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The Effect of Drying Variables on the Microwave–Vacuum-Drying Characteristics of Mulberries (*Morus alba* L.): Experiments and Multivariate Models

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Abstract: It is easy to cause increases in temperature and the gasification of water in materials, facilitated via supercharging and the generation of instantaneous strong pressure under the collaborative action of a microwave and a vacuum, thus facilitating the internal cell swelling of materials, changes in fibre structures, and the formation of loose and uniform microstructures. In this experiment, mulberries were dehydrated using microwave–vacuum drying technology. The drying characteristics were disclosed by using crispness as the evaluation index and multiple drying parameters (e.g., products' surface temperature, microwave power, chamber vacuum level and drying height) as the control variables. The optimised Two-term model can predict the dehydration process of mulberries under multiple drying variables, as determined through the experimental data. The optimal drying variables were determined according to the crispness of the dried mulberries. The optimal puffing quality of mulberries could be gained under a product surface temperature = 50 °C, microwave power = 5.45 W/g, a chamber vacuum level = 0.08 MPa and a drying height = 0 cm. The diffusion coefficient of the available water of the mulberries during the microwave–vacuum drying process ranges from 4.98×10^{-8} to 3.81×10^{-7}, and the activation energy for drying is 183.923 KJ/mol.

Keywords: mulberry; microwave–vacuum; mathematical model; water diffusion coefficient; activation energy

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1. Introduction

Mulberry (*Morus alba* L.) is rich in multiple nutrients, including vitamins, minerals, amino acids, polysaccharides and polyphenols. It is a kind of traditional Chinese food and drug that nourishes yin and skin, replenishes blood, promotes the secretion of saliva and relaxes the bowels [1]. Typically, mulberry is mature between April and June, with a water content of about 80%. Due to the concentrated mature period, great difficulties in harvest, and the thin pericarp and soft fruit of mulberries, it has poor storage performances. To decrease the loss risks during the post-harvest storage and processing of mulberries, drying technology has become an essential processing link to prolong the shelf life of mulberries. Common drying methods include spray-drying, hot air drying and fluid bed drying. All of these drying methods are based on heat transmission from the surface of the drying materials to the internal structures, but none of them are applicable for drying mulberries. Moreover, they quickly lead to the mulberry pericarps' hardening and burning, thus making it difficult to eliminate internal steam and extend the drying time, which ultimately results in an increase in energy consumption [2]. Microwave–vacuum-drying refers to the drying process of materials using a microwave under vacuum conditions. This technique can decrease the oxidising reaction of materials and achieve quick low-temperature drying from the inside to the outside. The temperature at which mulberries are dried must be kept below 60 °C because anthocyanin becomes inactive and loses its colour at temperatures above 60 °C [3].

The drying process is not only beneficial for the storage of food but it can also improve its taste quality and commercial value. In recent years, fruit and vegetable chips have become increasingly popular as snacks. Non-fried puffing avoids the production of harmful substances, such as oil residue and allylphthalamine, which is in line with the diet concepts of low oil, low calorie and healthy nutrition that are advocated for in today's society. Microwave bulking technology combines the processes of bulking, drying and sterilisation simultaneously. Its mechanism involves the conversion of microwave energy into heat energy within the material's deep layers. This leads to the rapid evaporation of moisture, resulting in increased steam pressure inside the material and causing it to expand. Dai, J et al. [4] found that the optimal drying parameters for microwave–vacuum-puffed banana chips were a drying temperature of 60 °C, a microwave power density of 28 W/g, a vacuum degree of 90 kPa and a slice thickness of 6 mm. Under these conditions, the banana chips achieved the best crispness. Monteiro [5] conducted a study on the impact of various drying methods on the microstructure and properties of banana slices. The findings indicated that microwave drying yielded superior crispness in the banana slices. Sun Jingru [6] found that oyster mushrooms that had been pre-treated with cellulase after microwave–vacuum-drying have outstanding quality, no curled edges, enhanced flavour and improved crispness. In a study of mushroom crisps, Qi Linlin et al. [7] demonstrated that consumers prefer products with a high crispness. The microwave puffing of fruit and vegetable crisps results in a product with desirable attributes, such as crunchiness, deliciousness and an authentic flavour. The crispness of these products is a crucial factor that significantly impacts their overall taste. It suggests a discussion of control parameters and the drying process of the microwave–vacuum-drying of mulberries, using crispness as a characteristic. Notably, the control parameters of microwave–vacuum-drying also influence the quality of other materials. Ekow, A.E et al. [8] explored the influences of microwave–vacuum-drying on the drying dynamic model and the quality of dried tomatoes. They found that the ascorbic acid retention rate of dried tomatoes was the highest when the microwave power was 200 W and the vacuum degree was 0.06 MPa. The maximum lycopene content (25.44 mg/100 g) in the dried tomatoes was achieved when the microwave power was 700 W and the vacuum degree was 0.04 MPa. Moreover, the Midilli model presented the highest degree of fitting among the 13 thin-layered drying models. Manish Dak et al. [9] discovered that microwave power, vacuum pressure and sample quality can significantly influence the quality properties and drying efficiency of dried *Punica granatum* L. During the drying process, a relatively low vacuum pressure can result in a higher-quality product. More studies on mulberry drying have been conducted in recent years, and the majority of these studies concentrate on the optimisation analysis of nutritional quality parameters. However, none of them concerned the crispness changes in the dried mulberries. During the ultrasonic-assisted extraction of anthocyanin in mulberry pulp, Lukić et al. [10] determined that the optimal temperature for relatively high anthocyanin activity was 20–60 °C. Hence, mulberry drying has piqued the interest of many scholars in recent years.

Although some scholars have proposed many thin-layered drying models, the microwave–vacuum-drying prediction model, which is truly applicable to mulberries, has to be further studied. Puttalingappa, Y.J. [11] improved the anti-oxidation resistance and drying rate of leaves of Moringa oleifera using the microwave–vacuum drying mode. The activation of the leaves of Moringa oleifera can increase as the microwave power is increased. By fitting between the moisture content (MC) of the experiment and the common thin-layered drying models, the fitting effect of the Midilli model better describes the drying process of Moringa oleifera, showing the highest R2 value. Kiranoudis et al. [12] studied the kinematic model for the microwave–vacuum-drying of fruits. McMinn [13] studied thin-layered models of lactose powder convection, microwave, microwave convection and microwave–vacuum-drying. Giri and Prasad [14] used the microwave power, vacuum degree and drying thickness as the test factors when exploring the drying characteristics of mushrooms, and the whole drying time was shortened by 70–90% compared with the convective drying time. Moreover, the rehydration performance was better. They also constructed a Page drying model of thin mushroom sheets and a mathematical model of the rehydration rate.

