Original Article
Journal of Biosystems Engineering
J. of Biosystems Eng. 41(1):43-50. (2016. 3)
http://dx.doi.org/10.5307/JBE.2016.41.1.043
eISSN : 2234-1862
pISSN : 1738-1266

Drying Characteristics of Sea Tangle Using Combination of Microwave and Far-Infrared Dryer

Chung-Su Han[1§], Tae-Hwan Kang[2§], Jeong-Hyeon Lee[3], Jin-Ho Won[1], Byeong-Hyo Cho[1], Sung-Chan Cho[1]*

[1]Department of Biosystems Engineering, Chungbuk National University, Cheong-Ju, Korea
[2]Major in Bio-Industry Mechanical Engineering, Kongju National University, Kong-ju, Korea
[3]Laboratory of Agricultural and Food Process Engineering, Hokkaido University, Sapporo, Japan

Received: February 3rd, 2016; Revised: February 18th, 2016; Accepted: February 24th, 2016

Abstract

Purpose: The present study is aimed at examining the drying characteristics of sea tangle through a combination of microwave and far-infrared drying experiment and finding the optimal drying conditions. **Methods:** Sea tangle was cleaned and cut into fine pieces (5mm) before they were subjected to combinational drying by microwave and far-infrared ray. The amount of specimen per drying is 2 kg. The finely cut pieces of sea tangle were preheated in a microwave dryer for three different lengths of time (10, 15, and 20 min). Subsequently, they were dried using a far-infrared dryer at tow temperatures (90°C and 100°C) at an air velocity of 0.8 m/s until the final moisture content reduced to 10%. **Results:** Sea tangle dried under the condition of 20 min of preheating in the microwave dryer and drying at 100°C by the far-infrared dryer. Of the drying models verified in this study, the logarithmic model showed high accuracy with the coefficient of determination R^2 >0.7825 and RMSE <0.1095. The rehydration ratio of sea tangle was the highest (12.87 g water/g dry matter) under the condition of 15 min of preheating in the microwave dryer and drying at 100°C by the far-infrared dryer. The energy consumption for the combination of microwave and far-infrared drying was the lowest (4.78 kJ/kg water) under the condition of 20 min of preheating in the microwave dryer and drying at 100°C by the far-infrared dryer. **Conclusions:** Considering the drying time, discoloration during drying, rehydration ratio, and energy consumption for the drying of sea tangle, the optimal drying conditions for high-quality sea tangle are 15 min of preheating in a microwave dryer and drying at 100°C by a far-infrared dryer.

Keywords: Combined drying, Far-infrared drying, Microwave drying, Sea tangle

Introduction

Sea tangle belongs to the brown algae family, and is scattered in the Pacific coast, mainly in Korea, Japan, and the Kamchatka Peninsula. In Korea, it is largely collected in Geojedo Island, Jeju Island, Heuksando Island, and Wando. Sea tangle is known to be good for health, because it lowers blood pressure, reduces cholesterol, and mitigates constipation (Kang et al., 2014). In addition, sea tangle is often used for fried kelp, tea, natural food, and various soups. In recent time, as people have more interest in health, the consumption of sea tangle is on a steady rise. The domestic production of sea tangle was 372,311 MT in 2014, second to laver (KSO, 2014).

However, sea tangle has high moisture content (90%), so it is difficult to preserve or store it. Therefore, sea tangle is currently stored and distributed after it is dried to low moisture content by solar drying or hot air drying (Kang et al., 2014). Solar drying and hot air drying do not require special facility; they can be readily used and are economical (Ning et al., 2014). However, they are easily affected by climate conditions; it takes a long time to dry the products, and hence the products could be discolored by oxidation or photochemical reaction during drying.

§These authors made equal contributions to this work.

