

Article

Microwave Drying Characteristics and Drying Quality Analysis of Corn in China

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Abstract: To identify the microwave drying characteristics of corn, microwave drying tests were conducted on corn. By taking the moisture content, drying rate, and drying temperature as indices, this research revealed the effects of different microwave powers and loads on the microwave drying characteristics of corn. Moreover, energy consumption and quality of dried corn were analysed under different drying conditions. The results demonstrate that microwave drying has significant energy-saving effects. The energy consumption by microwave drying is less than 0.3 times that used by electrothermal drying under the same load. Both microwave power and load exert significant influences on drying characteristics. Higher microwave power results in a greater average drying rate, wherein shorter periods of time are required to reach the maximum drying rate and higher temperatures of the corn. However, the load shows the opposite tendency. The smaller the load, the higher the temperature of the corn in the early stage of drying. However, as drying continues, the temperature curve changes significantly, and the temperature rises with the increase in load in the later stage of drying. In consideration of energy consumption and dried quality, the load of corn should be increased as appropriate, and the microwave intensity should be limited to no higher than 0.7 W/g in the experiment.

Keywords: microwave drying; corn; energy consumption of drying; drying quality



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1. Introduction

China is a large grain producer. According to statistics [1], the total grain output in China was 6.5789×10^8 tons in 2018, in which output of cereal grains reached 6.1019×10^8 tons; however, the annual grain loss caused by mildew in China ranges from 0.87% to 1.88%, accounting for 24.72% to 29.22% of total losses [2]. Properly reducing moisture content in grain can reduce loss of grains caused by mildew.

At present, the techniques commonly used for drying grain include hot-air drying, freeze drying, and microwave drying [3–5]. Of these techniques, microwave drying only works on polar molecules and is very popular due to its advantages, such as fast drying speed, lower energy consumption, and ease of control [6–10]. Hemis et al. [11,12] studied microwave drying of wheat, soybean and canola seeds, and established a new coupling model. However, in the process of drying research, we should not only pay attention to the drying rate and energy consumption, but also pay attention to the quality of the drying product. In the grain-drying process, different drying methods have different effects on taste and nutrition maintenance of grain [13]. Researchers have conducted a great amount of work on grain quality in microwave drying. Smith et al. [14] studied the effects of microwave power and drying time on surface lipid content, protein content, and the final viscosity of rice. Olatunde et al. [15] analyzed the effects of microwave drying on rice moisture removal, milled rice characteristics, and energy requirements, and concluded that the microwave energy should be 450–600 kJ/kg in order to maintain the quality of

rice. Shen et al. [16] investigated the effects of microwave drying on visual color and gamma-aminobutyric acid (GABA) of germinated brown rice (GBR) and found that a microwave intensity of 3–4 W/g is suitable. Yuan et al. [17] researched the influence of different microwave conditions on water migration, quality, lipase activity and the internal structure of rice, and determined that the optimum microwave treatment conditions are a microwave intensity of 1.29 W/g and a drying temperature of 60 °C. In order to reduce the drying temperature and better maintain the nutritional components of grains, modified microwave drying methods, such as microwave vacuum drying, are often used in grain drying [5,18]. However, compared with microwave drying, microwave vacuum drying has the disadvantages of long drying time, expensive equipment and high operation cost.

Corn is an annual plant which is not only grown for people to eat, but also can be made into high-quality feed for livestock [19]. As a main grain, corn is second only to wheat and rice in yield [20]. China is the second largest maize producer in the world, accounting for more than 20% of the world's total corn output. Researchers have, previously, conducted a series of studies on corn drying. Nourmohamadi-Moghadami et al. [21] studied the drying behavior of corn in a hot air-infrared dryer. They reported on the effects of inlet air temperature, infrared radiation intensity, and modes of the drying bed on moisture variation during drying process. Abasi et al. [22] investigated the effects of drying air temperature on the mechanical properties of corn kernels. They discovered that kernel deformation at the rupture point increases by 12% as the temperature increases from 40 °C to 70 °C; however, values of force, stress, toughness, and modulus of elasticity of corn decreased on average by 21%, 26%, 36% and 38%, respectively. In fact, like other grains, microwave drying conditions not only affect the drying characteristics of corn, but also have important effects on the drying quality of corn. Bualuang et al. [23] reported that 300 W was the most suitable drying condition; germinated maize had the highest nutritive value and antioxidant values under this condition. In fact, the moisture content, physical properties (such as hardness, bulk density, etc.) and nutritional properties (protein content and starch content) of corn in various regions are different, and their drying characteristics are also different. However, there are few reports on microwave drying of corn in China. In addition, crack rate and starch content are important indices of corn drying quality; however there are seldom researches about the effects of microwave drying conditions on these indices.

