THE IMPACT OF OHMIC HEATING ON RICE GRAIN HARDNESS AND HEATING UNIFORMITY COMPARED TO CONVENTIONAL COOKING METHODS
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欧姆加热与传统加热蒸煮米饭对米粒硬度与加热均匀性的影响

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ABSTRACT
This study investigated the effects of ohmic heating on rice grain hardness and heating uniformity compared to conventional cooking methods. A self-developed ohmic heating system was utilized to cook rice, and the performance was evaluated against that of a traditional heating. The uniformity of rice temperature and the hardness of rice grains under different water-to-rice ratios were measured using a 5-channel temperature acquisition system and a texture analyzer, and the performance of the two heating methods was comprehensively evaluated. The results indicated that the ohmic heating equipment effectively controlled the temperature variations at each stage, with the maximum heating rate error being 1.24% and the R^2 value of the heating curve fitting exceeding 0.9997. Compared to traditional cooking methods, although the temperature difference during the ohmic heating of rice reached 18.32~31.85℃, which is greater than the 21.42~29.94℃ observed in traditional heating, the hardness variation of rice at different locations was significantly lower than that achieved with conventional methods. This was primarily attributed to the fact that as the insulation time was extended, the hardness differences between different layers of rice gradually decreased, ultimately resulting in the hardness of the upper, middle, and lower layers of rice being within the range of 18~21 N, thus achieving a more uniform texture of the rice. The results show that ohmic heating technology has great potential to reduce the rice hardness, and provides theoretical basis and technical support for designing more efficient rice cooking equipment.

摘要
本文研究了欧姆加热对米饭粒硬度和加热均匀性的影响，并与传统烹饪方法进行了比较。使用了自行开发的欧姆加热系统对米饭进行烹饪，同时以传统电饭煲作为对照。采用 5 通道温度采集系统和质构仪测量了不同水米比例下的米饭温度均匀性和米粒硬度，全面评估了两种加热方式的性能。研究结果显示，欧姆加热设备有效控制了各阶段的温度变化，加热速率误差最大为 1.24%，加热曲线线性拟合 R^2 大于 0.9997。与传统烹饪方法相比，虽然欧姆加热米饭过程中温差达到 18.32~31.85℃，大于传统加热的 21.42~29.94℃，但是欧姆加热各个位置的米饭硬度差异远小于传统加热方法。这主要得益于随着保温时间的延长，不同层米饭之间的硬度差异逐渐减小，最终上中下层米饭硬度均在 18~21N 之间，实现了更均匀的米饭质地。研究结论表明，欧姆加热技术具有改善米饭烹饪品质的巨大潜力，为设计更高效的米饭烹饪设备提供了理论基础和技术支持。

INTRODUCTION
The primary method of rice consumption involves cooking the rice-water mixture to form rice, predominantly through traditional heating methods. However, traditional heating methods transfer heat via the container, leading to uneven heating and inconsistent rice quality. Therefore, scholars have recently adopted volumetric heating methods such as microwave and radio frequency to cook rice (*Thuengtung and Ogawa, 2020; Verma et al., 2024; Rostamabadi et al., 2024*). Although these methods enhance electrical energy utilization, they are hindered by high energy consumption, costs, safety issues, and failure rates, limiting their broader adoption.

Researchers have recently employed ohmic heating technology for rice cooking in order to enhance its overall quality. *Jittanit et al., (2017),* conducted ohmic heating and conventional heating tests on four types of rice samples. The study found that ohmic heating resulted in softer rice compared to conventional methods. Additionally, the energy consumption and energy cost of the ohmic method were approximately 73% to 90% of that of the conventional cooking method. Furthermore, ohmic cooking was demonstrated to be energy-efficient, reducing the come-up time of the conventional cooking method by 48%.

Specifically, the constant rate values indicated that ohmic cooking could soften rice grains at a greater rate compared to other cooking methods (*Gavahian et al., 2019*). Therefore, ohmic heating technology has great potential in rice cooking. However, existing studies have only selected samples from a specific location in the rice to compare and analyze the temperature and food properties under different heating methods (*Ding et al, 2020*), and have not analyzed the temperature and food property differences from a three-dimensional perspective. That is to say, the uniformity of heating and the hardness differences between ohmic heating and conventional heating have not been investigated.

A rice cooking device based on ohmic heating was developed in this study, which is capable of achieving precise temperature control, including temperature rise phase and insulation phase. The ohmic heating rate was then adjusted to make the heating process similar to that of traditional resistance wire heating. At different water-to-rice ratios, the differences and similarities between ohmic heating and traditional heating in terms of temperature uniformity and rice hardness were compared, and the reasons for these differences were explored. This study provides a theoretical basis for the design of a more comprehensive ohmic heating steamed rice cooking device.