In this study, the microwave–vacuum-drying process was used to analyse the effects of the product surface temperature, microwave power, chamber vacuum level and drying height on the drying characteristics and crispness of mulberries. The models of Henderson and Pabis, Lewis, Page, Two-term, Logarithmic, Two-term exponential, and the Weibull distribution 7 empirical equations were employed for the drying process. Then, to assess the mulberries' water loss, we determined the best prediction model. A heat and humidity transfer model under various drying parameters was established to investigate the water migration rule of the mulberries during drying. Experimental tests were conducted to validate the water loss process of the mulberries under different drying conditions. The drying process parameters with the best crispness retention were determined to obtain high-quality dried mulberries in the shortest time. This study is helpful in understanding the drying process of berry fruits and in providing references for improving the drying quality of fruits.

2. Methods

2.1. Materials and Methods

The therapeutic mulberry cultivar is purple-black and is harvested in Alar, Xinjiang. The container for harvested mulberries should be neither too large nor too deep to avoid the accumulation and extrusion of the mulberries. After the harvest of mulberries, any fruit that is mouldy, deformed or diseased is promptly removed. The remaining mulberries are then placed in a foam box with an ice pack and transported to the laboratory without delay. Through the use of a vernier calliper (Shanghai Shenhan Measuring Tools Co., Ltd. Products, Shanghai, China) and an electronic name (model: FA1104; Shanghai Anting Electronic Instrument Factory, Shanghai, China), the test object was measured and determined to be an individual complete with the dimensions of a longitudinal diameter of 33 ± 0.5 mm, a transverse diameter of 16.5 ± 0.5 mm and a single fruit weight of 3 ± 0.5 g per fresh mulberry. To prevent damage to the mulberries' extrusion and improve the storage time of the mulberries, the samples were placed in a single layer on a tray covered with spunlaced nonwoven fabric and refrigerated in a freezer at 4 ± 1 °C. Prior to testing, the mulberry samples were allowed to equilibrate at room temperature for a duration of 2 h in order to achieve a similar temperature to that of the surrounding environment. The microwave–vacuum drying oven used in the test (model: HTWB-01; Nanjing Huateng Machinery Technology Co., Ltd., Nanjing, China) is equipped with a temperature control module and temperature sensor to continuously monitor the surface temperature of the material. This ensured that the material remained at a predetermined temperature, preventing excessive heating during the drying process.

The product surface temperature (40, 45, 50 and 50 °C), chamber vacuum level (0.02, 0.04, 0.06 and 0.08 MPa), microwave power (1.82, 2.73, 3.64, 4.55 and 5.45 W/g) and drying position (0, 4 and 8 cm) were used as study variables. The specific test process is shown in Figure 1: (1) Before drying, 110 ± 3 g of the mulberry samples were spread evenly on the entire tray (tray size: 137 mm × 158 mm, mulberry thickness: 10 mm). (2) The tray was placed in the microwave–vacuum oven, and the mulberry samples were dried using the predetermined drying parameters and time interval. (3) The mulberry samples were promptly extracted and their water content was measured. (4) The mulberry samples were dried to a moisture content of 5% (wet basis) and subsequently analysed using a texture analyser (model: TMS-Pro; the embrittlement of mulberry samples was carried out by Beijing Yingsheng Hengtai Technology Co., Ltd., Beijing, China, and the sensory evaluation of the samples was carried out by the evaluation team). The analysis samples were averaged using three parallel tests. Using the oven method, the initial moisture content of the mulberry samples was determined to be 79.7% ± 0.5% [15].

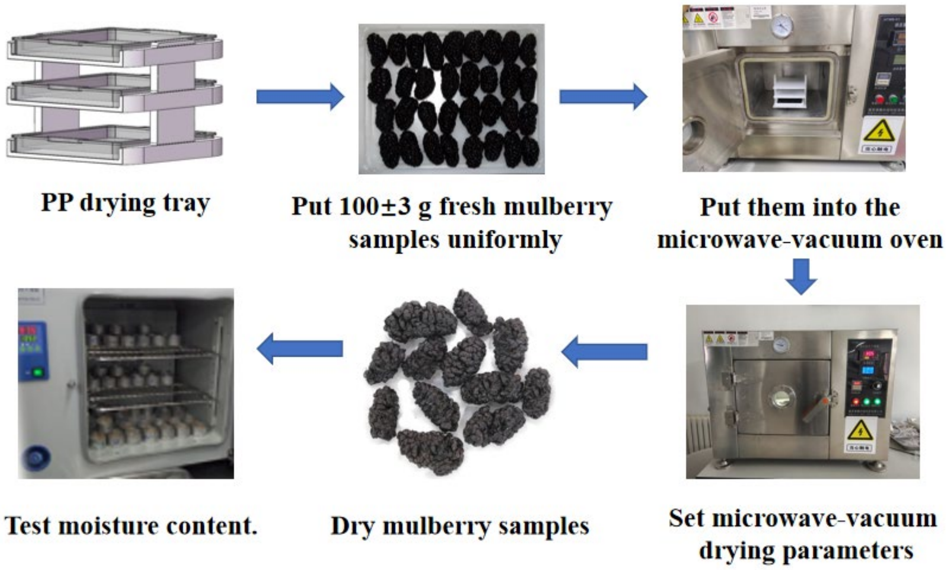


Figure 1. Flow chart of microwave–vacuum drying test for mulberries. (1) PP material drying tray; (2) 100 ± 3 g fresh mulberries are placed evenly (3) in the microwave vacuum drying oven; (4) parameters of the microwave vacuum drying are set; (5) mulberries are dried; and (6) the moisture content is determined.

2.2. Test and Calculation of Parameters

2.2.1. Determination of Moisture Content

The moisture content of the mulberry samples was tested using the direct drying method, with references to the national standard Wang, J. et al.'s test methods [15] were consistent (GB-5009.3-2016). The samples were dried in an oven at 105 °C and weighed every 1 h until they reached a constant weight (mass difference before and after drying <2 mg). The equations for calculating the moisture content (MC) are Equations (1) and (2):

$$MC_{wb} = \frac{m_t - m_d}{m_t} \times 100\% \quad (1)$$

$$MC_{db} = \frac{m_t - m_d}{m_d} \times 100\% \quad (2)$$

where

MC_{wb}—wet-based moisture content of the mulberries, %;
MC_{db}—dry-based moisture content of the mulberries, %;
m_t—total mass of the mulberries, g, and m_d—the dry material mass of the mulberries, g.