This study mainly investigated the influences of microwave power and load on the drying characteristics of corn. In addition, the energy consumption and quality of dried corn (crack rate and starch content) under different drying conditions were analysed to provide a theoretical basis for the drying process of corn in the future.

2. Materials and Methods

2.1. Test Materials

In this study, Wannuo 2000 corn samples were used and stored in a refrigerator for later use. The moisture content in corn kernels was determined to be 54.56% (w.b.) based on the ISO 6540-1980 standard.

2.2. Test Equipment

2.2.1. Microwave Drying Equipment

In this research, the microwave drying equipment was an improved M1-L213B microwave oven produced by Guangdong Midea Kitchen Electric Appliance Manufacture Co., Ltd., Foshan, China. The test system of the microwave drying is shown in Figure 1, which is mainly composed of three parts:

(1) A microwave oven. The M1-L213B microwave oven worked at a frequency of 2450 ± 50 Hz and a voltage of 220 V ($1 \pm 10\%$). A magnetron was installed in the microwave oven, and the rated input power and output power were 1150 W and 700 W, respectively. The cavity was a cuboid measuring $315 \times 325 \times 202$ mm;

(2) A test system. The mass of corn was measured by a JD2000-2 precision electronic balance with a precision of 0.01 g and a measuring range of 1000 g, which was developed by Shenyang Longteng Electronic Co., Ltd., Shenyang, China. The temperature was measured by utilising an ABSD-01A-WB on-line infrared thermometer developed by Shandong Gelin Electronic Technology Co., Ltd., Jinan, China, whose precision was ± 1 °C and which had a measurement range from 0 °C to 500 °C.

(3) A data acquisition system. By connecting the infrared thermometer and electronic balance with a computer, the mass of materials during drying was monitored and recorded in real time by employing data acquisition software.

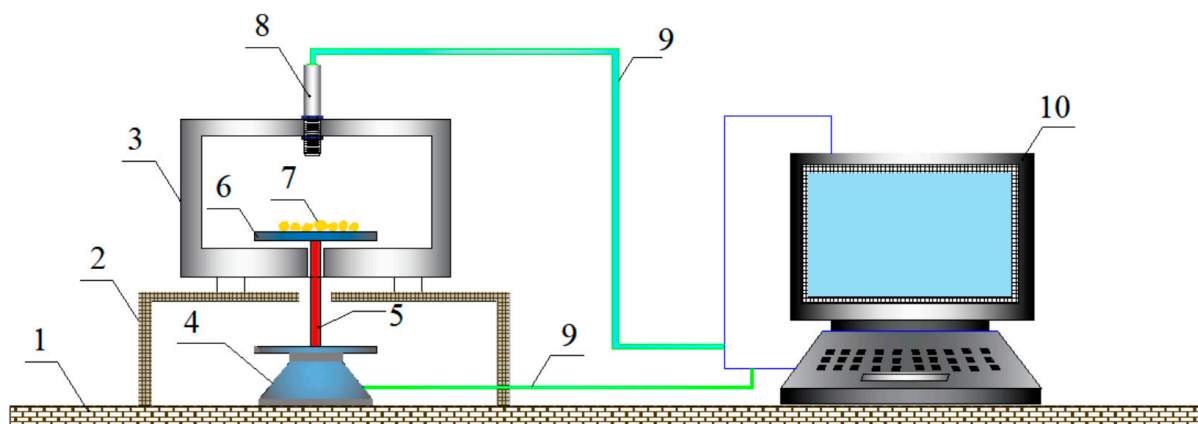


Figure 1. Microwave drying system of corn. 1—Test bench; 2—Bearing; 3—Microwave oven; 4—Electronic balance; 5—Stents; 6—Tray; 7—Corn; 8—Infrared thermometer; 9—Cable; 10—Computer.

2.2.2. Electrothermal Drying Equipment

An SFA-3 digital-display air-blast electrothermal drying oven produced by Shanghai Shibo Industrial Co., Ltd., Shanghai, China, was adopted. The mass test system and data acquisition system were the same as those used in the microwave drying equipment.