***Corresponding author:** Sung-Chan Cho
Tel: +82-43-261-2584; **Fax:** +82-43-271-4413
E-mail: sccho@cbnu.ac.kr

Moreover, these methods are likely to degrade the quality by destroying the nutritional components in the food (Ning et al., 2014). Of the two drying methods, hot air drying is the most widely used method to dry sea tangle. It has a shorter drying time than solar drying, but its energy efficiency is low, and the hot air can change the scent of sea tangle and destroy its inorganic ingredients. In addition, it has problems of case hardening and low restoring force (Lee et al., 2000).

Microwave drying method is characterized by low energy loss and high heating efficiency. Besides, it can sterilize dry foods (Ning, 2012). On the other hand, far-infrared drying has high thermal efficiency, and hence it rapidly raises the internal temperature of the product being heated, resulting in faster drying of the product than with hot air drying (Lee, 2015). Several research work have been conducted on some agricultural products to examine the combinational characteristics of microwave drying and vacuum drying (Kum et al., 1999) and hot air drying and microwave drying (Sharma and Prasad, 2001; Kim et al., 2003; Kassem et al., 2011). These researchers have reported that the combined drying methods can produce high quality of dried product as well as save drying time. However, insufficient number of studies has been domestically carried out on the combinational drying using microwave and far-infrared rays; no work has been reported on the drying of sea tangle with combined drying using microwave and far-infrared rays.

Therefore, the objective of this study was to evaluate the drying characteristics of sea tangle using combined microwave and far-infrared drying technique and establish the optimal drying conditions.

Materials and Methods

Sample

Sea tangle collected in Wando, Jeollanam-do Province, was used in the experiment. Its initial average moisture content was approximately 92.1%, w.b. (expressed as '%' hereafter). In addition, the initial average color of sea tangle before drying was as follows: the value of L (luminosity), a (redness), and b (yellowness) were 22.357, -2.002, and 0.468, respectively. Figure 1 shows the sea tangle before and after drying.

Experimental devices and methods

Figures 2 and 3 show the schematic diagram of a microwave drying equipment and a far-infrared dryer, respectively, used in this sea tangle drying experiment. In Figure 2, the size of the microwave dryer is 9,000×1,500×1,200 mm (L×H×W) and is composed of a microwave radiator (2M244-Ml, 1 kW), a transformer, shield chambers, and a control panel. The far-infrared dryer (Figure 3) is 5,500×1,800×900 mm (L×H×W) in size, and consists of a far-infrared ray radiator (MEP-550, Restoration, Hwaseong, Korea), drying chambers, air blower fan (DTB-420, Dongkun, Korea), and a control panel.

Sea tangle was cleaned and cut into fine pieces (5 mm) by a cutting machine before it was exposed to the combinational drying using microwave and far-infrared rays. The pieces were stacked 2 cm high on a conveyer belt and preheated by a microwave dryer for three different time durations (10, 15, and 20 min). Then, the preheated sea tangle was dried by the far-infrared dryer at temperatures of 90°C and 100°C at an air velocity of 0.8 m/s until the moisture content reduced to 10%. The test conditions

(a) (b)

Figure 1. Sea tangle before (a) and after (b) drying.

