

Optimizing Microwave Drying of Shiitake Mushrooms: Evaluating Step-Down Power Strategies for Enhanced Energy Efficiency and Product Quality

Wanchalee Pengpongsa¹, Weera Sriariyakul², Piyapong Pankaew³,
and Ponlakrit Kumklam^{3*}

Received: 9 September 2025

Revised: 19 December 2025

Accepted: 2 February 2026

ABSTRACT

Shiitake mushrooms (*Lentinula edodes*), known for their nutritional and therapeutic benefits, are prone to post-harvest spoilage due to their high perishability. Traditional hot air (HA) drying is energy-intensive and can compromise product quality, while continuous microwave (MW) drying carries the risk of thermal damage. This study explores the effectiveness of step-down MW power strategies to optimize drying efficiency, energy consumption, and product quality. Fresh Shiitake mushrooms with an initial moisture content of 285 % (d.b.) were dried using both constant MW power and step-down protocols. We analyzed the drying kinetics, specific energy consumption (SEC), color, shrinkage, and rehydration ratios. The results showed that increasing the MW power from 100 W to 450 W reduced the drying time by 50%, achieving evaporation rates of up to 18.92 % (d.b.)/min. The step-down MW drying at 450 W for 10 minutes followed by microwave power 200 W, resulted in the lowest SEC of approximately 18.89 MJ/kg_{water evaporated}. The drying process at a constant MW power of 450 W caused slight discoloration, while the step-down MW drying preserved the lightness color. Constant MW power drying led to more significant shrinkage compared to the step-down method. The highest rehydration ratio was 4.06,

¹Faculty of Science, Chandrakasem Rajabhat University, Bangkok, Thailand 10900

²College of Industrial Technology, King Mongkut's University of Technology North Bangkok, Bangkok, Thailand 10800

³Faculty of Science and Technology, Rajamangala University of Technology Phra Nakhon, Bangkok, Thailand 10800

*Corresponding author e-mail: ponlakrit.k@rmutp.ac.th

achieved with a constant MW power drying. The study concludes that a step-down MW drying optimizes energy efficiency while maintaining acceptable product quality. These findings offer valuable insights for producing dried Shiitake mushrooms and suggest potential for industrial application.

Keywords: Shiitake Mushrooms; Microwave Drying; Step-Down Drying; Energy Consumption; Shrinkage

Introduction

Shiitake mushrooms (*Lentinula edodes*), a globally cherished edible fungus, are prized for their umami flavor, high nutritional value, and therapeutic compounds such as lentinan, ergosterol, and antioxidants [1]. As the second most cultivated mushroom worldwide, their market demand is projected to grow at a compound annual growth rate (CAGR) of 6.4% through 2030 [2], driven by rising health-conscious consumer trends and applications in functional foods and nutraceuticals. However, fresh Shiitake mushrooms are highly perishable, with a post-harvest shelf life of fewer than 10 days under ambient conditions, necessitating efficient preservation methods to mitigate enzymatic degradation, microbial spoilage, and moisture-driven texture collapse [3]. Drying, a cornerstone of food processing, extends shelf life by reducing water activity while preserving bioactive constituents [4]. Conventional drying techniques, such as HA drying, remain energy-intensive and time-consuming, regularly compromising product quality through prolonged exposure to thermal stress, which accelerates non-enzymatic browning, structural shrinkage, and nutrient loss [5].

MW drying has emerged as a transformative technology in food dehydration, leveraging dielectric heating to volumetrically excite water molecules via high-frequency electromagnetic waves (2450 MHz). Unlike conductive/convective methods, MW energy penetrates materials, generating internal heat that rapidly vaporizes moisture, thereby reducing drying times by 30–60% compared to HA drying [6]. Recent advancements in MW drying, such as MW-HA and MW-infrared have demonstrated superior retention of color, texture, and phytochemicals in fruits and vegetables [7]. For instance, Zielinska and Markowski [8] reported that MW drying of blueberries preserved higher soluble solids in comparison with HA drying. However, unoptimized MW parameters, particularly excessive power density or prolonged exposure can induce localized overheating, leading to case hardening, pore collapse, and Maillard reaction-driven discoloration [9]. Such challenges underscore the need for adaptive power control strategies to balance drying efficiency with product integrity.

