Study on the drying characteristics of rice by microwave and hot air drying

Fangqing Ling  |  Tongsheng Sun

School of Mechanical Engineering, Anhui Polytechnic University, Wuhu, China

Correspondence
Tongsheng Sun, School of Mechanical Engineering, Anhui Polytechnic University, Wuhu, China, 241000. Email: suntongsheng@ahpu.edu.cn

Abstract
This study presents the experimental methods of microwave drying and hot air drying of rice to simultaneously improve the dry storage effect of rice, reduce the mouldy and spoilage of rice, and measure the moisture content, water activity and temperature changes. A thermal imaging camera was used to photograph the temperature distribution of rice at different times to study the changing law of rice drying characteristics and analyse the relationship between rice water activity and drying speed. Results show that the changes in the moisture content and water activity of rice are inversely proportional with time. A 400 W microwave drying has a more pronounced heating effect on rice than 850 W hot air drying. The efficiency of the first 20 min of rice drying is better than that of the last 20 min. The highest temperature of 40°C was reached after microwave drying for 8 min, while nearly 40°C was reached after hot air drying for 56 min. These results can be applied to further analyse the influence of different drying methods on rice water activity and guide the reduction of bacterial propagation in rice and the improvement of the quality of rice. This work provides a theoretical basis for choosing the optimal drying method.

1  |  INTRODUCTION

Rice is one of the main sources of food in my country. The problems encountered by newly harvested rice needs mainly involve transportation, drying, and storage. According to the specific statistics of relevant departments, more than 5 million tons of grains are lost annually due to moulds and deteriorate because of insufficient drying. Therefore, timely drying treatment of newly harvested rice is the top priority [1, 2]. Hot air drying is an outside-to-inside drying method that first heats the outer surface of the medium and then transfers the heat to the inside of the medium. Microwave drying is a fast drying method that simultaneously heats the inner and outer surface of the medium. These two techniques have different drying rates and heating effects on rice, and thus further affecting the change of rice water activity [3]. Studying the influence of microwave and hot air drying on rice water activity is helpful in choosing the most energy-saving and appropriate drying method. Mu et al. [4] studied the drying characteristics of apple slices under different infrared radiation distances and hot air temperatures and analysed the drying time, colour, hardness, brittleness, and rehydration of apple chips. Liu et al. [5] used hot air–microwave combined drying technology to dry red dates; explored the contents of phenolic substances, soluble sugars, organic acids, triterpene acids, vitamin C, total phenols, and total flavonoids in red dates under different processing methods; and compared their antioxidant capacities. Badmus et al. [6] studied the effects of different drying methods on the concentration and antioxidant activity of some important chemical substances in edible brown algae. Kay et al. [7] measured the organoleptic characteristics of samples prepared at different drying temperatures and evaluated the energy consumption of the drying process. All related research confirmed that different drying methods and drying conditions affect the characteristics and quality of the medium itself. The changes in various indicators during medium drying must be detected to improve the quality and efficiency of medium preparation. In this study, rice, an important food crop, is selected as the drying medium. Its moisture content and water activity curve are fitted under different drying methods and parameters. This work provides a reference for the timely drying of harvested rice and the prevention of mildew in rice storage. In addition, a thermal imager was used to photograph the changes

This is an open access article under the terms of the Creative Commons Attribution License, which permits use, distribution and reproduction in any medium, provided the original work is properly cited.

© 2021 The Authors. The Journal of Engineering published by John Wiley & Sons Ltd on behalf of The Institution of Engineering and Technology

J. Eng. 2021;2021:201–208.
in the temperature and physical characteristics of the rice under two different drying methods, hot air and microwave, to screen out the optimal drying method.

2 | EXPERIMENTAL MATERIALS

2.1 | Materials

Dry medium rice: Rice of the same variety was produced in the same area. During the experiment, the rice that was full and without husk was selected as the test material.

