Modelling the kinetics of microwave drying of shallot (Allium cepa) slices

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Abstract. Convective drying is typically used to dry shallot (Allium cepa) commercially. However, a long drying time with a relatively low efficiency has led to the pursuit of new and improved drying methods. Microwave drying was chosen to be used due to its numerous advantages such as improved drying time, high drying efficiency and better product quality. In this research, three microwave power (180 W, 300 W, 450 W) and convective drying at 100°C were used. Results showed that drying kinetics (moisture content and drying rates) decreased the fastest at higher microwave power and the slowest using convective drying. In order to determine the best model to describe the thin-layer drying kinetics, four semi-empirical models were used namely Newton, Page, Logarithmic and Two-term models. Page model was found to be the best in describing the thin-layer microwave drying kinetics. Effective diffusivity values increased with higher microwave power and were found to be in the range of \(6.62 \times 10^{-6}\) m\(^2\)/s to \(3.69 \times 10^{-5}\) m\(^2\)/s with convective drying being the lowest (\(6.62 \times 10^{-6}\) m\(^2\)/s) and 450W being the highest (\(3.69 \times 10^{-5}\) m\(^2\)/s). Microwave drying is therefore able to improve drying kinetics compared to convective drying.

1. Introduction
Drying is an age-old process that has high importance in many different food industries and it is used in food preservation to provide a longer shelf-life and safe storage for the food materials. Conventional methods such as sun drying and convective hot air drying are often chosen due to their relatively low cost as well as their ability to heat regardless of the size, structure and shape of the food item [1]. However, several disadvantages are associated with these drying methods namely relatively long drying time (sun drying), inconsistent quality, unattractive colour/appearance, off flavour/aroma and so on. Therefore, this has ultimately led to the pursuit of other drying methods that are more efficient and one that has been getting a lot of attention recently is microwave assisted drying. Compared to convective drying, there are numerous advantages such as improved drying rates, better drying/energy efficiency and improved product quality [2–4].
Shallot (Allium cepa) is a member of the onion family, which is smaller in size with dimensions typically around 2.5 cm (diameter) and 3 cm (height) [5]. Shallots have been widely used as food seasoning due to its nutritional and aromatic nature. In terms of dried shallots, it is typically produced in the forms of powdered, chopped and as well as flaked. These dried shallots are often used as flavor additives in various food dishes including processed food products. Malaysia imported 129.21 metric tonnes of onions and shallots (fresh or chilled) in 2020 which amounting to 55.41 million USD [6]. Most of the onions and shallots are imported from Pakistan, New Zealand and Greece. This trend is expected to increase and grow steadily in the coming years. Hence, there is a need to find an alternative drying method to dry shallots for preservation purpose and diversify the product range to add value to the raw materials. Hence, microwave drying is selected for this purpose due to the various advantages as reported in literature, e.g more efficient heating and better product quality.

The main aim of this research is to dry shallot using a non-conventional method of drying and investigate its drying kinetics as compared to convective drying. Therefore, research works had been carried out by drying shallot samples using a laboratory microwave oven with the following objectives:

- To determine the drying kinetics of the microwave drying process.
- To model the drying process using thin layer drying models.
- To determine the effective diffusivities during drying.

2. Materials and Methods

2.1. Drying experiment

Fresh shallots (Allium cepa) were purchased from a local supermarket in Putrajaya, Malaysia. Prior to conducting the experiment, the shallots were peeled and cut into thin circular shape using a sharp knife. The weight of every shallot slice was 9.00 ± 0.5 g with thickness of 0.65 ± 0.05 cm and diameter of 4.8 ± 0.1 cm.

Both the drying experiments (convective and microwave) were conducted using a programmable microwave oven (Model C-103FL, Samsung), which has a cavity with a dimension of 0.34 m × 0.34 m × 0.22 m. The samples were placed on the rotating glass turntable. Microwave drying was conducted at three power settings (180 W, 300 W and 450 W) namely low, medium and high microwave heating. Convective drying was conducted at 100 °C. The experiments were conducted for at least 30 minutes and it was dried until equilibrium moisture content (constant weights). However, convective drying was only conducted for only 40 minutes as the intention was to use it as a benchmark for comparison against microwave drying within the similar time range (30 - 40 minutes). All the experiments were replicated twice to obtain the mean values.