Stepwise MW power adjustment, a dynamic approach involving high initial power to rapidly remove free moisture followed by reduced power to gently eliminate bound water, has shown promise in mitigating thermal damage while also benefiting from the energy-efficient and moisture redistribution [10, 11]. Many research on MW optimization for Shiitake mushrooms remains sparse, with existing studies focusing narrowly on drying kinetics or isolated quality metrics. A holistic evaluation of MW regimes encompassing energy efficiency, and physical quality is critical to advancing industrial adoption.

This study addresses these gaps by systematically investigating the effects of constant and step-down MW power strategies on the drying behavior and quality attributes of Shiitake mushrooms. Specific objectives include the drying Kinetics, specific energy consumption (SEC) and quality evaluation in term of color, shrinkage, and rehydration ratio under varying MW powers. The research findings are offering a pathway to reduce energy consumption in food processing while meeting consumer demand for premium-quality dried products.

Materials and Methods

Experimental setup

The Shiitake mushrooms were dried using a microwave oven (Samsung model MS23F300EEK/ST) with chamber dimensions of 33 cm x 21 cm x 32 cm .The drying chamber was equipped with a 1150 W microwave magnetron (OM75S) with the operating frequency of 2450 MHz. The microwave magnetron was controlled by the controlled unit which equipped form the manufacture. The polytetrafluoroethylene plate with diameter of 26 cm was a container for placed samples. For HA drying, a tray dryer was utilized. This dryer features a forward-curved blade centrifugal fan powered by a 2.2 kW motor, along with three 1 kW heaters. The dimensions of the drying chamber are 52 cm x 52 cm x 52 cm.

Material preparation

Fresh Shiitake mushrooms with cap diameter of 5 cm. were purchased from a local supermarket and removed stalks.The initial moisture content of the mushrooms was around 280% (d.b.) The moisture content of mushrooms was measured by drying them in an oven (Memmert, Model UF75, Germany) at a temperature of 103 °C for 72 h, according to AACC method [12]. For each moisture content determination, it was done in triplicate and the average value was reported.

Drying of Shiitake mushroom

The mushrooms weighing 100 grams were placed on a drying plate and were dried under the conditions specified are shown in Table 1 with a drying air velocity of 3 m/s for the HA drying. The microwave power was controlled by a selected switch to set the electrical power input of 100, 200, 300 and 450 W. depend on each drying condition. The samples

were dried until their final moisture content did not exceed 10% (d.b.) Samples were taken out of the dryer every 10 minutes to determine their moisture content using an electronic balance (A&D, Model FX-2000i, Japan) with a precision of ± 0.01 gram. The dried samples were stored in a sealed aluminum bag and kept in a refrigerator at 4-6 °C for 3 days to allow for moisture equilibration and hardness stabilization before further analysis. Each drying experiment was performed in triplicate.

Color measurement

The color of Shiitake mushroom were examined by a spectrophotometer (Konica Minolta, CM-3500d, Japan) with a D65 illuminant and an observer angle of 10°. The color was described using the CIE color system. Prior to each measurement, the spectrophotometer was calibrated with a standard white plate having standard value of $L^*=93.19$, $a^*=1.12$, and $b^*=1.33$. where L^* , a^* , and b^* are the lightness/darkness, redness/greenness, and yellowness/blueness of the sample, respectively. Each color measurement was performed at different 3 positions around sample surface and 3 samples were used, an average value is reported.