2.2 | Instruments and equipment

Infrared thermal imager, microwave vacuum drying oven, blast drying oven, water activity metre, electronic analytical balance, capacitive grain moisture metre, and special glass heating vessel were used for microwave drying.

2.2.1 | Initial image of rice

As shown in Figure 1, the rice with a moisture content of 25% has a full and round appearance, bright colour, no cracking of the rice husk, normal smell, and no musty smell. The picture taken by a thermal imaging camera showed that the rice temperature is close to the ambient temperature with the highest of 25.9°C and the lowest of 23.4°C.

3 | HOT AIR AND MICROWAVE DRYING EXPERIMENT

3.1 | Experimental steps

The specific experimental steps are shown in Figure 2.

Pre-treatment of the rice test: The rice is screened, and those with full grains are selected. The soaking method is applied to obtain the rice with specific initial moisture content. A paper towel is used to absorb the surface moisture.

Microwave and hot air drying experiment: Prior to the experiment, the initial moisture content of the rice is measured with a capacitive grain moisture metre. The rice is then placed in a microwave vacuum drying oven or a hot air drying oven for drying and removed every 4 min. The internal water activity of the rice is measured using a water activity metre. The temperature of the rice is recorded with an infrared thermal imaging camera every 8 min. After complete cooling, the mass is weighed, the experimental data are recorded, and the rice moisture content is measured.

Analysis of experimental results: The experimental data of water content and water activity of rice under two drying methods are fitted and analysed, and the drying rule of rice was obtained. The infrared thermal imaging, colour, odour and shape of rice husk were compared to analyse the optimal drying method.

3.2 | Rice drying experiment

3.2.1 | Experimental initial parameters

The experimental parameters in this study are shown in Table 1.

3.2.2 | Experimental results

The experimental results of hot air drying and microwave drying of rice are shown in Table 2:

3.3 | Water content fitting

The change of rice moisture content during drying can help understand the specific drying situation of moisture, which plays an important role in the storage and management of rice [8, 9]. On the basis of the experimental data of water content, the
FIGURE 2  Experimental analysis process of rice drying

TABLE 1  Experimental parameters of hot air and microwave drying

| Hot air drying parameters | Microwave drying parameters |
|--------------------------|-----------------------------|
| Drying power (W)         | 850                          |
| Temperature resolution (°C) | 0.1                      |
| Microwave frequency (MHz) | 2.45                        |

Initial moisture content of rice 25%
Maximum experimental temperature (°C) 40

TABLE 2  Moisture content results using hot air and microwave drying

| Stage                  | Specimen number | Time(min) | The remaining mass of hot air drying rice (g) | Hot air drying rice moisture content | Hot air drying water activity | Microwave-dried rice remaining mass (g) | Microwave drying rice moisture content | Microwave drying water activity |
|------------------------|-----------------|-----------|---------------------------------------------|-------------------------------------|-------------------------------|----------------------------------------|----------------------------------------|-------------------------------|
| The first stage        | 1               | 0         | 100                                         | 24.80%                              | 0.933                         | 100                                    | 24.60%                                 | 0.938                         |
|                        | 2               | 4         | 98.2                                        | 23.40%                              | 0.923                         | 97.6                                   | 22.70%                                 | 0.889                         |
|                        | 3               | 8         | 97.2                                        | 22.60%                              | 0.894                         | 92.6                                   | 21.70%                                 | 0.763                         |
|                        | 4               | 12        | 96.3                                        | 21.90%                              | 0.826                         | 95.3                                   | 20.90%                                 | 0.708                         |
|                        | 5               | 16        | 95.7                                        | 21.50%                              | 0.789                         | 94.8                                   | 20.50%                                 | 0.671                         |
|                        | 6               | 20        | 95.2                                        | 21%                                  | 0.721                         | 94.3                                   | 20%                                     | 0.645                         |
|                        | 7               | 24        | 94.7                                        | 20.60%                              | 0.691                         | 93.6                                   | 19.40%                                 | 0.638                         |
| The second stage       | 8               | 32        | 94.1                                        | 20%                                  | 0.626                         | 92.9                                   | 18.8%                                  | 0.597                         |
|                        | 9               | 40        | 93.6                                        | 19.6%                                | 0.594                         | 92.4                                   | 18.4%                                  | 0.591                         |
|                        | 10              | 48        | 93                                          | 19.1%                                | 0.516                         | 92                                     | 18%                                    | 0.506                         |
|                        | 11              | 56        | 92.6                                        | 18.8%                                | 0.511                         | 91.6                                   | 17.7%                                  | 0.508                         |
Inverse proportional function is used to fit the water content equation in the form of [10, 11]:

