Original Research Article

Kinetics of a thin-layer microwave-assisted infrared drying of lentil seeds

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Abstract
Herein, we report the drying kinetics behavior of tempered lentil seeds (CDC Maxim variety) by utilizing a microwave-assisted infrared thermal method and thereby presenting a successful mathematical model for it. The drying characteristics of lentils using thin-layer microwave drying with and without hot air predrying were evaluated in a laboratory scale microwave dryer. The drying experiments were carried out at 300 and 750 W, and the predrying experiment was performed at room temperature (23°C). Out of several thin-layer mathematical models evaluated with the experimental data, Page model has been found the most appropriate model to predict drying process of lentils with high value of coefficient of determination (0.995), low values of chi-square (0.0012), root mean square error (0.0343), and mean relative percentage error (4.9997). Further, the influence of bioyield force and changes in the particle density of processed seeds have also been evaluated in the present study. The results showed that combination of low infrared power (0.375 kW) to the different microwave power levels led to a significant reduction of drying time. The results also showed that processing of lentil seeds significantly reduces the bioyield force of raw seeds, providing less firmness to the product and thereby shortening the cooking time. The above findings can facilitate the design and operation of infrared-assisted microwave drying of other legumes.

KEYWORDS
Drying process, infrared, lentils, mathematical model, microwave

1 | INTRODUCTION

Legumes are the dicotyledon seeds of plants belonging to the Fabaceae (Leguminosae) family with more than 18,000 species in approximately 750 genera (Hoover, Hughes, Chung, & Liu, 2010). The annual production of pulses ranks fifth in the world after wheat, rice, maize, and barley (Shuang-kui, Hongxin, Xiuzhu, & Jay-lin, 2014). Among legumes, lentil (Lens culinaris) is one of the most consumed protein source because of its high nutritional quality. Lentil remains were found alongside human habitations dating to 13,000 years BC, making it the oldest pulse crop and possibly one of the earliest crops domesticated in the Old World (Shyam, McNeil, & Stevenson, 2007). Due to the excellent nitrogen-fixing capacity inherited in cereal-based systems, and being a relatively drought-enduring plant, lentil becomes an excellent choice to grow worldwide (Matina, Timilsena, & B. A., 2017). According to Food and Agriculture Organization of the United Nations statistics (2018), Canada is the major lentil producer, with 43% of the total world’s lentil production, followed by India and Turkey. Collectively, these countries contribute about 70% of the whole world’s lentil production.

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From a nutritional perspective, lentil is a pulse crop low in fat and rich in carbohydrates, proteins, dietary fiber, vitamins, and minerals, so it is an excellent choice component in a healthy diet (Wang, Hatcher, Toews, & Gawalko, 2009). Pulses, in general, have been found to reduce the risk of cardiovascular disease, cancer, diabetes, osteoporosis, hypertension, gastrointestinal disorders, adrenal disease, reduction of LDL cholesterol, and obesity (Ahmed, Mulla, Al-Ruwalh, & Arfat, 2019; Subhani, Shand, Pickardb, & Wanasundara, 2015). The high amounts of protein in lentil provide an excellent source of essential amino acids, decreasing concerns about food security and protein malnutrition in the world (Boye, Zare, & Pletch, 2010). The legume-derived protein components can also be added into new innovative food products due to their wide range of functionalities like substitutes for meat and baked products.

Although these nutritional benefits of pulses/legumes have been well-documented, however, their use is very low than recommended intake levels (Boye et al., 2010). The reasons for these small intake levels include the following: pulses have some anti-nutritional components such as trypsin inhibitors, phytic acid, tannins, and oligosaccharides that reduce their digestibility (Wang et al., 2009); the existence of beany flavors in legumes could reduce their acceptance by people (Walker & Kochhar, 2007), and pulses need lengthy preparation or cooking time (Wang et al., 2009). To address these issues and increase the consumption of pulses, pretreatment with heat has been recommended. The effect of thermal heating, such as microwave, roasting, hydrothermal (boiling), and micronization (infrared radiation), on the structure of lentil has been studied extensively by different researchers (Gonzalez, Segall, & Arntfield, 2005; Subhani et al., 2015). It has been reported that the presence of high moisture content in lentil seeds before thermal processing would play an essential role in determining the physicochemical properties of lentil (Ma et al., 2011; Subhani et al., 2015).