Shrinkage and determination

The volumes of fresh and dried shiitake mushrooms were measured using the volumetric displacement method with n-heptane, which has a density of 0.684 g/cm³ as the working liquid. The percentage of shrinkage was calculated using the formula [13]

$$\text{Shrinkage (\%)} = 100(V_0 - V)/V_0 \quad (1)$$

where V_0 is the initial volume of the shiitake mushroom (m³) and V is the volume after drying (m³). This measurement was conducted with ten replications to ensure accuracy.

Table 1 Details of operating parameters for the drying tests.

Test No.	Drying conditions
1	Hot air temperature 60 °C (HA 60 °C)
2	Hot air temperature 80 °C (HA 80 °C)
3	Hot air temperature 100 °C (HA 100 °C)
4	Microwave power 100 W (MW 100 W)
5	Microwave power 200 W (MW 200 W)
6	Microwave power 300 W (MW 300 W)
7	Microwave power 450 W (MW 450 W)
8	Microwave power 450 W for 10 minutes follow by microwave power 200 W (MW 450 W for 10 minutes then MW 200 W)
9	Microwave power 450 W for 10 minutes follow by microwave power 100 W (MW 450 W for 10 minutes then MW 100 W)
10	Microwave power 450 W for 5 minutes follow by microwave power 200 W (MW 450 W for 5 minutes then MW 200 W)
11	Microwave power 450 W for 5 minutes follow by microwave power 100 W (MW 450 W for 5 minutes then MW 100 W)

Rehydration determination

Rehydration of dried samples was achieved by immersion in a dH₂O bath at 60 °C until a constant weight was reached. The rehydration ratio was calculated using the following equation [13]

$$\text{rehydration ratio} = M_2/M_1 \quad (2)$$

where M_1 and M_2 represent the weight of dried and rehydrated samples (kg), respectively.

Specific energy consumption

A kilowatt-hour meters (DAI-CHI, DD28, Thailand) was used to measure the total energy consumption of each drying treatment. The energy consumption was calculated based on the total energy used during the drying process relative to the total amount of evaporated moisture. This can be expressed with the following equation [14]

$$SEC = \frac{2.6(E_{MW})}{M_w} \quad (3)$$

Where SEC is the specific energy consumption (MJ/kg_{evaporated water}), E_{MW} is the electrical energy for the microwave magnetron to heating the samples (MJ), and M_w is the total amount of evaporated water (kg). The value of 2.6 is used as a conversion factor to translate electrical energy into primary energy.

Results and discussion

Drying kinetics of shiitake mushrooms

The drying kinetic of shiitake mushroom via the different MW power and hot air temperature was shown in Fig.1. According to the drying curve, the samples was dried with the MW radiator from initial moisture content at 285% (d.b.) to the final moisture content at 10% (d.b.) within the drying time of 25-50 minutes depend on the MW power. The drying characteristic was highly dependent on the MW power, higher MW power took the shorter drying time. Drying shiitake mushroom with the MW power of 100, 200, 300, and 450 W took the drying time of 50, 40, 35, and 25 minutes, respectively. The drying condition in the MW power of 450 W was saving time of 50% comparing with the drying condition of MW power of 100 W. The drying of shiitake mushroom with higher MW power resulted in higher temperature in the samples. A higher MW power caused a high energy MW penetrate into the sample, thus resulting in the high temperature of the sample and a rapid water evaporated rate as a consequence [15, 16].

As shown in Fig.1, the moisture content reduction of shiitake mushrooms which dried by the convectional hot air, increasing the drying temperature was affected the faster moisture content reduction. At the final moisture content of 10% (d.b.), the increasing of drying temperature from 60 °C up to 100 °C, the drying process was reduced the drying time of 40 minutes. This is because a higher drying air temperature creates a larger difference between the drying temperature and the material's surface temperature, thereby increasing the evaporated rate of moisture from the surface [17]. Comparing the drying of shiitake mushroom between using the MW and HA as the drying medium, the results was clearly that the samples moisture content was faster decreased with using the MW as the drying medium. The MW power was more influent effect to the evaporated rate. The samples could absorb the MW power which is the microwaves provided the rapid polarization and depolarization of water's charge as the shiitake mushroom is subject to a MW field, leading to the rapid production of thermal energy resulting in the faster transportation of moisture from the inside to the samples surface and the correspondingly higher rate of drying. This rapid moisture removal is attributed to enhanced effective moisture diffusivity, which increases exponentially with MW power due to intensified molecular agitation [18].