2.3. Test Methods and Indices

2.3.1. Test Methods

For the microwave drying test of corn, a certain amount of corn was weighed on the electronic balance and spread on a drying tray. The data acquisition system was set to collect data every minute. When the moisture content of the corn reached 13% (w.b.), drying was stopped. To measure the temperature of corn, an infrared temperature sensor was used. To ensure accuracy of test data, each group of tests was repeated three times and the average was taken. This project mainly explored the effects of microwave power (the emitted power by the magnetron) and loading amount on drying characteristics of corn. The test scheme is shown in Table 1.

Table 1. Experimental scheme of microwave drying.

Number	Microwave Power (W)	Sample Weight (g)
1	70	60
2	70	100
3	70	200
4	280	100

For the electrothermal drying test of corn, corn (100 g) was spread on the drying tray and then dried at ventilated air temperatures of 60, 80, 100, 120 and 140 °C, respectively. Each group of tests was carried out three times and the average value was taken. The specific test scheme of the electrothermal drying is shown in Table 2.

Table 2. Experimental scheme of electrothermal drying.

Number	Drying Temperature (°C)	Sample Weight (g)
1	60	100
2	80	100
3	100	100
4	120	100
5	140	100

2.3.2. Test Indices

Dry-basis moisture content (M) was determined by the following equation:

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

where M_t , m_t and m_d indicate the dry-basis moisture content of the materials at time t , the mass of the materials at time t , and the mass of dried materials, respectively.

Drying rate (DR) was determined by the following equation:

$$DR = \frac{dM_t}{dt} \quad (2)$$

Temperature (T) of the materials (°C) was measured using the on-line infrared temperature sensor or thermocouple.

For energy consumption (E) during drying, an electric energy meter was used to determine the power consumption E (MJ) in each test.

Average power (\bar{P}) was determined by the following equation:

$$\bar{P} = E \times 10^3 / t \quad (3)$$

where \bar{P} , E and t denote the average power during drying(kW), total power consumption (MJ) during drying and time (s) taken for drying the materials, respectively.

Crack rate was assessed by observing cracks with a magnifying glass after the samples undergoing different drying conditions were cooled to room temperature. If the length of cracks on corns was greater than half the corn length, they were regarded as cracked corns [24]. The average crack rates calculated from the three groups of samples under each drying condition were taken as the test results. The rate of cracking of corn was detected by a DM4 Solan electronic magnifying glass produced by Yukang Trading Co., Ltd. in Yiwu City, Zhejiang Province, China.

Starch content was assessed by virtue of the polarimeter; the samples under different drying conditions were measured and the average starch contents calculated from the three groups of samples under each drying condition were taken as the test results. A WZZ-2SS automatic polarimeter, developed by Shanghai Tecfront Electronic Technology Co., Ltd., shanghai, China, was used to detect the presence of corn starch.

3. Results and Discussion

3.1. Effects of Microwave Power on Drying Characteristics of Corn

The curves of the moisture content, drying rate and temperature of corn under different microwave irradiation powers are shown in Figures 2–4.

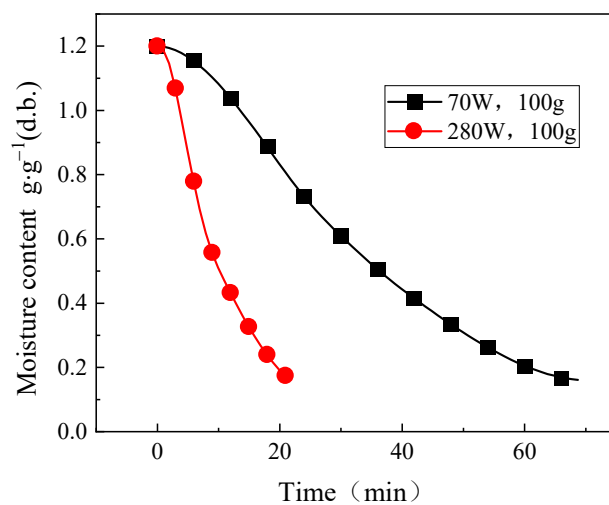


Figure 2. Moisture content of corn under different microwave powers.