In the present study, the use of microwave thermal heating method in combination with the infrared process is the other novel thermal treatment, which can be used in the processing of legumes like red lentils. The combination of infrared with microwave would help in reducing the drying time of the lentils. Microwave thermal process leads to the accumulation of moisture at the food surface, so infrared heating can be added to remove the surface moisture of materials (Ozturk, Sakyany, & Ozlem Alifak, 2017). This method of dual processing will increase the porosity inside the seeds, resulting in the reduction of lentils cooking time by making lentils softer. The amount of this rise is highly dependent on thermal methods and its condition. For example, time of drying, temperature, and the amount of tempering moisture before drying play vital role for this aim in micronization thermal processing (Scanlon, Segall, & Cenkowski, 1999; Subhani et al., 2015; Zheng, Fasina, Sosulski, & Tyler, 1998). Researchers showed that superheated steam would be generated from the moisture of tempered lentil in high-temperature micronization (Arntfield et al., 2001; Cenkowski & Sosulski, 1997; Ilyasov & Krasnikov, 1991), and the porosity of lentils alters when this steam vents from weak spots, such as intercellular vertices (Mackenzie, 1950).

The lengthy cooking time of legumes like lentils is one of the reasons for their reduced acceptability among consumers. Therefore, the pretreatment of these nutritionally beneficial legumes with combination of microwave and infrared method can be used to address this issue. Hence, the present study was aimed to investigate the drying kinetics of tempered lentil seeds by using new microwave–infrared dual thermal processing technique and providing a mathematical model for the process. Further, to investigate the effect of this developed process on the reduction in cooking time of lentil, the particle density and bioyield force of processed seeds have been measured and were compared with raw lentil seeds.

## 2 | MATERIALS AND METHODS

### 2.1 | Lentil seeds

In the present research, the commercially available red lentil seeds (CDC Maxim variety) were procured from a local producer in Saskatchewan, Canada.

### 2.2 | Preparing seeds for thermal process

Thermal processing of seeds was performed and tempered to three higher levels of moisture contents (19%, 31.6%, and 47.1% dry basis). To increase the moisture content of the sample, predetermined amounts of deionized water was added to lentil seeds in sealed jars as per standard protocols.

To calculate the required amount of water, the following formula was used:

\[
W = \frac{L \times (\text{Moisture}_0 - \text{Moisture}_r)}{(100 - \text{Moisture}_0)},
\]

where W is the weight of water required (grams), L is the weight of lentil seeds (grams), Moisture\(_0\) is the moisture content required at tempering, and Moisture\(_r\) is the moisture content of seeds before tempering. The moisture content of lentil seeds before and after tempering will be determined using the method. The initial moisture content of lentil seed was found to be 8.5% dry basis (7.8% wet basis).

### 2.3 | Thermal process procedure

Advantium™ oven (GE Company, Louisville, USA) was used for infrared–microwave heating. The maximum powers of microwave and the upper halogen infrared lamps in this device are 0.70 and 0.75 kW, respectively. Two levels of microwave power, 0.35 and 0.7 kW, and three levels of infrared power 0, 0.375 and 0.75 kW were selected to
perform drying of tempered lentil seeds until they return to their initial moisture content. During this process, the loss in weight of samples were recorded at varied time intervals from 15 s to 1 min, and drying experiments were performed in triplicates.