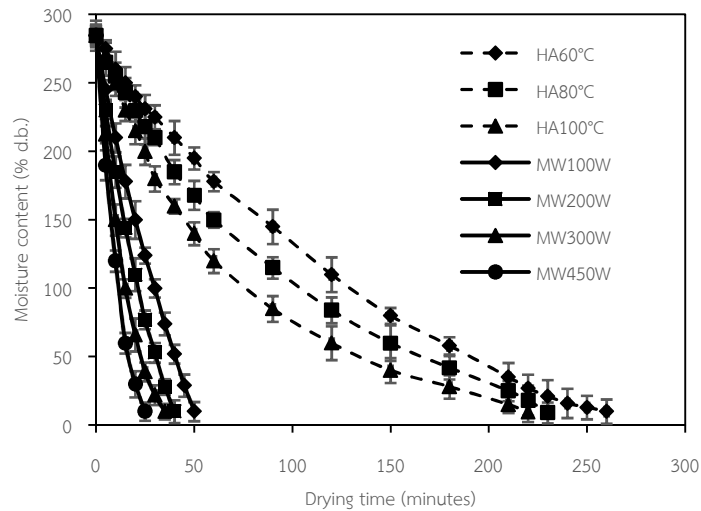


Figure 1 Effect of microwave power and hot air temperatures on moisture content reduction.

Fig.2 showed that the drying rate versus the moisture content of drying shiitake mushroom via the different drying air temperature and MW power. All drying conditions, the samples with higher moisture content were affected on higher drying rates as expected. Materials with higher moisture has less water evaporated resistance than dry materials. The result is clearly that the drying rate of drying shiitake mushroom via the MW drying was higher than dried with HA drying in the range of 2-17% (d.b.)/min depended on the moisture content. The highest drying rate was 18.92% (d.b.)/min at the drying condition of MW 450 W, drying samples with HA drying resulted the highest drying rate of was 4.20% (d.b.)/min at the drying air temperature of 100 °C. The significant different results showed that MW drying could significantly affected the moisture evaporated. Furthermore, increasing of MW power of 350% resulted the maximum drying rate increase of 138%, and increasing of the drying air temperature of 66.66% resulted the maximum drying rate increase of 61.53%, these results seem that the drying shiitake mushroom with the MW drying more influent affected the water evaporated compare with HA drying but the comparison directly was not fair because the MW and HA drying affected the water evaporated with different mechanism. Therefore, the energy consumption in the drying process is the right approach to compared the efficiency of different drying method that will discuss in the specific energy consumption section.

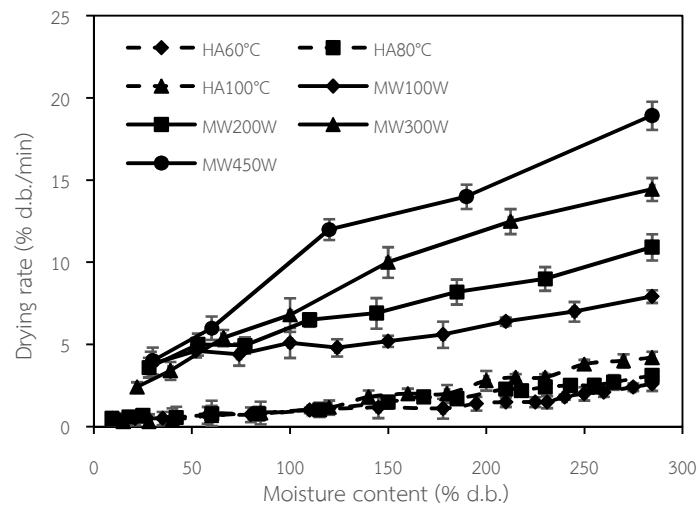


Figure 2 Variation in drying rate at difference drying condition.