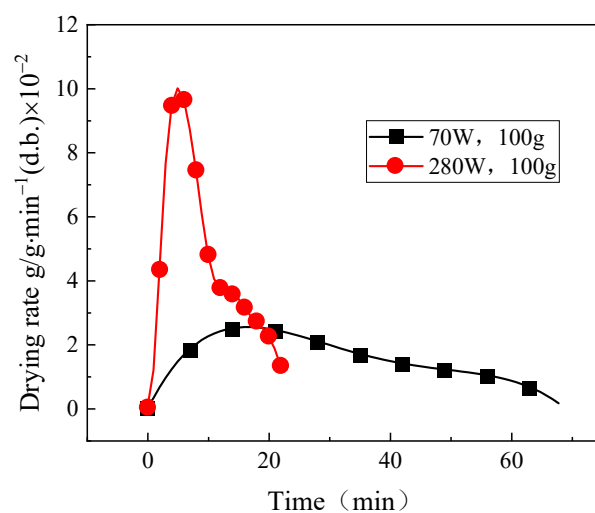


Figure 3. Drying rate of corn under different microwave powers.

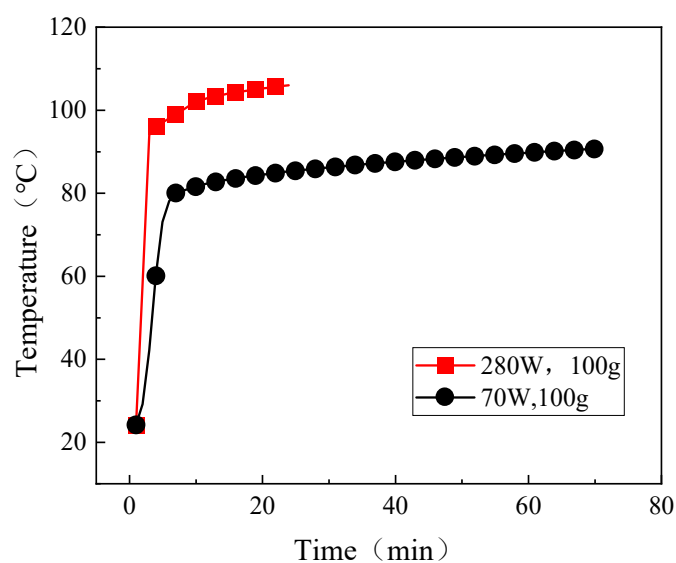


Figure 4. Drying temperature of corn under different microwave powers.

As shown in Figures 2–4, the effect of microwave power on moisture content and drying rate of corn is similar to that of carrot [25], parsley [26] and wheat seeds [12]. The higher the microwave power, the greater the average drying rate, the less the time required to reach the maximum drying rate, and the higher the temperature of the materials. Under a load of 100 g, at 70 W and 280 W, it takes 69 min and 22 min for the moisture content of corn to be reduced to 13% (w.b.). Moreover, the average drying rates, separately, are $1.51 \times 10^{-2} \text{ g/g} \cdot \text{min}^{-1}$ (d.b.) and $4.74 \times 10^{-2} \text{ g/g} \cdot \text{min}^{-1}$ (d.b.). At 70 W, the maximum drying rate ($2.51 \times 10^{-2} \text{ g/g} \cdot \text{min}^{-1}$ (d.b.)) of corn is reached at 17 min, when the drying temperature is 83 °C; at 280 W, the drying rate of corn reaches a maximum of $10.00 \times 10^{-2} \text{ g/g} \cdot \text{min}^{-1}$ (d.b.) at 5 min. In this case, the drying temperature reaches 97 °C, which is 14 °C higher than that obtained at 70 W. The energy consumption during microwave drying at 70 W is 0.468 MJ, while that at 280 W is 0.608 MJ; therefore, when a certain mass of corn is dried by microwave irradiation, increasing the applied microwave power can reduce the drying time, albeit with greater energy consumption.