2.2.2. Calculation of Moisture Ratio

The calculation formula of the moisture ratio (MR) of the mulberry sample in the process of microwave–vacuum-drying is [16] as follows:

$$MR = \frac{M_t - M_e}{M_o - M_e} \quad (3)$$

where

MR—moisture ratio of the mulberries;
M_t—dry-based mulberry moisture content at t, %;
M_o—wet-based mulberry moisture content at t, %;

M_e—balanced dry-based moisture content of the mulberries, %.

Since the balanced moisture content of the dried mulberries is considerably less than and, the above equation can be simplified as follows [17]:

$$MR = \frac{M_t}{M_o} \tag{4}$$

2.2.3. Calculation of Drying Rate

The formula for calculating the drying rate (DR) of the mulberry samples under different drying conditions is [18] as follows:

$$DR = \frac{M_{t1} - M_{t2}}{t_2 - t_1} \tag{5}$$

where

DR—drying rate of mulberries;
M_{t1}—dry-based moisture content of mulberries at t_1, g/g;
M_{t2}—dry-based moisture content of mulberries at t_2, g/g.

2.2.4. Crispness

The crispness was tested by using the FTC TL-Pro texture analyser [19] (model: TMS-Pro, manufacturer: Beijing Yingsheng Hengtai Technology Co., Ltd., Beijing, China), with probe number 432-009. The measurement conditions were introduced as follows: pre-test speed = 2.0 mm/s, test speed = 1.0 mm/s, post-test speed = 2.0 mm/s, compression degree = 50% and the interval between the two compressions = 5 s. The sample centre was selected for determination, and 5 repeated experiments were conducted to take the average value (the number of mulberries was single, and a new sample was replaced before each test for brittleness detection). The difference in brittleness between the products was reflected by the initial modulus (the ratio of the hardness of the first cycle in the texture analyser TPA mode to the average peak value), and the texture index that was measured in this test was the brittleness.

2.2.5. Sensory Evaluation

In this study, the sensory evaluation of the dried mulberries was conducted using an evaluation group scoring system, which was slightly adjusted based on the national standard [20]. Ten (20–40 years old) personnel, including five males and five females, with experience in the research and development of crisp foods, were selected. The quality of the dried mulberries was described based on their appearance, sweetness, crispness, smokiness (fine particles produced in the chewing process [21]) and the 4 evaluation indexes, respectively. The full score was 5, while the total score was 20. The evaluation criteria are shown in Table 1, while the score value represents the average score of the evaluation team composed of 10 people.

Table 1. Sensory evaluation criteria for dried mulberries.

Indicator	Score	Quality Description and Scoring Criteria
Appearance (5 points)	>2.5~5	Uniform colour, purplish black, the overall appearance is compact and complete
	0~2.5	Uneven colour, yellow brown, the overall appearance is not compact
Sweetness (5 points)	>2.5~5	The characteristic sweetness of mulberries is intense
	0~2.5	It basically has the special sweet taste of mulberries
Crispness (5 points)	>2.5~5	It has a good crispness
	0~2.5	Less crispy
Smoky (5 points)	>2.5~5	No smoke sensation, respiratory tract irritation during chewing
	0~2.5	Smoke sensation, respiratory irritation when chewing

2.2.6. Analysis of Data

The degree of fitting between the predicted values of mathematical models and test values can be evaluated using the determination coefficient (R^2), chi-square (χ^2) and root mean square (RMSE) [22,23]. The calculation formulas are determined as follows:

$$R^2 = 1 - \frac{\sum_{i=1}^{N}\left(M_{rexp,i} - M_{rpre,i}\right)^2}{\sum_{i=1}^{N}\left(\overline{M_{rexp,i}} - M_{rpre,i}\right)^2} \tag{6}$$

$$\chi^2 = \frac{\sum_{i=1}^{N}\left(M_{rexp,i} - M_{rpre,i}\right)^2}{N - z} \tag{7}$$

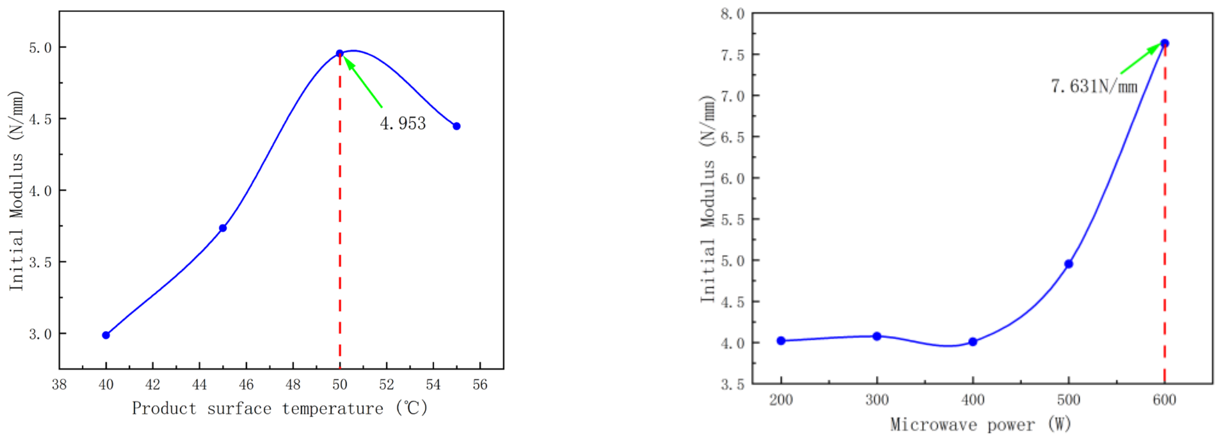
$$RMSE = \sqrt{\frac{\sum_{i=1}^{N}\left(M_{rexp,i} - M_{rpre,i}\right)^2}{N}} \tag{8}$$

In the formula, M_{rpre}, i is the predicted water ratio for the i-th experiment, M_{rexp}, i is the water ratio for the i-th experiment and N is the number of experiments. When the chi-square and root mean square are smaller and the coefficient of determination is larger, the model-fitting effect is better.

3. Results and Discussion

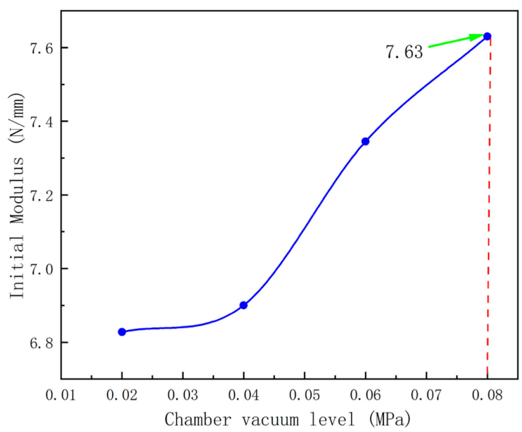
3.1. Effects of Product Surface Temperature on Crispness

The effects of the product surface temperature on the drying rate and crispness of the mulberries during microwave–vacuum-drying when the chamber vacuum level is 0.08 MPa, the microwave power is 4.55 W/g and the drying position is at the lower layer are shown in Figure 2a,e.