MATERIALS AND METHODS

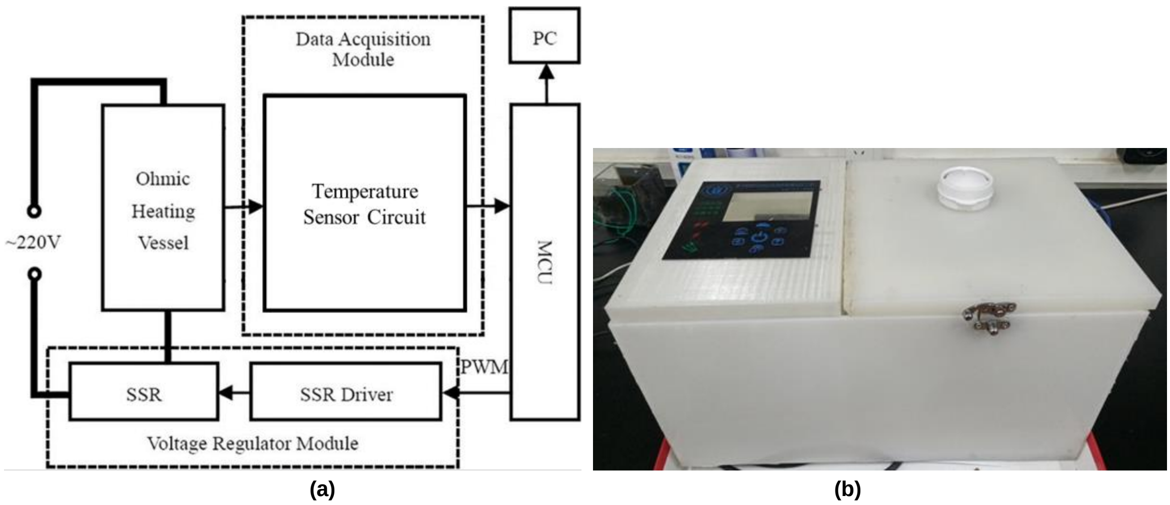
Materials

The rice used for the experiment was selected for uniform grain quality and it was japonica rice of high-quality. The initial moisture content was 11.86 ± 0.19% on a wet basis. The rice was packaged and filled with carbon dioxide, and stored in a cool, ventilated and dry place. As home cooking of rice typically uses tap water, this experiment also used tap water. Prior to each set of experiments, the water was stored in a large container to ensure the consistency of the tap water quality (*Kanjanapongkul, 2017*).

Rice cooking method

(1) Ohmic heating

Ohmic heating, also known as resistive heating or Joule heating, is fundamentally based on the electrical conductivity of food materials to directly convert electrical energy into thermal energy. When an electric field is applied across the two ends of the material, the current passes through the material, causing heat generation within it, thereby achieving heating. The ohmic heating system (Fig.1) consisted of a sinusoidal alternating current power supply (OYHS-9805, Ouyang Huas Power Co., Ltd., Shenzhen, China), a self-made control system, an ohmic heating vessel, and a personal computer (ZX6-CP5S1, Hasee Computer Co., Ltd., Shenzhen, China) (*Ding et al., 2021*). The sinusoidal alternating current power supply was set to output an AC voltage of 220 V. Temperature measurements were taken at the center of the rice-water interface. The temperature data collected by the control system were transmitted to the personal computer via serial communication for storage and analysis. The ohmic heating vessel used for cooking rice was fabricated from five 5 mm thick acrylic plates welded together. The lid was a foam board equipped with a sealing rubber gasket. The electrodes were made of a pair of 1 mm 316L stainless steel plates (*Jun et al., 2007*).



(a) (b)

Fig. 1 - Schematic diagram and appliance of ohmic heating system for rice cooking

(2) Traditional heating

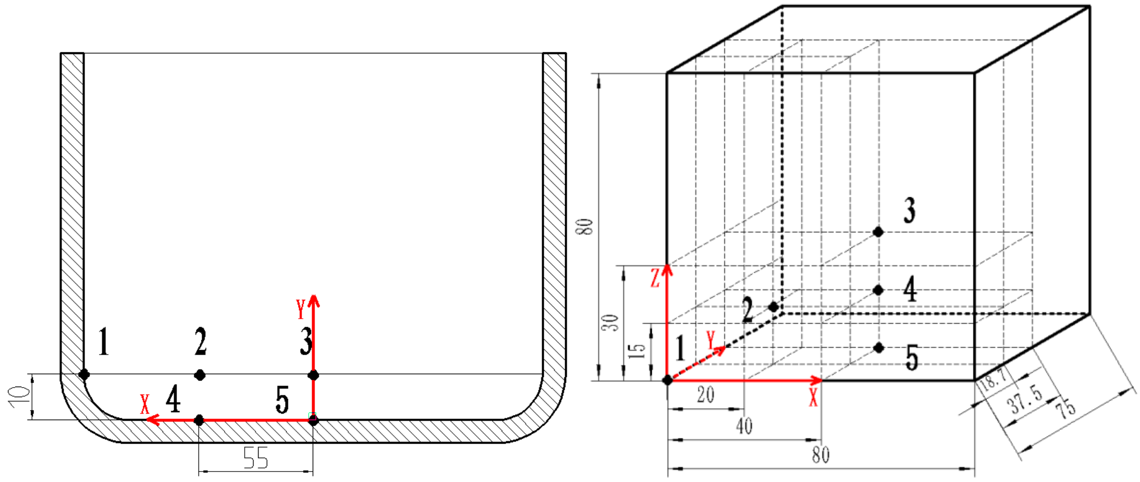
A traditional rice heating appliance, the resistance wire type non-high-pressure electric rice cooker (FD10E, Guangdong Tianji Electric Co., Ltd., China), was utilized. The data acquisition module of the ohmic heating rice cooking system was employed to monitor the temperature at the center of the rice-water mixture within the electric rice cooker.