As shown in Figures 2 and 3, the microwave drying process of corn can be divided into three stages from the macroscopic perspective, i.e., the preliminary period (the increasing rate drying period), the first period (the constant rate drying period) and the second drying period (the falling rate drying period), which is in accordance with the microwave drying of most agricultural products [5,26]. Using a load of 100 g of corn, at 70 and 280 W, the preliminary period during the microwave drying of corn are found in the first 12 and 4 min, respectively. In this period, the average drying rates are 1.35×10^{-2} and $5.65 \times 10^{-2} \text{ g/g} \cdot \text{min}^{-1}$ (d.b.), respectively. As shown in Figure 4, the temperature of the corn samples rises rapidly and the average heating rates reach 4.86 and 18.00 °C/min during the preliminary period, respectively. This indicates that in the preliminary period of microwave drying, water molecules in corn vibrate rapidly under the action of microwaves, resulting in the generation of frictional heat. The internal temperatures of the samples increase rapidly, and a temperature gradient between the air in the drying chamber and samples is generated, which encourages moisture inside the corn to spread outwards [27–30]. Hence, the more powerful the microwave irradiation, the faster the drying process. The first period during the microwave drying of corn is found between 12 to 22 and 4 to 7 min and the average drying rates are 2.57×10^{-2} and $9.46 \times 10^{-2} \text{ g/g} \cdot \text{min}^{-1}$ (d.b.), respectively. In this drying period, the heating rate of the materials is slow, with averages of 0.26 and 6.67 °C/min. Moreover, the drying rate tends to be stable, which occurs because the speed of water migration inside the corn becomes gradually lower than that of water evaporation from the surface of corn. At 280 W, the first period is very short. This is because the higher the microwave intensity, the more microwave energy is absorbed by water molecules in corn, which leads to a faster temperature rise and accelerated evaporation such that the first period shortens. The second period during the microwave drying of corn is found between 22 to 69 and 7 to 22 min, respectively, in which the average drying rates are 1.33×10^{-2} and $3.55 \times 10^{-2} \text{ g/g} \cdot \text{min}^{-1}$ (d.b.), respectively. In this period, the temperatures of the materials tend to stabilise at about 90 and 105 °C, respectively, while the drying rate decreases. This is due to the gradual decrease of the microwave absorption ability of corn, which occurs concomitantly with the decrease of water content [31,32].

3.2. The Effects of Load on the Microwave Drying Characteristics of Corn

The curves of the moisture content, drying rate, and temperature of corn under different loads thereof are shown in Figures 5–7.

As demonstrated in Figures 5 and 6, the influence of loading on the moisture content and the drying rate of corn during microwave drying were similar to influences seen in carrot [25]. Under the same microwave power, the greater the load, the slower the average drying rate, such that it takes more time to reach the maximum drying rate and leads to a smaller maximum drying rate. At 70 W, when the load is 60, 100, and 200 g, the drying time is 44, 69, and 95 min, respectively; furthermore, the average drying rates are 2.37×10^{-2} , 1.51×10^{-2} , and $1.10 \times 10^{-2} \text{ g/g} \cdot \text{min}^{-1}$ (d.b.), respectively. In addition, the maximum

drying rates are 3.40×10^{-2} , 2.51×10^{-2} , and 1.62×10^{-2} g/g·min⁻¹ (d.b.) and the time required to reach the maximum drying rate is 14, 17, and 23 min, respectively. As shown in Figure 7, the heating of the materials presents different trends with changes in the load. In the initial stage of drying, the smaller the load, the higher the temperature. As drying continues, the temperature, under a larger load, gradually exceeds that under a smaller load. At 7 min, the temperature under a load of 100 g exceeds that under a load of 60 g. At 8 min, the temperature under a load of 200 g is higher than that under 60 g; however, at 12 min, the temperature under a load of 200 g is higher than that under a load of 100 g. Under loads of 60, 100, and 200 g, the final temperatures are 79, 90, and 95 °C, respectively. The main reason for this is as follows: in the initial stage, the moisture content in the materials is high, which confers a stronger ability to absorb microwave energy. The smaller the load, the greater the energy absorbed per unit mass of material, so the temperature rises faster. Meanwhile, as the drying process continues, the smaller the load, the lower the moisture content and the weaker the ability to absorb microwave energy, so the heating rate also commences more slowly. This causes the temperature of the materials to increase with increased load soon afterwards.

Table 3 shows energy consumption during the microwave drying of corn under different loads. With increasing load, the energy consumption increases, while energy consumption per unit mass decreases, which is similar to trends seen in carrot [25]. At 70 W, the energy consumption per unit mass at a load of 200 g is only 62.59% and 70.77% of those under loads of 60 g and 100 g. Therefore, in the drying process, the load can be increased as appropriate.