Fig.3 showed the effect of step-down the MW power on change of moisture content of the shiitake mushroom during drying process. The results show that the moisture reduction was significantly decreased when the MW power decreased at the drying time of 5 and 10 minutes depend on drying condition. This phenomenon is different when observe form several research papers that report about drying of agriculture product using step wise drying air temperature which report the moisture content reduction was exponentially decreased along the drying time [19-21]. This is indicated that the different mechanism of the water evaporated on drying samples with MW and HA drying was generated the different drying kinetic curve. For the reason that the MW drying can penetrated directly to the inside of samples, the molecule of water is oscillated that generated the thermal energy resulted in water evaporated rapidly [10]. Which is different from dried the samples with HA that evaporated the moisture at the samples surface, the during time of the moisture diffusion depended on the drying resistance of materials.

The moisture reduction of shiitake mushroom that dried with MW 450 W for 10 minutes in earlier stage was faster decreased than that dried of the MW450W for 5 minutes as shown in Fig.3. This is indicated that the enhancing the energy input of drying at the earlier stage was significant effect the drying kinetic which explain that the drying rate was higher at the earlier stage because the samples have more moisture after that the drying rate was slowly decreased because the moisture diffusion need time to travel from inside to the sample surface [17]. Since decreased the MW power at the second stage, the moisture content reduction at the drying condition of MW200W was faster decreased compared with the

drying condition of MW 100 W as expected. At the final moisture content at 10% (d.b.), the drying condition of MW 450 W for 10 minutes then MW 200 W resulted the shorter drying time than that of MW 450 W for 10 minutes then MW 100 W was about 2 minutes and the drying condition of MW 450 W for 10 minutes then MW 200 W resulted the shorter drying time than that of MW 450 W for 5 minutes then MW 200 W was about 8 minutes. It can be seen that duration time drying in the earlier stage was more affect the moisture reduction. Nevertheless, higher microwave power during the second stage resulted in a shorter drying time.

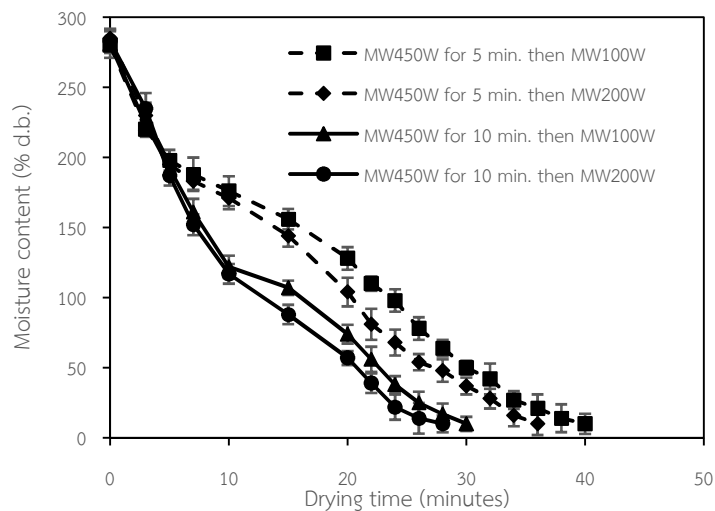


Figure 3 Effect of microwave power and hot air temperatures on moisture content reduction.

