The influence of continuous and periodic microwave drying on rosemary: drying and temperature kinetics

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Abstract. Continuous microwave is a heavily studied drying method known for its effectiveness and efficiency, however, it leads to overheating in most cases. The primary objective of the present research is conducting and evaluating a comparative study of continuous and periodic microwave drying on rosemary for various power levels (6, 9 and 12 W/g) and different pulse ratios to overcome the overheating challenge. The evaluation and assessment were based on drying and temperature kinetics. Drying kinetic study revealed that periodic and continuous microwave drying at 12 W/g had the least drying duration of 12.5 and 11 mins, respectively. Likewise, both processes had the highest drying rates of 0.364 and 0.461 kg H$_2$O/kg dry basis min. The temperature kinetic study showed that the periodic microwave drying (71.4°C) resulted in a lower maximum sample temperature than continuous microwave drying (79.2°C). The periodic microwave drying with higher pulse ratios had a more even heating throughout the drying process than lower pulse ratios. Thereby, periodic microwave drying at 12 W/g and the highest pulse ratio was deemed to be the most suitable drying process for rosemary. The four thin layer models, namely Page, Modified Page, Midilli & Kucuk and Modified Midilli & others, were the most suitable to describe the drying kinetics of rosemary.

1. Introduction
Drying is the oldest form of preservation technique that remains unparalleled, even to this day [1]. Drying is a common and cost-effective method of reducing the moisture content from perishable natural sources [2]. Freshly harvested spices and herbs contain a high quantity of bound and unbound moisture. They are subjected to drying to reduce the moisture content to a desirable level (less than 10%) [3]. Thus, microbial growth and its proliferation could be hindered and the shelf life of the product would be prolonged. Additional benefits include enhanced sensory (flavour, colour, aroma) characteristics and preserved nutritional value. These days, drying is often executed as a post-harvest processing operation before downstream processing. Reduced weight and volume of the product, resulting from drying, lower the storage and transportation costs that further benefit the various industries [4]. Driven by the consumer’s demand of purchasing products that primarily consists of constituents from plants and herbs, drying is implemented in a controlled manner by considering all the key factors for maximum quality final products. Some of the determining factors for assessing the drying performance include the total drying period, energy consumption, drying rate among others.
Conventional drying methods include sun drying, solar drying and hot air drying. At present, 85% of the industrial driers are convective type paired with hot air or combustion gases as the hot medium [5]. On special occasions, freeze-drying is implemented on fruits as it is more effective in preserving the physical characteristics. Nevertheless, it is a highly intensive and energy-consuming technique as freeze-drying is estimated to consume 10-30% more energy when compared with the simpler techniques [6]. For this reason, it is not utilized on a more general basis. Besides, the drying process is already a complex process comprising heat, momentum and mass transfer. Evidence suggested that 10-15% of the national industrial energy consumption in some developed countries can be attributed to drying [6]. The research community have proposed many complex drying processes ranging from combined drying methods to hybrid drying methods. However, to date, microwave technology maintains its position as the technique with the highest potential to be integrated into the industrial sectors.

Currently, the microwave is a household name as it is regularly used for domestic purposes from heating to thawing etc. Microwave drying (MD) relies on the effective dielectric volumetric heating of charged groups (water) that constantly polarise and depolarise due to the rapidly alternating magnetic field [4]. The frictional heat generated by the water molecules results in the evaporation of moisture content. In comparison to conventional heating which relies on the diffusion of heat from the outside inwards, the penetration of microwave energy allows for more effective heating from the inside out. Its advantages of rapid heating, shorter processing time with less energy consumption is a well-known fact in the research community [6, 7]. However, the non-uniform heating of microwave drying is also a known disadvantage.

The non-uniform heating resulting from MD arises from the fact that the moisture is spread unevenly in the sample material. Periodic microwave (PM) drying was proposed as one of the ways in combating this challenge. In PM drying, the microwave is applied in pulse mode in an on/off manner, allowing for the heat generated during the “on” period to be distributed during the “off” period. Several studies of PM drying has shown to be effective for natural herbs in the past [8, 9]. The application of continuous and vacuum microwave is also proven to be equally effective when compared to conventional heating methods in terms of effectiveness and efficiency [6, 10]. However, both methods failed to solve the issue of overheating. The current study aims to evaluate the application of PM drying on a commercially valuable herb, *Rosmarinus officinalis* L. (rosemary) by conducting a comparative study between continuous and periodic microwave drying. The analysis and evaluation of the drying methods will be based on two crucial aspects, drying (drying duration and drying rate) and temperature (maximum and final temperature of herb) kinetics. Additionally, the current study also aims to evaluate thin-layer drying kinetic models for the periodic microwave drying of rosemary.