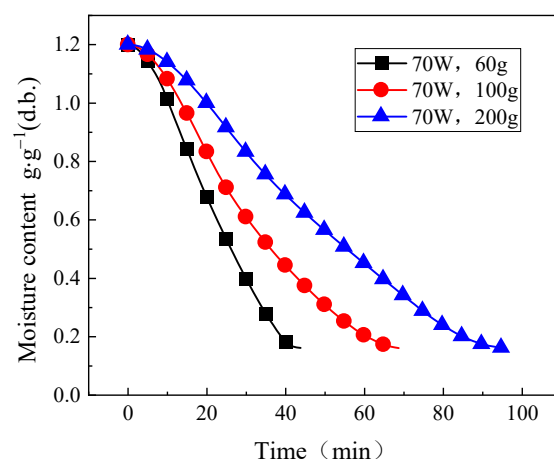


Figure 5. Moisture content of corn with different loads.

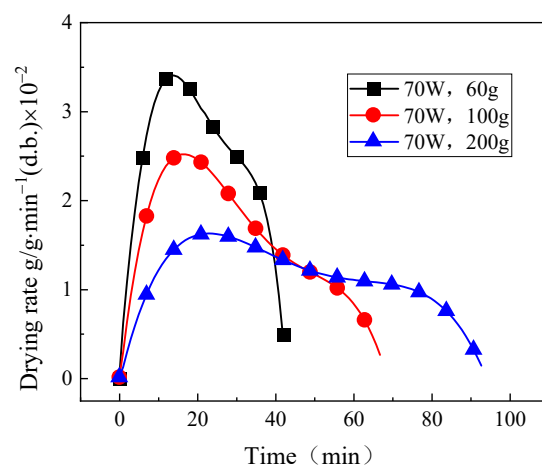


Figure 6. Microwave drying rate of corn with different loads.

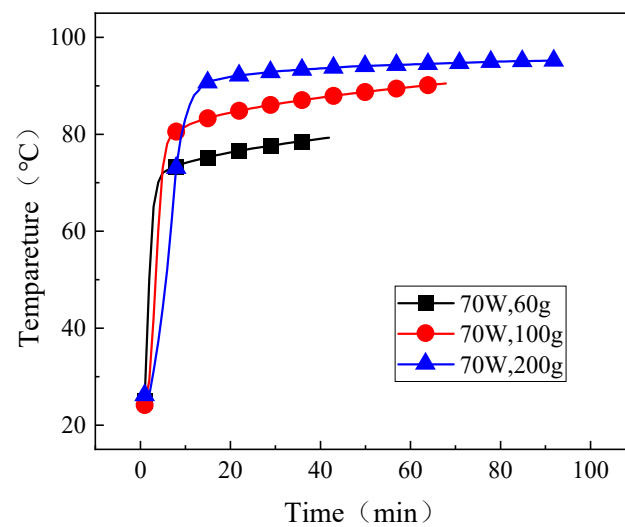


Figure 7. Microwave drying temperature of corn with different loads.

Table 3. Microwave drying energy consumption of corn in different loads.

Load (g)	Drying Time (min)	Energy Consumption (MJ)	Energy Consumption Per Unit Mass (MJ/kg)
60	44 ± 1	0.317 ± 0.007	5.28 ± 0.108
100	69 ± 2	0.468 ± 0.013	4.68 ± 0.147
200	95 ± 2	0.662 ± 0.015	3.31 ± 0.073

3.3. Comparison between Microwave Drying and Electrothermal Drying of Corn

In the same way, 100 g of corn was selected and dried electrothermally at 60, 80, 100, 120, and 140 °C. The moisture content and drying rates of microwave drying and electrothermal drying are illustrated in Figures 8 and 9.

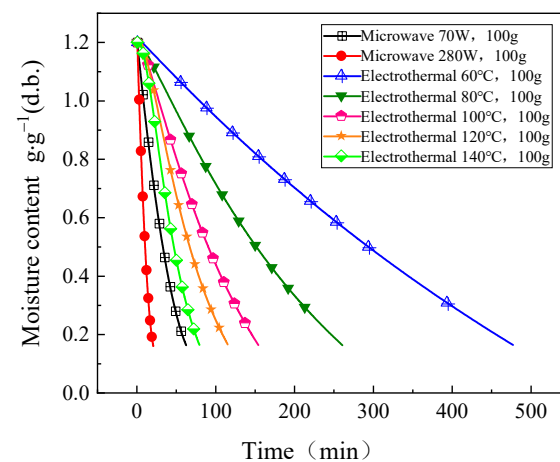


Figure 8. Comparison of moisture content curves between microwave drying and electrothermal drying.