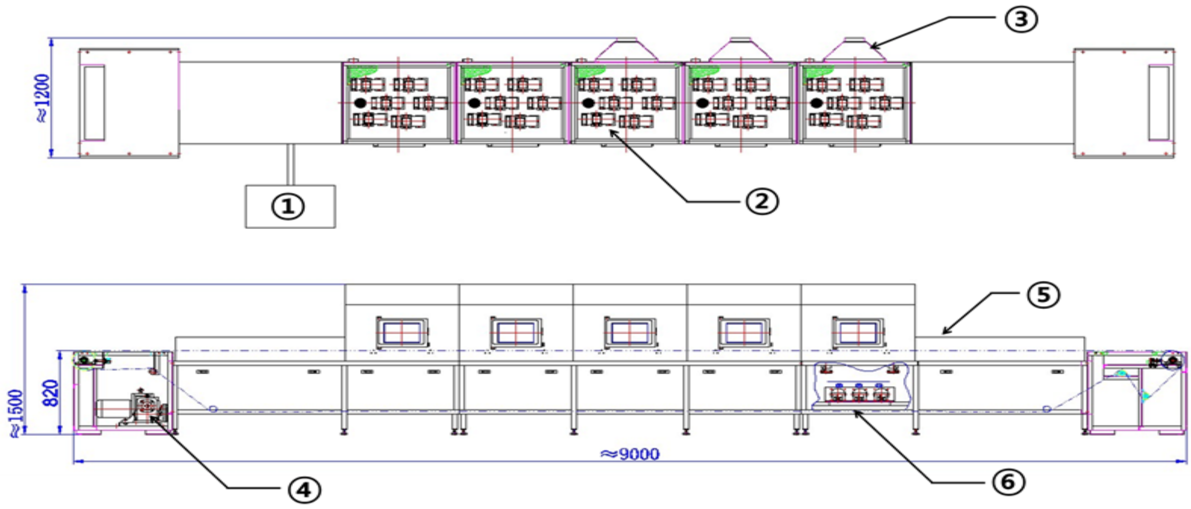


Figure 2. Schematic diagram of the microwave dryer. ① Control panel, ② Microwave generator, ③ Outlet, ④ Motor, ⑤ Shield chamber, ⑥ Electric transformer.

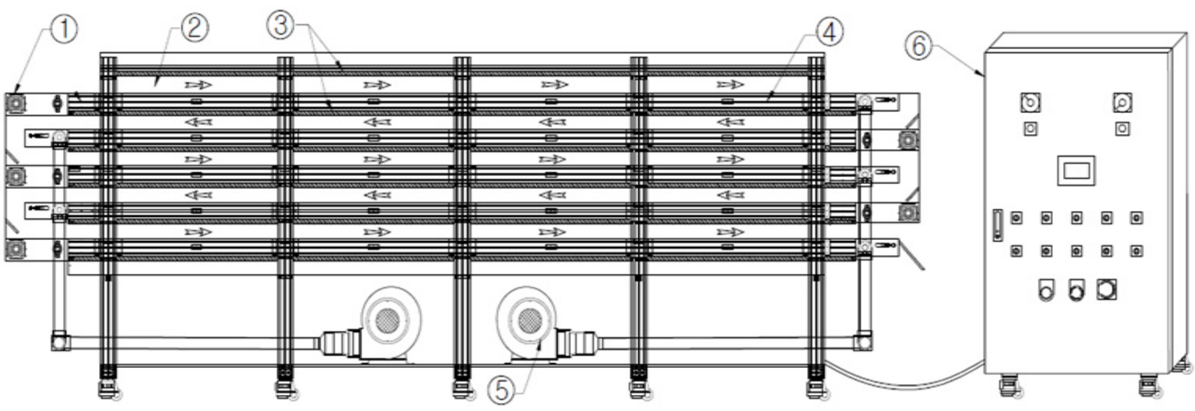


Figure 3. Schematic diagram of the far-infrared dryer. ① Motor, ② Drying chamber, ③ Far-infrared heater, ④ Belt conveyer, ⑤ Blast fan, ⑥ Control panel.

were determined by conducting basic experiments.

The moisture content, drying time, color, rehydration ratio, and energy consumption of the samples at each test condition were measured for comparison. For the control group, the fine pieces of sea tangle were dried only by the far-infrared dryer.

Moisture content

The air oven method (KFDA, 2012) was used to determine the moisture content of sea tangle. Samples of approximately 10 g were placed in air-oven (0F-11E, Jeio Teck, Korea). The operating temperature was 105°C and the samples were kept in the oven for 24 hrs. The determination of moisture content was repeated five times before and after drying.