2.4 | Thin-layer mathematical modeling

Four semiempirical thin-layer models as shown in Table 1 were selected to fit the data obtained by the drying process of lentil seeds. Moisture ratio in the models was calculated by the following equation:

\[
MR = \frac{M_i - M_e}{M_i^0 - M_e^0},
\]

where \(M_0\), \(M_i\), and \(M_e\) are moisture content at any time of drying (% d.b), initial moisture content (% d.b), and equilibrium moisture content (% d.b), respectively. To select the best model explaining the variation in drying experimental data, the coefficient of determination \(R^2\), reduced chi-square \(\chi^2\), root mean square error (RMSE), and the mean relative percentage error (MRPE) were used as performance indicators as presented in Table 2.

2.5 | Particle density

The true volume of lentil samples was determined using a gas pycnometer (Micrometrics AccuPyc 1340). Based on the weight of the sample, the true density was calculated.

2.6 | Mechanical properties

The mechanical properties of raw and tempered lentil seeds were measured by using Instron machine (Model Instron 3366, Massachusetts, USA) equipped with a 50-kN load cell and integrator. The seeds were compressed between the plates of the machine until the first fracture occurred. This point in the force-deformation curve is known as bioyield point. In this study, the seeds were placed horizontally between the plates, and tests were carried out at a loading rate of 10 mm min\(^{-1}\) for loading directions.

| TABLE 1 | Thin layer mathematical models |
|----------|--------------------------------|
| **Model name** | **Mathematical equation** |
| Newton (Mujumdar, 1987) | \(MR = \exp(-kt)\) |
| Page (Diamante & Munro, 1993) | \(MR = \exp(-kt^q)\) |
| Henderson and Pabis (Zhang & Litchfield, 1991) | \(MR = \alpha \exp(-kt)\) |
| Wang and Singh (Wang & Singh, 1978) | \(MR = 1+at+bt^2\) |

2.7 | Data analysis

The analysis of variance was performed using SPSS software and the general linear model, whereas the Tukey’s Multiple Mean Comparison tests were carried out to determine the differences between various treatments.

3 | RESULTS AND DISCUSSION

3.1 | Drying behavior and evaluation of thin-layer drying models

The variations in the moisture content with drying time for different tempered lentil seeds at different microwave powers and infrared power have been presented in Figures 1 and 2. The final moisture contents of dried samples was observed in this study, and it was found that the time of drying for lentils is lowest when low microwave power (0.35 kW) combined with no infrared power and the highest time was recorded for the process where high microwave and infrared power was used (0.7 and 0.75 kW). The mean comparison of the time of drying under different condition also reveals that the microwave power from 0.35 to 0.7 kW will significantly reduce the drying time, and combining low infrared power of 0.375 kW to the different microwave power levels will result in the reduction of drying time, especially when low microwave power is using. However, adding higher infrared power to the process does not change the drying time noticeably compared with the process using low microwave power. This can be attributed to the different mechanisms of mass transfer in the microwave and infrared drying protocols. Microwave leads to transferring water from inside layers of seeds to outside layers, and the optimum infrared energy is needed to evaporate the available water from the outside layers. Hence, it seems that the low infrared power provides enough energy for the vaporization of transferred water in the outer layers, and the rise in infrared power can just increase the temperature of these layers of lentils.

Thereafter, the drying data obtained for the different tempered lentil seeds were fitted to the different drying models, and the performance indicators of these models have been given in Table 3.
was found that the coefficient of determination ($R^2$), reduced chi-square ($\chi^2$), root RMSE, and MRPE of these models have the ranges from 0.911 to 0.995, 0.0012 to 0.0061, 0.0343 to 0.0775, and 4.9997 to 12.9737, respectively. Out of all the studied models, Page model has the highest value of $R^2$ and the lowest values of $\chi^2$, RMSE, and MRPE, which makes this model as the most appropriate model to describe microwave–infrared drying process of tempered lentil seeds.