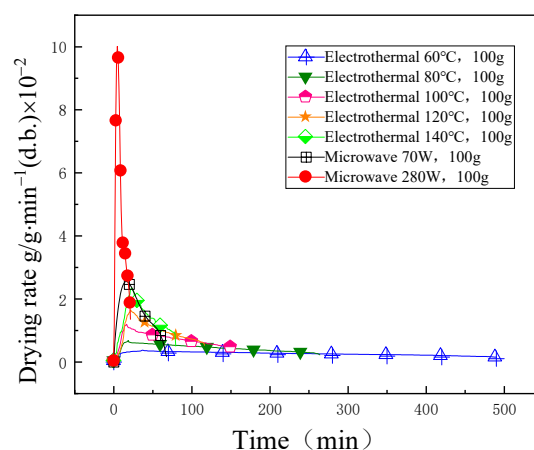


Figure 9. Comparison of drying rate between microwave drying and electrothermal drying.

Figures 8 and 9 show that microwave drying is much faster than electrothermal drying. Even if electrothermal drying is performed at a high temperature of 140 °C, it takes 78 min, which is 1.13 and 3.55 times longer than drying under microwave powers of 70 W and 280 W. Its maximum drying rate is $2.31 \times 10^{-2} \text{ g/g}\cdot\text{min}^{-1} \text{ (d.b.)}$, which is 0.92 and 0.23 times that of the maximum rate during microwave drying at 70 W and 280 W, respectively. This is mainly because during microwave drying, the internal temperature of the materials is high and the direction of heat conduction is consistent with that of moisture diffusion, which is conducive to moisture evaporation [15,23].

The energy consumptions using different drying methods are shown in Table 4. As shown in Table 4, microwave drying has obvious energy-saving effects. The energy consumption during microwave drying at 70 W is 0.108, 0.186, 0.113, 0.090, and 0.093 times that of electrothermal drying at 60, 80, 100, 120, and 140 °C, respectively. The average power during microwave drying at 280 W is close to that of electrothermal drying at 100 °C, while the latter is 6.80 times that of the former in terms of energy consumption. Chua [6] and Pratap Singh [18] also obtained similar results. The main reason is that microwaves only act on polar molecules, so the heating efficiency is increased, and the energy loss is lower [33,34].

Table 4. Comparison of energy consumption between microwave drying and electrothermal drying.

Number	Drying Conditions	Energy Consumption E (MJ)	Time t (min)	Average Power \bar{P} (kW)
1	Electrothermal, 60 °C	4.320 ± 0.147	478 ± 16	0.151 ± 0.005
2	Electrothermal, 80 °C	2.520 ± 0.112	267 ± 12	0.157 ± 0.007
3	Electrothermal, 100 °C	4.140 ± 0.137	168 ± 6	0.411 ± 0.014
4	Electrothermal, 120 °C	5.220 ± 0.155	110 ± 3	0.791 ± 0.023
5	Electrothermal, 140 °C	5.040 ± 0.148	78 ± 2	1.077 ± 0.032
6	Microwave, 70 W	0.468 ± 0.014	69 ± 2	0.115 ± 0.004
7	Microwave, 280 W	0.608 ± 0.018	22 ± 1	0.460 ± 0.014

4. Comparison of Qualities of Corn after Microwave Drying and Electrothermal Drying

The crack rate and starch content are important indices used to measure quality of dried grain [35]. Cracks are induced by stress in the process of cereal grain drying and dehydration. Grain with stress cracks will continue to increase the degree of cracking in subsequent mechanical processing, resulting in the exposure of internal starch and enhancement of water absorption, so that the dried quality decreases. Starch is the most abundant organic matter in corn. If it is kept at a high temperature for a long time, it will be gelatinised, which changes the hardness, quality, and colour of the corn. As illustrated in Figures 10 and 11, when the microwave power is enhanced or electrothermal temperature

is increased, the rate of cracking of corn increases and the starch content decreases. Under a load of 100 g, a high dried quality can be obtained by electrothermal drying at 60 °C and 80 °C and by microwave drying at 70 W. Their rates of cracking are 21.975%, 27.305%, and 31.268% and the starch contents are 71.16%, 68.43%, and 61.32%, respectively. Therefore, when microwave drying is performed, considering the crack rate and starch content for measuring quality, the microwave intensity cannot be too strong, and the intensity of the microwave drying should not exceed 0.7 W/g in the experiment.

