Ultrasonics Sonochemistry 92 (2023) 106287

Contents lists available at ScienceDirect

Ultrasonics Sonochemistry

journal homepage: www.elsevier.com/locate/ultson

Ultrasonic assisted far infrared drying characteristics and energy consumption of ginger slices

Dongyan Zhang, Dan Huang *, Yixiao Zhang, Yijun Lu, Shuai Huang, Guiliang Gong, Lijun Li

Department of Mechanical and Electrical Engineering, Central South University of Forestry and Technology, Changsha 410004, China

ARTICLE INFO

Keywords:
Far infrared drying
Ultrasonic pretreatment
Ginger slices
Energy consumption
Color change

ABSTRACT

Three drying methods, including far infrared drying, infrared convection drying, and ultrasonic pretreatment assisted far infrared drying, were adopted in the drying of ginger slices. The effects of main parameters (ultrasonic pretreatment power and time, far infrared temperature and power, sample thickness, infrared convection temperature) on the drying kinetics, energy consumption, and color change were investigated and discussed in detail. The results showed that the drying process of ginger slices was controlled by falling rate period. For far infrared drying, the drying rate increased with the increase of infrared temperature and decrease of sample thickness, while the infrared power had no obvious effect on the drying process. The infrared convection drying showed the fastest drying rate and the smallest color change, however, the energy consumption was the highest. For ultrasonic pretreatment assisted far infrared drying, an appropriate ultrasonic pretreatment time and power would promote the far infrared drying process and the energy consumption was only slightly increased. However, the color change was relatively large. The ultrasound technology showed its greatest potential to enhance the drying rate at the early stage of drying and increasing ultrasonic power was more effective than prolonging the pretreatment time in promoting far infrared drying.

1. Introduction

The root of the ginger plant, which is widely cultivated in Southeast Asian countries like India, China, Philippines, Malaysia, and Thailand [11], is known as ginger [4]. Since ancient times, ginger has been used as spice and medicine all over the world [1,7,18]. It is approved as an edible and medicinal material in China by the Chinese Ministry of Healthy [7]. Both fresh and dried ginger are popular in cooking. Ginger can be used to treat the common cold, flu-like symptoms, and even dysmenorrhea [18], as well as arthritis, rheumatism, muscle pain, indigestion, vomiting and nausea. It has the functions of anti-inflammatory, antipyretic, antibacterial, gastrointestinal motility and antioxidant activity [2,18,21]. However, edible fresh ginger has a high moisture content of 85 %-95 % w.b., which is sensitive to microbial damage [18]. The high moisture content makes ginger easy to suffer from water loss, shrinkage and fibrosis during the storage, and it is also easy to breed bacteria, leading to the mildew of ginger and therefore affecting its quality. Every year, the loss of ginger due to improper storage reaches 20 %-40 % of the total output, resulting in huge economic losses [30]. Therefore, the drying of ginger is imperative.

Dried ginger product accounts for a large share of the market, and it not only facilitates storage but also reduces transportation costs. In recent years, there have been many research reports on the drying of ginger at home and abroad. The drying methods mainly include traditional hot air drying, microwave drying, vacuum drying, spray drying, etc. In addition, there are also combined drying methods such as microwave-hot air and microwave vacuum drying [22]. Liao et al. [14] found that hot air drying was the most suitable method for mass production and processing of gingerol, and the yield of hot air drying ginger powder was 12.6 %. Compared with other drying methods, hot air drying has the advantages of low cost and simple operation. However, the drying rate is too low, the loss of volatile substances in ginger is large, and the product is prone to browning and deformation during the drying process. Spray drying can directly convert liquid materials into powder, and the finished product has good water solubility. However, the type of dried ginger is limited and it is not easy to prepare ginger liquid before drying. Jangam and Thorat [9] showed that the higher the temperature and air velocity in spray drying, the lower the retention rate of 6-gingerol. While Hawlader et al. found that the retention of 6-gingerol in vacuum drying was higher than that in hot air drying and

* Corresponding author.
E-mail address: hiwactb@163.com (D. Huang).

https://doi.org/10.1016/j.ultsonch.2022.106287
Received 30 September 2022; Received in revised form 20 December 2022; Accepted 28 December 2022
Available online 30 December 2022

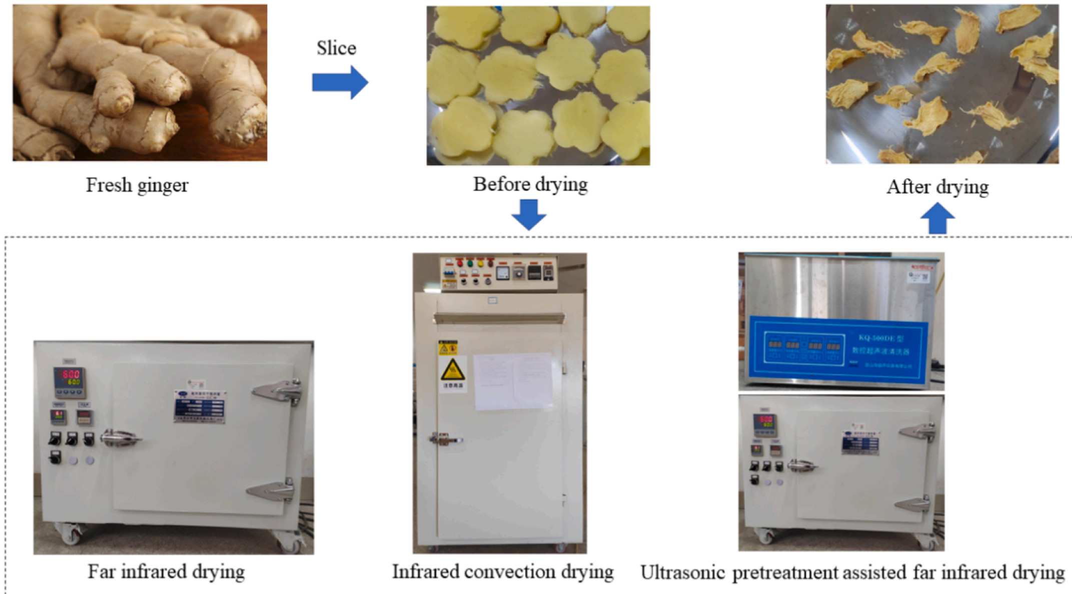


Fig. 1. Experimental apparatus.

freeze drying [6], however, the energy consumption of vacuum drying was very large. Microwave drying is fast and energy saving, however, it is easy to cause local overheating during the drying process, resulting in burns or coking of material corners. Besides, the microwave energy is likely to damage the internal structure of materials, leading to poor rehydration of finished products [22]. Combined drying methods can effectively avoid the burning and browning and the drying rate is fast. The disadvantage is that more parameter variables need to be controlled, such as microwave heating time, power density, vacuum degree, etc., and the process is relatively complicated.

Infrared drying is a drying method that materials directly absorb infrared rays and convert them into heat energy to achieve the effect of heating and drying [17]. Compared with hot air drying, it has the advantages of fast drying rate, high production efficiency and energy saving. The technology is already widely used in fruits and vegetables. For example, Huang et al. [8] used infrared drying technology to dry stevia and found that it not only improved the drying rate but also maintained the quality of dried stevia products. Fernando and Amaratunga [5] observed that the pepper pods and their components (seeds, pedicels, placenta) can be dried in a short time by far infrared drying and the color change of pepper can be effectively improved.

Infrared convection drying is a hybrid drying method, which combines the advantages of infrared drying and air convection drying. Zhou et al. [29] found that infrared convection drying technology performed well in the drying of spring onion rods, as it not only improved the drying process, but also maintained the quality of dried onion products. Łechtańska et al. [13] studied different drying methods of green pepper and found that infrared convection drying could significantly shorten the drying time, improve the color of products and save energy consumption.

Ultrasonic pretreatment assisted drying as a new non-thermal processing technology has been widely used in food industry [16]. Ultrasonic pretreatment technology can make the cell tissue compress or expand rapidly, form “micro channel” inside the material, promote the migration of water in the cell, and thus achieve the purpose of improving the drying rate. Aydar et al. [3] studied the optimal drying conditions of Inula viscosa leaves under ultrasonic pretreatment assisted microwave drying, and found that the contents of DPPH and TPC in Inula viscosa leaves were the highest after 30 min ultrasonic treatment. Xu et al. [24] studied the effect of ultrasound frequency on the mass transfer, drying kinetics and quality characteristics of infrared dried pineapple slices. Their results showed that ultrasonic pretreatment improved the microstructure of slices, shortened drying time and improved flavor and enzyme inactivation.