The constant values in the models have been derived by equations using the microwave power, infrared power, and initial moisture content of samples before drying as input variables. According to that, the Page model can be demonstrated as following:

\[
\text{Page Model: } MR = \exp(-kt^n),
\]

\[
k = 0.901\times\ln(MWP) + 0.682\times\text{IRP} + 0.538\times\ln(IMC) + 1,
\]

\[
n = -0.457\times\ln(MWP) + 0.275\times\text{IRP} + 0.047\times\ln(IMC) - 0.961,
\]

where MWP, IRP, and IMC are microwave power (kW), infrared power (kW), and initial moisture content before drying (% d.b), respectively.

### 3.2 | Thermal treatment and changes in particle density

The changes in the particle density of lentil seeds before and after tempering and drying processes have been shown in Figure 3. It is clearly seen from the figure that there is a significant reduction in particle density values of the raw lentil seeds when their moisture contents increase ranging from 1.441 (gr/cm³) for the grain with 8.5 (% d.b) moisture content to 1.368 (gr/cm³) for the grain with 47.1 (% d.b) moisture content. This reduction in particle density with increase in moisture content indicated that the rise in mass due to the gaining water to increase the moisture of grain is lower than the accompanying volumetric expansion of the seed. The reported results are in congruence with the observations of other researchers (Bhattacharya, Hampapura, & Suvendu, 2005; Gharibzahedi, Ghasemlou, Razavi, Jafarii, & Faraji, 2011; Irvine, Jayas, White, & Brixton, 1992; Maneesh Kumar, Sarat Chandra, & Debnath, 2018).

Furthermore, it is significant if the reduction in particle density of lentil, which is created by increasing its moisture content, can be maintained during thermal processing. Therefore, the porosity will be made inside the grain by removing the moisture. Because the moisture diffusivity in the air space is considerably higher than in solids,
the seeds with higher porosity will have higher water uptake rate leading to reduction of cooking time. Scanlon et al. (2005) also evaluated the effects of micronization thermal treatment on the water uptake rate and rewetting coefficient of lentil and showed that micronization would increase such properties. They also reported a significant rise in moisture uptake rate for micronized lentils tempered to 17% moisture content from 13% initial moisture content, whereas for the higher tempered micronized lentils (25 to 45% moisture content), the rise was incremental and steady.

The particle densities of thermally processed lentil seeds have also been shown in Figure 3. The results clearly reveal that the reduction in particle densities of the processed grains are mainly dependent on the moisture contents prior to different thermal treatments, in a way that the drop in the particle densities of dried samples was just observed for those tempered to 19 and 31.6 (% d.b) moisture content. The different powers of microwave and also the addition of different powers of infrared did not show any significant effect in this reduction.

However, the particle densities of dried lentil seeds tempered to the highest moisture content 47.1 (% d.b) and under different thermal treatments were not statistically different from the raw lentil seeds. This trend is not compatible with our expectation of reducing this property with drying treatment. This can be due to the fact that such behavior can be found by looking at the final shape of these processed seeds as presented in Figure 4. As shown in Figure 4, it is clear that the rupture of seed coat and puffing of seeds occurred for the dried lentil grains tempered to 47.1% d.b (Figure 4d) and with lesser intensity for those tempered to 31.6% (Figure 4c) as compared with raw untreated lentils (Figure 4a). However, the seeds tempered to 18% d.b were not puffed as presented in Figure 4b. The studies show that when samples were placed in the pycnometer device, its helium gas can penetrate inside the seed between the grain’s cotyledons, which

FIGURE 2  Variation of moisture ratio against drying time at 0.7 kW microwave powers and different infrared powers for lentil seeds tempered to various moisture contents (a) tempered to 19%; (b) tempered to 31.6%, (c) tempered to 47.1%

TABLE 3  Results of performance indicators of different thin-layer drying models of tempered lentil seeds

| Model            | R²   | χ²   | RMSE | MRPE |
|------------------|------|------|------|------|
| Newton           | 0.911| 0.0061| 0.0775| 12.9737 |
| Page             | 0.995| 0.0012| 0.0343| 4.9997 |
| Henderson and Pabis | 0.94 | 0.0042| 0.0638| 10.4772|
| Wang and Singh   | 0.969| 0.0022| 0.0461| 6.8777 |
results in measuring the lower total volume of seeds and presents higher density volume. It must be considered that even this phenomenon happened, especially for seeds tempered to the highest moisture content, their particle density did not exceed than the raw samples.