2. Materials and Methods

2.1. Plant materials sample preparation
Rosemary (*Rosmarinus officinalis* L.) potted plants were purchased in a large quantity from Delima Tani (Selangor, Malaysia). The leaves were separated and thoroughly washed immediately after purchasing. The leaves were patted dry and cut into uniform pieces approximately 1 cm long. The leaves were separated into equal amounts (2 kg) and kept in a shaded and cool area in a sealed bag before being subjected to the different drying methods.

2.2. Different drying methods
Two different drying methods were investigated in this study (continuous microwave and period microwave). For each respective drying method, the sample mass was measured periodically with a weighing balance. Drying was stopped when the mass of the sample was approximately ±0.1g in between successive readings.
2.2.1. **Continuous microwave drying.** The leaf samples were placed in a tray on top of the turntable and dried with a commercial microwave (Model **MS32J5133GM**, Samsung Electronics, South Korea) with 2450 Hz frequency and 1000 W maximum output power. Drying was executed with three different power levels of 6, 9 and 12 W/g.

2.2.2. **Periodic microwave drying.** Drying was executed in the same manner as a continuous microwave at the same power levels with the same equipment, however, microwave radiation was introduced periodically in an on/off manner, where the power was on for the duration of the “on” period and turned for the “off” period. The drying conditions were taken from literature for the herbs, sage, oregano and dill [9, 11]. The aforementioned herbs belong to the same herb family of “Lamiaceae” with similar structural morphology and compound composition as rosemary. Thus, it seemed fitting to narrow the drying condition based on similar herbs for the current study as displayed in table 1, where PR denotes pulse ratio.

| Sample Code | Microwave power (W/g) | On (s) | Off (s) |
|-------------|-----------------------|-------|--------|
| PR 1        | 6                     | 15    | 15     |
| PR 2        | 9                     | 15    | 15     |
| PR 3        | 12                    | 15    | 15     |
| PR 4        | 15                    | 15    | 15     |
| PR 5        | 30                    | 15    | 15     |
| PR 6        | 60                    | 15    | 15     |
| PR 7        | 60                    | 15    | 15     |
| PR 8        | 60                    | 15    | 15     |
| PR 9        | 60                    | 15    | 15     |

2.3. **Drying kinetics and thin layer modelling**

The drying kinetics were evaluated using the moisture content, ratio and drying rate experimental data. The moisture content \(MC\) was calculated using equation (1) [13].

\[
MC \text{ (dry basis)} = \frac{w_i - w_{db}}{w_i} \tag{1}
\]

Where \(MC\) is the moisture content (kg water/kg dry matter), \(w_i\) and \(w_{db}\) are the initial and bone dry weight (g) of the sample. Moisture ratio \(MR\) was determined using the data of \(MC\) and the following equation (2).

\[
MR = \frac{M - M_e}{M_o - M_e} \tag{2}
\]

Where \(M\), \(M_e\) and \(M_o\) are the given, initial and equilibrium moisture content (kg H\(_2\)O/kg dry basis). The drying rate \(DR\) (kg H\(_2\)O/kg dry basis min) was calculated using equation (3) as follows:

\[
DR = \frac{M_{t+\Delta t} - M_t}{\Delta t} \tag{3}
\]

Where \(M_{t+\Delta t}\) is the moisture content (kg H\(_2\)O/kg dry basis) at any given time and \(t\) is the drying time (s). Several thin-layer models (table 2) were used to evaluate the kinetics of the most suitable drying methods using the data of \(MR\). The selection of models was based on the different theories they were derived from, thus, multiple theoretical, empirical and semi-empirical models were adopted in this study [14,15].