(**a**) (**b**)

Figure 2. *Cont.*



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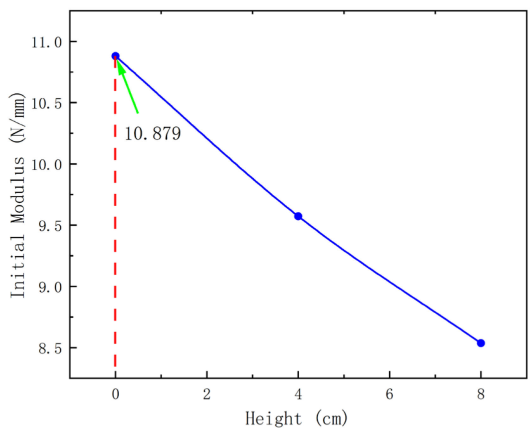

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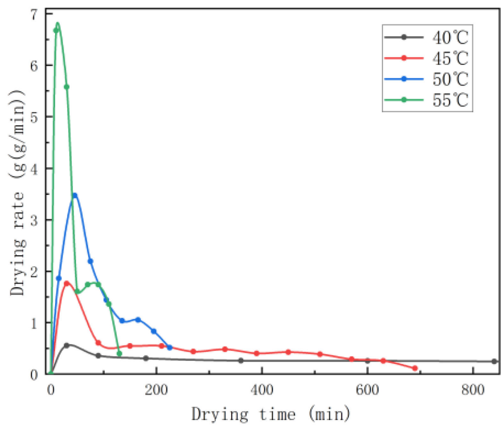

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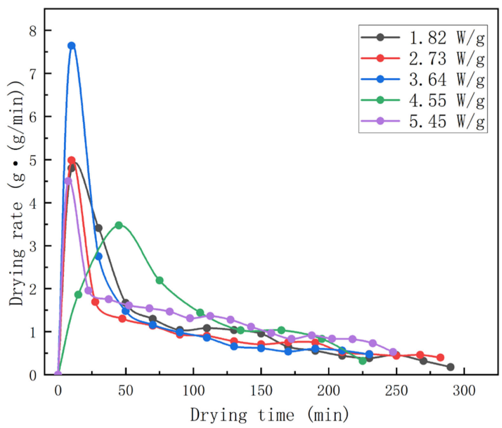

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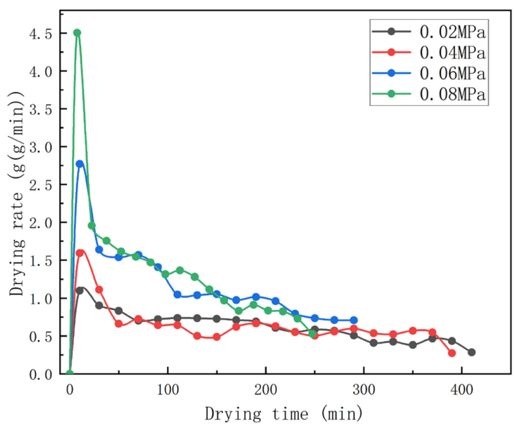
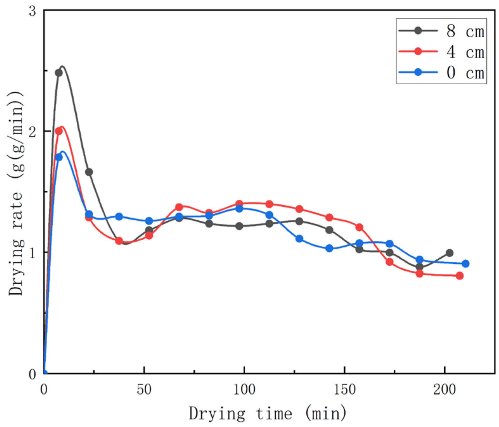


(**g**)



(**h**)

Figure 2. (**a**) The effect of product surface temperature on the brittleness of mulberry crisps; (**b**) the effect of microwave power on the brittleness of mulberry crisps; (**c**) the effect of chamber vacuum level on the brittleness of mulberry crisps; (**d**) the effect of drying position on the brittleness of mulberry crisps; (**e**) the effect of product surface temperature on the drying rate of mulberries; (**f**) the effect of microwave power on the drying rate of mulberries; (**g**) the effect of chamber vacuum level on the drying rate of mulberries; (**h**) the effect of drying position on the moisture content of mulberries.

The texture quality of food is a sensory manifestation of the substrate and structural properties of the food. The crispness of dried mulberries directly affects the taste of the food and is also a determining factor in the quality of the crisp products [24]. Crispness reflects the stress that induces sample breaking. In this experiment, several extrusion processes were carried out on the products, and the degrees of extrusion were 50% and 30%, respectively. To imitate chewing actions, the system retreated in compression displacement by 10 mm after each compression. Figure 2a shows that the crispness of the puffing-dried mulberries increased first and then decreased as the product surface temperature increased. The crispness of the dried mulberries reached 4.953 N/mm at 50 °C. At this moment, the dried mulberries achieved the best taste. The crispness of the mulberries decreased significantly when the product surface temperature was higher than 50 °C. Based on this, it can be inferred that a high temperature has a significant impact on the internal structures of mulberries. This might be because the water in mulberries evaporates more quickly upon temperature rises within 40~50 °C. The internal tissues of mulberries swell quickly due to high vapour pressure [25]. As a result, loose and porous honeycomb structures are formed in dried mulberries, thus increasing their crispness. Suwanchote [26] discovered that microwave–vacuum-dried durian had a similar structure to commercially fried durian slices in his research on durian drying. This is related to the extrusion effect in a vacuum environment. When the drying temperature is set to 55 °C, the hardness of dried mulberries increases due to the excessive temperature, and the crispness decreases accordingly. Under the above conditions, 50 °C is the optimal temperature to retain the crispness of mulberries.

