and \(M_{e}\) is the dry matter in kilograms. \(E_{\text{microwave}}\) was calculated by Equation 12:

\[
E_{\text{microwave}} = t \times p \tag{12}
\]

where, \(t\) and \(p\) are the time in seconds and power in watts, respectively (Alvi et al., 2019; Khan et al., 2016).

### 2.6 Determination of DPPH activity

The antioxidant activities (DPPH activity) of the samples were determined by the method described in literature (Barkat et al., 2018; Curi et al., 2019). In this method, sample (0.5 mL) material in the form of extract obtained from Microwave and methanol extraction method added in methanol-based DPPH (4% w/v) solution; subsequently vigorous shaking of the mixture was carried out. Afterwards, the mixture was placed in darkness (overnight) and absorbance was measured at 515 nm using a spectrophotometer (IRMECO, Germany). The sample results of DPPH activity were reported in terms of percentage (%).

### 2.7 Total phenolic and flavonoid contents

Total phenolic compounds (TPC) were determined according to the method of Sun et al. (2005) with minor modifications (Aydar, 2020; Lu et al., 2011). In this method, Folin–Ciocalteu reagent was diluted with distilled water to prepare ten-time dilutions. Afterwards, a small portion of this solution (0.75 mL) was mixed with extracted sample (0.1 mL) and incubated for ten minutes. Subsequently, sodium carbonate solution (0.75 mL) was mixed with solution and placed in the dark conditions for forty-five minutes. Finally, absorbance reading of sample was measured at 765 nm with spectrophotometer (IRMECO, Germany). Besides, a calibration curve of absorbance was sketched against the different concentrations of gallic acid (0, 5, 10, 15, 20, 30 and 40 mg/L). The sample values were calculated and reported as gallic acid equivalent (mg/g).

For total flavonoid contents (TFC) determination, 1 mL of extract was mixed in 3 mL solution of methanol containing aluminum chloride and potassium acetate. This solution was further diluted by adding 5.6 mL of distilled water and placed at room temperature for half an hour. Afterwards, sample absorbance was determined with spectrophotometer (IRMECO, Germany) at 415 nm wavelength. The standard curve of quercetin was taken as reference and sample values were expressed in terms of quercetin equivalents (Ghafar et al., 2017).

### 2.8 Statistical analysis

All the experiments were performed in triplicates and their means along with standard errors were reported. The JMP® (SAS Institute, USA) was used to perform analysis of variance and Tukey’s test that determine the level of significance and comparison between treatments. Moreover, fitness of the models was determined by the values of \(R^2\), RMSE, SSE, RPD and Chi square (Guiné, 2018; Mota et al., 2010; Roberts et al., 2008; Equation 13-16).

\[
\text{Root Mean Square Error (RMSE)} = \sqrt{\frac{1}{N} \sum_{i=1}^{n} (V_{\text{exp,}i} - V_{\text{model,}i})^2} \tag{13}
\]

\[
\text{Sum of Square Error (SSE)} = \frac{1}{N} \sum_{i=1}^{n} (V_{\text{exp,}i} - V_{\text{model,}i})^2 \tag{14}
\]

\[
\text{Chi Square (CS)} = \frac{1}{N - n_p} \sum_{i=1}^{n} (V_{\text{exp,}i} - V_{\text{model,}i})^2 \tag{15}
\]

\[
\text{Relative Percent Deviation (RPD)} = 100 \frac{1}{N} \sum_{i=1}^{n} \frac{V_{\text{exp,}i} - V_{\text{model,}i}}{V_{\text{exp,}i}} \tag{16}
\]