Test method

During the experiments with the two heating methods, 100 g of rice was weighed using an electronic balance, and tap water at 25°C was mixed with the rice according to the water-to-rice ratios (v/w) of 1.25:1, 1.50:1, 1.75:1, and 2.00:1, and then soaked in a water bath maintained at a constant temperature of 25°C for 30 minutes (*Ding et al., 2020*).

To standardize the heating process of both traditional and ohmic heating for rice cooking, a thermocouple was used to record the central temperature of the rice-water mixture in the traditional heating method. Based on the traditional heating process, the temperature control program of the ohmic heating control system was modified to ensure that the central temperature changes in ohmic heating were the same as those in traditional heating.

To compare the hardness uniformity and temperature uniformity of rice cooked by the two heating methods, temperature measurements and hardness sampling were taken at five different positions in both heating containers, as shown in Fig. 2. The cross-section of the electric rice cooker is circular, so the bottom center of the heating pot was taken as the origin, and temperature measurements and sampling were taken at points 1 (110, 10), 2 (55, 10), 3 (0, 10), 4 (55, 0), and 5 (0, 0). The cross-section of the ohmic heating tank is square, so the bottom corner was taken as the origin, and temperature measurements and sampling were taken at points 1 (0, 0, 0), 2 (20, 18.7, 15), 3 (40, 35.5, 30), 4 (40, 35.5, 15), and 5 (40, 35.5, 0).



all dimensions are in mm

(a) (b)

Fig. 2 - Schematic diagram of temperature collection and sample collection point in electric rice cooker (a) and ohmic heating device (b)

After cooking the rice, approximately 50 rice grains from each location were collected and placed in a sealed bag (80 mm × 120 mm), with air expelled and the bags sealed. The rice was then cooled to approximately 23°C, which is room temperature.

Temperature control comparison

After soaking, the rice-water mixture was poured into the electric rice cooker for rice cooking. The temperature change at the central point was measured, and the cooking process in the traditional heating was divided into two stages: heating and insulation. The heating process was further divided into a heating lag phase and a uniform heating phase. During the uniform heating phase, as the water-to-rice ratio increased from 1.25:1 to 2.00:1, the heating rate decreased from 5.034°C/min to 4.344°C/min. Therefore, the heating rate of the ohmic heating device was set to 5°C/min. During the insulation phase, the temperature of the rice in the electric rice cooker was maintained at 97.95 ± 0.5°C. It took approximately 20 minutes from the moment the insulation indicator light was turned on until the buzzer sounded. Thus, the insulation temperature of the ohmic heating device was set to 98°C, with an insulation time of 20 minutes.

Table 1

Traditional heating and ohmic heating temperature parameters

Heating Method	Traditional heating				Ohmic heating			
Water-rice ratio(v/w)	1.25:1	1.50:1	1.75:1	2.00:1	1.25:1	1.50:1	1.75:1	2.00:1
Heating fitting equation (T, ℃; t, s)	T=0.0839 t+5.3403	T=0.0823 t+3.7058	T=0.0807 t+4.8436	T=0.0724 t+6.4575	T=0.0826 t+22.214	T=0.0825 t+21.424	T=0.0823 t+22.877	T=0.0825 t+22.222
R^2	0.9848	0.9887	0.9882	0.9869	0.9997	1.0000	0.9999	1.0000
Heating rate (℃/min)	5.034	4.938	4.842	4.344	4.956	4.95	4.938	4.95
Relative error (%)	-	-	-	-	0.88%	1%	1.24%	1%
Minimum temperature(℃)	97.06	95.48	97.36	98.03	97.5	97.87	97.93	97.75
Maximum temperature(℃)	98.38	98.28	98.39	98.22	98.93	98.62	98.5	98.81
Maximum temperature difference(℃)	1.32	2.80	1.03	0.19	1.43	0.75	0.57	1.06
Mean insulation temperature (℃)	98.05	97.80	97.87	98.10	98.15	98.12	98.06	98.44
Standard deviation of insulation temperature	0.23	0.69	0.16	0.05	0.27	0.16	0.10	0.27

(1) Heating Lag Phase

During the initial 4 minutes of the heating cycle of traditional heating, despite continuous power supply and output, the temperature remains constant. This is attributed to the gradual heating of the heating plate, which subsequently transfers heat to the inner pot. Only after the inner pot reaches a certain temperature does the rice-water mixture begin to heat up. This heating method exhibits a certain degree of heating lag. In contrast, Ohmic heating is a volumetric heating method. Once the rice-water mixture is electrified, it immediately heats up, with no heating lag.