Figure 2e shows that the drying process of mulberries with rises in temperature consists of three stages, including the fast-ascending stage, the fast-descending stage and the balance stage. This can be explained as follows: The acceleration stage is very short, and is the pre-heating stage of the mulberries. The temperature inside the dry cavity increases quickly from 0 °C to the preset temperature under the action of the machine's power. In the pre-heating stage, the free water inside the mulberries is removed gradually. After the temperature-monitoring probe inside the cavity detects that the material surface has reached the preset temperature, the power decreases to 0 W/g. The drying rate curve forms a quick decreasing trend with the reduction in microwave power. Most drying processes of mulberries occur in the constant-speed stage when there is no temperature difference within and outside of the materials. Moreover, the drying rate at this stage is apparently influenced by the product's surface temperature. The drying rate increased with the increase in microwave temperature. Given the same other control parameters, the drying time generally decreases with an increase in temperature, while the pre-heating time and drying time are shortened gradually. This conforms to the variation laws of traditional drying rate curves [27]. The fast-drying stage is extremely short, and most drying processes occur in the constant-speed stage, in which the drying rate is apparently influenced by the drying temperature. The drying rate increases with the increase in the drying temperature and the drying time under 40 °C is 10 times that under 55 °C. With an increase in temperature, the time to dry mulberries to the safe moisture content shortens gradually. Therefore, microwave temperature significantly influences dehydration during the drying process. The drying time is greatly prolonged when the microwave temperature is lower than 50 °C. Therefore, the moisture content of mulberries decreases quickly when the microwave temperature is higher than 50 °C. The overall drying rate under the conditions of a shorter drying time is at a higher level. The variation trends in drying rates under different drying conditions are basically consistent. However, excessive temperatures may influence the crispness of mulberries. Specifically, the flavour of dried mulberries is optimal at 50 °C. Thus, 50 °C is chosen as the ideal microwave temperature.

This section may be divided into subheadings. It should provide a concise and precise description of the experimental results, their interpretation, as well as the experimental conclusions that can be drawn.

3.2. Effects of Microwave Power on the Crispness of Mulberries

The effects of microwave power on the drying rate and crispness of mulberries during microwave–vacuum-drying when the product surface temperature is 50 °C, the chamber vacuum level is 0.08 MPa and the drying position is at the lower layer are shown in Figure 2b,f.

In Figure 2b, the crispness of the puffed mulberries presents a rising trend with the increase in microwave power. When the microwave power increases from 1.82 W/g to 5.45 W/g, the crispness changes from 4.02 N/mm to 7.63 N/mm. When the microwave power is 600 W, the crispness of dried mulberries is 7.63 N/mm and the best quality of the dried mulberries is achieved. This might be because with the increase in microwave power, the microwave energy absorbed by the unit mass of the mulberries increases, producing greater steam pressure in the mulberries and expanding the pores inside the mulberries. Hence, the crispness of the dried mulberries increases. Duan Liuliu [28] analysed water migration changes under different microwave power density conditions. The study found that the free water removal rate was positively related to microwave power, and the time consumption under high microwave power was short. These findings were verified mutually with the analysis results. To sum up, microwave power during drying significantly influences the crispness of mulberries.

In Figure 2f, the rising section of the drying rate curve of the mulberries becomes increasingly steeper as the microwave power increases from 1.82 W/g to 3.64 W/g, and the drying rate increases from 4.8 g (g/min) to 7.64 g (g/min). In the pre-heating stage, when microwave power increases from 4.55 W/g to 5.45 W/g, the drying rate changes insignificantly. This can be explained as follows: Except for the temperature control of the drying device, both the internal and external structures of the materials are heated via microwave drying, and the capacity for materials to absorb the microwave energy is determined by their dielectric properties. In the pre-heating stage of mulberries, the capacity of the removed free water to absorb the microwave energy is generally the same. Hence, the quick ascending stage of the drying rate curve is usually the same. In the constant-speed drying stage, the higher microwave energy brings a higher drying rate, more energy transformed by the materials in unit time and a shorter drying time. The drying process is generally divided into the acceleration stage, deceleration stage and constant-speed stage. When the microwave intensity is relatively low, the drying process is mainly controlled in the acceleration stage and the constant-speed stage. When the microwave strength is relatively high, the drying process is mainly controlled in the deceleration stage [29]. In theory, there is more energy that can be transformed by materials in unit time if the microwave power is higher [30–33], thus enabling the realisation of drying in a shorter period. However, the microwave power in the microwave–vacuum-drying device used in this study is only related to the time it takes for the material surface temperature to reach the preset value. The crispness of dried mulberries is highest when the microwave power is 5.45 W/g.

3.3. Effects of Chamber Vacuum Level on the Crispness of Mulberries

The effects of the chamber vacuum level on the drying rate and crispness of mulberries during microwave–vacuum-drying when the product surface temperature is 50 °C, the microwave power is 5.45 W/g and the drying position is at the lower layer are shown in Figure 2c,g.

In Figure 2c, the crispness of the mulberries increases from 6.82 N/mm to 7.63 N/mm in the microwave–vacuum-drying process as the chamber vacuum level decreases from 0.02 MPa to 0.08 MPa. The absolute value of the chamber vacuum level means that the current environmental air pressure is lower than the ordinary pressure, and the higher absolute value of the chamber vacuum level indicates a greater gap between the environmental air pressure and ordinary pressure. The chamber vacuum level is negative, and the smaller chamber vacuum level indicates a higher degree of vacuum. With the reduction in the chamber vacuum level, the absolute value of the chamber vacuum level increases and the air pressure in the closed cavity declines, accompanied by a reduction in the saturated vapour pressure of the water. Given the same heating conditions, it is easier to remove the water from materials. The microwave–vacuum-drying of camellia seeds also presents similar laws [31]. According to the observation of the dried mulberries under different chamber vacuum levels, the crispness of dried mulberries is poorer given the lower chamber vacuum level. Therefore, it is suggested to increase the chamber vacuum level in the drying process to acquire high-quality dried mulberries. The crispness of dried mulberries is optimal when the chamber vacuum level is 0.08 MPa.

In Figure 2g, the drying rate of the microwave–vacuum-drying of mulberries increases to different extents with the increase in the chamber vacuum level in the drying cavity. When the chamber vacuum level decreases from 0.02 MPa to 0.08 MPa, the time to dry 25% dry-based moisture content decreases from 407 min to 245 min. Additionally, the drying rate increases relatively quickly by increasing the chamber vacuum level when the chamber vacuum level is relatively low. In the constant-speed stage of drying, the influence of changes in the chamber vacuum level after 0.06 MPa on the drying rate decreases notably. This might be because when the chamber vacuum level increases to a fixed value, the vaporisation of water and the evaporating temperature are negatively related to the chamber vacuum level. Since the latent heat of vaporisation increases with the increase in the chamber vacuum level, there are mild changes in the heat energy consumed for the evaporation of the water [32]. Hence, the further increase in the chamber vacuum level has an insignificant influence on the drying rate. During drying, the highest drying rate and the best crispness of mulberries are achieved when the chamber vacuum level is 0.08 MPa.

3.4. Effects of Drying Height on the Crispness of Mulberries

The effects of drying height on the drying rate, water loss rate and crispness of mulberries during microwave–vacuum-drying when the product surface temperature is 50 °C, the microwave power is 5.45 W/g and the chamber vacuum level is 0.08 MPa are shown in Figure 2d,h.