### 3 Results and discussions

#### 3.1 Drying rate

Drying rates of fenugreek leaves were calculated with the help of Equation 1 and results have been shown in Figure 2.
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Evident that drying rate initially increased swiftly and reached up to 4.5 g/100 g.min within two minutes when heated at 100 W power (Figure 2a, b). At this point, maximum amount of moisture had been removed from the product surface. Afterward, value of drying rate decreased significantly indicating the reduction in moisture contents of the samples. Thus, drying rate of fenugreek leaves followed the parabolic trend in microwave based drying system (Figure 2b, c). Initially, the higher values of drying rate were due to higher moisture levels of leaves that absorbed more energy of microwaves; resulting in a prompt temperature rise. It stimulates the rapid evaporation process from the product surface (Figure 2b, c). After 50% moisture removal, less moisture level was present in sample for evaporation, compared to initial time; thereby reduced rate of drying (Soyosal et al., 2006; Therdthai & Zhou, 2009; Wang et al., 2007). This lowering of the drying rate as a function of time was attributed to the reduced availability of free moisture as previously discussed in literature (Alvi et al., 2019; Khan et al., 2016, 2019). Besides, effect of microwave power on drying rate of leaves was observed. It was noted that the drying rate of leaves was increased from 1.79 to 4.56 ± 0.05 g/(100 g.min) when power was increased from 30 to 100 W. It indicated that increase in power had significantly increased the drying rate. Thereby, reducing the processing time; ultimately the processing cost.

Moreover, ANOVA was performed to assess the influence of independent variables on drying rate as linear, interaction and quadratic and residual coefficients. It was obvious that a significant effect of variables on drying rate (Table 1) was evident especially in terms of linear and quadratic effects. Besides, the authenticity of second order polynomial was evaluated through the values of coefficient of determination ($R^2$) and F-test. The resultant value for $R^2$ (0.98) is close to one and indicated the less variation in response model. Thus, this model may be used to explain current experimentation. The second order polynomial model equation obtained by response surface methodology analysis for drying rate is as follows (Equation 17):

$$DR = 3.167 + 0.638P - 1.160T - 0.065MC + 0.432P \times T - 0.429P \times MC + 0.076T \times MC + 0.082P^2 + 0.555T^2 - 4.371MC^2$$

(17)

where, P, T and MC represent the power in watts, time in minutes and moisture content in percentage. These model values were compared with experimental ones and experimental drying rate was good fit with the predicted values (Figure 2d) as supported by the statistical values for predicted and actual drying rate ($R^2$=0.895, p<0.0001).
Table 1. Analysis of Variance for drying rate of fenugreek leaves.

| Source          | DF | F Ratio | Prob > F | Remarks     |
|-----------------|----|---------|----------|-------------|
| Linear          |    |         |          |             |
| Model           | 9  | 53.7554 | 0.0037   | Significant|
| Power           | 1  | 9.1391  | 0.0061   | Significant|
| Time            | 1  | 8.1236  | 0.8881   | Non-Significant|
| MC              | 1  | 0.0200  |          |             |
| Interaction     |    |         |          |             |
| Power × Time    | 1  | 2.7962  | 0.101    | Non-Significant|
| Power × MC      | 1  | 6.9177  | 0.011    | Significant|
| Time × MC       | 1  | 0.0238  | 0.8777   | Non-Significant|
| Quadratic       |    |         |          |             |
| Power²          | 1  | 0.3749  | 0.5428   | Non-Significant|
| Time²           | 1  | 31.912  | <0.0001  | Significant|
| MC²             | 1  | 130.327 | <0.0001  | Significant|
| Error           | 57 |         |          |             |
| Total           | 66 |         | <0.0001  | Significant|

DF indicates degree of freedom and F represents F-test.

Table 2. Influence of microwave power on the effective diffusion and specific energy consumption during MADE processing of fenugreek leaves.

| Power (W) | Average value (10⁻²²) | First falling rate period (10⁻¹²) | Second falling rate period (10⁻¹²) | Drying Time (min) | Specific Energy (MJ/kg) |
|-----------|-----------------------|-----------------------------------|-----------------------------------|-------------------|------------------------|
| 30        | 0.74ᵃ                  | 0.67ᵇ                             | 0.15ᶜ                             | 21 ± 1.5ᵇ        | 2.39ᶜ                  |
| 50        | 2.20ᵇ                 | 2.05ᶜ                             | 0.2ᵈ                             | 13 ± 1.25ᵇ      | 2.47ᵇ                  |
| 80        | 3.22ᵇ                 | 5.49ᵈ                             | 0.46ᵇ                            | 8 ± 0.4ᵇ        | 2.33ᵈ                  |
| 100       | 7.67ᵈ                 | 8.13ᵇ                             | 1.64ᵇ                            | 5 ± 0.5ᵈ        | 1.86ᵇ                  |

3.2 Drying time and moisture ratio

During MADE processing, time and power levels were evaluated. It is evident from the results that maximum time (21 min) was required for drying at power 30 W of microwave (Table 2). By increasing the power, drying time was reduced significantly, and minimum time required for complete drying was 5 min at power 100 W. The difference in drying time may be attributed to variation in heating intensity among the different power levels (Coolong et al., 2008; Özdemir & Altan, 2011).