(2) Heating Temperature Rise Phase

After the rice begins to heat up with both heating methods, the actual heating rate of ohmic heating is between 4.938°C/min and 4.956°C/min, with an error less than 1.24% from the preset heating rate. The linear fitting correlation coefficient R^2 for the traditional heating's temperature rise curve ranges from 0.9848 to 0.9887, which is lower than that of the ohmic heating device, ranging from 0.9997 to 1.0000. This indicates that the temperature of the ohmic heating has a better linear relationship with time, with a stable and constant rate of temperature rise. Considering both the heating rate error and the linear fitting, the control system has a good control effect on the heating rate of ohmic heating.

(3) Insulation Phase

In the insulation phase, initially, the heating plate of the traditional heating continues to be electrified and generates heat, causing the rice temperature to gradually reach its maximum. After heating ceases, while heat is lost with the steam, the high-temperature ceramic inner pot continues to provide a small amount of heat to the rice until the 20-minute insulation period ends. The insulation temperature difference under different water-to-rice ratios ranges from 0.19°C to 2.80°C, and the standard deviation of the insulation temperature is between 0.05 and 0.69. In contrast, the ohmic heating device, under the influence of the PID algorithm, is always in a dynamically input state according to the temperature change, meaning the internal temperature of the rice-water mixture fluctuates around 98°C. The insulation temperature difference under different water-to-rice ratios is between 0.57°C and 1.43°C, with a standard deviation of the insulation temperature ranging from 0.10 to 0.27. Both the temperature difference and standard deviation are slightly better than those of the traditional heating. The results show that the PID algorithm can effectively control the insulation temperature, and the insulation effect of the ohmic heating device is slightly better than that of the traditional heating.

Temperature uniformity measurement method

Temperature during the heating process is a critical factor affecting the hardness of food. To better understand the temperature variations at different locations during the rice cooking process, T-type armored thermocouples from a 5-channel temperature acquisition system (model WRCK-191, Shanghai Wolan Instrument Co., Ltd., Shanghai, China) were vertically inserted through the foam board and secured at the five points shown in Fig. 2. The tips of the thermocouples were used to monitor the temperature changes at five locations in the heating container in real time. To avoid the influence of the current on the thermocouples during ohmic heating, the T-type armored thermocouples were insulated with Teflon tubes *(Zhou et al., 2005)*. After the temperature data were collected by the microcontroller, they were sent to the PC in real time via serial communication and stored. Prior to temperature measurement, the thermocouples were calibrated using the water bath method at temperatures of 15, 25, 40, 50, 60, 75, and 95°C. The experiments showed that the temperature differences between different thermocouples were less than 0.25°C, making them suitable as temperature sensors for assessing uniformity.

Methods for measuring hardness of rice grains

Experiments were designed with a water-to-rice ratio of 1.50:1. One hundred grams of rice was evenly divided into three portions, and the rice was layered into three strata using cheesecloth for the ohmic heating experiment, with the ohmic heating conditions remaining constant. The power supply was halted at insulation times of 0, 5, 10, 15, and 20 minutes, respectively, to measure the changes in the hardness of the rice at different strata as a function of insulation time.

Four intact rice grains from the rice samples cooked under different conditions were taken and placed in a cross shape at the center of the texture analyzer's (TA-XTC, Shanghai Baosheng Industrial Development Co., Ltd., China) stage to test their hardness, as shown in Fig. 3. The test employed a TA/36 cylindrical probe, with a pre-test speed of 3 mm/s, test speed and post-test speed of 1 mm/s, a trigger force of 5 g, 70% deformation compression, and a 5-second compression interval (*Miao et al., 2016; Zhu et al., 2010; Zhou et al., 2017*). The experiment was repeated six times with 24 rice grains.