Color of dried shiitake mushrooms

Table 2 showed the color of dried shiitake mushroom under different drying conditions. The shiitake mushroom dried using the step-down MW power at the drying condition of MW450W for 10 minutes then MW200W, exhibited higher lightness (L^*), redness ($+a^*$) and yellowness ($+b^*$) compared to the other drying conditions. The mean values of lightness for red and yellow were 32.31, 6.61, and 0.91, respectively. This is attributed to the higher MW power during the first stage of the drying process, which allowed the step-down temperature technique to minimize non-enzymatic browning reactions [22, 23]. The lightness of samples was affected from combined the two factors that the MW power and the drying time. As showed in Table 2, the drying condition of MW 450 W for 10 minutes then MW 200 W was resulted more lightness than that the MW 450 W for 5 minutes then MW 200 W. This is paradoxical because the drying with higher MW power should be more effected to the non-enzymatic browning reactions, the samples

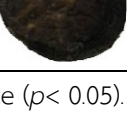
were darkness, conversely, the drying condition of MW 450 W for 10 minutes, then MW 200 W has shorter drying duration of minutes, these factors were simultaneous effect to the samples's color.

Shrinkage percentages and rehydration ratio of dried shiitake mushrooms

The shrinkage of dried shiitake mushrooms is one of several factors that influence a customer's decision to purchase the product. On the shelf, shiitake mushrooms should have an appealing appearance, characterized by bright colors, good plumpness, and symmetrical dimensions. Most customers tend to prefer these qualities.

Shrinkage percentages of shiitake mushroom was showed in Fig.4. In case of constant MW power, at the final moisture content of 10% (d.b.), the mushroom was shrunk insignificantly, there was shrinkage value in the range of 75.6-84.4%. While drying the mushroom with step -down MW power method, the shrinkage value was in the range of 30.2-65.7%. There was significantly shrunk compared with constant MW power drying. As shown in Fig.4, the drying condition of MW 450 W for 10 minutes then MW 200 W, the samples were more shrunk compare with the drying condition of MW 450 W for 10 minutes then MW 100 W about of 36.3%, and in the same way, the drying condition of MW 450 W for 5 minutes then MW 200 W, the samples were more shrunk compare with the drying condition of MW 450 W for 5 minutes then MW 100 W about of 11.1%. This experiment is concluded that the higher microwave intensity in case of step-down MW power drying effects more shrinkage. High drying temperatures can lead to the collapse of the internal structure, which impedes water penetration during rehydration. The macroscopic properties of the product are determined by its microstructure [24, 25]. Since dried foods are typically soaked in water before cooking or consumption, rehydration is a critical criterion.

Table 2 Color of dried shiitake mushrooms under various drying conditions.

Drying condition	L^*	a^*	b^*	Drying time (minutes)	Product appearance
MW 100 W	29.53±0.99 ^c	4.59±0.55 ^b	0.73±0.41 ^d	50±0.07 ^g	
MW 200 W	28.41±0.15 ^{bc}	2.69±0.06 ^a	-1.38±0.18 ^{ab}	40±0.23 ^h	
MW 300 W	28.20±1.90 ^{ab}	4.80±0.38 ^{bc}	0.27±1.07 ^{cd}	35±0.18 ⁱ	
MW 450 W	28.70±0.13 ^{bc}	5.35±0.23 ^{cde}	0.30±0.45 ^{cd}	25±0.13 ^j	
MW 450 W for 10 minutes then MW 200 W	32.31±1.04 ^d	6.61±0.48 ^f	0.91±0.61 ^d	28±0.43 ^c	
MW 450 W for 10 minutes then MW 100 W	29.73±0.54 ^c	5.15±0.72 ^{bcd}	-1.44±.71 ^{ab}	30±0.21 ^a	
MW 450 W for 5 minutes then MW 200 W	27.76±1.62 ^{ab}	5.62±0.23 ^{de}	-1.92±1.01 ^a	36±0.46 ^f	
MW 450 W for 5 minutes then MW 100 W	30.99±0.02 ^c	5.84±0.10 ^e	-0.60±0.11 ^{bc}	40±0.28 ^e	

Different superscript letters in the same column indicate statistical difference ($p < 0.05$).