Drying rate

Drying rate was expressed as moisture ratio. The moisture ratio was calculated by converting the weights measured after different drying durations into moisture content, and is expressed by Equations (1) and (2) (Henderson and Perry, 1976; Keum et al., 2003).

$$MR = \frac{M_t - M_e}{M_0 - M_e} \quad (1)$$

$$M_e = \frac{M_0 \cdot M_f - M_m^2}{M_0 + M_f - 2M_m} \quad (2)$$

MR : Moisture ratio
M_t : Moisture content at time t (%, d.b.)
M_e : Equilibrium moisture content (%, d.b.)

M_0 : Initial moisture content (%, d.b.)
M_m : Moisture content in the middle of drying time (%, d.b.)
M_f : Final moisture content on completion of drying time (%, d.b.)

Drying model

Empirical models (presented in Table 1) that are commonly applied for food materials were applied here to describe the drying kinetics of sea tangle.

The empirical constants for the drying models were determined by nonlinear regression analysis using statistical software SAS (Statistical Analysis System ver. 9.2, SAS Institute Inc., USA). In addition, second-order polynomial model (Equation 3) was used to account for the influence of three factors (volume V, drying temperature Y, and air velocity AV) on the empirical constants (Ning et al., 2013). The goodness of fit for each model was evaluated based on statistical parameters R^2 and RMSE.

$$\text{Model constants} = a_0 + a_1 \cdot (V) + a_2 \cdot (T) + a_3 \cdot (AV) + a_4 \cdot (V)^2 + a_5 \cdot (T)^2 + a_6 \cdot (AV)^2 + a_7 \cdot (V \cdot T) + a_8 \cdot (T \cdot AV) + a_9 \cdot (V \cdot AV) \quad (3)$$

V = Volume (cm^3)
T = Drying temperature (°C)
AV = Air velocity (m/s)

Color

The changes in the color of sea tangle before and after drying were measured in terms of L, a, and b with a color difference meter (JX-777, C.T.S., Japan). The color was repetitively measured 10 times and expressed as an average value. The color difference $\triangle E$, which shows the overall change in color, was calculated using Equation (4) (Rhim et al., 1989; Lee et al., 2010).

Table 1. Semi-theoretical and empirical drying models

No.	Model name	Model
1	Page	MR=exp(-P · t^q)
2	Henderson	MR=a_1 · exp(-k_1 · t)
3	Logarithmic	MR=a_2 · exp(-k_2 · t)+c
4	Lewis	MR=exp(-k_3 · t)
5	Modified Wang and Singh	MR=C+B · t+A · t^2

MR : moisture ratio

$$\triangle E = (\triangle E^2 + \triangle a^2 + \triangle b^2)^{0.5} \quad (4)$$

$\triangle E$: Difference in the values of color after and before drying
$\triangle L$: Difference in the values of lightness after and before drying
$\triangle a$: Difference in the values of redness after and before drying
$\triangle b$: Difference in the values of yellowness after and before drying

Rehydration ratio

The rehydration ratio was measured by the following procedure: 10±0.5 g of dried sea tangle of was placed in a beaker with distilled water at 100°C and the weight of the sea tangle was measured 30 min later (Li, 2009).