Moisture ratio (MR) of fenugreek was calculated according to Equation 2 and results are shown in Figure 3. The value of MR at different powers of microwave (30, 50, 80, & 100 W) were compared (Figure 3) and results indicated that MR rapidly decreased at 100 W. This rapid decrease in MR indicates the swift drying of leaves consequently reducing the processing time. Furthermore, the experimental moisture ratio is in good agreement with predicted moisture ratio (<0.0001) with good authenticity (R²=0.997) of predicted values (Figure 3d).

Additionally, MR was predicted by various model equations (Equations 3-8) and compared with experimental values. According to statistical analysis, R² value was highest for Midilli model (0.9988) followed by two term model (0.9958), which indicates the good fit of the model (Table 3). However, higher values of RMSE (0.739) and RPD (20.25) values did not favour the model fitness with experimental values. Thus, two term model (Equation 4) was selected which had lower values of RMSE (0.018) and RPD (0.167) compared to Midilli. This model was further used to predict MR values and calculate the values of effective diffusion during the drying process of fenugreek leaves.

3.3 Diffusivity coefficient

The diffusive coefficient was calculated by using Equation 9 and 10. The results obtained had shown that diffusion process was controlled by the falling rate period. In this study, two phases of falling rates were observed that occurred in a constant slope. This slope determined the values of effective diffusion individually. The cut off value between these two falling rate periods was 0.3 of moisture ration. The effective diffusivities in the first falling rate period were influenced by the microwave powers and the range of values were 0.67 to 8.13 (10⁻¹² m²/s). Likewise, the values of effective diffusion in the second phase were influenced by power and values varied from 0.15 to 1.64 (10⁻¹² m²/s). The values of second period were about eight times smaller than first falling rate period (Table 2).

The average values of effective diffusion of fenugreek leaves during drying process at 30–100 W varied in the range of 0.73 to 7.67 (10⁻¹⁴ m²/s) (Table 2). The diffusivity coefficient increased with the increase of microwave power and results were in agreement with the research reported in literature (Alvi et al., 2019; Mahjoorian et al., 2016).

3.4 Specific energy consumption

The energy consumption of microwave assisted drying and extraction method was calculated and shown in Table 2. It is evident from the results that 80, 50 and 30 W consumed more energy (2.33, 2.47 and 2.39 MJ/kg, respectively) compared to 100 W (1.8672 MJ/kg). This may be attributed to lowest processing time (5 minutes) at 100 W processing compared to...
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Figure 3. Response surface plots, moisture ratio as a function of time and power (a), moisture ratio as a function of power and moisture content (b), moisture ratio as function of time and moisture content (c), comparison of experimental and predicted moisture ratio (d).

Table 3. A statistical analysis of various thin layer drying models used in this study to predict the MR.

| MODEL NAME               | MODEL CONSTANT | R2  | CHI (f)   | SSE   | RMSE  | RPD  |
|--------------------------|----------------|-----|-----------|-------|-------|------|
| MIDILLI                  | n = 1.244      | 0.9988 | 0.573 | 1.991 | 0.739 | 20.25 |
|                          | κ = 0.066      |     |           |       |       |      |
|                          | α = 0.997      |     |           |       |       |      |
|                          | β = 0.005      |     |           |       |       |      |
| TWO TERM                 | α = 1.037      | 0.9958 | 3.242×10⁻⁴ | 3.413×10⁻⁴ | 0.018 | 0.167 |
|                          | κ = 0.102      |     |           |       |       |      |
|                          | β = 1.133e⁻⁴  |     |           |       |       |      |
|                          | κ₁ = -0.265    |     |           |       |       |      |
| PAGE                     | n = 1.061      | 0.9947 | 0.29  | 4.335×10⁻⁴ | 0.525 | 194.95 |
|                          | κ = 0.084      |     |           |       |       |      |
| TWO TERM EXPONENTIAL     | α = 1.476      | 0.9941 | 4.621×10⁻⁴ | 4.865×10⁻⁴ | 0.021 | 1.792 |
|                          | κ = 0.114      |     |           |       |       |      |
| DIFFUSION APPROXIMATION  | α = 38.873     | 0.9935 | 5.039×10⁻⁴ | 5.304×10⁻⁴ | 0.022 | 0.877 |
|                          | κ = 0.079      |     |           |       |       |      |
|                          | β = 0.995      |     |           |       |       |      |
| Verma                    | α = 0.504      | 0.9934 | 5.142×10⁻⁴ | 5.412×10⁻⁴ | 0.022 | 0.425 |
|                          | κ = 0.096      |     |           |       |       |      |
|                          | g = 0.096      |     |           |       |       |      |
others (21 minutes @ 30 W); longer the processing time, higher the energy consumption. Thus, heating the food products at 100 W is sustainable in terms of time, cost and energy utilization.