2.2. Drying kinetics

The weights of the samples were measured by taking out the samples from the microwave oven at time interval of every 5 minutes. An analytical balance (Metler Toledo, USA) was used to weigh the samples and thereafter the samples were returned to the oven for drying. Moisture content (Mt) was determined according to equation (1) using the oven method [7].

\[
\text{Moisture content: } M_t = \frac{\text{Mass of sample (g)} - \text{Bone dry mass (g)}}{\text{Bone dry mass (g)}}
\]  

Bone dry mass was determined by subjecting the final dried samples in an air ventilated oven (Memmert, Germany) at 105 °C for at least 24 hours.

Drying rates (g water/g dry solid.hr) were determined by taking the gradient at each data point along the moisture content profile.

2.3. Mathematical modelling

Modelling using thin layer drying models were carried out using the Newton, Page, Logarithmic and Two-term models [8] as shown in table 1. The justification of using these models were to evaluate the fitting accuracy based on number of constant in the models namely one constant (‘k’ in Newton), two
constants (‘k’ and ‘n’ in Page), three constants (‘a’, ‘k’ and ‘c’ in Logarithmic) and four constants (‘a’, ‘b’, ‘k’ and ‘g’ in Two-term).

**Table 1. Semi-empirical thin layer drying models.**

| Model        | Equation               |
|--------------|------------------------|
| Newton       | \( MR = \exp^{kt} \)   |
| Page         | \( MR = \exp^{kn} \)   |
| Logarithmic  | \( MR = a \exp^{kt} + c \) |
| Two-term     | \( MR = a \exp^{kt} + b \exp^{gt} \) |

where \( MR \) = moisture ratio, \( M_i \) = initial moisture content and \( M_e \) = equilibrium moisture content as shown in equation (6).

**Moisture ratio:** \( MR = \frac{M_i - M_e}{M_i - M_e} \)  

In order to evaluate and determine the constants (a, b, c, g, k and n) of the selected models, non-linear regression analyses were performed by using Excel SOLVER (MS office, USA) by minimizing the sum of the square of the residuals (SSR) as shown in equation (7). The analyses were performed for the mean moisture ratio values determined from the experimental moisture contents. The models were evaluated for root mean square error (RMSE), coefficient of determination (\( R^2 \)) and Chi square (\( \chi^2 \)) as shown in equations (8) – (10). The best model selected having the lowest RMSE and \( \chi^2 \) but with the highest \( R^2 \) values.

\[
SSR = \sum_{i=1}^{N} (MR_{pre} - MR_{exp})^2
\]

\[
R^2 = 1 - \frac{\sum_{i=1}^{N} (MR_{pre} - MR_{exp})^2}{\sum_{i=1}^{N} (MR_{pre} - MR_{exp})^2}
\]

\[
\chi^2 = \frac{\sum_{i=1}^{N} (MR_{pre} - MR_{exp})^2}{(N-z)}
\]

\[
RMSE = \left[ \frac{1}{N} \sum_{i=1}^{N} (MR_{pre} - MR_{exp})^2 \right]^{1/2}
\]

Where subscripts exp and pre denote experimental and predicted values at each drying time, respectively. N and z denote the number of observations and constants, respectively.

2.4. Effective diffusivity

In order to determine the effective moisture diffusivity, Fick’s second law equation was used as shown in equation (11) by assuming an infinite slab geometry [9].

\[
MR = \frac{8}{\pi^2} \sum_{n=0}^{\infty} \frac{1}{(2n+1)^2} \exp\left(-\frac{(2n+1)^2 \pi^2 D_e t}{4L^2}\right)
\]

where \( L \) is the half thickness of sample (m) and \( D_e \) is the effective diffusivity (m²/s).