Figure 2d shows that the crispness of dried mulberries decreases from 10.879 N/mm to 8.536 N/mm when the mulberries move from the lower layer to the upper layer. In Figure 2h, the drying rate at different positions has a relatively insignificant influence, because the evaporation rate of water in products is mainly affected by microwave power. Given the same power, there is no obvious difference in the drying rate of mulberries at different positions. Guo Minghui [31] carried out the conventional low-temperature drying of wood-sawn timber in a drying chamber and found no significant differences in the visible drying defects at different positions, both at the front and the rear. The drying time of mulberries at the lower layer is slightly longer than that of the upper and middle layers, because the temperature-sensing probes in the microwave–vacuum-drying oven can only monitor the temperature of the top layer, and the temperature of the lower layer is lower than that of the upper layer. Hence, it takes a longer time to dry the bottom layer of products during the simultaneous drying of the three layers. The vacuum holes of this drying device are located at the lower parts of the side surface of the drying cavity. The optimal crispness of dried mulberries is achieved under low-temperature and long-time drying.

3.5. Influence of Different Control Parameters on the Sensory Evaluation of Dried Mulberries

Smokiness is the sensation of discomfort resulting from the inhalation of particulate matter produced during the fragmentation of food within the nasal cavity. The term smoky refers to the generation of dust during the crushing process, typically associated with the release and dispersal of fine particles composed of solid substances [34]. The results of the sensory evaluation are shown in Table 2. The surface temperature of the product has a great influence on the appearance of dried mulberries, and drying them at low temperatures can better retain the external shape of the mulberries. The influence of changing the control parameters on the sweetness and smoke perception of the mulberries was not evident based on the evaluation results. The optimal conditions for achieving the crisp taste of mulberries were determined through a crispness evaluation. These conditions included a product surface temperature of 50 °C, a power of 5.45 W/g, a chamber vacuum level of 0.08 Mpa and a tray height of 0 cm. These results were consistent with the measurements obtained from the texture analyser. Overall, the sweetness and crispness are better, and the impression of smokiness is lessened, even though some of the sensory characteristics of the appearance are lost during the drying process.

Table 2. Sensory evaluation of dried mulberries using different experimental control parameters.

Sample		Appearance	Sweetness	Crispness	Smoky	Overall Sensory Evaluation Score
Product surface temperature (°C)	40	4.78 ± 0.16 c	3.57 ± 0.43 bc	2.16 ± 0.37 a	3.28 ± 0.44 ab	13.79 ± 1.4 bc
	45	3.58 ± 0.35 bc	3.42 ± 0.31 b	2.38 ± 0.28 a	3.52 ± 0.12 b	12.9 ± 1.06 b
	50	2.52 ± 0.26 a	3.51 ± 0.25 b	2.84 ± 0.18 a	3.62 ± 0.16 b	12.49 ± 0.85 b
	55	1.77 ± 0.91 a	3.75 ± 0.95 bc	2.86 ± 0.14 a	4.40 ± 0.47 bc	12.78 ± 2.47 bc
Microwave power (W/g)	1.82	4.35 ± 0.26 c	3.29 ± 0.13 b	2.64 ± 0.32 a	4.26 ± 0.09 c	14.69 ± 0.8 bc
	2.73	3.85 ± 0.21 bc	3.19 ± 0.96 b	2.59 ± 0.15 a	4.35 ± 0.24 c	13.98 ± 1.56 bc
	3.64	3.42 ± 0.58 b	3.35 ± 0.31 b	2.61 ± 0.41 a	4.62 ± 0.36 c	13.56 ± 1.66 bc
	4.55	2.89 ± 0.25 a	3.58 ± 0.14 b	3.28 ± 0.44 ab	4.58 ± 0.25 c	14.33 ± 1.08 bc
	5.45	2.37 ± 0.54 a	3.58 ± 0.24 b	3.94 ± 0.73 b	4.63 ± 0.36 c	14.52 ± 1.87 bc
Chamber vacuum level (MPa)	0.02	2.54 ± 0.36 a	3.64 ± 0.16 b	3.58 ± 0.38 b	3.94 ± 0.52 bc	13.7 ± 1.42 b
	0.04	3.34 ± 0.34 b	3.76 ± 0.24 bc	3.62 ± 0.54 b	4.12 ± 0.24 bc	14.84 ± 1.36 bc
	0.06	3.54 ± 0.16 bc	4.02 ± 0.12 c	4.07 ± 0.54 bc	4.58 ± 0.34 c	16.21 ± 1.16 c
	0.08	4.26 ± 0.28 c	4.21 ± 0.26 c	4.21 ± 0.40 bc	4.69 ± 0.15 c	17.37 ± 1.09 c
Drying position (cm)	8	4.48 ± 0.36 c	3.75 ± 0.85 bc	4.81 ± 0.22 c	3.68 ± 0.74 bc	16.27 ± 2.17 c
	4	4.65 ± 0.58 c	3.54 ± 0.25 b	4.67 ± 0.13 c	3.84 ± 0.35 c	16.7 ± 1.31 c
	0	4.24 ± 0.16 c	4.31 ± 0.52 bc	4.88 ± 0.11 c	3.63 ± 0.19 c	17.06 ± 0.98 c

Note: a, b, and c indicate food tasting sensory ratings: excellent, good, and average.

3.6. Drying Kinetic Model of Mulberries

The mathematical model of the microwave–vacuum heating process mainly refers to the heat and mass transfer model in the heating process, and it represents the material absorption of microwave energy and the water diffusion rate. The coupling of momentum, heat and mass is the essential attribute in the whole process, which can be inferred successively rather than through the construction of a new drying model. It only has to choose the appropriate mathematical model with the best-fitting effect from the known thin-layered drying models. The adjustment according to special conditions is only needed if there is no completely appropriate mathematical model. According to Chinese and foreign studies on thin-layer equations of drying models for humidity-containing porous media, seven representative semi-empirical and empirical drying mathematical models were screened [35,36] (Table 3).

Table 3. Drying kinetic model.

Serial Number	Model Name	Model Equation
1	Henderson and Pabis	MR = a exp(−kt)
2	Lewis	MR = exp(−kt)
3	Page	MR = exp(−ktn)
4	Two-term	MR = a1 exp(−k1t) + a2 exp(−k2t)
5	Logarithmic	MR = a exp(−kt) + c
6	Two-term exponential	MR = ae − kt + (1 − a)e − kat
7	Weibull distribution	MR = e − (t/a)β

Note: MR: Moisture ratio; a, β, c, e, k, t, n: function variable values.