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| PR 8        | 60                    | 15    | 15     |
| PR 9        | 60                    | 15    | 15     |
2.4. Temperature kinetics

The temperature of the samples was measured periodically for continuous and periodic drying using an infrared thermometer (DIT-500, Sonel SA, Poland). The temperature of the samples was taken until the drying process was deemed completed from the drying kinetic study. This was done to monitor the temperature fluctuations during the drying procedures. A temperature profile was created for each respective drying procedure.

2.5. Statistical analysis

The coefficients of the thin-layer kinetic models were determined by fitting the experimental data via Matlab 2021a (The MathWorks Inc., USA). Two statistical criteria, namely, coefficient of determination ($R^2$), root mean square error (RMSE), were used for the validation as given in equations (4) and (5) respectively.

\[
R^2 = \frac{\sum_{i=1}^{n} (y_i - \hat{y}_i)^2}{\sum_{i=1}^{n} (y_i - \bar{y})^2}
\]  
\[
RMSE = \sqrt{\frac{\sum_{i=1}^{n} (y_i - \hat{y}_i)^2}{n}}
\]

where $y_i$ and $\hat{y}_i$ are the predicted and experimental values of moisture content respectively and $n$ denotes the number of experiments carried out.

3. Results and Discussion

3.1. Drying kinetics and modelling

The drying rate curves of rosemary at different power levels and different microwave pulse ratios are graphically presented in figures 1, 2 and 3. The total drying period and the average drying rates are shown in table 3. The correlation between the PRs and the drying period can be noted instantly. In general, as the PR at 6 W/g was increased from 1 to 3, the drying period drastically increased from 22 to 40 mins which are in accordance with the literature [12]. This behaviour continued as the average drying rates of PR 1, 2 and 3 were 0.221, 0.127 and 0.128 kg H$_2$O/kg dry basis min. It would seem that at lower PRs, the heat generation by microwave was more effective to evaporate the bound and unbound moisture than higher PRs due to the shorter on/off periods. The unbound moisture at the surface of the sample evaporates at the beginning of the drying process, on the other hand, the bound moisture in the plant...
matrix takes more time to evaporate and diffuse out of the sample [11]. The quick evaporation of the unbound moisture at lower PRs can be noted from the sharp increase of the drying rates in the initial stage (figure 1), also noted as a constant drying stage. A peak of the maximum drying rate was achieved approximately at the same time for all PRs as noted in figures 1, 2 and 3. The falling rate stage, which denotes the heat and moisture transfer through internal diffusion, that follows immediately differentiates all the PRs [14]. Lower PRs with shorter “off” periods increase the drying rates. Thus, the resulting evaporation of unbound and bound moisture was faster leading to a reduced overall drying period. A similar trend was observed for the remaining power levels where lower PRs had less drying time with higher drying rates.

Figure 1. Drying rate of rosemary at 6 W/g for different pulse ratios.

Figure 2. Drying rate of rosemary at 9 W/g for different pulse ratios.
Figure 3. Drying rate of rosemary at 12 W/g for different pulse ratios.

Further evaluation of the graph reveals the fluctuating drying rates at lower PRs. The fluctuation could be a result of the evaporation of bound moisture in the plant’s matrix that is spread unevenly. The longest drying period among all the powers was recorded for 6 W/g with a duration of 39 to 40 mins and the lowest drying rates of 0.127 and 0.128 kg H₂O/ kg dry basis min. Additionally, the shortest period and the highest drying rate of 12.5 mins and 0.364 kg H₂O/ kg dry basis min was obtained for 12 W/g. This was expected as the rate of absorption of microwave energy increases at higher powers [5].

Table 3. Total drying period and drying rate for all drying methods.

| Drying methods | Sample code | Total drying period (min) | Average drying rate (kg H₂O/ kg dry basis min) |
|----------------|-------------|---------------------------|-----------------------------------------------|
| PM at 6 W/g    | PR 1        | 22                        | 0.221                                         |
|                | PR 2        | 39                        | 0.127                                         |
|                | PR 3        | 40                        | 0.128                                         |
|                | PR 4        | 14.5                      | 0.379                                         |
| PM at 9 W/g    | PR 5        | 23                        | 0.237                                         |
|                | PR 6        | 28                        | 0.192                                         |
|                | PR 7        | 12.5                      | 0.364                                         |
| PM at 12 W/g   | PR 8        | 20                        | 0.235                                         |
|                | PR 9        | 26                        | 0.182                                         |
| CM 6 W/g       | --          | 20                        | 0.232                                         |
| CM 9 W/g       | --          | 15                        | 0.308                                         |
| CM 12 W/g      | --          | 11                        | 0.431                                         |