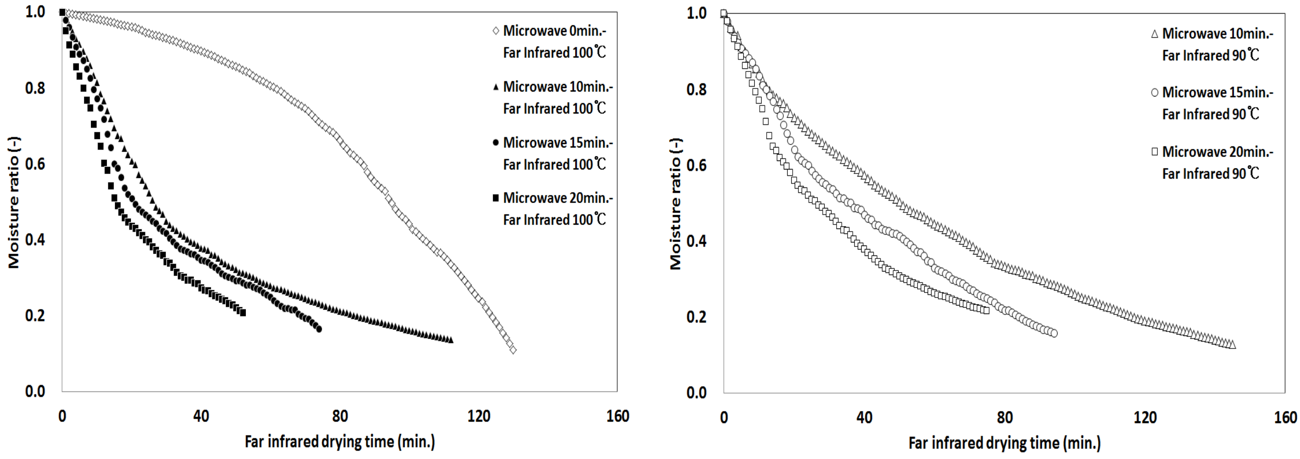
Energy consumption

The energy consumption during far-infrared drying was measured using an integrating watt meter (CW121, YOKOGAWA, Japan) and the measured values were converted into energy consumption to remove 1 kg of moisture.

Results and Discussion

Drying rate

Figure 4 shows a comparison of the changes in the drying rate of sea tangle using only far-infrared drying method and using combinational drying method, with microwave and far-infrared rays. As seen in the figure, when the combinational drying method is applied to dry sea tangle, the drying time is shorter when the preheating time in the microwave dryer is longer and the far-infrared drying temperature is higher. The moisture contents of sea tangle for microwave preheating times of 10, 15, and 20 min are found to be 77.27%, 62.12%, and 46.35%, respectively, which is 14.8~45.72% less than the initial moisture content (92.07%). When the combinational drying method was applied for drying sea tangle, it took 145, 94, and 75 min, for the final moisture content to reach 10±0.5%; for microwave preheating times of 10, 15, and 20 min, respectively, and for far-infrared drying temperature of 90°. It was observed that under the same far-infrared drying temperature, the drying time of sea tangle was 19 to 70 min shorter at 20 min of microwave preheating time than for 10 minutes and 15 min. In addition, when



(A) (B)

Figure 4. Drying curves for sea tangle with different microwave preheating times and far infrared drying temperature of 100°C (A) and 90°C (B).

Table 2. Statistical results of the measured values fitted to the predicted values for drying models

Models		Microwave 10min.		Microwave 15min.		Microwave 20min.	
		90°C	100°C	90°C	100°C	90°C	100°C
Page	R^2	0.8160	0.9184	0.9916	0.9792	0.9264	0.9076
	RMSE	0.1008	0.0672	0.0214	0.0330	0.0598	0.0673
Henderson	R^2	0.8451	0.8913	0.9944	0.9682	0.8799	0.8742
	RMSE	0.0925	0.0775	0.0175	0.0407	0.0764	0.0784
Logarithmic	R^2	0.7825	0.9490	0.9816	0.9860	0.9504	0.9339
	RMSE	0.1096	0.0531	0.0315	0.0271	0.0491	0.0569
Lewis	R^2	0.8350	0.8819	0.9945	0.9648	0.8697	0.8586
	RMSE	0.0954	0.0808	0.0173	0.0429	0.0795	0.0832
Modified Wang and Singh	R^2	0.6443	-0.1086	0.9709	0.9559	0.8530	0.8750
	RMSE	0.1401	0.2476	0.0396	0.0480	0.0845	0.0782

RMSE : root mean square error

the far-infrared drying temperature was 100°C, the drying took 112, 74, and 52 min for microwave preheating times of 10, 15, and 20 min. When only far-infrared drying method was used, the drying time was 130 min at drying temperature of 100°C. Therefore, the drying time with the combinational drying method was shorter than with far-infrared drying alone.