To the author’s knowledge, few investigations have been done on the ultrasonic pretreatment assisted far infrared drying of ginger slices and systematic comparison and analysis of a series of infrared drying of ginger slices has not been reported. Thus, in this paper, the effects of three different infrared drying methods (far infrared drying, infrared convection drying and ultrasonic pretreatment assisted far infrared drying) on the drying characteristics, energy consumption and color change of ginger slices were investigated and compared. The purpose of this paper is to provide data reference for the design and optimization of infrared drying of ginger, and provide guidance for the energy saving and emission reduction of ginger drying industry.

2. Materials and methods

Shandong rhubarb ginger was used in this experiment. Fresh ginger was stored in an artificial climate chamber at 6.0 ± 0.5℃. Before drying, the ginger was taken out and placed at room temperature for about 1 h. The ginger was cleaned and cut to the desired thickness with a slicer along the growth direction of the ginger wire. Then the samples were put in a mold to keep the shape and area of the ginger slices consistent. In the experiments, 20 ± 0.5 g fresh ginger slices with an initial moisture content of 95.880 ± 0.01 % w.b. were used. The samples were spread in a single layer and put into a stainless steel experimental tray for drying. A precision electronic balance was used to measure the weight and the value was recorded every 15 min. Energy consumption during the drying process was measured by an electric meter. Continuous drying until the moisture content of ginger slices was below 2 % w.b. Two groups of parallel tests were performed under each experimental condition, and the average value was used.

The instruments used in this experiment were: YLHW-long-wave infrared drying oven for laboratory, with heating power of 2000 W, built-in four 500 W infrared lamps, and the overall dimension of the drying oven is 450 × 350 × 400 mm; KQ-500DE numerical control ultrasonic cleaner, capacity 22.5 L, ultrasonic frequency 40 Hz, ultrasonic input power 500 W, total input power 1300 W; YC-900 infrared convection drying oven, temperature control accuracy ≤±1℃; WR-10 precision colorimeter, repeated accuracy $\Delta E < 0.08$; HC5003X precision electronic balance, the precision is 0.01 g and the external dimension is 385 × 275 × 425 mm. The experimental apparatus is shown in Fig. 1.

For far infrared drying, the effects of drying temperature, infrared power and sample thickness were studied as follows: 1. The infrared power was set as 1000 W, sample thickness was 3 mm, and the temperature was 50℃, 60℃ and 70℃; 2. The infrared power was set as 1500 W, temperature was 70℃, and the sample thickness was 3 mm, 4 mm and 5 mm; 3. The temperature was set as 60℃, thickness was 3 mm, and the infrared power was 500 W, 1000 W and 1500 W.

For infrared convection drying, the sample thickness was set as 3 mm, and the drying temperature was 50℃, 60℃ and 70℃.

For ultrasonic pretreatment assisted far infrared drying, the ginger slices with a thickness of 3 mm were put into the ultrasonic cleaner, and the conditions were set as follows: 1. The ultrasonic time was set as 5 min, and the ultrasonic power (ultrasonic density) was 200 W (1.43 kW/m^2), 250 W (1.79 kW/m^2), 300 W (2.14 kW/m^2), 350 W (2.5 kW/m^2) and 400 W (2.86 kW/m^2); 2. The ultrasonic power was set as 200 W, and the pretreatment time was 5 min, 10 min, 15 min, 20 min and 25 min. After the ultrasonic treatment, the ginger slices were taken out, and the surface moisture was absorbed with filter paper. The weight was measured and then the samples were put into the far infrared drying oven under the conditions of infrared power of 500 W and drying temperature of 70℃. Another group of sample with a thickness of 3 mm, an infrared power of 500 W and a drying temperature of 70℃ without ultrasonic pretreatment was used as the control group.

The instantaneous moisture content was calculated as follows:

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

where M_t is the instantaneous moisture content on dry basis, m_t is the instantaneous mass, and m_d is the dry weight. The dry weight was obtained by hot air drying at 105℃ until the weight change did not exceed 0.05 g.

The instantaneous moisture content on wet basis was calculated as follows:

$$W_t = \frac{m_t - m_d}{m_0} \times 100\% \quad (2)$$

where W_t is the moisture content on wet basis and m_0 is the initial mass. The initial water content of fresh ginger was found to be 95.880 ± 0.01 % w.b.

The drying rate DR was calculated as follows:

$$DR = \frac{M_t - M_{t+\Delta t}}{\Delta t} \quad (3)$$

where Δt is the time interval.

The color parameters of fresh and dried ginger slices were measured by precision colorimeter, and each measurement was repeated for five times to get the average value. The total color change was calculated as follows:

$$\Delta E = \sqrt{(\Delta L)^2 + (\Delta a)^2 + (\Delta b)^2} \quad (4)$$

where L, a,b indicate the brightness, red and green, yellow and blue degree, respectively; ΔL,Δa,Δb indicate the difference of L, a,b before and after drying.

The experimental data was processed by Excel, and the figures were drawn by the Origin 2021. The results were statistically analyzed by ANOVA and Waller-Duncan post hoc comparison of the means at $p < 0.05$ using SPSS Statistics 21 software.

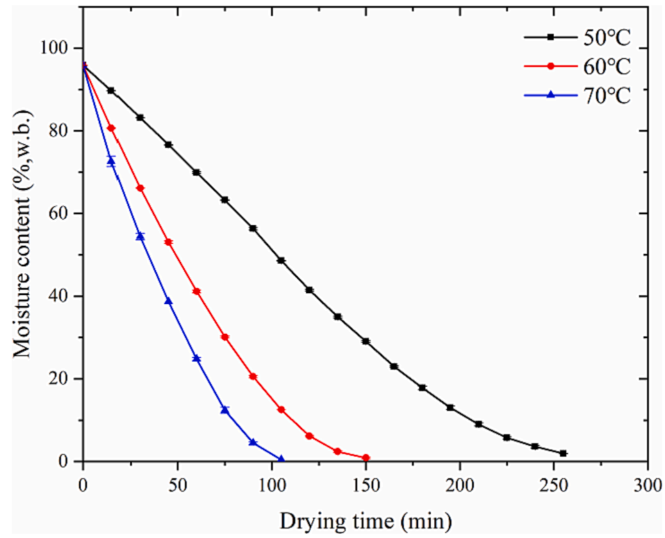


Fig. 2. Moisture content variation of ginger slices at different temperatures.

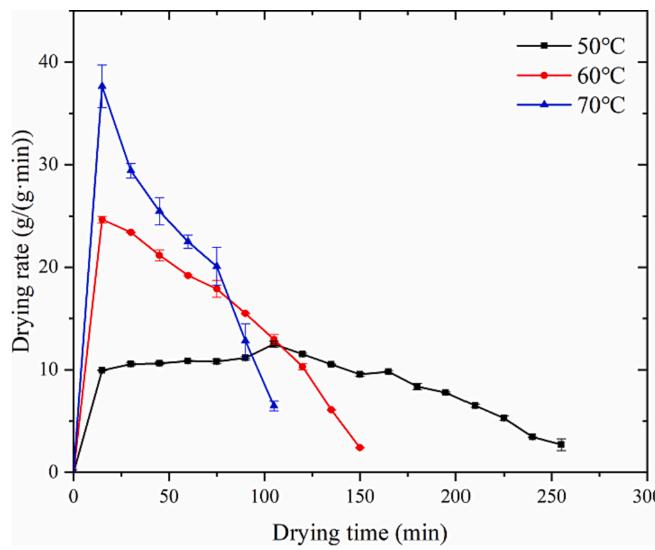


Fig. 3. Drying rate variation of ginger slices at different temperatures.