Fig.5 showed the rehydration ratio of dried shiitake mushrooms under different drying conditions. As expected, the rehydration ratio of the samples increased with longer soaking times. Samples dried using constant MW power drying exhibited higher rehydration ratios compared to those dried with a step-down MW drying. The highest rehydration ratio for the constant MW power drying ranged from 3.83 to 4.06 higher than that dried at step-down MW drying in the range of 1.55-1.62 time. This phenomenon can be explained by the fact that drying samples with constant MW power resulted in a faster reduction of moisture, leading to larger pore sizes in the samples [26, 27]. Furthermore, the rehydration ratio was

correlated with the shrinkage percentage of the samples, as shown in Fig.4. It was observed that samples with higher shrinkage percentages tended to have higher rehydration ratios. Similar results were reported by Nathakaranakule et al. [26] who explained that high MW power contributed to larger pore diameter and an increased void area fraction in the samples. It is important to note that dried shiitake mushrooms become harder and require soaking in water before cooking, and a greater swelling is preferable.

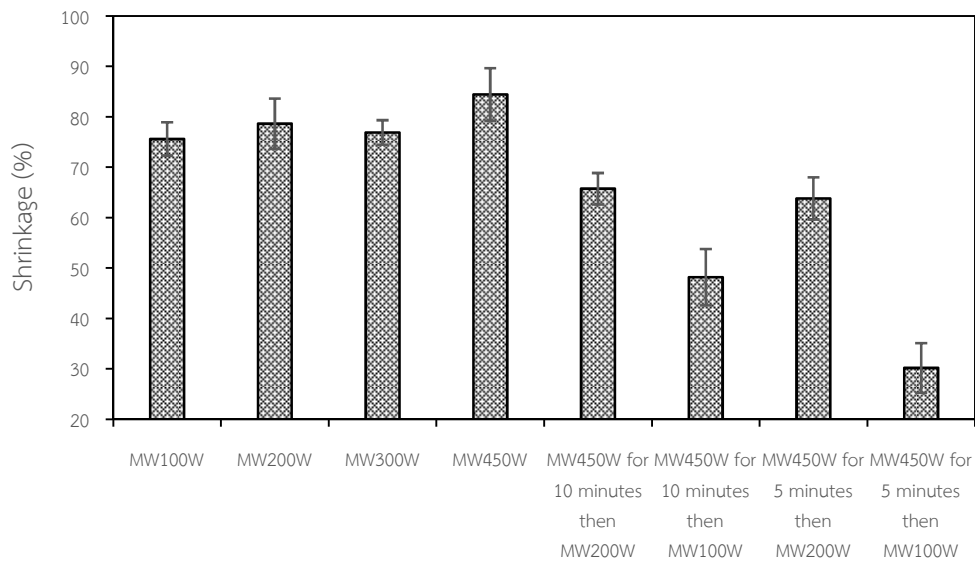


Figure 4 Shrinkage percentages of dried shiitake mushrooms under different drying conditions.

Specific energy consumption

The energy consumption of the drying process was evaluated in terms of specific energy consumption (SEC) that derived from the energy consumption of the microwave radiator and amount of evaporated water. Fig.6 showed the SEC of the drying process under various operating conditions. The SEC was dominated by the drying time duration, the drying condition of MW 450 W for 10 minutes then MW200W was consumed lowest SEC which the value of 18.89 MJ/kg_{water evaporated}. In case of drying with constant the MW power, the SEC was significantly decreased with increased the MW power. As increased the MW power from 100 W up to 450 W, the SEC was decreased of 57.44%. In case of the step-down MW power drying, the SEC of the drying condition of MW450W for 10 minutes then MW200W was less than the drying condition of MW450W for 5 minutes then MW100W about of 55.97%.