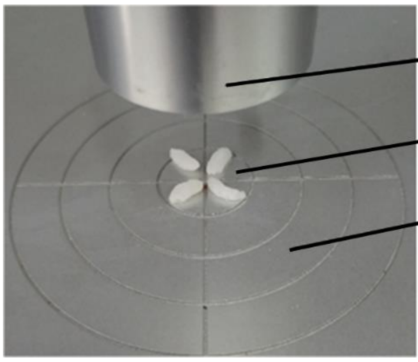
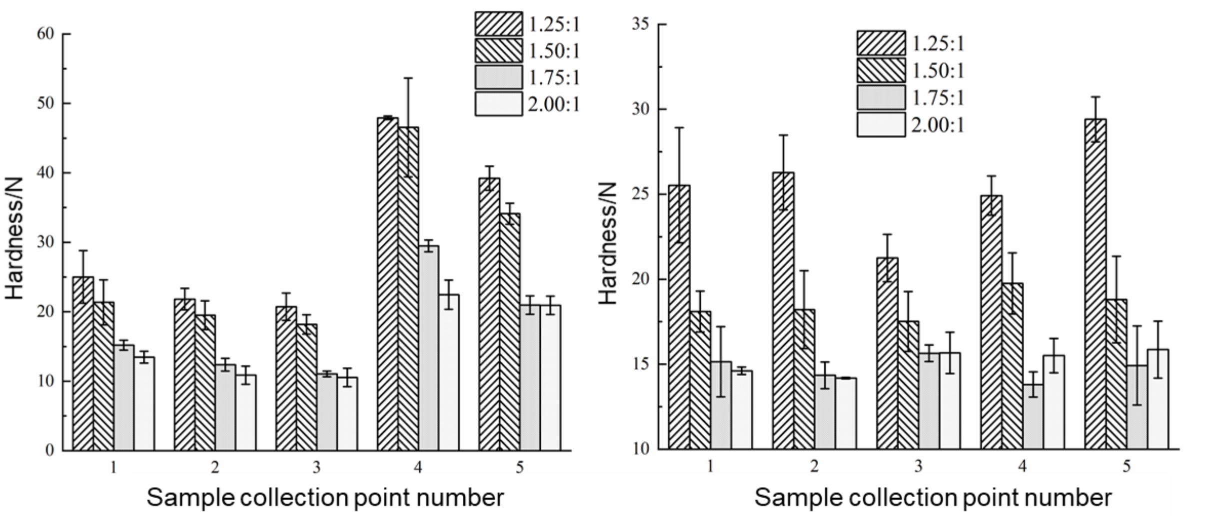


Fig. 3 - Rice grain placement diagram during rice hardness test

RESULTS AND ANALYSIS

Effect of heating method on hardness of rice grains

The hardness of rice at different sampling points in the traditional heating and ohmic heating equipment under different water-to-rice ratios is shown in Fig. 4. The results indicate that regardless of the heating method, the hardness at the same location decreases with an increase in the amount of water added. As can be seen from Fig. 4a, under the same water-to-rice ratio in traditional heating, there is a significant difference in hardness. The rice grains near the heating pot wall are harder, especially at point 4, which is harder than point 5, followed by point 1, while points 2 and 3 show little difference and have the lowest hardness. As shown in Fig. 4b, under the same water-to-rice ratio, the differences in hardness at various locations in ohmic heating are smaller. Table 5-5 indicates that under the same water-to-rice ratio, the standard deviation of the hardness of rice cooked in the traditional heating is much greater than that of ohmic heating, thus the hardness of rice cooked by ohmic heating is more uniform. The poor uniformity in hardness and the occurrence of scorching in rice cooked by the traditional heating (Fig. 5) are mainly due to the uneven heating of the rice during the cooking process in the traditional heating. Overheating leads to the loss of moisture in the rice, increasing its hardness and resulting in scorching. Therefore, it is necessary to study the temperature differences at different locations in the rice-water mixture during the rice cooking process.



(a) (b)

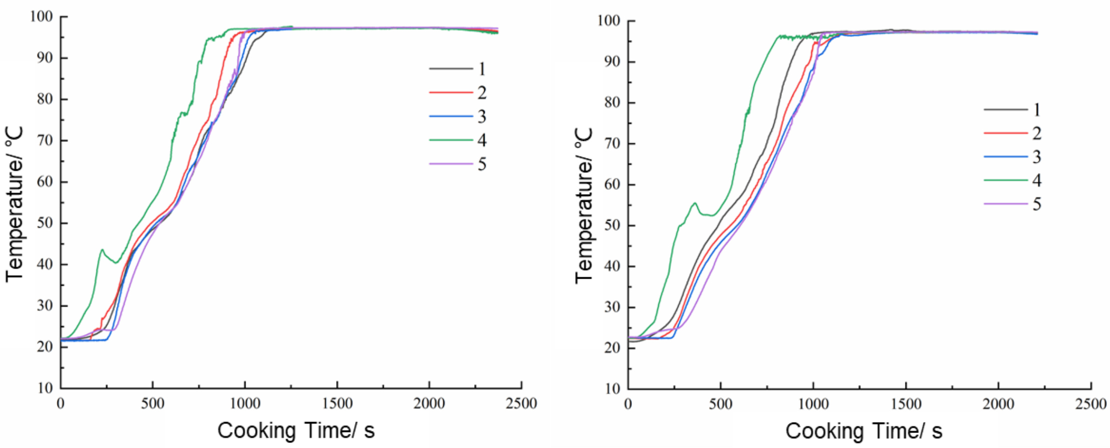
Fig. 4 - Rice hardness of rice at different sampling points in traditional heating (a) and Ohmic heating equipment (b) under different water-rice ratio

(a) (b)

Fig. 5 - Rice shape at the bottom of rice cooked by traditional heating (a) and ohmic heating (b) with a water-to-rice ratio of 1.50:1

Effect of heating method on temperature uniformity

During the cooking of rice with the two heating methods, a 5-channel temperature acquisition system was used to measure the temperature changes at different locations of the rice-water mixture. The specific temperature curves and analysis are as shown in Fig. 6 and Fig. 7.