3. Result and discussion

3.1. Far infrared drying

3.1.1. Effect of drying temperature

Fig. 2 and Fig. 3 show the influence of temperature on the drying characteristics of ginger slices with a sample thickness of 3 mm and a far infrared power of 1000 W. The drying time of ginger slices at 50, 60, 70℃ was 225, 150, 105 min, respectively. With the increase of temperature, the drying time was shortened and the drying rate was accelerated. The drying time at 70℃ was 53.3 % shorter than that at 50℃. The maximum drying rates of 50 and 70℃ were 12.515 g/(g•min) and 37.658 g/(g•min), respectively, indicating that the drying rate was increased by 3 times when the temperature was increased by 20℃. This is consistent with the results of Moon et al., in which the sea cucumber was dried by far infrared drying and the drying rate was also increased with temperature [15]. Xu et al. [25] also obtained the same results by drying figs with far infrared. This may be because with the increase of drying temperature, a large temperature difference between the inside of ginger slices and the environment was formed. The internal temperature was increased by absorbing the energy of infrared radiation, which

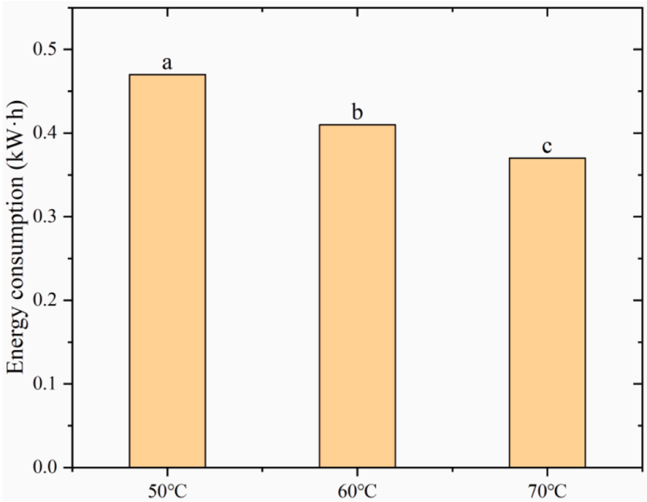


Fig. 4. Energy consumed by ginger slices at different temperatures.

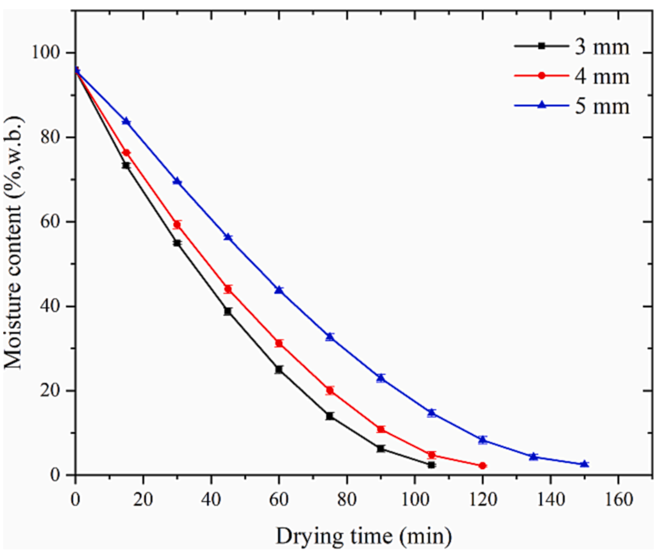


Fig. 5. Moisture content variation of ginger slices at different slice thicknesses.

increased the driving force of moisture inside the ginger slices and accelerated the evaporation of moisture. Thus, the higher the temperature, the more energy absorbed and the faster the drying rate.

Fig. 4 shows the energy consumed by ginger slices at different temperatures. When the temperature in the infrared drying oven was set as 50℃, 60℃ and 70℃, the total energy consumed during the drying process was 0.47, 0.41 and 0.37 kW·h, respectively. Obviously, as the temperature increased, the energy consumption decreased. The energy consumption at 70℃ was the lowest and 21 % less than that at 50℃. Although the drying oven needs more power consumption per unit time to maintain a higher temperature of 70℃, the significant reduction of the drying time reduces the total energy consumption. That is, the increase in temperature accelerates the drying rate and compensates for the energy consumed by the increase in temperature. From the perspective of energy consumption, higher temperature is more suitable for the drying of ginger slices.

3.1.2. Effect of sample thickness

Fig. 5 and Fig. 6 show the influence of sample thickness on the drying characteristics of ginger slices at 1500 W and 70℃. As shown in Table 1, the thickness also had a significant influence on the moisture loss ($p <$ 0.001). When the thickness of ginger slice was 3 mm, 4 mm and 5 mm, the drying time was 105 min, 120 min and 150 min and the maximum drying rate was 36.578 g/(g•min), 31.544 g/(g•min) and 22.960 g/(g•min), respectively. The thinner the ginger slice, the faster the drying rate and the shorter the drying time.

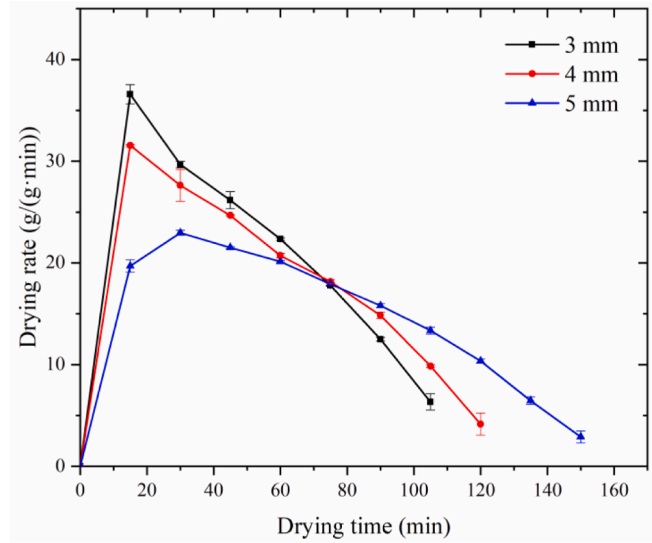


Fig. 6. Drying rate variation of ginger slices at different slice thicknesses.

Table 1
ANOVA results for the effects of variables on the moisture loss.

Variables	Sum of squares	Degree of freedom	F-Value	*p*-Value	Sig.
Infrared temperature	836.316	2	915.531	< 0.001	***
Sample thickness	116.389	2	263.428	< 0.001	***
Infrared power	3.168	2	2.643	0.218	–
Infrared convection temperature	303.820	2	13.802	0.031	*
Ultrasonic pretreatment time	42.725	4	5.923	0.039	*
Ultrasonic power	96.159	4	23.124	0.002	**

Note: * indicates that $p < 0.05$, ** indicates that $p < 0.01$, *** indicates that $p < 0.001$, - indicates that $p > 0.05$.

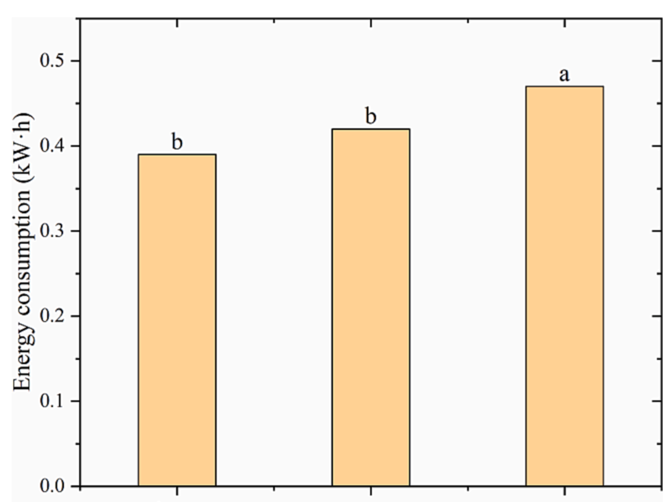


Fig. 7. Energy consumed by ginger slices at different slice thicknesses.

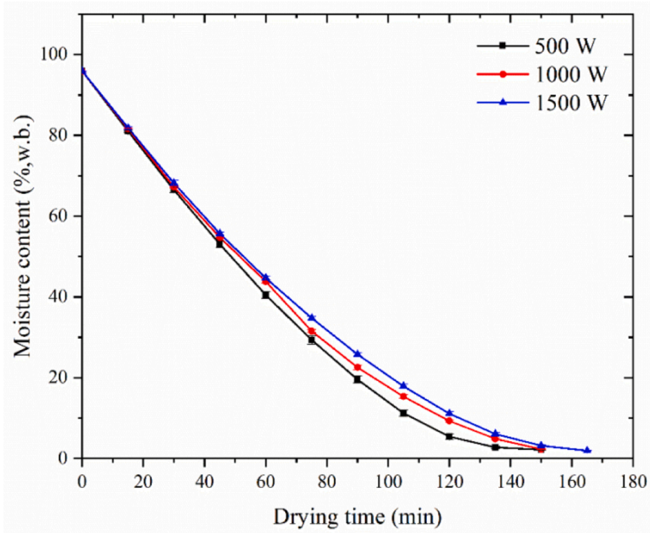


Fig. 8. Moisture content variation of ginger slices at different powers.