The equation can be simplified by using only the first term (n = 0) and applying natural log at both sides of the equation as follows [10].

\[
\ln MR = \ln\left(\frac{8}{\pi^2} \frac{\pi^2 D_e t}{4L^2}\right)
\]

The slope of the liner graph can be used for estimation of \( D_e \) values (equation (13)).

\[
Slope = \frac{\pi^2 D_e t}{4L^2}
\]
3. Results and Discussion

3.1. Drying kinetics

Figure 1 shows the changes in the moisture ratio of the shallot slices during microwave (MW) and convective (CONV) drying. It could be observed that over time, the moisture ratio decreased exponentially and the drying time was recorded within the range of 30 - 40 minutes. Demiray et al. [2] reported similar observation where higher MW power (557 W) recorded shorter drying time (40 minutes) and vice versa. Drying at 450 W MW power took the shortest time to dry the shallot slices as compared to those at 300 W and 180 W. This is mainly due to the greater excitement of water molecules under the action of higher MW power. Also, a faster heating rate promotes better heat transfer within the sample and vaporizes the internal moisture to the surface [11]. Eventually this enhances mass transfer and results in a shorter drying time. Meanwhile, convective drying shows the slowest reduction in moisture content owing to the heating mechanism which is dependent on the driving force between the hot air and sample.

![Figure 1](image)

**Figure 1.** Variation of moisture ratios with drying time for microwave and convective drying.

Figure 2 shows the changes in drying rates with moisture ratio during microwave and convective drying. Microwave drying at 450 W and 300 W showed a more distinct falling rate period as compared to that at 180 W and convective drying. However, initial warming up period was reported by Demiray et al. [2] for microwave drying at 328 - 557 W which could be due to the different quantity of samples used (70 g) as compared to current works (45 g). The higher the sample quantity the greater amount of moisture need to be heated/evaporated which could require significant amount of initial warming up/heating. It can be seen that the overall drying rate was higher at higher MW power and the lowest in convective drying. Initial drying rates were -0.934 kg water/kg dry solid.min, -0.628 kg water/kg dry solid.min and -0.188 kg water/kg dry solid.min for microwave drying at 450 W, 300 W, 180 W, respectively, and -0.088 kg water/kg dry solid.min for convective drying. This shows that microwave drying is able to improve the drying rates especially at the early stage of drying when the product moisture content is higher and able to absorb more microwave energy to facilitate drying.
### 3.2. Mathematical Modelling

Table 2 – 5 show the drying constants as well as the statistical parameters ($R^2$, $\chi^2$ and RMSE) determined from regression analyses. The $R^2$ values for all the models were in the range of 0.94 to 0.9995, $\chi^2$ values were in the range of $7.28 \times 10^{-5}$ to $1.49 \times 10^{-2}$ and the RMSE were in the range of 0.00752 to 0.1. Based on the criteria, the Page model showed the highest $R^2$ values and the lowest $\chi^2$ and RMSE values in all drying experiments. This implies that the Page model outperformed other models and it is the best in describing the thin layer drying kinetics of the shallot slices.

**Table 2. Results of mathematical modelling (MW power =180 W).**

| Model      | Constant       | $R^2$   | $\chi^2$     | RMSE  |
|------------|----------------|---------|---------------|-------|
| Newton     | $k = 0.053$    | 0.9516  | $1.12 \times 10^{-2}$ | $1.0 \times 10^{-1}$ |
| Page       | $k = 0.005$, $n = 1.783$ | **0.9916** | **1.50 \times 10^{-3}** | **3.40 \times 10^{-2}** |
| Logarithmic| $a = 1.099$, $k = 0.058$, $c = 0$ | 0.9413  | $1.20 \times 10^{-2}$ | $9.10 \times 10^{-2}$ |
| Two-term   | $a = 0.549$, $k = 0.058$, $b = 0.549$, $g = 0.058$ | 0.9413  | $1.50 \times 10^{-2}$ | $9.10 \times 10^{-2}$ |