The absorption of high microwave energy can be noted for continuous microwave (CM) drying as well. CM at 12 W/g was determined to be the most efficient method amongst all with the lowest drying period and highest drying rate of 11 mins and 0.431 min⁻¹, respectively. Moreover, there were no “off” periods during CM drying, therefore, continuous evaporation of both bound and unbound moisture took place rapidly [7].

3.2. Temperature kinetics
The maximum and final temperatures of the plant samples are presented in table 4. The influence of the PRs on the temperatures are quite evident from the results. With the increasing PRs, the maximum sample temperatures of all the PM drying decreases, similarly to the drying rates. As the “off” period increases concurrently with the PR, more time is spared for the distribution of the heat generated by the microwave
As the heat dissipates throughout the sample, slower evaporation of bound moisture takes place, thus, a lower drying rate. However, this also allows for more even heating of the samples and reduces localised heating in places of high moisture content. This trend was consistent for all power levels, although, one noticeable anomaly was the maximum final temperature of power 9 W/g at PR 6 is lower than that of power 6 W/g at PR 3. There is a possibility that less bound moisture was present in the plant’s matrix leading to lesser heat generation, thus, the lower temperature was obtained. Given the complicated structural morphology of plants, such unfamiliar results are to be expected that requires further study. The maximum temperature reached for the PM drying at 12 W/g (71.4°C) is lower than CM at 9 W/g (75.4°C). As expected, which no time interval for the heat to dissipate, CM drying generated more heating leading to high sample temperatures.

According to the literature, both microwave heating duration and wattages are known factors that affect the sample’s final temperature [16]. Longer heating time and higher microwave power allow for more absorption of microwave radiation [17]. The continuous heat generation leads to a higher final temperature. However, previous works of literature were solely focused on CM and could follow this theory. However, in current research, the application of microwave in a periodic manner showed more subdued drying at lower final temperatures for higher wattages as well. This would be highly beneficial as PM drying can prevent localised overheating together with preventing the decomposition of natural compounds present in rosemary that possess ethnopharmacological properties and are thermolabile [18].

The temperature profiles of the PM drying (figures 3, 4 and 5) imitate the drying rate curves where the lower PRs show heavy fluctuations in temperature, irrespective of the power levels. Since rosemary is a herb known to possess thermo-sensitive compounds, the higher PRs would be more suited drying process, even though they take a longer drying duration. Thus, it was deduced that PM at 12 W/g and PR 9 would be the most suitable drying process for rosemary. Despite moderate drying duration and rates, more even heating would have a lesser impact on the beneficial compounds present in them. Therefore, this drying condition was chosen for the thin layer kinetic modelling study.

Table 4. Maximum and final surface temperature for all drying methods.

| Drying methods | Samples | Maximum surface temperature (°C) | Final surface temperature (°C) |
|----------------|---------|----------------------------------|--------------------------------|
| PM at 6 W/g    | PR 1    | 70.8                             | 47.6                           |
|                | PR 2    | 63.5                             | 44.1                           |
|                | PR 3    | 64.9                             | 50.7                           |
|                | PR 4    | 70.3                             | 55.6                           |
| PM at 9 W/g    | PR 5    | 57.3                             | 48                             |
|                | PR 6    | 62.2                             | 50.7                           |
|                | PR 7    | 71.4                             | 48.6                           |
| PM at 12 W/g   | PR 8    | 65.2                             | 50.1                           |
|                | PR 9    | 67.9                             | 48.6                           |
| CM 6 W/g       | --      | 66.8                             | 50.4                           |
| CM 9 W/g       | --      | 75.4                             | 60.6                           |
| CM 12 W/g      | --      | 79.2                             | 65.9                           |
Figure 4. The temperature profile of IM drying at 6 W/g.

Figure 5. The temperature profile of IM drying at 9 W/g.