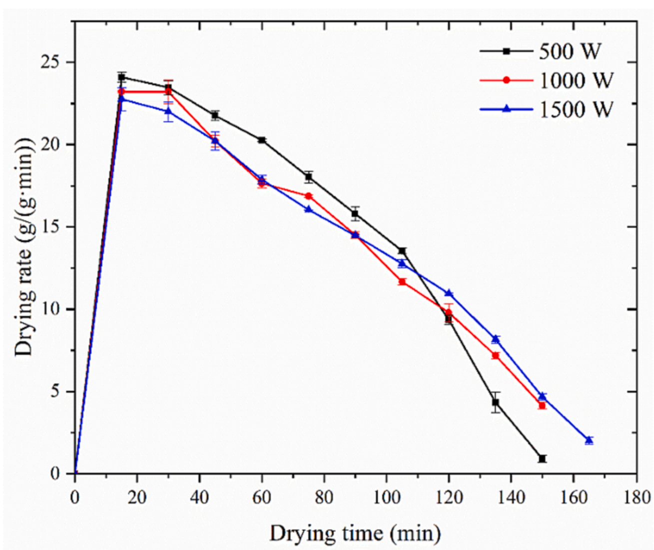


Fig. 9. Drying rate variation of ginger slices at different powers.

At the same time, Fig. 7 shows that the thicker the ginger slice is, the more power is consumed. The reason for this phenomenon may be that the migration distance of moisture in ginger slices was long when the slice was thick. The internal temperature of ginger slices was increased by absorbing infrared energy. When the temperature and power were fixed the same, the activity of water molecules was also the same. As the ginger slices became thicker, it would take more time and energy for the equally active water molecules to escape from the ginger slices, thus the drying rate was slower and the drying time was longer. Sadin et al. [20] also found that with the increase of tomato slice thickness, the infrared drying rate slowed down and the drying time became longer. Kabiru et al. [12] also observed the same phenomenon when studying the effect of mango slice thickness on the hot air drying kinetics.

3.1.3. *Effect of infrared power*

Fig. 8 and Fig. 9 show the influence of infrared power on the drying characteristics of ginger slices with a thickness of 3 mm and a drying temperature of 60℃. As can be seen from Fig. 8, the moisture content of ginger slices decreased continuously with the extension of drying time. When the far infrared power was 500 W, 1000 W and 1500 W, the drying time of ginger slices was between 150 and 165 min. As shown in Table 1, infrared power seems to have no obvious effect on the moisture loss of ginger slices ($p > 0.05$). The maximum drying rates of 500 W, 1000 W and 1500 W shown in Fig. 9 were 24.088, 23.212 and 22.755 g/(g•min), respectively. The drying rate at 500 W was the highest in the early stage of drying and then decreased. The drying time at 500 W and 1000 W was almost the same and both a little bit lower than that at 1500 W. There are two possible reasons for this phenomenon. First, the power of the far infrared drying oven used in this experiment was controlled by the number of infrared lamps, i.e., the more infrared lamps in operation, the greater the power of the far infrared drying oven. Although the overall power of the drying oven became larger at higher infrared power, the light intensity (average energy flow density) did not change substantially as the current passing through each lamp was constant. Second, the infrared energy could quickly penetrate into the ginger slices, the material temperature increased rapidly, and the moisture removal was fast, however, the moisture content in a single piece of ginger slice was limited, which made it hard to identify the impact of infrared power in the rapid drying process, resulting in the phenomenon that infrared power had little influence on the drying kinetics of ginger slices. Zhang et al. [27] investigated the infrared drying characteristics of purple cabbage and also found that the influence of infrared power was not

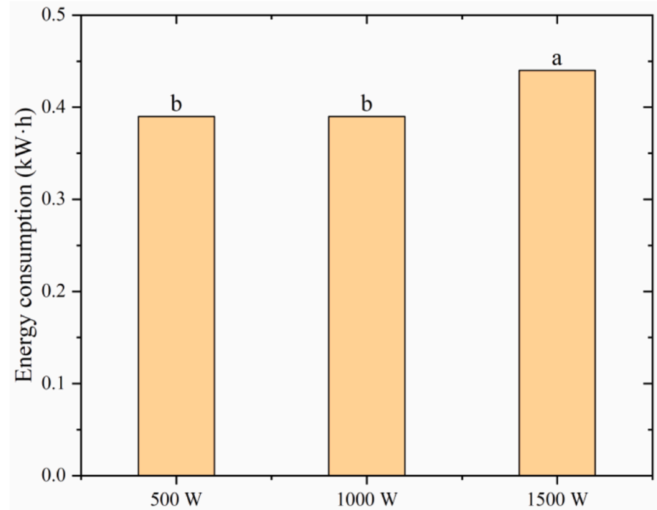


Fig. 10. Energy consumed by ginger slices at different powers.

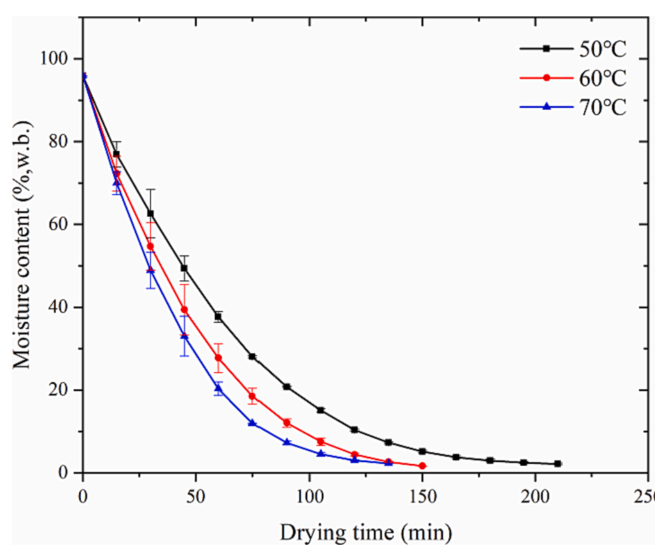


Fig. 11. Moisture content variation of ginger slices at different temperatures.

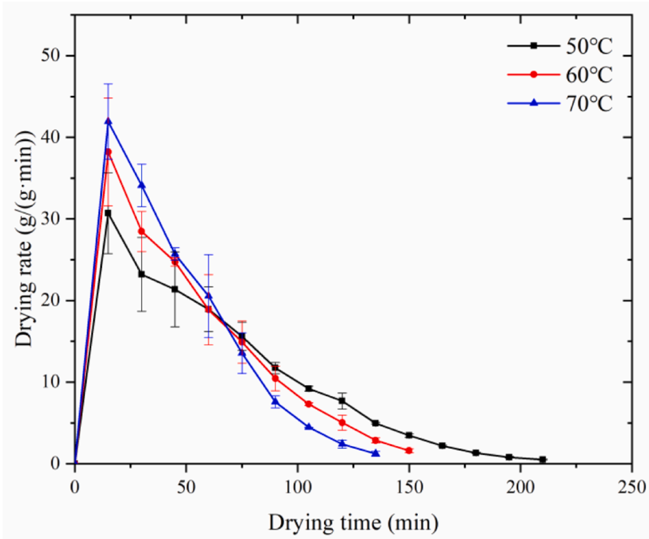


Fig. 12. Drying rate variation of ginger slices at different temperatures.

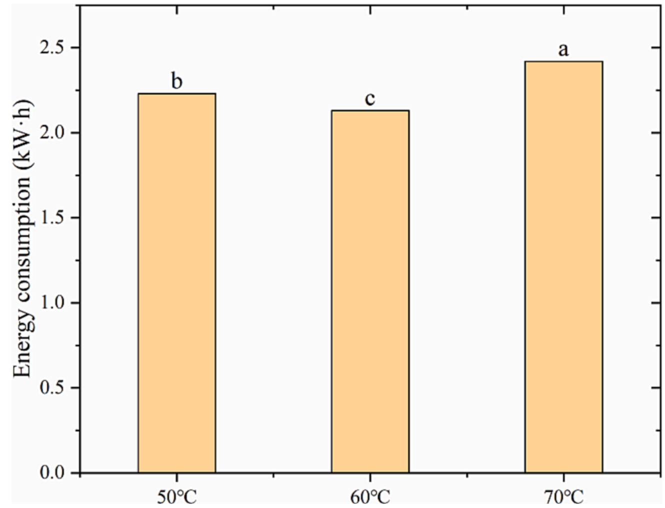


Fig. 13. Energy consumed by ginger slices at different temperatures.