**Table 3. Results of mathematical modelling (MW power = 300 W).**

| Model      | Constant       | $R^2$   | $\chi^2$     | RMSE  |
|------------|----------------|---------|---------------|-------|
| Newton     | $k = 0.126$    | 0.9861  | $2.40 \times 10^{-2}$ | $4.60 \times 10^{-2}$ |
| Page       | $k = 0.041$, $n = 1.491$ | **0.9995** | **7.28 \times 10^{-5}** | **7.53 \times 10^{-3}** |
| Logarithmic| $a = 1.035$, $k = 0.129$, $c = 0$ | 0.9851  | $3.00 \times 10^{-3}$ | $4.47 \times 10^{-2}$ |
| Two-term   | $a = 0.517$, $k = 0.129$, $b = 0.517$, $g = 0.129$ | 0.9851  | $3.59 \times 10^{-3}$ | $4.47 \times 10^{-2}$ |
Table 4. Results of mathematical modelling (MW power = 450 W).

| Model      | Constant | R²     | \( \chi^2 \)  | RMSE          |
|------------|----------|--------|----------------|---------------|
| Newton     | k = 0.178| 0.9889 | \( 1.40 \times 10^{-3} \) | \( 3.50 \times 10^{-2} \) |
| Page       | k = 0.072, n = 1.471 | **0.9964** | **7.62 \times 10^{-4}** | **2.39 \times 10^{-2}** |
| Logarithmic| a = 1.011, k = 0.180, c = 0 | 0.9889 | 1.94 \times 10^{-3} | 3.48 \times 10^{-2} |
| Two-term   | a = 0.506, k = 0.180, b = 0.506, g = 0.180 | 0.9889 | 2.42 \times 10^{-3} | 3.48 \times 10^{-2} |

Table 5. Results of mathematical modelling (convective).

| Model      | Constant | R²     | \( \chi^2 \)  | RMSE          |
|------------|----------|--------|----------------|---------------|
| Newton     | k = 0.048| 0.9607 | \( 7.75 \times 10^{-3} \) | \( 8.3 \times 10^{-2} \) |
| Page       | k = 0.007, n = 1.602 | **0.9906** | **1.46 \times 10^{-3}** | **3.37 \times 10^{-2}** |
| Logarithmic| a = 1.078, k = 0.052, c = 0 | 0.9528 | 8.71 \times 10^{-3} | 7.62 \times 10^{-2} |
| Two-term   | a = 0.539, k = 0.052, b = 0.539, g = 0.052 | 0.9528 | 1.04 \times 10^{-2} | 7.62 \times 10^{-2} |

According to Hii and Ogugo [8], the correction factor ‘n’ in the Page model has no theoretical meaning but it is merely a correction factor to improve the fitting accuracy. The page model also has the inherent advantage that a good fitting can be obtained with only a few constants (two constants k and n) that need to be determined. Figure 3 (a - d) shows fitting of the experimental data to the various thin layer models used in this study.

Figure 3. Fitting of the various thin layer models to experimental data (solid line [—] graph indicates the best fitted model with equation displayed).
3.3. Effective diffusivity

Table 6 shows the effective diffusivity (D_e) values determined from the drying experiments. The D_e values ranged from 0.66 × 10^{-5} to 3.69 × 10^{-5} m^2/s which are well within the range reported in the literature for food products [12]. The D_e values also increased as the MW power output increased.

| Experiment      | D_e (×10^{-5} m^2/s) |
|-----------------|----------------------|
| Convective      | 0.66±0.02            |
| Microwave (180 W) | 0.70±0.01            |
| Microwave (300 W) | 2.85±0.04            |
| Microwave (450 W) | 3.69±0.07            |