The shortened drying time may be attributed to internal heat generation; liquid moves within the material when it is exposed to microwave (Ning, 2012).

Drying model

To verify the fitness of five drying models, the determination coefficients, R^2 and RMSE, for these models are presented in Table 2. As seen in Table 2, the drying methods, except the Modified Wang and Singh drying model, have R^2 above 0.7825 and RMSE below 0.1096. From the analysis of the results in Table 2, it can be seen that the logarithmic model is the best for describing the drying behavior of sea tangle with the combined drying process using microwave preheating and far-infrared drying.

Figure 5 shows the comparison between experimental data and logarithmic model results. In this, there is a difference between the measured and estimated values at the middle stage of drying, regardless of the microwave preheating time and far-infrared drying temperature.

Color

Figure 6 shows a comparison of the changes in $\triangle E$

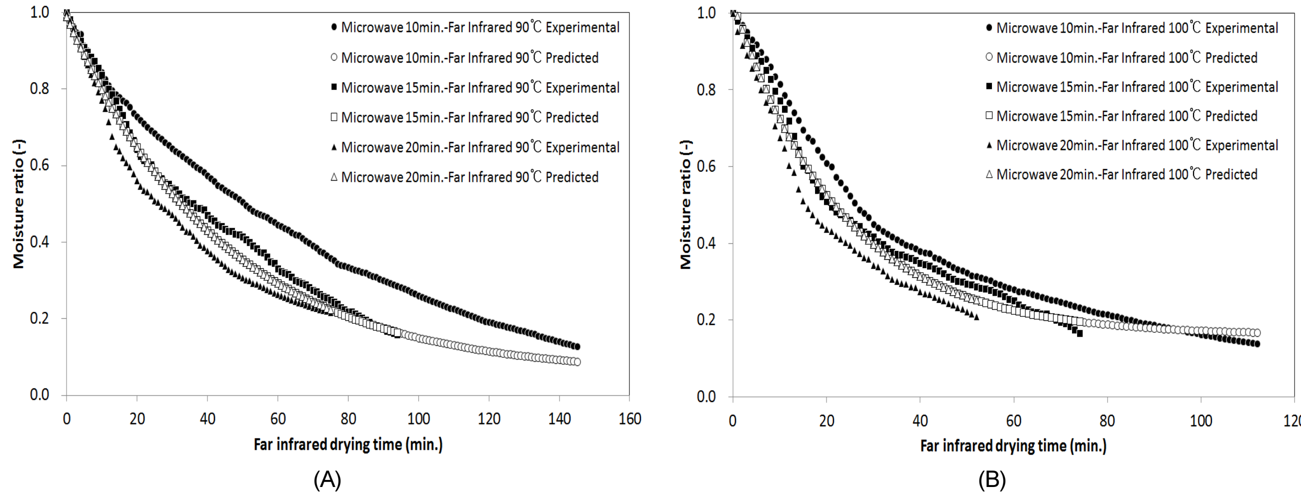


Figure 5. Variations in experimental and predicted moisture ratios with far infrared drying time after microwave drying by the logarithmic model at drying temperature of 100°C (A) and 90°C (B).

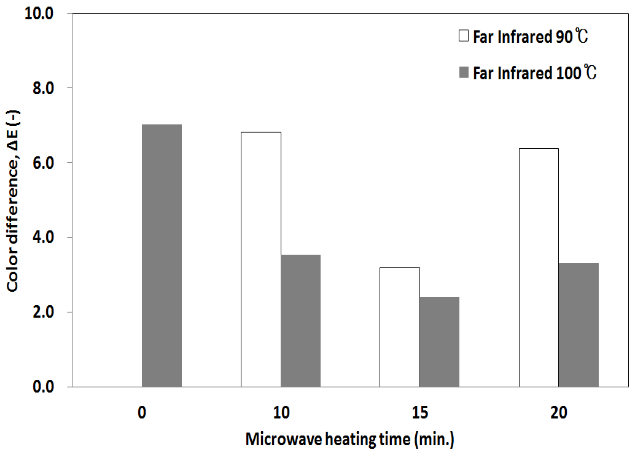


Figure 6. Color difference in sea tangle dried by the combined drying process.