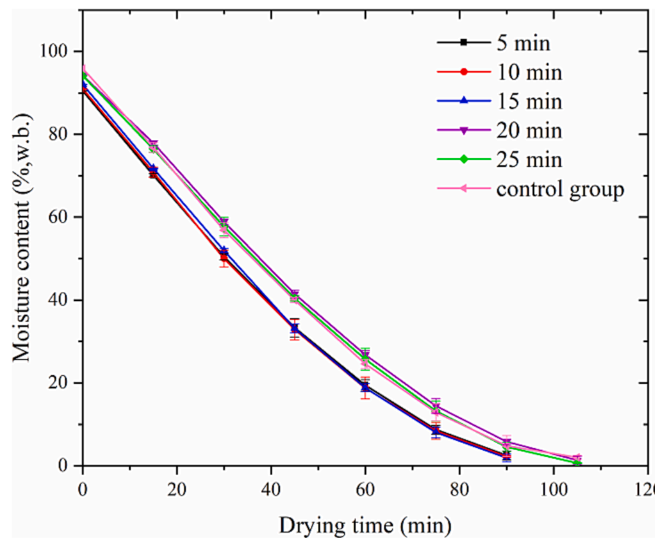


Fig. 14. Moisture content variation of ginger slices at different ultrasonic times.

obvious, which was consistent with the result in this paper.

Fig. 10 shows the total energy consumed by ginger slices at different power levels. As can be seen from the figure, the energy consumed by ginger slices at 500 W, 1000 W and 1500 W was 0.39, 0.39 and 0.44 kW·h, respectively. At 1500 W, the power consumption was the highest, which may be due to the high power required by the drying oven and the relatively long drying time. The power consumption of ginger slices at 500 W and 1000 W was equal. This is because the drying time at 1000 W was slightly shorter, however the power required by the drying oven was larger. The reduced energy consumption due to the shortened drying time just compensated for the energy used for higher power. The experimental results showed that the infrared power of 500 W may be more suitable for the drying of ginger slices in terms of the drying rate and energy consumption.

3.2. Infrared convection drying

3.2.1. Effect of drying temperature

Fig. 11 and Fig. 12 show the influence of drying temperature on the infrared convection drying characteristics of ginger slices with a thickness of 3 mm. Fig. 11 shows that the moisture content decreases with the extension of drying time and the increase of temperature. The drying time at 50, 60 and 70℃ was 210 min, 150 min and 135 min, respectively. Fig. 12 shows that the highest drying rate was at 70℃, which was 41.938 g/(g•min), followed by 60℃ (38.205 g/(g•min)) and 50℃ (30.688 g/(g•min)). The infrared convection dryer in this experiment uses infrared lamps to radiate heating, and the convective air is directly sent into the drying oven by the blower. The air temperature is the room temperature, which is basically unchanged. The variation of drying temperature is induced by infrared heating, which is similar to the conventional infrared drying. As expected, the higher the drying temperature, the faster the ginger slices drying. Compared with pure infrared drying, the drying rate of infrared convection drying was increased a lot. For example, the maximum drying rate of pure infrared drying at 3 mm, 1000 W, 50℃ and 70℃ was 12.515 g/(g•min) and 37.658 g/(g•min), respectively, while the corresponding value of infrared convection drying at 3 mm, 50℃ and 70℃ was 30.688 g/(g•min) and 41.938 g/(g•min), respectively; the maximum drying rate of pure infrared drying at 3 mm, 500 W, 60℃ was 24.088 g/(g•min), while the corresponding value of infrared convection drying at 3 mm, 60℃ was 38.205 g/(g•min). It indicates that the drying rate under infrared convention drying was increased by up to 145 %. This is because the moisture that escapes from the surface of the ginger slices can be quickly taken away by the convective air during the drying process, which accelerates the drying rate.

Fig. 13 shows the energy consumed by ginger slices at different temperatures during infrared convection drying. It was found that the energy consumption at 50, 60 and 70℃ was 2.23, 2.13 and 2.42 kW·h, respectively. The energy consumption was the lowest when the temperature was 60℃, indicating that the energy consumed when the temperature was increased by 10℃ was less than that consumed by a long drying time at a low temperature of 50℃. However, the highest energy consumption was at 70℃, indicating that when the temperature was increased by 20℃, the overall energy consumption was higher. Obviously, 60℃ is more suitable for infrared convection drying from the perspective of energy consumption.

3.3. Effect of ultrasonic pretreatment on far infrared drying

3.3.1. Effect of ultrasonic time

Fig. 14 and Fig. 15 show the influence of different ultrasonic pretreatment time on the drying characteristics of ginger slices with an ultrasonic power of 200 W, a sample thickness of 3 mm, a far infrared power of 500 W and a drying temperature of 70℃. The drying

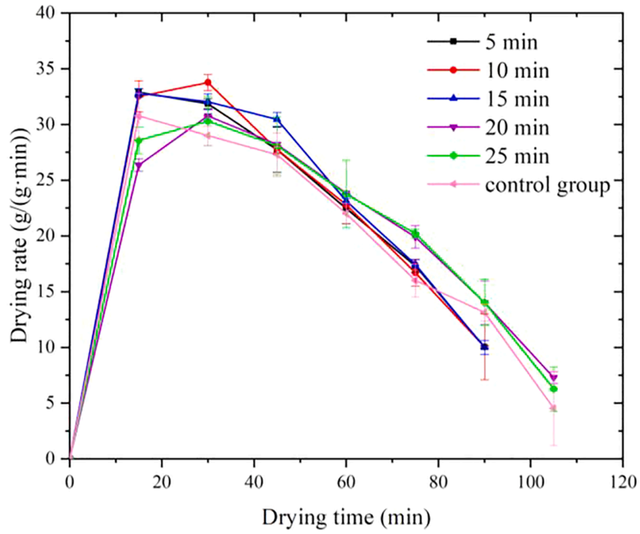


Fig. 15. Drying rate variation of ginger slices at different ultrasonic times.

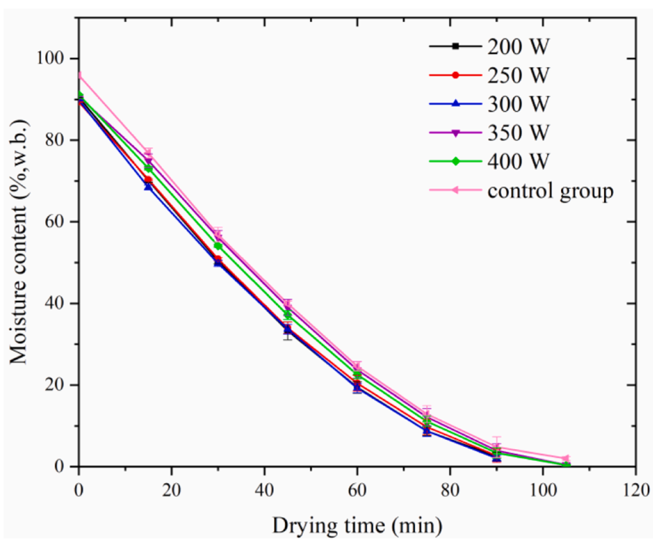


Fig. 16. Moisture content variation of ginger slices at different ultrasonic powers.

characteristic of ginger slice without ultrasonic pretreatment was also shown in the figures as a control group. From Fig. 14, one can see that the moisture content of ginger slices decreased gradually with the extension of drying time. The moisture content of ginger slices at pretreatment times of 5 min, 10 min, 15 min was lower than that without pretreatment, however, the difference was not obvious when the ultrasonic pretreatment time was relatively long, namely 20 min and 25 min. The drying rate presented in Fig. 15 shows that the drying process has a downward trend. When the ultrasonic pretreatment time was 5 min, 10 min and 15 min, the drying rate was firstly faster and then slower than that of the control group. This may be because the free water first migrated from the ginger slices and then the bound water. With the ultrasonic pretreatment, the cell tissue of ginger slices was slightly expanded [19], resulting in the free water in the cells escaping more easily and faster through the enlarged channel than the control group in the early stage of drying. However, when the moisture content in the pretreated samples decreased to a low value, the remaining water with a low degree of freedom was difficult to migrate outward. Thus the drying rate slowed down in the later stage of drying [26].