On average, the D_e values of microwave drying is at a higher order of magnitude (10^{-5} m^2/s) compared to convective drying (10^{-6} m^2/s). This is also in agreement with the trend reported by Demiray et al. [2] for similar product within the range of 2.59 × 10^{-7} to 5.08 × 10^{-8} m^2/s for microwave drying as compared to 3.49 × 10^{-8} to 9.44 × 10^{-8} m^2/s for convective drying while Asiah et al. [13] reported D_e values at a much higher order of magnitude (10^{-9} m^2/s) for convective drying. However, Khan et al. [14] reported a lower D_e value at 1.27 × 10^{-11} m^2/s which could be due to the lower MW power used (100 W). Furthermore, microwave energy is normally transmitted intermittently during drying and at low power output this resulted in a slower diffusion process at this setting. This shows that microwave drying is able to improve the drying kinetics of drying of shallot slices due to the better heat transfer mechanism attributed MW energy.

4. Conclusions

Drying experiments were conducted using two different methods namely microwave (180 W, 300 W and 450 W) and convective drying (100 °C). Drying rates were found to be the highest in the 450W MW power output followed by 300 W, 180 W and lastly the convective drying. The greater MW power could provide a better heating mechanism by exciting the water molecules through microwave within the inner vicinity of the sample. Mathematical modelling showed that the Page model was the best in describing the thin layer drying characteristics of shallot slices. The effective diffusivity (D_e) values were found ranging from 0.66 × 10^{-5} to 3.69 × 10^{-5} m^2/s with convective drying being the lowest value obtained and microwave drying at 450 W being the highest. The effective moisture diffusivity values increased as the MW power increased from 180 W to 450 W. On average, the D_e values of microwave drying is at a higher order of magnitude (10^{-5} m^2/s) compared to convective drying (10^{-6} m^2/s).

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References

[1] Litzler M 2007 Understanding drying Food Technology 61 97–100
[2] Demiray E, Seker A and Tulek Y 2017 Drying kinetics of onion (Allium cepa L.) slices with convective and microwave drying Heat and Mass Transfer/Waerme- und Stoffuebertragung 53 1817–27
[3] Onwude D I, Hashim N, Janius R, Abdan K, Chen G and Oladejo A O 2017 Non-thermal hybrid drying of fruits and vegetables: A review of current technologies Innov. Food Sci. Emerg. 43 223–38
[4] Feng L, Zhang M and Adhikari B 2014 Effect of water on the quality of dehydrated products: A review of novel characterization methods and hybrid drying technologies Dry. Technol. 32 1872–84
[5] Gupta K et al. 2003 Salad crops: Root, bulb and tuber crops’ Encyclopedia of Food Sciences and Nutrition 5060–73
[6] Anon 2021 www. tridge.com (accessed 2 April 2021)
[7] Hii C L, Law C L and Cloke M 2009 Modeling using a new thin layer drying model and product quality of cocoa J. Food Eng. 90 191–8
[8] Hii C L and Ogugo J F 2014 Effect of pre-treatment on the drying kinetics and product quality of star fruit slices J. Eng. Sci. Technol. 9 122–34
[9] Crank J 1975 The Mathematics of Diffusion second ed. Clearendon Press, Oxford, UK
[10] Yap J Y, Hii C L, Ong S P, Lim K H, Abas F and Pin K Y 2020 Effects of drying on total polyphenols content and antioxidant properties of Carica papaya leaves J. Sci. Food Agric. 100 2932–7
[11] Chandrasekaran S, Ramanathan S and Basak T 2013 Microwave food processing – A review Food Res. Int. 52 243–61
[12] Zogzas N P, Maroulis Z B and Marinos-Kouris D 1996 Moisture diffusivity data compilation in foodstuffs Dry Technol. 14 2225–53
[13] Asiah N, Djaeni M and Hii C L 2017 Moisture transport mechanism and drying kinetic of fresh harvested red onion bulbs under dehumidified air Int. J. Food Eng. 13
[14] Khan M K I, Maan A A, Aadil R M, Nazir A, Butt M S, Rashid M I and Afzal M I 2019 Modelling and kinetic study of microwave assisted drying of ginger and onion with simultaneous extraction of bioactive compounds Food Sci Biotechnol. 29 513–9