### 3.5 DPPH, total phenolic and flavonoid contents

DPPH, TPC and TFC contents of MADE extract were compared with methanol-based extraction method (Table 4). The results indicated that liquid sample, obtained through MADE processing, exhibited better values of TFC, TPC and DPPH activity compared to methanol-based extraction method. These findings were comparable to the literature values (Cheng et al., 2013; Khan et al., 2016). Moreover, higher values of TPC, TFC and DPPH activity in comparison with methanol-based extraction method exhibited that the proposed technique (MADE) did not affect the activity of bioactive compounds of extract and this claim was supported by the findings of Ferreira et al., 2018 who reported that microwave drying does not affect the bioactive compounds (BACs) values of the product.

### 4 Conclusion

In this study, MADE technique was evaluated for drying of fenugreek leaf as well as the extraction of BACs from these leaves. The drying time of MADE process was significantly reduced (75%) at highest processing power (100 W) and it consumed less energy compared to other microwave powers. Likewise, the drying rate values were found to be very high (4.56 ± 0.05 g/100 g.min) at 100 W that reduced the moisture content rapidly and ease in swift drying. Similarly, the MR values decreased quickly at 100 W compared to other powers and lowest energy (1.8672 MJ/kg) was consumed. Thus, 100 W for 5 min considered to be the optimum for drying of fenugreek leaves. Moreover, BACs extracted through MADE technique exhibited better TPC, TFC, and DPPH values compared to methanol-based extraction process. Based on these findings, it can be concluded that microwave based drying and extraction is an efficient and sustainable process compared to both traditional methods of drying and extraction.

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### References

Agbede, O. O., Oke, E. O., Akinfenwa, S. I., Wahab, K. T., Ogundipe, S., Aworant, O. A., Arinkoola, A. O., Agarry, S. E., Ogunleye, O. O., Osuolale, F. N., & Babatunde, K. A. (2020). Thin layer drying of green microalga (Chlorella sp.) paste biomass: drying characteristics, energy requirement and mathematical modeling. Bioresearch Technology Reports, 11, 100467. http://dx.doi.org/10.1016/j.birete.2020.100467.

Al-Harabseh, M., Al-Muhtaseb, A. H., & Magee, T. R. A. (2009). Microwave drying kinetics of tomato pomace: effect of osmotic dehydration. Chemical Engineering and Processing: Process Intensification, 48(1), 524-531. http://dx.doi.org/10.1016/j.cep.2008.06.010.

Ali, A., Oon, C. C., Chua, B. L., Figiel, A., Chong, C. H., Wojdylo, A., Turkiewicz, I. P., Szumni, A., & Lyczko, J. (2020). Volatile and polyphenol composition, anti-oxidant, anti-diabetic and anti-aging properties, and drying kinetics as affected by convective and hybrid vacuum microwave drying of Rosmarinus officinalis L. Industrial Crops and Products, 151, 112463. http://dx.doi.org/10.1016/j.indcrop.2020.112463.

Alvi, T., Khan, M. K. I., Maan, A. A., Nazir, A., Ahmad, M. H., Khan, M. I., Sharif, M., Khan, A. U., Afzal, M. I., Umer, M., Abbas, S., & Qureshi, S. (2019). Modelling and kinetic study of novel and sustainable microwave-assisted dehydration of sugarcane juice. Processes, 7(10), 712. http://dx.doi.org/10.3390/pr7100712.