\[
f(x) = \frac{p_1 \times x^2 + p_2 \times x + p_3}{x + q_1}
\]

where \(p_1, p_2, p_3, q_1\) are the curve fitting coefficients.

Inverse proportional curve fitting method (rational) in MATLAB is used to fit the moisture content change data during hot air drying of rice, and the fitting curve is shown in Figure 3.

According to the calculation of the fitting results, the square of the range is 0.9994, the standard mean-variance RMSE is 0.0005509, and the fitting correlation coefficient is 0.9991. Hence, the fitting curve is in good agreement with the data points. The curve fitting coefficient shows the water content of hot air drying rice. The rate fitting equation is

\[
w_h = -0.0002941 \times t^2 + 0.1889 \times t + 3.522
\]

Inverse proportional function curve fitting method (rational) in MATLAB is also used to fit the moisture content change data during the microwave drying of rice. The fitting curve is shown in Figure 4.

According to the calculation of the fitting results, the square of the range is 0.9984, the standard average variance RMSE is 0.02228, and the fitting correlation coefficient is 0.9797, indicating that the curve is in agreement with the data points. The curve fitting coefficient shows the water content of microwave-dried rice can be seen. The rate fitting equation is

\[
w_m = \frac{-0.0002576 \times t^2 + 0.1762 \times t + 2.924}{t + 11.9}
\]

3.3.1 Water activity curve fitting equation

Water activity refers to the ratio of the vapour pressure of water when a substance such as food or medicine reaches equilibrium in a closed container in relation to the saturated vapour pressure of pure water at the same temperature [12]. Water exists in rice in the form of free and bound water. Bound water is combined with rice protein, soluble substances such as sugar and salt. This part of bound water cannot be used directly. Free water is formed because of the capillary action existing in the water in the interstices of rice. Compared with bound water, free water is more active and easier to evaporate. This type of water is the medium of all biochemical reactions in the food [13, 14].

Water activity refers to the existing state of water in rice, that is, the degree of combination or freeness of water and rice. A high water activity indicates a low degree of water binding to the rice and a high degree of dissociation and vice-versa. The growth and reproduction of various microorganisms in rice are determined by its water activity rather than its water content. For example, the water activity of rice determines the germination time, growth rate, and mortality of \textit{Aspergillus flavus} inside the rice. Controlling the water activity of rice is beneficial to inhibit the reproduction of microorganisms and improve its storage quality [5, 15].

The water activity data obtained from the experiment are inputted into a program written in MATLAB. The proportional function curve fitting method (rational) is used to fit the relationship between water activity and time during hot air drying of rice. The curve is shown in Figure 5.

Fitting results show that the square of the range is 0.9858, the standard average variance RMSE is 0.02228, and the fitting correlation coefficient is 0.9797, indicating that the curve is in agreement with the data points. The curve fitting coefficient shows the water activity of hot air drying rice. The degree
The fitting equation is

\[ A_{wh} = \frac{0.934 \times t^2 - 143.9 \times t + 1.068 \times 10^4}{t + 1.104 \times 10^3} \] (4)

The relationship between water activity and time during rice microwave drying is also fitted, and the fitted curve is shown in Figure 6.