Figure 6. The temperature profile of IM drying at 12 W/g.
3.3. Thin layer kinetic modelling

A total of seventeen models from diverse backgrounds were chosen to describe the drying kinetics of PM drying of rosemary. The basis of model selection were semi-theoretical models which consider the simplistic form of internal and external diffusion of heat and mass transfer [14]. These models were all derived from its predecessor, Fick’s law of diffusion or Newton’s law of cooling with the major difference being the number of model constants in them. The other basis is the empirical formula, solely derived from the experimental data without any regard to the fundamentals of the drying process.

Table 5. Kinetic variables for the drying model for periodic microwave drying at 12 W/g and PR 9.

| Model                        | Constants and Coefficients | Value | $R^2$ | RMSE |
|------------------------------|---------------------------|-------|-------|------|
| Page                         | $k$                       | 0.0089| 0.9977| 0.0166|
|                             | $n$                       | 1.9560|       |      |
|                             | $k$                       | 0.0555|       |      |
| Modified Page (III)          | $d$                       | 1.5600| 0.9976| 0.2028|
|                             | $n$                       | 1.9070|       |      |
|                             | $k$                       | 0.3754|       |      |
|                             | $a$                       | -80.48|       |      |
| Modified Henderson and Pabis | $b$                       | 3.179 |       |      |
|                             | $c$                       | 78.79 |       |      |
|                             | $g$                       | 0.1698|       |      |
|                             | $h$                       | 0.3814|       |      |
|                             | $k$                       | 0.03446|     |      |
| Logarithmic                 | $a$                       | 2.334 |       | 0.026|
|                             | $b$                       | -1.195|       |      |
|                             | $k_1$                     | 0.1158|       |      |
| Two-term                    | $k_2$                     | 10.42 |       |      |
|                             | $a$                       | 1.295 |       |      |
|                             | $b$                       | 626   |       |      |
| Two-Term Exponential        | $k_1$                     | 0.01118|     |      |
|                             | $k_2$                     | 0.000479|     | 0.0584|
|                             | $a$                       | 16.96 |       |      |
| Wang & Singh                | $k$                       | -0.05185|     | 0.98  |
|                             | $b$                       | -0.0000351|     | 0.0494|
|                             | $a$                       | 0.008118|    |      |
| Weibull                     | $b$                       | -0.9913| 0.9978| 0.017|
|                             | $n$                       | 1.989 |       |      |
| Peleg                       | $a$                       | 19.26 |       | 0.98  |
|                             | $b$                       | -0.01122|     | 0.0494|
| Verma & Others              | $a$                       | 54.96 |       | 0.0412|
|                             | $g$                       | 0.2157|       |      |
|                             | $k$                       | 0.05348|     |      |
| Midilli & Kucuk             | $a$                       | 1.141 |       | 0.9945| 0.027|
|                             | $b$                       | -0.02086|    |      |
| Modified Midilli & Others   | $a$                       | 2.334 |       | 0.9949| 0.026|
|                             | $b$                       | -1.195|       |      |

Based on the results (table 5), the ones presented in the paper are those with a high $R^2$ (>0.95) and low RMSE (<0.0778), while the rest were excluded. All the models displayed high accuracy as the difference of $R^2$ was determined to be merely 0.033%. Amongst all of the models, the simpler ones including Page, Modified Page, Midilli & Kucuk and Modified Midilli & others were marginally better.
The major difference between the simple and complex models are the number of constants. The simple models such as Page, Modified Page, Logarithmic, Midilli & Kucuk and Modified Midilli & others consists of one drying constant ($k$) as they consider the drying process to be a one stage process. The complex ones such as Modified Henderson and Pabis, Two-term or Two-term exponential have two drying constants ($k_1$ and $k_2$) as they consider drying to be a two-step process. Generally, the complex ones work better for the hot-air drying process as the drying takes place in two steps: i) evaporation of moisture from the surface, ii) diffusion of heat into the internal parts of the herbs followed by evaporation and diffusion of moisture from the internal parts to the surface. As for microwave drying methods, moisture on the surface and internal parts of the herbs are volumetrically heated simultaneously [4]. Therefore, there is a possibility that the simple models were slightly better in predicting the drying kinetics than the complex ones.