Anoopkumar, A., Anees, E. M., & Sudhikumar, A. V. (2020). Exploring the mode of action of isolated bioactive compounds by induced reactive oxygen species generation in Aedes aegypti: a microbes based double-edged weapon to fight against Arboviral diseases. International Journal of Tropical Insect Science, 40(3), 1-13. http://dx.doi.org/10.1007/s42690-020-00104-z.

Aydar, A. Y. (2020). Investigation of ultrasound pretreatment time and microwave power level on drying and rehydration kinetics of green olives. Food Science and Technology. In press. http://dx.doi.org/10.1590/fst.15720.

Aylanc, V., Eskin, B., Zengin, G., Dursun, M., & Cakmak, Y. S. (2020). In vitro studies on different extracts of fenugreek (Trigonella spruneriana BOISS.): phytochemical profile, antioxidant activity, and enzyme inhibition potential. Journal of Food Biochemistry, 44(11), e13463. http://dx.doi.org/10.1111/jfbc.13463. PMid:32931607.

Barkat, N., Singh, J., Jayaprakasha, G. K., & Patil, B. S. (2018). Effect of harvest time on the levels of phytochemicals, free radical-scavenging activity, α-amylase inhibition and bile acid-binding capacity of spinach (Spinacia oleracea). Journal of the Science of Food and Agriculture, 98(9), 3468-3477. http://dx.doi.org/10.1002/jsfa.8862. PMid:29287247.

Bishnoi, S., Sheoran, R., Ray, A., & Sindhu, S. C. (2016). Mathematical modeling of hot air drying of fenugreek leaves (Trigonella Foenum-Gracum) in cabinet dryer. International Journal of Food and Nutritional Sciences, 5(3), 170.

Borda-Yeps, V. H., Chejne, F., Daza-Olivella, L. V., Alzate-Arbelaez, A. F., Rojano, B. A., & Raghavan, V. G. (2019). Effect of microwave and infrared drying over polyphenol content in Vaccinium meridionale (Swartz) dry leaves. Journal of Food Process Engineering, 42(1), e12939. http://dx.doi.org/10.1111/jfpe.12939.

Cheng, A., Chen, X., Jin, Q., Wang, W., Shi, J., & Liu, Y. (2013). Comparison of phenolic content and antioxidant capacity of red and yellow onions. Czech Journal of Food Sciences, 31(5), 501-508. http://dx.doi.org/10.17221/566/2012-CJFS.

Coolong, T. W., Randle, W. M., & Wicker, L. (2008). Structural and chemical differences in the cell wall regions in relation to scale firmness of three onion (Allium cepa L.) selections at harvest and...
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during storage. Journal of the Science of Food and Agriculture, 88(7), 1277-1286. http://dx.doi.org/10.1002/jsfa.3219.

Cur, P. N., Salgado, D. L., Mendonça, K., Pio, R., Ferreira, J. L. G., & Souza, V. R. (2019). Influence of microwave processing on the bioactive compounds, antioxidant activity and sensory acceptance of blackberry jelly. Food Science and Technology, 39(Suppl. 2), 386-391. http://dx.doi.org/10.1590/fst.18618.

Darvishi, H., Azadbakht, M., Rezaeiasl, A., & Farhang, A. (2013). Drying characteristics of sardine fish dried with microwave heating. Journal of the Saudi Society of Agricultural Sciences, 12(2), 121-127. http://dx.doi.org/10.1016/j.jssas.2012.09.002.

Doymaz, I. (2005). Sun drying of figs: an experimental study. Journal of Food Engineering, 71(4), 403-407. http://dx.doi.org/10.1016/j.jfoodeng.2004.11.003.

Duc-Pham, N., Khan, M. I. H., Joardder, M., Rahman, M., Mahiuddin, M., Abesinhe, A. N., & Karim, M. (2019). Quality of plant-based food materials and its prediction during intermittent drying. Critical Reviews in Food Science and Nutrition, 59(8), 1197-1211. http://dx.doi.org/10.1080/10408397.2018.1481426.