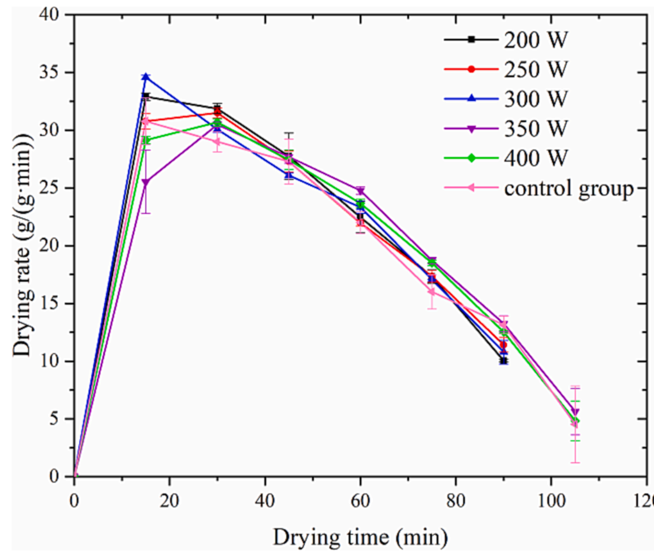


Fig. 17. Drying rate variation of ginger slices at different ultrasonic powers.

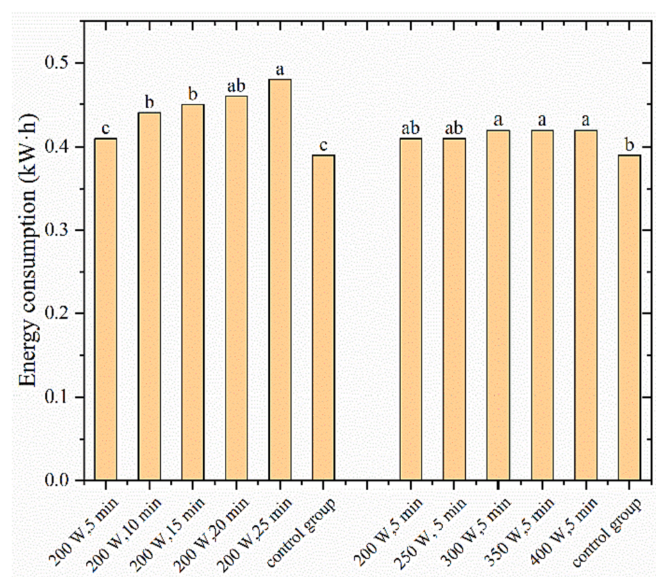


Fig. 18. Energy consumed by ginger slices at different ultrasonic power and time.

3.3.2. *Effect of ultrasonic power*

The influence of ultrasonic power on the drying characteristics of ginger slices with an ultrasonic pretreatment time of 5 min, a sample thickness of 3 mm, an infrared power of 500 W and a drying temperature of 70℃ is shown in Fig. 16 and Fig. 17. As can be seen from Fig. 16, the moisture content of all the ultrasonic pretreated ginger slices had the same trend. When the ultrasonic power was 300 W, the moisture content was the lowest, and the drying time was the shortest. However, the drying effect was not very ideal when the ultrasonic power was increased to 350 W or 400 W. Though the moisture content of these two groups was lower than that of the control group, their moisture content was always higher than that of other pretreated samples at the same drying time. From Fig. 17, one can see that the initial drying rate at 300 W was the highest, and the maximum drying rate of 200–300 W groups was higher than that of the control group, indicating that the ultrasonic pretreatment could promote the far infrared drying of ginger slices when the ultrasonic power was appropriate. This is because ultrasonic pretreatment can change the microstructure of ginger slices [28], and the

Table 2
Box-Behnken design and results.

Exp.	Input variables				Response variables		
	X_1 (W)	X_2 (min)	X_3 (°C)	X_4 (mm)	Y_1 (min)	Y_2 (kW·h)	Y_3
1	300(1)	10(0)	60(0)	5(1)	135	0.607	11.335
2	250(0)	10(0)	60(0)	4(0)	110	0.49	10.786
3	200(-1)	5(-1)	60(0)	4(0)	150	0.496	12.83
4	250(0)	5(-1)	50(-1)	4(0)	165	0.591	10.893
5	200(-1)	10(0)	70(1)	4(0)	90	0.486	15.187
6	250(0)	10(0)	70(1)	5(1)	90	0.457	10.944
7	250(0)	10(0)	60(0)	4(0)	120	0.49	9.403
8	250(0)	5(-1)	60(0)	3(-1)	90	0.394	10.276
9	200(-1)	15(1)	60(0)	4(0)	135	0.563	18.972
10	250(0)	10(0)	70(1)	3(-1)	75	0.406	10.893
11	250(0)	15(1)	70(1)	4(0)	90	0.47	12.275
12	200(-1)	10(0)	60(0)	3(-1)	120	0.457	16.191
13	250(0)	10(0)	60(0)	4(0)	130	0.448	9.801
14	250(0)	15(1)	50(-1)	4(0)	180	0.568	16.759
15	300(1)	10(0)	60(0)	3(-1)	90	0.425	13.683
16	250(0)	5(-1)	70(1)	4(0)	90	0.42	10.801
17	250(0)	15(1)	60(0)	3(-1)	100	0.446	14.792
18	300(1)	10(0)	70(1)	4(0)	75	0.418	12.793
19	200(-1)	10(0)	50(-1)	4(0)	165	0.521	18.994
20	300(1)	10(0)	50(-1)	4(0)	150	0.502	13.732
21	250(0)	10(0)	50(-1)	5(1)	165	0.771	12.008
22	250(0)	5(-1)	60(0)	5(1)	120	0.494	10.671
23	250(0)	10(0)	60(0)	4(0)	120	0.485	9.812
24	250(0)	10(0)	60(0)	4(0)	120	0.49	8.502
25	300(1)	5(-1)	60(0)	4(0)	110	0.457	10.349
26	250(0)	10(0)	50(-1)	3(-1)	135	0.448	14.728
27	300(1)	15(1)	60(0)	4(0)	105	0.49	11.132
28	250(0)	15(1)	60(0)	5(1)	125	0.559	12.573
29	200(-1)	10(0)	60(0)	5(1)	120	0.479	14.22

cavitation and mechanical effects of ultrasound produce many microchannels inside the ginger slices, which makes the moisture easily and quickly remove during the drying process. If the ultrasonic power is too large, the moisture migration channel will be destroyed, thus the subsequent drying is hindered and the drying rate is reduced [23].

Fig. 18 shows the energy consumed by the far infrared drying of ginger slices pretreated with different ultrasonic times and powers. As shown in the figure, with the increase of ultrasonic power or the extension of ultrasonic processing time, the consumption of electric energy will increase. When the power increased from 200 W to 400 W, the energy consumption was increased by only 0.01 kW·h, however, when the pretreatment time increased from 5 min to 25 min, an extral energy of 0.07 kW·h was consumed. Therefore, it seems that increasing the ultrasonic power is more energy-saving than increasing the pretreatment time when the promotion effect is not much different.

3.4. Optimization of ultrasonic pretreatment assisted far infrared drying

The response surface analysis method (RSM) was conducted to optimize the ultrasonic pretreatment assisted far infrared drying process. The infrared power was set to a fixed value of 500 W according to the single-factor experiments. As the ultrasonic power, ultrasonic pretreatment time, infrared temperature and sample thickness have significant effects on the drying process, four independent variables, including ultrasonic power (X_1), ultrasonic pretreatment time (X_2), infrared temperature (X_3) and sample thickness (X_4), were studied by Box-Behnken Design (BBD). The responses were drying time (Y_1), energy consumption (Y_2) and total color change (Y_3). The design matrix consisted of 29 trials, which was shown in Table 2.

The experimental responses of drying time, energy consumption and total color change were also presented in Table 2. It can be seen from the table that the drying time varied from 75 to 180 min, which was the shortest at an infrared temperature of 70°C and the longest at a temperature of 50°C. The energy consumption increased with the increase of ultrasonic power, ultrasonic time, infrared temperature and sample thickness. The value ranged from 0.394 to 0.771 kW·h. Besides, higher infrared temperature also increased the total color change, however, the increase of ultrasonic power or ultrasonic time can alleviate the color change to a certain extent.