Fitting results show that the square of the range is 0.9718, the standard average variance RMSE is 0.02838, and the fitting correlation coefficient is 0.9597, indicating that the curve is in agreement with the data points. The curve fitting coefficient shows the water activity of microwave-dried rice. The degree of fitting equation is

\[ A_{wm} = \frac{-0.0007987 \times t^2 + 0.4256 \times t + 15.58}{t + 16.33} \] (5)

4 | ANALYSIS OF RESULTS

4.1 | Moisture content drying rate analysis

Drying rate is defined as the mass of moisture vapourised in a unit area of wet material per unit time [16, 17]. When the contact surface of dry material and drying medium cannot be determined, the drying rate is expressed by drying strength \( N_t \) calculated using formula (6) [18]. The rice moisture content curve (Figure 7) and the drying rate curve (Figure 8) are drawn according to the above fitting equation:

\[ N_t = \frac{-dM_m}{dt} = \frac{Y_{t+1} - Y_t}{t_{t+1} - t_t} \] (6)

Figures 7 and 8 show that the total moisture content curve of rice grains shows a decline trend of rapid, rapid, and gentle. The entire drying process can be simply divided into two stages, namely, rapid and slow drying. In the first 24 min, the moisture content of the rice is high, the drying rate is relatively large, and the decline accounts for most of the overall decline. The reason for this change in the curve is that the surface water of rice would preferentially exchange heat with hot air to convert to water vapour evaporation, or polarisation and friction under the influence of high-frequency electromagnetic field would generate heat to convert to water vapour evaporation.

After 24 min, the value of the paddy drying rate is reduced and changes slowly. This phenomenon occurs because after the surface water of rice evaporates, the internal water must be first transferred to the surface of the rice and then evaporate. The permeation rate of the water from the inside to the outside of the rice is lower than the evaporation rate of the water at the surface. As a result, the overall drying rate of the rice grains decreases and gradually becomes flat, and the change of the moisture content curve almost maintains a parallel downward trend.

As shown in the figure, 400 W microwave drying is faster and more efficient than 850 W hot air drying.

4.2 | Water activity analysis

On the basis of the fitting equation, the water activity curves of different drying methods are drawn as shown in Figure 9. The water activity of rice under the two drying methods also
shows a trend of rapid decline and then deceleration. The 400 W microwave drying induces more evident changes than the 850 W hot air drying curve. In the first 24 min, the water activity of the microwave-dried rice decreases substantially with a large amplitude and then declines gradually. By contrast, the water activity curve of the hot air-dried rice maintains a certain speed and then gradually decreases. This difference is due to the fast drying rate of microwave-dried rice and the loss of a large amount of free water leading to the fast drop in water activity. After 24 min, the dry rice transitions from the first stage of rapid drying to the second stage of slow drying. The internal moisture of the rice penetrates to the surface and then evaporates. The drying speed is limited by the internal moisture penetration rate, and the water activity decline rate slows down. The curve tends to be flat.

### 4.3 Research on rice temperature change

During rice drying using microwave vacuum drying oven and blast drying oven, an infrared thermal imaging camera is used to photograph the rice, measure the temperature change of the rice at each time period (Figures 10 and 11), and observe the colour, smell, and shape of rice husk (Table 3) [19–21].

As shown in Table 3, the temperature of the hot air drying of rice increases slowly. After 56 min, the maximum temperature of rice is close to the set temperature of 40°C and the temperature of microwave drying increases rapidly. After 8 min, the maximum temperature of rice has reached 40°C and then fluctuates continuously. Although the minimum temperature of both methods gradually increases from the initial temperature with time, the temperature of microwave drying is basically higher than that of hot air drying.

As shown in Figure 10, the initial high-temperature area of rice under hot air drying is located in the area directly opposite the hot air outlet. When the rice heat gradually diffuses from the middle high-temperature area to the surrounding low-temperature area, the temperature in the low-temperature area gradually increases. Figure 11 shows that because the electromagnetic wave emission port in the microwave drying oven is located on the right side of the rectangular parallelepiped cavity and is under the coupling of the electromagnetic and temperature fields, the centre of the glass disc in the drying cavity is the peak position of the electromagnetic wave.