Table 3. ANOVA results for $\triangle E$ according to drying conditions

SOURCE	DF	SS	MS	F	P
Corrected model	5	37.601a	7.520	0.705	0.631
Intercept	1	431.001	431.001	40.379	0.000
Microwave	2	32.024	16.012	1.500	0.262
Temperature	1	1.859	1.859	0.174	0.684
Microwave × Temperature	2	3.718	1.859	0.174	0.842
Error	12	128.088	10.674		
Total	18	596.690			
Corrected total	17	165.688			

DF : Degree of Freedom, SS : Sum of Squares, MS : Mean Squares

(color difference) before and after drying of sea tangle by the combined drying process. The color differences ($\triangle E$) were 6.82, 3.19, and 6.38, under the conditions of 10, 15, and 20 min, respectively, of microwave preheating time and far-infrared drying temperature of 90°C. Thus, the value of $\triangle E$ with 15- min microwave preheating time was lower by 3.19~3.69 than that with 10-min and 20-min preheating times. In addition, $\triangle E$ was found to increase by 7.04, 3.53, 2.42, and 3.32, under the conditions of 10, 15, and 20 min, respectively, of microwave preheating time and far-infrared drying temperature of 100°C. When only the far-infrared drying method was applied, $\triangle E$ was found to be 3.51~4.62 higher than that for the combined method. Table 3 shows the statistics of $\triangle E$ for various drying conditions. As seen in Table 3, the significance probabilities (P-values) for microwave preheating time and far-infrared drying temperature are found to be 0.262 and 0.684, respectively, which are greater than the significance level of 0.05. It means that the color change ($\triangle E$) is not affected by microwave preheating time and far-infrared drying temperature from statistical point of view.

Rehydration ratio

Figure 7 shows a comparison of the rehydration ratios of dried sea tangle dried by far-infrared drying alone and by the combined process. The rehydration ratios of the dried sea tangle are found to be 7.99, 10.93, and 9.05 g water/g dry matter under the conditions of 10, 15, and 20 min, respectively, of microwave preheating time and far-infrared drying temperature of 90°C. In addition, the

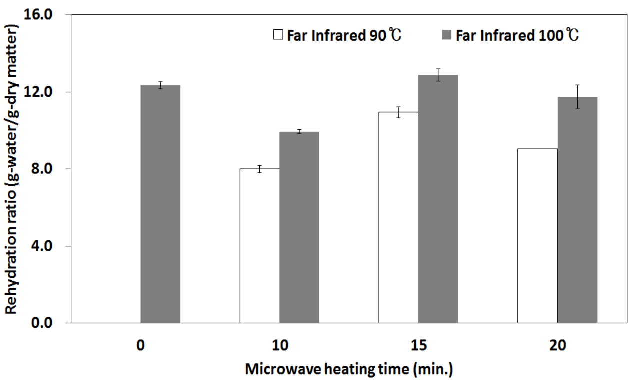


Figure 7. Comparison of rehydration with the combined drying process.