El Sohaimy, S. A., Hamad, G. M., Mohamed, S. E., Amar, M. H., & Al-Hindi, R. R. (2015). Biochemical and functional properties of Moringa oleifera leaves and their potential as a functional food. Global Advanced Research Journal of Agricultural Science, 4(4), 188-199.

Ferreira, S. S., Passos, C. P., Cardoso, S. M., Wessel, D. F., & Coimbra, M. A. (2018). Microwave assisted dehydration of broccoli by-products and simultaneous extraction of bioactive compounds. Food Chemistry, 246, 386-393. http://dx.doi.org/10.1016/j.foodchem.2017.11.053. PMid:29291863.

Gamboa-Santos, J., & Campanole, L. A. (2019). Application of osmotic dehydration and microwave drying to strawberries coated with edible films. Drying Technology, 37(8), 1002-1012. http://dx.doi.org/10.1080/07373937.2018.1481426.

Ghafar, F., Nazrin, T., Salleh, M., Hadi, N. N., Ahmad, N., Hamzah, A. A., & Azahari, A. (2017). Total phenolic content and total flavonoid content in moringa oleifera seed. Galeri Warisan Sains, 1(1), 23-25.

Guiné, R. (2018). Variation of physical properties of fruits with drying and kinetic study. Life Science Press, 1(1), 40-47.

Hihat, S., Remini, H., & Madani, K. (2017). Effect of oven and microwave drying on phenolic compounds and antioxidant capacity of coriander leaves. International Food Research Journal, 24(2), 503-509.

Jahanbakshi, A., Kaveh, M., Taghinezhad, E., & Rasooli Sharabiani, V. (2020). Assessment of kinetics, effective moisture diffusivity, specific energy consumption, shrinkage, and color in the pistachio kernel dehydration and microwave drying to strawberries coated with freeze drying methods on physical and nutritional quality of fenugreek leaves. Research Journal of Agricultural Science, 3(4), 977-978.

Khan, M. K. I., Ansar, M., Nazir, A., & Maan, A. A. (2016). Sustainable dehydration of onion slices through novel microwave hydro-diffusion gravity technique. Innovative Food Science & Emerging Technologies, 33, 327-332. http://dx.doi.org/10.1016/j.ifset.2015.12.010.

Khan, M. K. I., Maan, A. A., Aadil, R. M., Nazir, A., Butt, M. S., Rashid, M. I., & Afzal, M. I. (2019). Modelling and kinetic study of microwave assisted drying of ginger and onion with simultaneous extraction of bioactive compounds. Food Science and Biotechnology, 29(4), 513-519. http://dx.doi.org/10.1007/s10068-019-00695-5. PMid:32296562.

Kushwaha, S., & Mustafa, N. (2012). Comparison of cabinet, microwave and freeze drying methods on physical and nutritional quality of fenugreek leaves. Trends in Food Science & Technology, 86, 59-67. http://dx.doi.org/10.1016/j.tifs.2019.02.047.

Mahjoorian, A., Mokhtarian, M., Fayyaz, N., Rahmati, F., Sayyadi, S., & Ariapi, P. (2016). Modeling of drying kiwi slices and its sensory evaluation. Food Science & Nutrition, 5(3), 466-473. http://dx.doi.org/10.1002/fsn3.414. PMid:28572931.

Martins, C. P., Cavalcanti, R. N., Couto, S. M., Moraes, J., Esmerino, E. A., Silva, M. C., Raices, R. L. S., Gut, J. A. W., Ramaswamy, H. S., Tadini, C. C., & Cruz, A. G. (2019). Microwave processing: current background and effects on the physicochemical and microbiological aspects of dairy products. Comprehensive Reviews in Food Science and Food Safety, 18(1), 67-83. http://dx.doi.org/10.1111/1541-4377.12409.

Monton, C., Luprasong, C., & Charioechai, L. (2019a). Acceleration of turmeric drying using convection and microwave-assisted drying technique: an optimization approach. Journal of Food Processing and Preservation, 43(9), e14096. http://dx.doi.org/10.1111/jfpp.14096.

Monton, C., Luprasong, C., & Charioechai, L. (2019b). Convexion combined microwave drying affect quality of volatile oil compositions and quantity of curcuminoinds of turmeric raw material. Revista Brasileira de Farmacognosia, 29(4), 434-440. http://dx.doi.org/10.1002/j.bjp.2019.04.006.