(a) **(b)**

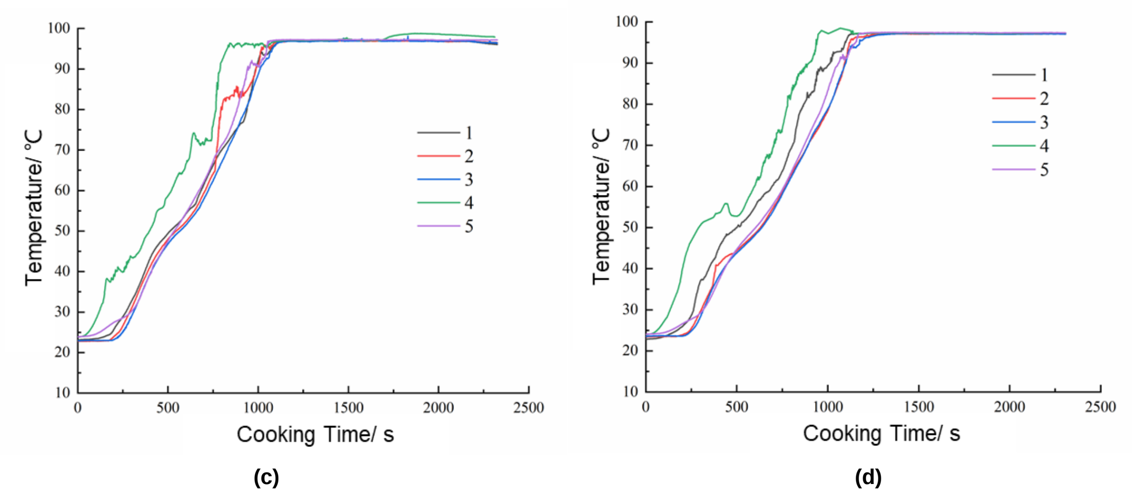


Fig. 6 - Traditional heating temperature curve of rice water mixture at the water-rice ratio of 1.25:1(a), 1.50:1(b), 1.75:1(c), 2.00:1(d)