3.7. Verification of the Drying Kinetic Model

The errors between the microwave–vacuum-drying test data of the mulberries and the seven mathematical models are listed in Table 4. The results showed that the Two-term model has relatively high accuracy, with an R^2 range of 98.7−99.9%, an X^2 range of 0.1−1.67% and an RMSE range of 0.7−3.4%. The optimised Two-term model equations are shown in Table 5. Constants of coefficients in Table 5 are used to predict the dehydration conditions during mulberry drying under the four drying variables.

Table 4. Model error.

Drying Conditions	Model Number	R^2	X^2	RMSE
Product surface temperature	1	0.983~0.994	0.007~0.051	0.023~0.423
	2	0.981~0.994	0.007~0.034	0.024~0.037
	3	0.982~0.996	0.004~0.040	0.019~0.036
	4	0.997~0.999	0.0036~0.0039	0.012~0.018
	5	0.996~0.989	0.006~0.010	0.020~0.029
	6	0.995~0.996	0.006~0.008	0.020~0.022
	7	0.982~0.994	0.007~0.034	0.024~0.037
Microwave power	1	0.952~0.987	0.018~0.050	0.036~0.054
	2	0.927~0.985	0.057~0.109	0.032~0.067
	3	0.983~0.996	0.004~0.042	0.019~0.033
	4	0.996~0.999	0.003~0.009	0.007~0.016
	5	0.973~0.993	0.020~0.041	0.022~0.040
	6	0.988~0.993	0.019~0.020	0.021~0.028
	7	0.927~0.985	0.057~0.109	0.032~0.067
Chamber vacuum level	1	0.867~0.990	0.040~0.498	0.027~0.107
	2	0.852~0.990	0.043~0.557	0.028~0.113
	3	0.944~0.993	0.024~0.178	0.023~0.070
	4	0.987~0.999	0.001~0.167	0.007~0.034
	5	0.987~0.998	0.002~0.185	0.011~0.034
	6	0.987~0.998	0.002~0.185	0.011~0.034
	7	0.852~0.990	0.043~0.557	0.028~0.113
Position height	1	0.948~0.972	0.069~0.151	0.050~0.071
	2	0.930~0.958	0.103~0.199	0.062~0.082
	3	0.991~0.996	0.009~0.023	0.020~0.029
	4	0.995~0.997	0.013~0.028	0.017~0.023
	5	0.993~0.997	0.008~0.014	0.018~0.025
	6	0.993~0.997	0.008~0.014	0.018~0.025
	7	0.930~0.958	0.103~0.199	0.062~0.082

Table 5. Statistical results, constants and coefficients of the Two-term model under different drying conditions.

Temperature/°C	Power/W	Chamber Vacuum Level/MPa	Height/cm	a1	a2	k1	k2	R^2	X^2	RMSE
40	500	0.08	0	1.0028	−0.0122	0.0011	−0.0019	0.9968	0.0036	0.0183
45	500	0.08	0	−0.0019	0.9492	−0.0051	0.0029	0.9902	0.0106	0.0272
50	500	0.08	0	1.2030	−0.2030	0.0114	2.3519	0.9986	0.0039	0.0118
55	500	0.08	0	0.2481	0.7710	0.0428	0.0170	0.9957	0.0059	0.0202
50	200	0.08	0	0.8131	0.1887	0.008	0.0657	0.9963	0.0087	0.0157
50	300	0.08	0	0.8760	0.1240	0.0062	2.6926	0.9913	0.0301	0.0233
50	400	0.08	0	0.3413	0.6589	0.0937	0.0084	0.9991	0.0034	0.0075
50	500	0.08	0	1.2030	−0.2030	0.0114	56.416	0.9986	0.0039	0.0118
50	600	0.08	0	0.9672	0	0.0073	−0.0499	0.9965	0.0042	0.0154
50	600	0.02	0	−0.0035	0.9905	−0.0113	0.0061	0.9961	0.0206	0.0186
50	600	0.04	0	31.8664	−30.8849	−0.0005	−0.0006	0.9993	0.0011	0.0075
50	600	0.06	0	29.4302	−28.4779	−0.0012	−0.0012	0.9867	0.1669	0.0340
50	600	0.08	0	0.9672	0	0.0073	−0.0499	0.9965	0.0042	0.0154
50	600	0.08	8	−42.8892	43.8979	0.0015	0.0016	0.9967	0.0135	0.0175
50	600	0.08	4	59.9441	−58.9205	0.0009	0.0009	0.9946	0.0285	0.0227
50	600	0.08	0	91.0552	−90.0602	0.0181	0.0183	0.9956	0.0123	0.0201

3.8. Verification of the Humidity–Heat Transfer Model

The relation curves of the dry-based moisture content of mulberries and the time during microwave–vacuum-drying under different control parameters are shown in Figure 3 (the test was repeated three times to obtain an average value). Solid lines represent the actual data, while dotted lines represent the prediction data. The prediction curve of the moisture content is consistent with the actual condition of the mulberry drying. The results showed that the optimised Two-term model equation can effectively predict water content changes in mulberries under different drying techniques.

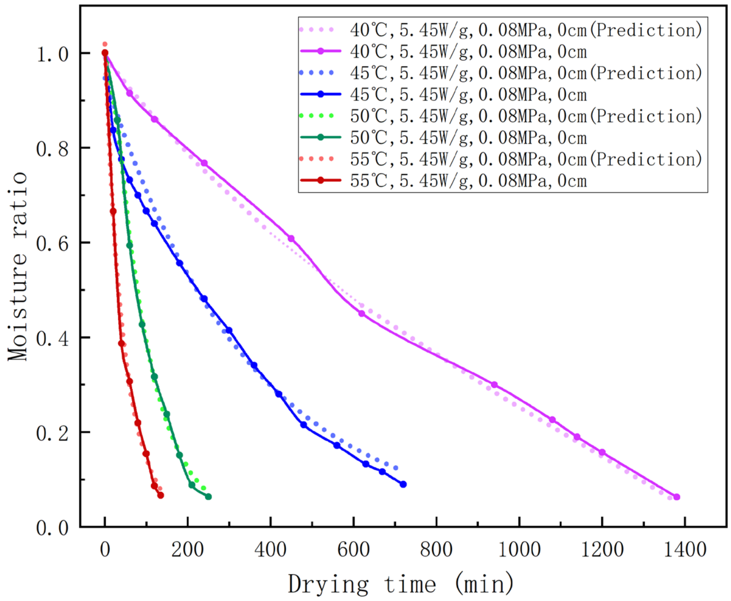


Figure 3. Two-term model validation.