Although the models were derived from different theories, Page and Modified Page from Newton’s law of cooling while Midilli & Kucuk and Modified Midilli & others from Fick's law of diffusion, all of these models have displayed high accuracy in kinetics studies in the literature [17, 18]. According to a review study, 24% of the reviewed literature chose Midilli & Kucuk as the best drying kinetic model [14]. Therefore, based on the statistical criteria, it was deduced that simple models are sufficient to describe the drying kinetics of rosemary.

4. Conclusion
The present research investigated the drying and temperature kinetics of periodic and continuous microwave drying on rosemary for different power and pulse ratios. Lower PRs were more efficient with a shorter drying duration for all powers. Among all the drying processes, periodic and continuous microwave drying at 12 W/g had the least drying duration of 12.5 and 11 mins, respectively. Likewise, both processes had the highest drying rates of 0.364 and 0.461 kg H$_2$O/ kg dry basis min. However, the maximum sample temperature for periodic microwave drying at 12 W/g (71.4°C) was lower than continuous microwave drying at 9 W/g (75.4°C). This is a result of the application of microwave periodically, allowing time for heat generated to spread out through the sample. The temperature profile of higher PRs showed more even drying than the lower PRs, making it more suitable for drying herbs. Thus, this study suggests that the periodic microwave drying at 12 W/g at the highest PR of 9 (60 on 60 off) was the most befitting drying process amongst the ones investigated. Simple semi-theoretical models such as simpler ones including Page, Modified Page, Midilli & Kucuk and Modified Midilli & others were deemed the best to describe the drying kinetics of rosemary.

Acknowledgements
The authors would like to acknowledge Taylor's University Lakeside for providing financial support under the research grants TRGS/MFS/1/2017/SOE/008

References
[1] Thamkaew G, Sjöholm I and Galindo F G 2020 Crit. Rev. Food Sci. Nutr. 1–24
[2] Ali A, Chua B L and Ashok G A 2018 J. Eng. Sci. Technol. 13
[3] Zambrano M V, Dutta B, Mercer D G, MacLean H L and Touchie M F 2019 Trends Food Sci. Technol. 88 484–96
[4] Jin W, Mujumdar A S, Zhang M and Shi W 2018 Food Eng. Rev. 10 34–45
[5] Aghilinategh N, Rafiee S, Gholikhani A, Hosseinpur S, Omid M, Mohtasebi S S and Maleki N 2015 Food, Sci. Nutr. 3 519–526
[6] Klemes J, Smith R and Kim J-K 2008 (Woodhead Publishing)
[7] Calín-Sánchez Á, Szumniy A, Figiel A, Jałoszyński K, Adamski M and Carbonell-Barrachina Á A 2011 J. Food Eng. 103 219–27
[8] Chua L Y W, Chua B L, Figiel A, Chong C H, Wojdylo A, Szumniy A and Choong T S Y 2019
Molecules 24 1397

[9] Esturk O 2012 Food Bioprocess Technol. 5 1664–1673

[10] Soysal Y, Arslan M and Keskin M 2009 Food Sci. Technol. Int. 15 397–406

[11] Ali A, Choo C O, Chua B L, Figiel A, Chong C H, Wojdylo A, Turkiewicz I P, Szumny A and Łyczko J 2020 Ind. Crops Prod. 151 112463

[12] Esturk O and Soysal Y 2010 Tarim Bilim. Derg. 16 26–36

[13] Kumar S K 2015 J. Food Process. Technol. 6 10–2

[14] Onwude D I, Hashim N, Janius R B, Nawi N M and Abdan K 2016 Compr. Rev. Food Sci. Food Saf. 15 599–618

[15] Hii C L, Law C L and Cloke M 2008 J. Eng. Sci. Technol. 3 1–10

[16] Szumny A, Figiel A, Gutiérrez-Ortíz A and Ángel A C-B 2010 J. Food Eng. 97 253–60

[17] Figiel A 2009 J. Food Eng. 94 98–104

[18] Ali A, Chua B L and Chow Y H 2019 TrAC - Trends Anal. Chem. 118

[19] Soysal Y, Öztekin S and Eren Ö 2006 Biosyst. Eng. 93 403–13

[20] Hosain Darvishi 2012 VI-Postharvest Technol. Process Eng. 14 1–14