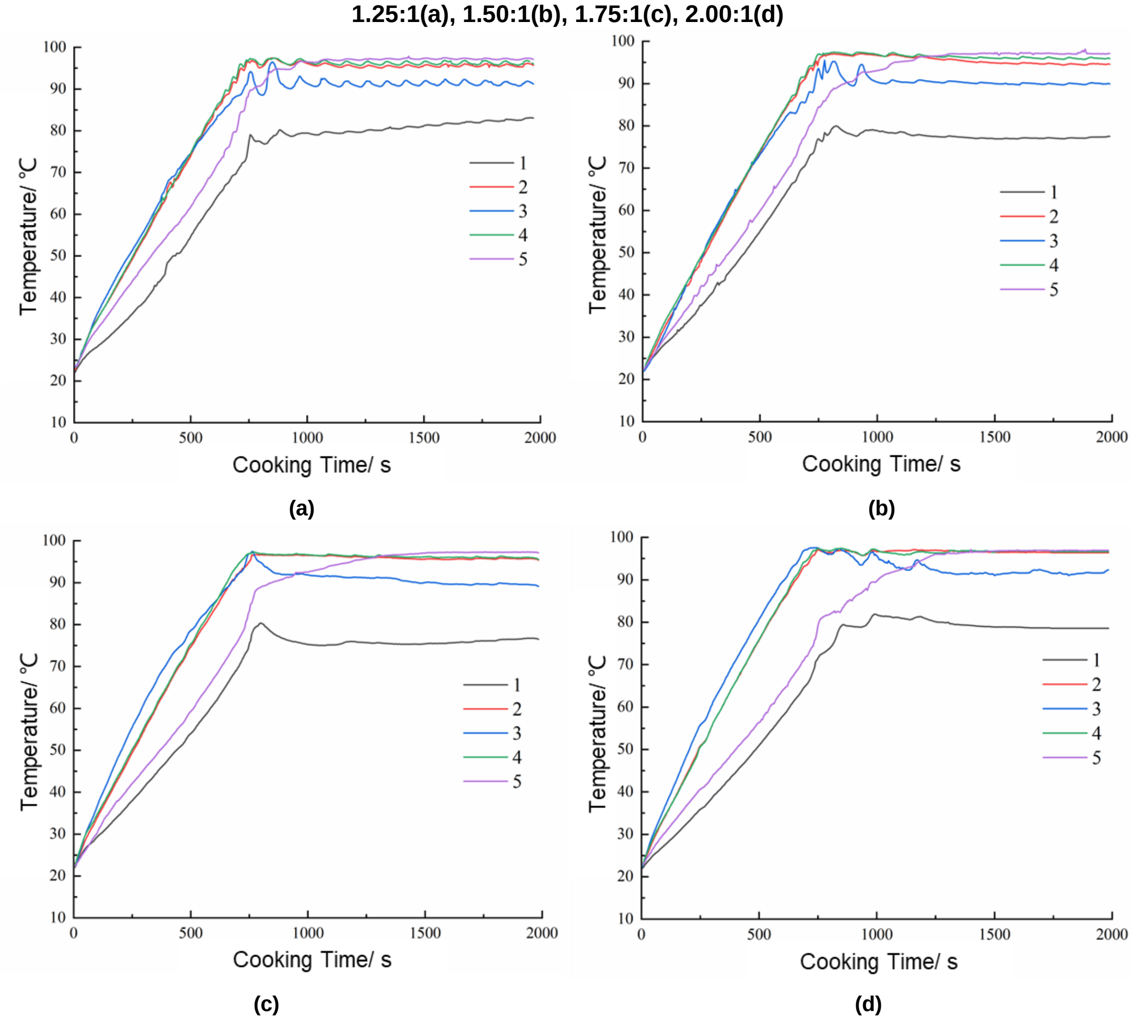


Fig. 7 - Ohmic heating temperature curve of rice water mixture at the water-rice ratio of 1.25:1(a), 1.50:1(b), 1.75:1(c), 2.00:1(d)

Fig. 6 indicates that the temperature at point 4 (the heating plate area) in the electric rice cooker is significantly higher than at other locations, and the temperature at point 1 (near the inner wall) is also slightly higher than at points 2, 3, and 5. Table 2 shows that the maximum temperature difference across the four water-to-rice ratios ranges from 21.42°C to 29.94°C. Comparing the hardness of rice cooked at different locations in the electric rice cooker reveals that the temperature near the heating inner wall is higher and the hardness of the rice is also higher. In particular, the hardness at point 4 is greater than at point 5, followed by point 1, while points 2 and 3 show little difference and have the lowest hardness. This suggests that hardness is related to temperature, meaning that the hardness of the finished rice is also higher where the temperature is higher, and scorching phenomena occur at locations with higher temperatures.

Table 2

The internal maximum temperature difference of the two heating methods at different water-rice ratios

Water-Rice Ratio (v/w)	Traditional heating (℃)	Ohmic heating (℃)
1.25:1	24.50	20.45
1.50:1	29.94	18.32
1.75:1	21.67	24.60
2.00:1	21.42	31.85

The temperature curves for ohmic heating, as shown in Fig. 7, clearly demonstrate that at the same height, the temperature at point 1 is significantly lower than at point 5, and the temperature at point 2 is slightly lower than at point 4. This indicates that the temperature closer to the container wall is lower. This can be attributed to the fact that point 1 is situated at the bottom corner, where heat dissipates in three directions, while point 5 is near the center of the container bottom where heat primarily dissipates in one direction towards the bottom. Point 2 is closer to the container wall than point 4. This is primarily because the heating method involves the food generating its own heat. The side of the rice near the wall loses more heat to the surroundings, hence the lower temperature. That is, the internal temperature of the rice-water mixture in ohmic heating is higher than the external temperature, which is quite different from the temperature distribution in traditional heating.

At different heights on the same cross-section (points 3, 4, and 5), during the heating phase, the temperature at point 3 is slightly higher than at point 4, while point 5 is significantly lower. This is due to point 3 initially being in the water layer, with rice settling at the bottom due to gravity. On the same cross-section, the material is the same, with the vertical section from top to bottom consisting of a water layer, a loose rice layer, and a compact rice layer. The conductive substances in the rice are released into the water, making the electrical conductivity of the water layer greater than that of the rice-water mixture layer. The bottom rice (point 5) is more compact, leading to a decrease in electrical conductivity from top to bottom, resulting in the water layer generating more heat and warming up more quickly. Point 5, however, has the lowest temperature due to its low electrical conductivity and heat dissipation.

During the insulation phase, the temperature at the top layer (point 3) gradually decreases after reaching the set insulation temperature and then remains stable. There are two main reasons: firstly, the gradual reduction of water in the upper layer, leading to increased porosity and a decrease in electrical conductivity, resulting in less heat generation. Secondly, the upper rice is in contact with air, leading to relatively more heat loss. The temperature at point 5 continues to increase during the early stages of the insulation phase, eventually surpassing points 3 and 4. The main reasons are that the bottom rice-water mixture always has more water, with a relatively higher electrical conductivity than points 3 and 4, continuously generating heat. Additionally, the contact surface temperature with the container gradually increases, meaning that point 5 has no heat loss, resulting in the highest temperature. With the increase in the water-to-rice ratio in ohmic heating, the maximum temperature difference increases from 18.32℃ to 31.85℃.