3.3 | Thermal treatment and changes in bio-yield point

To obtain a general idea of the compression curve shapes of samples, force-deformation curves for raw lentil seed and dried seeds tempered to various moisture contents under the thermal processing condition of 0.35 and 0.375 kW of microwave and infrared powers were presented in Figure 5. The first fracture point was considered as bio-yield point presenting the crack creation in the seed. The multiple fractures followed by this point also shows the expansion of cracks inside the grain. Bhattacharya et al. (2005) also found a similar trend in the compression curve of raw and dehulled lentil seed.

The quantities of forces associated with the bioyield point for dried grains are appropriate values to compare the amount of seeds softness. The samples with lower bioyield forces are less firm; hence, they will be cooked faster. The multiple mean comparisons of these values for raw and processed lentil seeds has been demonstrated in Figure 6. It is clear that doing thermal processing will significantly reduce the bioyield force of raw lentil seeds. In addition, the results revealed that the amount of moisture content before drying is the key determining factor to this reduction, in a way that in the same condition of grains thermal processing, those tempered to higher moisture contents represented lower bioyield points.

It is also expected that by increasing the power of the microwave, a lower bioyield force will be achieved, due to the rise in the rate of drying and water movement in the seed, although the
results showed that increasing microwave power from 0.35 to 0.7 kW slightly reduces the bioyield points just for those samples tempered to 19% and 31.6% d.b. Combing infrared method to microwave thermal process is also an effective way of decreasing bioyield force just for those tempered to 19% and 36.1% d.b. However, for these samples, adding higher infrared power 0.75 kW to microwave method did not meaningfully change the bioyield points compared with the similar treatments with low infrared power. The bioyield force of lentil seeds for this treatment (tempered to 31.6% d.b and drying under low power of microwave and infrared condition) had the value of 9 (N), which is in the smallest mean group. Besides this treatment, thermal processing of those samples tempered to 47.1% d.b leads to the bioyield force in the lowest mean group, and various thermal condition did not significantly affect the values.

4 | CONCLUSIONS

The analysis of drying time of lentils reveals that increasing the microwave power from 0.35 to 0.7 kW will significantly reduce the drying time. Combining low infrared power of 0.375 kW to the different microwave power levels results in the reduction of drying time, especially when low microwave power is used. However, adding higher infrared power in various thermal processes did not noticeably change the drying time compared with the conditions using lower infrared power. Among different thin layer models, Page model has been found the most significant model to describe...
drying process of lentil in this study by having the high value of the coefficient of determination and low amounts of reduced chi-square, RMSE, and MRPE. Thermal process of lentil seeds tempered to 19% and 32% (d.b) decreases the particle density of lentil grains compared with raw lentil seeds, proving the expansion happened in the seeds, which leads to the reduction of cooking time. The rupturing of seed coat and puffing of seeds was observed for the thermal process of lentil grains tempered to 47% (d.b) and with lesser intensity for those tempered to 31.6% (d.b), affecting particle densities measurement. Hence, the use of particle density property is not enough to evaluate the effect of thermal processing on cooking time. Thermal processing of lentil seeds with microwave-infrared combination significantly decreases the byproduct force of raw seeds, providing the less firmness to the product, and hence, they need shorter cooking time.

DATA AVAILABILITY STATEMENT
The data that support the findings of this study can be made available by the corresponding author upon reasonable request.

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CONFLICT OF INTEREST
Authors confirm that there is no conflict of interest in the work.

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