---

**FIGURE 9** Water activity curve of two drying methods

**FIGURE 10** Temperature change of hot air drying rice (a) temperature distribution at 8 min, (b) temperature distribution at 24 min, (c) rice state at 56 min, and (d) temperature distribution at 56 min
distribution in the cavity. The centre of the disk is heated the most, and the temperature of the rice in the centre is the highest. The surrounding temperature is substantially lower than that in the centre. When the microwave continues to dry, the temperature in the surrounding area gradually increases.

Microwave drying simultaneously heats up the inside and the surface; hence, the drying is uniform. Hot air drying heats the surface through convective heat transfer of hot air; hence, the drying is uneven and slow. Therefore, the colour of rice grains under microwave drying is fuller and brighter, the aroma of rice is stronger, and the degree of drying is more thorough than under hot air drying. Rice husks under microwave drying are also easier to crack than those under hot air drying.

5 | CONCLUSION

The influence of hot air drying and microwave drying on rice drying is studied. The experimental data are used to analyse the drying characteristics of rice moisture content and water
activity. The rice temperature and grain physical characteristics under the two drying methods are compared. The following conclusions are drawn:

The change curve of rice moisture content is an inverse proportional function. A high moisture content leads to a fast drying rate and vice-versa. The effect of microwave drying of rice moisture content is more evident than that of hot air drying.

The change curve of rice water activity with time is an inverse proportional function, and its change trend is affected by the drying rate. Given that microwave drying has a more evident effect than hot air drying, the water activity of rice under the former is significantly changed than that under the latter, and the reduction of free water is substantial. This condition inhibits the propagation of bacteria in rice and improves the quality of rice.

In the first stage, the drying efficiency of rice is high, and the moisture content decreases rapidly. In the second stage, the changes in the drying rate and water activity tend to be flat, and the changes in the moisture content curve are almost parallel downward trend. These phenomena are affected by the infiltration rate of the water inside the rice to the surface of the rice.

On the basis of the changes in water content and water activity of rice, the effect of microwave drying at 400 W is more evident than that of 850 W hot air drying. Hence, microwave drying is better than hot air drying under the same conditions.

The heating effect of microwave drying on rice is more evident than that of hot air drying. When the temperature increases, the moisture in the rice easily evaporates under steam pressure. Therefore, the microwave drying rate is more efficient than hot air drying. The colour and smell of rice under this method are better than those under hot air drying, but the husks crack more.

The results are helpful in the drying and storage of newly harvested rice and reducing the loss of rice due to deterioration. In the future, a comprehensive study on the changes in the drying and storage of various nutrients in rice under different factors must be conducted. Reasonable and efficient drying equipment and granaries must be developed to improve the quality of rice.

**NOMENCLATURE**

- $t$ heating time
- $w_{ht}$ moisture content of hot air drying
- RMSE standard mean variance
- $w_m$ moisture content at time $t$ of microwave drying
- $AW_r$ water activity of rice
- $AW_h$ water activity of hot air drying
- $AM_m$ moisture activity of microwave drying
- $N_d$ drying rate
- $Y_{t+1}$ moisture content of dry basis when the time is $t+1$
- $Y_t$ moisture content of dry basis when the time is $t$

**ACKNOWLEDGEMENT**

This work is supported by the Scientific Research Project of Education Department of Anhui Province (No. KJ2020ZD38)