From the temperature changes of the rice-water mixture at various locations during ohmic heating for rice cooking, it can be seen that although the temperature uniformity in ohmic heating is generally acceptable, even with certain temperature differences during the ohmic heating process, there is no occurrence of excessively high temperatures. As shown in Fig. 4b, the differences in hardness at various locations under the same water-to-rice ratio in ohmic heating are smaller, indicating that the internal hardness of the rice cooked by ohmic heating is more uniform. However, the temperature curve shows that during the heating phase, the upper water layer temperature is higher than the middle, and the bottom temperature is the lowest. Observations reveal that the upper rice absorbs water and expands more quickly, thus the uniformity of the hardness of rice cooked by ohmic heating is influenced not only by temperature but it may also be related to the ohmic heating process.

Influence of holding stage on hardness of different rice layers during ohmic heating

Experiments were designed with a water-to-rice ratio of 1.50:1. Rice was divided into three layers using cheesecloth for the experiment, and the hardness of the rice at different layers was measured as a function of the insulation time. As shown in Figure 8, the following results were obtained: after heating was completed without insulation, the hardness of the upper layer of rice was approximately 35.89±3.29 N, the middle layer was 49.15±2.84 N, and the lower layer was 63.48±10.22 N. There was a significant difference in hardness, with the upper layer of rice being softer.

As the insulation time increased, after 5 minutes of insulation, the moisture in the upper layer was gradually absorbed, and the hardness of the rice decreased to 17.18±3.10 N. Subsequently, the hardness change was not significant, while the hardness of the middle and lower layers of rice decreased more, with the lower layer still having the highest hardness of 27.39±2.32 N. At 10 minutes of insulation, the hardness of the middle layer of rice reached an equilibrium value (15.64 N to 18.76 N). The hardness of the bottom layer of rice continued to decrease but remained higher than that of the middle and upper layers. After 15 minutes of insulation, the hardness of the rice across all layers tended to stabilize, with no significant differences in hardness observed.

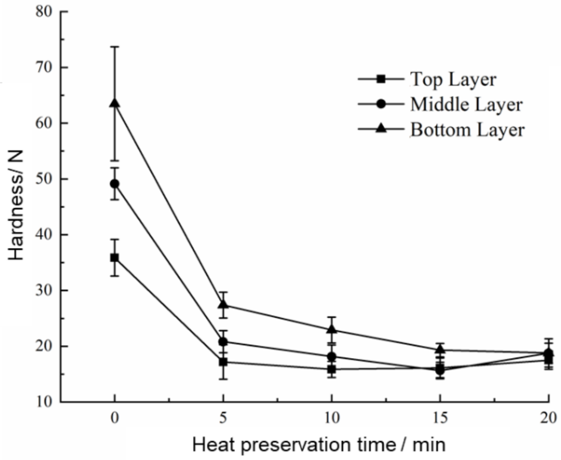


Fig. 8 - The hardness of different layers of rice varies with the holding time

This indicates that during the heating phase, the upper part of the rice, due to its higher temperature, absorbs water and expands, softening earlier. As the rice gradually absorbs water, the free liquid in the upper layer decreases, leading to the formation of gaps, which in turn causes a decrease in electrical conductivity and a reduction in heat generation. Meanwhile, the lower layer still contains liquid, and the rice continues to be heated and absorbs water, gradually softening until the rice cooking is completed.

Thus, it is demonstrated that although the upper layer of the rice-water mixture is at a higher temperature than the lower layer during the ohmic heating process, leading to a faster softening of the upper rice, the softening rate of the upper rice gradually decreases in the later stages of insulation due to the reduction of moisture. In contrast, the lower rice continues to soften, ultimately resulting in a more uniform hardness of the rice cooked by ohmic heating.

CONCLUSIONS

In this study, a self-made ohmic heating device was utilized to cook rice and compared with traditional heating devices in terms of the hardness of rice grains and temperature changes at various positions within the container. The results indicated that the ohmic heating device effectively controlled the temperature changes at each stage, with a maximum heating rate error of 1.24% and a linear fitting R^2 greater than 0.9997, thereby ensuring that the ohmic heating process was similar to traditional heating. As the water-to-rice ratio increased, the rice grains absorbed more water, leading to a decrease in the hardness of the cooked rice. Additionally, the heating method significantly affected the hardness and temperature uniformity of the rice. Specifically, compared to traditional cooking methods, although the temperature difference at different positions during the ohmic heating process reached 18.32~31.85°C, which was greater than the 21.42~29.94°C observed in traditional heating, the hardness difference of rice at various positions was much smaller with ohmic heating. This was primarily attributed to the fact that as the insulation time was extended, the hardness difference between different layers of rice gradually decreased, ultimately resulting in a hardness range of 18~21 N for the upper, middle, and lower layers of rice, achieving a more uniform hardness. In contrast, the traditional heating method led to uneven hardness in the rice and the presence of burnt spots, indicating that ohmic heating could more effectively maintain the consistency of rice hardness.

However, ohmic heating requires the placement of electrodes on both sides of the food, through which an electric current passes to heat the food. Consequently, the food species to be heated must possess a sufficient amount of free ions, that is, a higher electrical conductivity. Additionally, the corrosion of electrode plates and the safety of equipment usage are urgent issues that need to be addressed before the large-scale application of ohmic heating.

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