The regression equations of drying time (Y_1), energy consumption (Y_2) and total color change (Y_3) were obtained by Design Expert software and were shown in Table 3. A large F value and a small p value ($p <$ 0.0001) indicated that the model was significant at the 95 % confidence level.$R^2 > 0.85$ indicated that the model adequately represented the actual relationship between the independent variables and the response values.

The drying process should have a shorter drying time, a lower energy consumption and a lower total color change. The total response expression is as follows:

$$Y = Y_1 + Y_2 + Y_3 \tag{5}$$

The model in Table 3 was substituted into Eq. (5), and the optimum drying condition was obtained by MATLAB when the minimum value of Y was achieved. The calculated results showed that the optimal conditions were at an ultrasonic time of 15 min, an ultrasonic power of 200 W, a far infrared temperature of 70°C and a sample thickness of 5 mm. Under the optimal conditions, the predicted drying time was 82 min, the energy consumption was 0.461 kW·h and the total color change was 11.102.

Validation experiments were conducted at the optimum drying conditions to verify the predicted response values. Two parallel experiments were performed and the average value was used. The drying time and energy consumption were recorded, and the color of the dried products was measured. The experimental results showed that the drying time was 90 min, the energy consumption was 0.452 kW·h, and the total color change was 11.685. The difference between the experimental value and predicted value was <10 %.

3.5. Comparison of three infrared drying methods

3.5.1. Drying characteristics

The maximum drying rate of infrared convection drying was higher than that of far infrared drying, indicating that the addition of convective air effectively accelerated the evaporation of moisture. The moisture escapes from the surface of the ginger slices, and the convective air can quickly take it away, hence accelerating the drying process.

The far infrared drying was not expectantly promoted by the increase of ultrasonic power or the extension of ultrasonic pretreatment time. Compared with the control group, the moisture content of ultrasonic pretreatment at 5, 10 and 15 min was smaller, however, when the

Table 3
ANOVA results for response parameters.

Responses	Models	F-Value	p-Value	R^2
Drying time	$Y_1 = 119.66 - 9.58X_1 + 0.83X_2 - 37.5X_3 + 12.08X_4 + 2.5X_1X_2 + 11.25X_1X_3 - 3.75X_2X_3 - 1.25X_2X_4 - 3.75X_3X_4$	17.00	<0.0001	0.9042
Energy consumption	$Y_2 = 0.4914 - 0.0086X_1 + 0.0203X_2 - 0.062X_3 + 0.0659X_4 - 0.0085X_1X_2 - 0.0122X_1X_3 + 0.04X_1X_4 + 0.0183X_2X_3 + 0.0033X_2X_4 - 0.068X_3X_4$	8.35	<0.0001	0.8622
Total color change	$Y_3 = 9.66 - 1.95X_1 + 1.72X_2 - 1.19X_3 - 0.73X_4 - 1.34X_1X_2 + 0.717X_1X_3 - 0.0943X_1X_4 - 1.1X_2X_3 - 0.6535X_2X_4 - 0.6928X_3X_4 + 3.14X_1^2 + X_2^2 + 1.96X_3^2 + 0.9992X_4^2$	20.04	<0.0001	0.9525

Table 4
Color change of ginger slices at different drying methods.

Drying method	Experimental conditions		Color change value
Far infrared drying	3 mm,1000 W	50℃	15.806
		60℃	14.670
		70℃	18.789
	70℃,1500 W	3 mm	14.411
		4 mm	8.492
		5 mm	16.546
	60℃,3 mm	500 W	10.204
		1000 W	11.063
		1500 W	10.611
Infrared convection drying	3 mm	50℃	7.556
		60℃	7.087
		70℃	6.231
Ultrasonic pretreatment assisted far infrared drying	200 W	5 min	18.065
		10 min	18.773
		15 min	19.899
		20 min	17.342
		25 min	19.873
		25 min	15.873
	5 min	200 W	18.065
		250 W	8.665
		300 W	14.789
		350 W	13.536
		400 W	11.508
	control group		12.147

pretreatment time was extended to 20–25 min, the moisture content was almost coincided with the control group. Increasing the ultrasonic power was more effective than prolonging the ultrasonic time in promoting the far infrared drying of ginger slices. As shown in Fig. 15 and Fig. 17, the groups (e.g., ultrasonic pretreatment time of 5, 10, 15 min groups and ultrasonic pretreatment power of 200, 250, 300 W groups) presented higher drying rates than the control group in the early stage of drying, indicating that the ultrasound technology showed its greatest potential to enhance the drying rate at the beginning of the drying process. However, as the drying process continued, the moisture content of the slices decreased and the diffusion of moisture from the inside of the slices to its surface and environment also decreased, thus the drying rate decreased. Jarahizadeh and Taghian Dinani [10] also reported that the ultrasonic pretreatment mainly improved the drying process in the initial stage of drying, but it was not obvious in the final stage of drying.

3.5.2. *The energy consumption*

As a blower is installed in the infrared convection drying oven, the corresponding energy consumption is about 5 times that of far infrared drying oven. Thus, far infrared drying method is more energy saving than infrared convection drying method.

The energy consumption of ultrasonic pretreatment assisted far infrared drying is also larger than that of far infrared drying under the conditions here. This is because the ultrasonic pretreatment process will consume about 0.01–0.07 kW·h of electric energy, while the increased drying rate and reduced drying time by ultrasonic pretreatment cannot make up for the energy consumption. The shorter the pretreatment time and the smaller the power, the less energy is consumed.

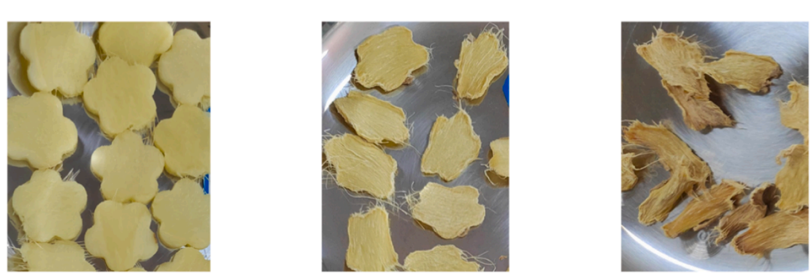
3.5.3. *The color change*

Table 4 shows the color change of ginger slices under three different infrared drying methods. According to the table, when the far infrared drying temperature was 70℃, the sample thickness was 4 mm, and the infrared power was 1500 W, the color change of ginger slices was the smallest and the maintenance of color was the best. For the infrared convection drying, the effect of temperature on the color change was not obvious, and the color change was the smallest at 70℃ due to the shortened drying time. For ultrasonic pretreatment assisted far infrared drying, the color change value was the smallest at an ultrasonic power of 250 W and a pretreatment time of 5 min. With the increase of power and the extension of the treatment time, the color change value decreased. The difference of color change under different drying methods is relatively large. The average color change value is the smallest under infrared convection drying, followed by far infrared drying and ultrasonic pretreatment assisted far infrared drying. In fact, as shown in Fig. 19, at the early stage of drying, the color change of ginger slices was not obvious. However, at the end of drying, due to the serious moisture loss and high temperature drying, the color of ginger slices became dark and the color change value increased.

4. Conclusion

In this paper, the drying characteristics, energy consumption and color change of ginger slices under far infrared drying, infrared convection drying, ultrasonic pretreatment assisted far infrared drying were studied. The main results were as follows:

(1) With the extension of drying time, the moisture content of ginger slices reduced, the drying rate decreased, and the drying process was controlled by the falling rate drying.
(2) For the far infrared drying, with the decrease of thickness and the increase of temperature, the drying rate accelerated, and the energy consumption decreased. In terms of drying rate and energy consumption, the drying conditions of a thickness of 3 mm, a drying temperature of 70℃, and an infrared power of 500 W are suitable.
(3) For infrared convection drying, the drying rate was accelerated and the drying time was shortened with the increase of temperature. However, the energy consumption at 60℃ was 0.29 kW·h



(a) Fresh ginger (b) The medium stage of the drying (c) Dried ginger

Fig. 19. Color change of ginger slices during drying.

less than that at 70℃, and only 15 min was saved at 70℃. Thus, 60℃ is more suitable for infrared convection drying.