Mota, C., Luciano, C., Dias, A., Barroca, M. J., & Guiné, R. (2010). Convective drying of onion: Kinetics and nutritional evaluation. Food and Bioproducts Processing, 88(2-3), 115-123. http://dx.doi.org/10.1016/j.fbp.2009.09.004.

Nagarlapalli Venkata, K. C., Swaroop, A., Bagchi, D., & Bishayee, A. (2017). A small plant with big benefits: fenugreek (Trigonella foenum-graecum Linn.) for disease prevention and health promotion. Molecular Nutrition & Food Research, 61(6), 1600950. http://dx.doi.org/10.1002/mnfr.201600950. PMid:28266134.

Navale, S., Supriya, U., Harpale, V., & Mohite, K. (2014). Effect of solar drying on the nutritive value of fenugreek leaves. International Journal of Engineering and Advanced Technology, 4(2), 133-136.

Ozdemir, C., & Altan, Y. (2011). Morphological and anatomical investigations on three Allium L. (Liliaceae) species of east Anatolia, Turkey. Bangladesh Journal of Botany, 40(1), 9-15. http://dx.doi.org/10.3329/bjb.v40i1.7990.
Roberts, J. S., Kidd, D. R., & Padilla-Zakour, O. (2008). Drying kinetics of grape seeds. *Journal of Food Engineering*, 89(4), 460–465. http://dx.doi.org/10.1016/j.jfoodeng.2008.05.030.

Rocha, R., & Melo, E. (2011). Influence of drying process on the quality of medicinal plants: a review. *Journal of Medicinal Plants Research*, 5(33), 7076–7084. http://dx.doi.org/10.5897/JMPRX11.001.

Shrivastava, V., & Kumar, A. (2016). Experimental investigation on the comparison of fenugreek drying in an indirect solar dryer and under open sun. *Heat and Mass Transfer*, 52(9), 1963–1972. http://dx.doi.org/10.1007/s00231-015-1721-1.

Singh, S., Singh, P. P., & Dhaliwal, S. S. (2004). Multi-shelf portable solar dryer. *Renewable Energy*, 29(5), 753–765. http://dx.doi.org/10.1016/j.renene.2003.09.010.

Sun, T., Tang, J., & Powers, J. R. (2005). Effect of pectolytic enzyme preparations on the phenolic composition and antioxidant activity of asparagus juice. *Journal of Agricultural and Food Chemistry*, 53(1), 42–48. http://dx.doi.org/10.1021/jf0491299 PMID:15631507.

Soysal, Y., Öztekin, S., & Eren, Ö. (2006). Microwave drying of parsley: modelling, kinetics, and energy aspects. *Biosystems Engineering*, 93(4), 403–413. http://dx.doi.org/10.1016/j.biosystemseng.2006.01.017.

Sunil, V., Varun, & Sharma, N. (2014). Experimental investigation of the performance of an indirect-mode natural convection solar dryer for drying fenugreek leaves. *Journal of Thermal Analysis and Calorimetry*, 118(1), 523–531. http://dx.doi.org/10.1007/s10973-014-3949-2.

Thamkaew, G., Sjöholm, I., & Galindo, F. G. (2020). A review of drying methods for improving the quality of dried herbs. *Critical Reviews in Food Science and Nutrition*. In press. http://dx.doi.org/10.1080/10408398.2020.1765309. PMID:32423234.

Therdthai, N., & Zhou, W. (2009). Characterization of microwave vacuum drying and hot air drying of mint leaves (*Mentha cordifolia* Opiz ex Fresen). *Journal of Food Engineering*, 91(3), 482–489. http://dx.doi.org/10.1016/j.jfoodeng.2008.09.031.

Wang, Z., Sun, J., Chen, F., Liao, X., & Hu, X. (2007). Mathematical modelling on thin layer microwave drying of apple pomace with and without hot air pre-drying. *Journal of Food Engineering*, 80(2), 536–544. http://dx.doi.org/10.1016/j.jfoodeng.2006.06.019.

Yilmaz, A., & Alibas, I. (2017). Determination of microwave and convective drying characteristics of coriander leaves. *JBES*, 11(32), 75–85.