**ORCID**

Tongheng Sun https://orcid.org/0000-0003-2053-2437

**REFERENCES**

1. Zheng, G., Sun, L.: Study effect of different drying temperature and drying air speed on paddy quality. Sci. Technol. Cereals Oils Foods 28(04), 173–176 (2020)
2. Luo, C., et al.: Current status of rice drying using microwave drying technology and drying test research on continuous microwave dryer. Farm Prod. Process. (03), 74–77–80 (2020)
3. Mimb, N.P., Nhut, V.M., Phuong, N.K.: Microwave vacuum drying behaviour on quality of dried Piper betle leaf. Res. Crops 20(4), 815–821 (2019)
4. Mu, J., et al.: Drying characteristics of infrared radiation combining hot air for apple slices. Sci. Technol. Food Ind. 37(07), 92–96–169 (2016)
5. Liu, Q., Wang, Q., Cui, S.: Effects of different pretreatment methods on quality characteristics and antioxidant activity of jujube drying by combined hot-air-microwave drying. Food Res. Dev. 41(24), 124–130 (2020)
6. Badmus, U.O., Taggart, M.A., Boyd, K.G.: The effect of different drying methods on certain nutritionally important chemical constituents in edible brown seaweeds. J. Appl. Phycol. 31(2), 3883–3897 (2019)
7. Kay, K., et al.: Influence of novel infrared freeze drying of rose flavored yogurt melts on its physicochemical properties, bioactive compounds and energy consumption. Food Bioprocess Technol. 12(12), 2062–2073 (2019)
8. Dawit, H.: Reducing post harvest loss of maize by manufacturing and introducing of air tight silos grain storage in selected areas of Tigray, Ethiopia. Asian. Res. J. Agric. 11(4), 1–10 (2019)
9. Chiniforush, A.A., Valipour, H., Akbarnezhad, A.: Water vapor diffusivity of engineered wood: Effect of temperature and moisture content. Constr. Build. Mater. 224, 1040–1055 (2019)
10. Muhammad, Y., Syanipanin Laksmita, W., Robert, M.: Effect of storage time on moisture content of Rastalis trisperma seed and its effect on acid value of the isolated oil and produced biodiesel. Energy Rep. 5, 1375–1380 (2019)
11. Mu, Q.Y., et al.: Water-retention curves of loess under wetting–drying cycles. Géotechnique Lett. 11(2), 1–6 (2019)
12. Zhou, Z., et al.: Minimum water activity of Aspergillus niger. China Pharm. 29(17), 60–63 (2020)
13. Wilson, C., et al.: Feasibility of using spectral profiles for modeling water activity in five varieties of white quinoa grains. J. Food Eng. 238, 95–102 (2018)
14. Liu, X., Guan, X., Xing, F.: Effect of water activity and temperature on the growth of Aspergillus flavus, the expression of aflatoxin biosynthetic genes and aflatoxin production in shelled peanuts. Food Control 82, 325–332 (2017)
15. Huang, X., et al.: Research progress in microbiological control technology of low water activity food. Food Ferment. Ind. (23), 1–7 (2020)
16. Ameri, B., Salah, H., Mouldou, B.: Influence of drying methods on the thermodynamic parameters, effective moisture diffusion and drying rate of wastewater sewage sludge. Renewable Energy 147, 1107–1119 (2020)
17. Nobusuke, K., et al.: Drying behavior of sludge with drying accelerator. Drying Technol. 38(1-2), 38–47 (2020)
18. Wu, J., et al.: The drying characteristic and mathematical modeling of various drying method of seahorse. Mod. Food Sci. Technol. 36(12), 133–142 (2020)
19. Jing, X., Qun, F., Liu, X.: Influences of high grade rice drying on its quality. Cereal Food Ind. 21(05), 16–19 (2014)
20. Neutron, D., et al.: Effects of drying temperature and genotype on morphology and technological, thermal, and pasting properties of corn starch. Int. J. Biol. Macromol. 165, 354–364 (2020)
21. González-Pérez, J.E., et al.: Mass transfer and morphometric characteristics of fresh and osmohydrated white mushroom pilei during convective drying. J. Food Eng. 262, 181–188 (2019)

**How to cite this article:** Ling F, Sun T. Study on the drying characteristics of rice by microwave and hot air drying. J Eng. 2021:2021–2101–208.
https://doi.org/10.1049/jte2.12027