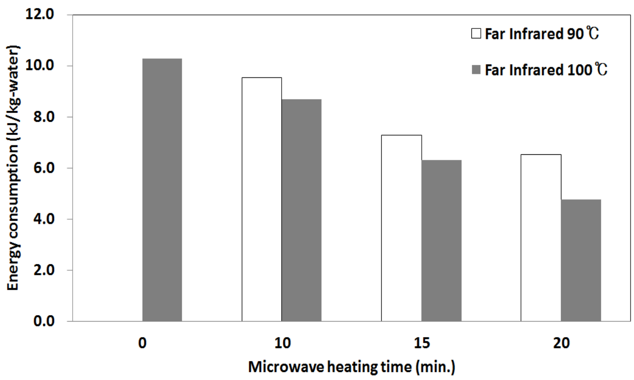


Figure 8. Comparison of energy consumption at the combined drying process

Table 4. ANOVA results for rehydration ratio according to drying conditions

SOURCE	DF	SS	MS	F	P
Corrected model	5	61.665a	12.333	114.359	0.000
Intercept	1	1841.881	1841.881	17079.139	0.000
Microwave	2	45.193	22.596	209.530	0.000
Temperature	1	11.237	11.237	104.197	0.000
Microwave × Temperature	2	5.235	2.617	24.270	0.000
Error	12	1.294	0.108		
Total	18	1904.840			
Corrected total	17	62.959			

DF : Degree of Freedom, SS : Sum of Squares, MS : Mean Squares

ratios were 9.94, 12.87, and 11.73 g water/g dry matter under the conditions of 10, 15, and 20 min, respectively, of microwave preheating time and far-infrared drying temperature of 100°C. When only the far-infrared drying method (100°C) was applied, the rehydration ratio was 12.35 g water/g dry matter. The reason why the rehydration ratio at 100°C was higher than that at 90°C is that sea tangle has higher contraction and higher restoring force at higher drying temperature (Han, 1994). In addition, when only far-infrared drying was applied for drying sea tangle, the rehydration ratio was found to be higher than when the combined drying process was applied. This can be explained by the cellular damage in sea tangle due to the rapid rise in its internal temperature. Table 4 presents the statistics of rehydration ratios under various drying conditions. The significance probability (P-value) of microwave preheating time and far-infrared drying temperature were found to be lower than the significance level of 0.05.

Energy consumption

Figure 8 shows a comparison of energy consumption to remove 1 kg of moisture of sea tangle for far-infrared drying alone and for the combined drying process. The energy consumption for the drying of sea tangle was found to be 9.55, 7.28, and 6.54 kJ/kg water under the conditions of 10, 15, and 20 min, respectively, of microwave preheating time and far-infrared drying temperature of 90°C. In addition, these values were 10.28, 8.70, 6.32, and 4.78 kJ/kg water under the conditions of 0, 10, 15, and 20 min, respectively, of microwave preheating time and far-infrared drying temperature of 100°C. Thus, the energy consumption is lower when the far-infrared drying temperature is higher and the microwave preheating time is longer. In addition, when far-infrared drying was applied alone, energy consumption was found to be the highest.

Conclusions

In this study, a combined drying process (microwave preheating and far-infrared drying has been investigated for its suitability to produce high quality sea tangle.

It was found that the drying rate of sea tangle is shorter when the microwave preheating time is longer and the far-infrared drying temperature is higher. Especially, the drying rate was found to be highest for microwave preheating time of 20-minute and far-infrared drying temperature of 100°C of. The logarithmic model adequately described the combined drying process of sea tangle $R^2 >$ 0.7825 and RMSE < 0.1095. $\triangle E$ was found to be higher by 3.51~4.62 with far-infrared drying alone than the combined drying process. Particularly, the values of $\triangle E$ were 3.19

and 2.41, drying temperature 90°C and 100°C, respectively, these were the lowest values, and were observed for 15-minute microwave preheating time. The rehydration ratio of sea tangle was found to be higher at far-infrared drying temperature of 100°C than at 90°C. Particularly, the highest value of 12.87 g water/g dry matter was observed for 15-min microwave preheating time, and at all the temperature of far-infrared drying. Energy consumption with the combined drying process was low at high drying temperature and long preheating time. Its lowest value was 4.78 kJ/kg water for 20-min microwave preheating time and far-infrared drying temperature of 100°C. In conclusion, it is the most appropriate drying condition for producing high quality sea tangle is, 15-min microwave preheating time followed by far-infrared drying temperature of 100°C.

Conflict of Interest

The authors have no conflicting financial or other interests.

Acknowledgments

This work was supported by the research grant of Chungbuk National University in 2014.

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