(4) Appropriate ultrasonic pretreatment time and power can effectively promote the far infrared drying of ginger slices. Increasing ultrasonic power is more effective than increasing ultrasonic pretreatment time. Optimization of ultrasonic pretreament assisted far infrared drying showed that the optimal conditions were at an ultrasonic time of 15 min, an ultrasonic power of 200 W, a far infrared temperature of 70℃ and a sample thickness of 5 mm.

(5) Compared with far infrared drying method, infrared convection drying method had faster drying rate and smaller color change, but higher energy consumption; the ultrasonic pretreatment can promote the far infrared drying of ginger to a certain extent, but the energy consumption would increase slightly.

CRediT authorship contribution statement

Dongyan Zhang: Software, Formal analysis, Data curation, Writing – original draft. **Dan Huang:** Writing – review & editing, Resources, Funding acquisition. **Yixiao Zhang:** Validation, Investigation. **Yijun Lu:** Validation, Investigation. **Shuai Huang:** Software, Formal analysis. **Guiliang Gong:** Supervision. **Lijun Li:** Supervision.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

This work has been supported by the Nature Science Foundation of Hunan (2022JJ40860; 2021JJ41081) and Hunan Provincial Key Research and Development Program (2021NK2023).

References

[1] E.K. Akpinar, S. Toraman, Determination of drying kinetics and convective heat transfer coefficients of ginger slices, Heat Mass Transf. 52 (10) (2016) 2271–2281.
[2] A.M.A. Ali, M.E.M. El-Nour, S.M. Yagi, Total phenolic and flavonoid contents and antioxidant activity of ginger (Zingiber officinale Rosc.) rhizome, callus and callus treated with some elicitors, J. Genet. Eng. Biotechnol. 16 (2) (2018) 677–682.
[3] A.Y. Aydar, T. Aydın, T. Yılmaz, A. Kothakota, S.C. Terezia, C.F. Leontin, R. Pandiselvam, Investigation on the influence of ultrasonic pretreatment on color, quality and antioxidant attributes of microwave dried Inula viscosa (L.), Ultrason. Sonochem. 90 (2022), 106184.
[4] K. Chapchaimoh, N. Poomsa-Ad, L. Wiset, J. Morris, Thermal characteristics of heat pump dryer for ginger drying, Appl. Therm. Eng. 95 (2016) 491–498.
[5] A.J. Fernando, S. Amaratunga, Application of far-infrared radiation for sun-dried chili pepper (Capsicum annum L.): drying characteristics and color during roasting, J. Sci. Food Agric. (2021).
[6] M. Hawlader, C.O. Perera, M. Tian, Comparison of the retention of 6-gingerol in drying of ginger under modified atmosphere heat pump drying and other drying methods, Drying Technol. 24 (1) (2006) 51–56.
[7] B. Huang, G. Wang, Z. Chu, L. Qin, Effect of oven drying, microwave drying, and silica gel drying methods on the volatile components of ginger (Zingiber officinale Roscoe) by HS-SPME-GC-MS, Drying Technol. 30 (3) (2012) 248–255.
[8] X. Huang, W. Li, Y. Wang, F. Wan, Drying characteristics and quality of Stevia rebaudiana leaves by far-infrared radiation, LWT. 140 (2021), 110638.
[9] S.V. Jangam, B.N. Thorat, Optimization of spray drying of ginger extract, Drying Technol. 28 (12) (2010) 1426–1434.
[10] H. Jarahizadeh, D.S. Taghian, Influence of applied time and power of ultrasonic pretreatment on convective drying of potato slices, Food Sci. Biotechnol. 28 (2) (2019) 365–376.
[11] E. Jayashree, R. Visvanathan, J. Zachariah, Quality of dry ginger (Zingiber officinale) by different drying methods, J. Food Sci. Technol. 51 (11) (2014) 3190–3198.
[12] A.A. Kabiru, A.A. Joshua, A.O. Raji, Effect of slice thickness and temperature on the drying kinetics of mango (Mangifera indica), International Journal of Research and Review in Applied Sciences 15 (1) (2013) 41–50.
[13] J. Łechtańska, J. Szadzińska, S. Kowalski, Microwave-and infrared-assisted convective drying of green pepper: Quality and energy considerations, Chem. Eng. Process. 98 (2015) 155–164.
[14] F. Liao, S. Cui, Z. Zhou, Q. He, L. Li, Z. Li, X. You, Comparison of ginger powder properties by three processing technology, Chinese Food Additives. 73–77 (2012).
[15] J.H. Moon, M.J. Kim, D.H. Chung, C.H. Pan, W.B. Yoon, Drying Characteristics of Sea Cucumber (S tichopus japonicas S elenka) Using Far Infrared Radiation Drying and Hot Air Drying, J. Food Process. Preserv. 38 (4) (2014) 1534–1546.
[16] J. Ni, C. Ding, Y. Zhang, Z. Song, Impact of different pretreatment methods on drying characteristics and microstructure of goji berry under electrohydrodynamic (EHD) drying process, Innov. Food Sci. Emerg. Technol. 61 (2020), 102318.
[17] D. Nowak, P.P. Lewicki, Infrared drying of apple slices, Innov. Food Sci. Emerg. Technol. 5 (3) (2004) 353–360.
[18] R. Osae, G. Essilfie, R.N. Alolga, E. Bonah, H. Ma, C. Zhou, Drying of ginger slices—Evaluation of quality attributes, energy consumption, and kinetics study, J. Food Process Eng 43 (2) (2020) e13348.
[19] P.B. Pathare, G. Sharma, Effective moisture diffusivity of onion slices undergoing infrared convective drying, Biosyst. Eng. 93 (3) (2006) 285–291.
[20] R. Sadin, G.-R. Chegini, H. Sadin, The effect of temperature and slice thickness on drying kinetics tomato in the infrared dryer, Heat Mass Transf. 50 (4) (2014) 501–507.
[21] Y. Sivasothy, W.K. Chong, A. Hamid, I.M. Eldeen, S.F. Sulaiman, K. Awang, Essential oils of Zingiber officinale var. rubrum Theilade and their antibacterial activities, Food Chem. 124 (2) (2011) 514–517.
[22] J. Sun, J. Gong, P. Song, Z. Zheng, Research progress on technology of ginger drying, Food Industry. (2020).
[23] F. Wan, W. Li, Y. Luo, B. Wei, X. Huang, Effects of ultrasonic pretreatment on far infrared vacuum drying properties and quality of lycium barbarum, Chinese Herbal Medicine. 51 (2020) (2020) 4654–4663.
[24] B. Xu, E.S. Tiliwa, B. Wei, B. Wang, Y. Hu, L. Zhang, H. Ma, Multi-frequency power ultrasound as a novel approach improves intermediate-wave infrared drying process and quality attributes of pineapple slices, Ultrason. Sonochem. 88 (2022), 106083.
[25] W. Xu, Y. Pei, G. Zhu, C. Han, M. Wu, T. Wang, J. Sun, Effect of far infrared and far infrared combined with hot air drying on the drying kinetics, bioactives, aromas, physicochemical qualities of Anoectochilus roxburghii (Wall.), Lindl. LWT. 162 (2022) 113452.
[26] L. Yuan, X. He, R. Lin, S. Cheng, Effects of ultrasound pretreatment on water state and hot-air drying characteristics of kiwifruit, Chinese Journal of Agricultural Engineering. 37 (2021) (2021) 263–272.
[27] Zhang L, Yu X, Bai J, Xu P, Ma H, Zhou C. Effect of infrared drying technology on drying characteristics of purple cabbage. Modern Food Technology. 33(2017): 202-209+176 (2017).
[28] Z. Zhang, L. Han, T. Jin, Y. Peng, Experimental study the effect of ultrasonic pretreatment on the quality of pinapple dried by heat pump, Food and Fermentation Industry 48 (2022) (2022) 111–116.
[29] C. Zhou, Z. Wang, X. Wang, A.E. Yagoub, H. Ma, Y. Sun, X. Yu, Effects of tri-frequency ultrasound-ethanol pretreatment combined with infrared convection drying on the quality properties and drying characteristics of scallion stalk, J. Sci. Food Agric. 101 (7) (2021) 2809–2817.
[30] D. Zhu, L. Wang, L. Zhao, Y. Ge, X. Cao, J. Li, Research progress on processing technology of ginger power, Chinese Condiments. 41 (2016) (2016) 150–153.