4. Calculation of the Effective Water Diffusion Coefficient and Activation Energy

4.1. Effective Water Diffusion Coefficient

The effective water diffusion coefficient is an essential parameter to calculate and simulate the water migration mechanism of materials in the drying process. It discloses the water diffusion volume passing through a unit area per second when the water concentration gradient is one. The whole water transfer process of mulberries is described through Fick's second Law [37]:

$$\frac{\partial M}{\partial t} = D_{eff}\frac{\partial^2 M}{\partial r^2} \tag{9}$$

Since dried mulberry samples look like cylinders, the initial conditions and boundary conditions of geometry can be determined [26–28]:

$$M = M_0;\ t = 0,\ 0 \le r \le R \tag{10}$$

$$\frac{\partial M}{\partial r} = 0;\ t > 0,\ r = 0 \tag{11}$$

$$M = M_e; t > 0, r = R \tag{12}$$

where M_0 is the initial moisture content (%); M_0—balanced moisture content (%); t—drying time (min) and r—radius of cylinder (m).

Crank proposed a water diffusion formula that is applicable to solving the cylindrical geometric particles. The initial water content of materials is assumed to be distributed uniformly, and the diffusion coefficient is held constant. The volume contraction in the drying process is ignored [37,38].

$$MR = \frac{4}{\pi^2}\exp\left(-\pi^2\frac{D_{eff}t}{r^2}\right) \tag{13}$$

where—D_{eff} is the diffusion coefficient of available water (m^2/s).

The equation is further simplified:

$$\text{In}(\text{MR}) = \text{In}\left(\frac{4}{\pi^2}\right) - \left(\frac{\pi^2 D_{\text{eff}}}{r^2} t\right) \quad (14)$$

4.2. Calculation of Activation Energy

Activation energy refers to the energy needed for the removal of each unit of water from materials in the drying process. A higher activation energy indicates that more energy is needed by the materials. The Arrhenius equation calculates the activation energy through the diffusion coefficient of the available water (D_{eff}) and temperature (T) in the drying process of materials [38].

4.3. Calculation of the Diffusion Coefficient of Available Water in Mulberries

Table 6 shows that the diffusion coefficient of the available water in mulberries presents a growth trend with the increase in the product surface temperature. It increases from 4.98×10^{-8} to 5.74×10^{-7}. However, the diffusion coefficient of water in mulberries shows no obvious variation trends under changes in microwave power, chamber vacuum level and height range. The linear equation of the diffusion of the available water generally decreases with the reduction in the volume of mulberries. The effective moisture diffusion coefficient range of mulberries under different microwave powers is 2.17×10^{-7}–3.37×10^{-7} $D_{eff}(m^2/s)$. The effective moisture diffusion coefficient range of mulberries under different chamber vacuum levels is 2.17×10^{-7}–3.37×10^{-7} $D_{eff}(m^2/s)$. The effective moisture diffusion coefficient range of mulberries under different heights is 2.17×10^{-7}–3.37×10^{-7} $D_{eff}(m^2/s)$.

Table 6. Effective water diffusion coefficient of mulberries under different drying conditions.

	Product Surface Temperature/°C	**Microwave Power/W/g**	**Chamber Vacuum Level/MPa**	**Height/cm**	**Linear Equation Expression**	**R^2**	**$D_{eff}(m^2/s)$**
Product surface temperature	40	4.55	0.08	0	InMR = −0.0017t + 0.1334	0.9312	4.98×10^{-8}
	45	4.55	0.08	0	InMR = −0.0038t + 0.1101	0.9678	1.11×10^{-7}
	50	4.55	0.08	0	InMR = −0.0115t + 0.1519	0.9893	3.37×10^{-7}
	55	4.55	0.08	0	InMR = −0.0196t − 0.0245	0.9924	5.74×10^{-7}
Microwave power	50	1.82	0.08	0	InMR = −0.0089t − 0.09	0.9924	2.61×10^{-7}
	50	2.73	0.08	0	InMR = −0.0074t + 0.0068	0.9707	2.17×10^{-7}
	50	3.64	0.08	0	InMR = −0.0097t − 0.2368	0.9818	2.84×10^{-7}
	50	4.55	0.08	0	InMR = −0.0115t + 0.1519	0.9893	3.37×10^{-7}
	50	5.45	0.08	0	InMR = −0.0094t + 0.1203	0.9236	2.75×10^{-7}
Chamber vacuum level	50	5.45	0.02	0	InMR = −0.0062t + 0.3955	0.8603	1.82×10^{-7}
	50	5.45	0.04	0	InMR = −0.0083t + 0.1513	0.9608	2.43×10^{-7}
	50	5.45	0.06	0	InMR = −0.0067t + 0.4569	0.7868	1.96×10^{-7}
	50	5.45	0.08	0	InMR = −0.0094t + 0.1203	0.9236	2.75×10^{-7}
Height	50	5.45	0.08	8	InMR = −0.013t + 0.3196	0.9328	3.81×10^{-7}
	50	5.45	0.08	4	InMR = −0.0128t + 0.3507	0.9296	3.75×10^{-7}
	50	5.45	0.08	0	InMR = −0.0121t + 0.2617	0.9590	3.54×10^{-7}

4.4. Calculation of Activation Energy of Dried Mulberries

When the temperature increases from 313.15 K to 328.15 K, the effective diffusion coefficient increases from 16.83 KJ/mol to 14.31 KJ/mol. The linear equation is y = 18019x − 40.648, so the InD0 in the activation energy calculation formula is −40.684, Ea/R is 10819. In the experiment, the diameter of the mulberry sample is 0.017 m, and the activation energy can be obtained to be 183.923 KJ/mol, indicating that the drying of mulberries requires a large amount of energy.

5. Conclusions

In this study, the effects of microwave–vacuum-drying parameters on the crispness of dried mulberries are analysed comprehensively to evaluate the quality of dried mulberries. The kinematic model of multiple drying variables for the microwave–vacuum-drying of mulberries is constructed and optimised. Some major research conclusions can be drawn as follows:

(1) The Two-term model is the most accurate at predicting the dehydration process of mulberries in the microwave–vacuum-drying apparatus, according to a comparative analysis of drying models. Moreover, the optimal equation coefficients that are applicable to temperature, power, vacuum degree and drying height are determined.
(2) In the microwave–vacuum-drying process of mulberries, the temperature, power and chamber vacuum level are the major influencing factors of the drying rate of the mulberries. Microwave power is the primary cause of the increasing crispness of dried mulberries.
(3) The technological parameters to achieve the highest crispness under microwave–vacuum-drying conditions include temperature = 50 °C, power = 5.45 W/g, chamber vacuum level = 0.08 MPa and local tray height = 0 cm.
(4) The diffusion coefficient of the available water during the microwave–vacuum-drying of mulberries ranges from 4.98×10^{-8} to 3.81×10^{-7}, and it is positively related to temperature. The drying activation energy of mulberries is 183.923 KJ/mol.

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