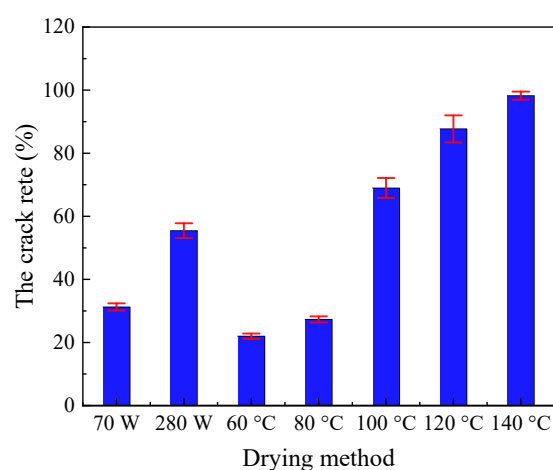


Figure 10. Comparison of crack rates in different drying methods.

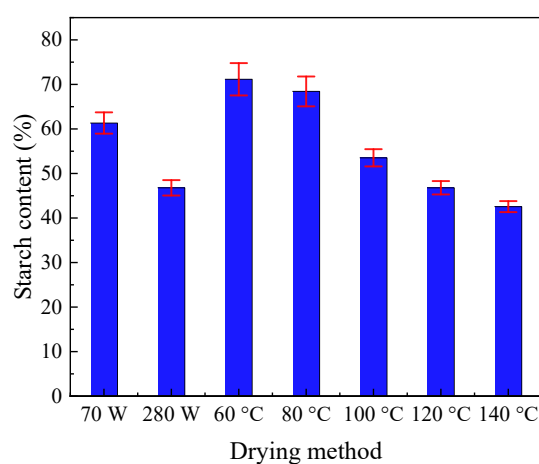


Figure 11. Comparison of starch content in different drying methods.

5. Conclusions

To explore the microwave drying characteristics of corn, drying tests were conducted on corn under different loads and microwave irradiation powers and a comparative test was conducted with electrothermal drying. The following conclusions are drawn:

(1) Macroscopically, the microwave drying stage of corn can be divided into the increasing rate drying period, the constant rate drying period and the falling rate drying period. In different periods, corn shows different drying characteristics. In the increasing rate drying period, the drying rate and heating rate increase rapidly. In the constant rate drying period, the drying rate tends to be stable, while the temperature increases slowly. In the falling rate drying period, the drying rate reduces slowly, and the temperature tends to be stable;

(2) Microwave power and load affect the drying characteristics of corn such that the higher the microwave power, the greater the average drying rate, which leads to a shorter period of time being required to reach the maximum drying rate and higher temperature

of corn. However, the load shows the opposite influence. In the initial stage of drying, the smaller the load, the higher the temperature of the corn. As drying continues, the temperature of the corn when drying a larger load becomes much higher than that under a smaller load. The phenomenon whereby the temperature of the corn increases with the increase of the load arises at a later stage;

(3) Microwave drying is much faster than electrothermal drying. Under the same load, the time taken for electrothermal drying at 140 °C is 1.13 and 3.55 times that under microwave drying at 70 W and 280 W. Microwave drying confers significant energy-saving effects. Microwave drying at 280 W requires a similar average power to electrothermal drying at 100 °C; however, in terms of energy consumption, the latter requires 6.80 times that of the former;

(4) Considering energy consumption during drying and dried quality, the load can be increased within a certain range and the intensity of microwave drying should not exceed 0.7 W/g in the experiment. These results are useful in the selection of optimum drying conditions during microwave drying of corn.

In order to further expand the research findings of this paper, it is necessary to establish drying kinetic models and calculate the drying kinetics parameters. In addition, the surface color, nutritional content and rehydration parameters of corn also need testing under different drying conditions.

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Data Availability Statement: All data used to support the findings of this study are included within the article.

Conflicts of Interest: The authors declare that they have no conflict of interest regarding the publication of this paper.

Nomenclature

Nomenclature	Subscripts and Superscripts
M dry-basis moisture content ($\text{g}\cdot\text{g}^{-1}$ (d.b.))	t time (min)
DR drying rate ($\text{g}/\text{g}\cdot\text{min}^{-1}$ (d.b.))	d dried materials
T temperature of the materials (°C)	
E energy consumption during drying (MJ)	
\bar{P} average power (kW)	

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