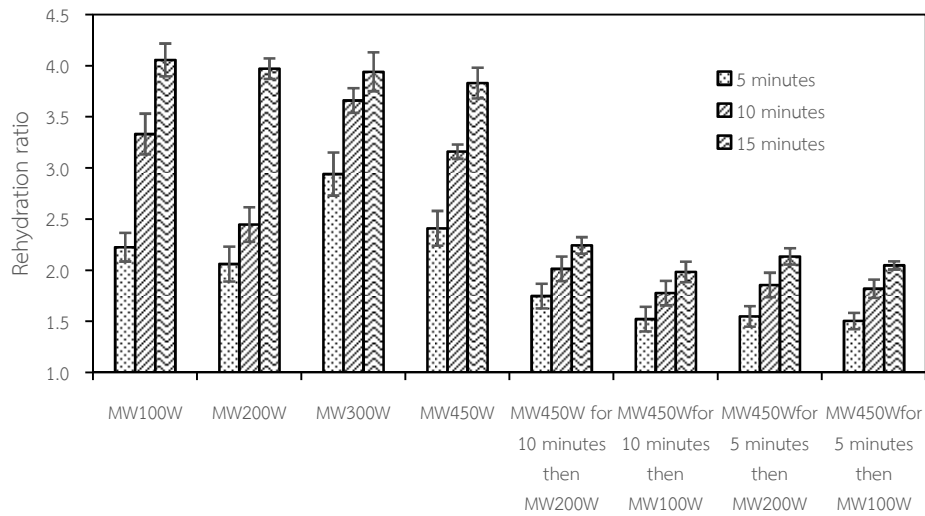


Figure 5 Effect of soaking time on the rehydration ratio of dried shiitake mushrooms under different drying conditions.

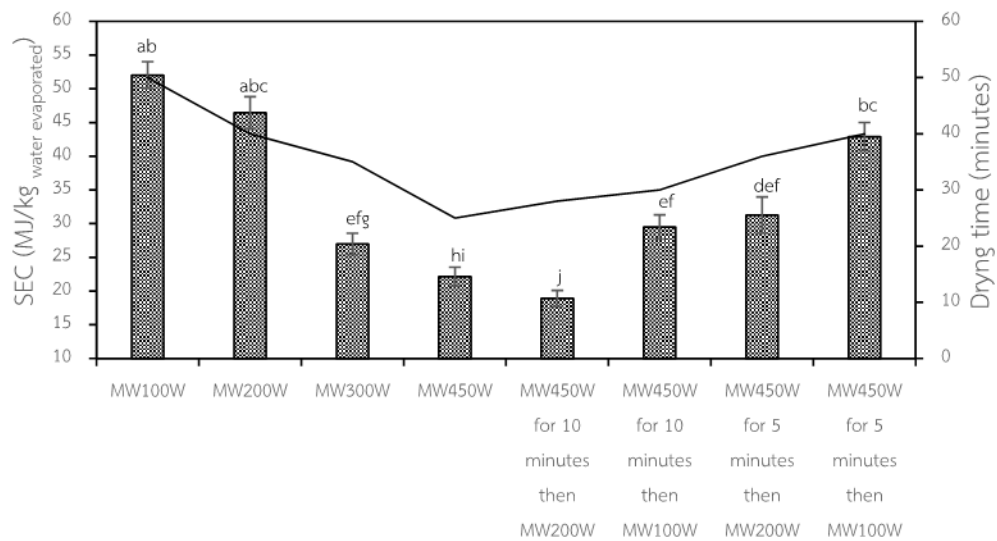


Figure 6 Specific energy consumption of drying process and drying times under different drying conditions. Different letters above the data point mean that the values are significantly different ($p < 0.05$).

The higher microwave intensity enhanced the water evaporated and affected the shorter drying time that reduced the SEC. For energy saving, a step-down MW power at MW 450 W for 10 minutes then MW 200 W is recommended for drying shiitake mushroom. To minimize drying time, a constant MW power drying at MW 450 W is preferable. However, when selecting drying conditions, it is essential to consider both the quality of the shiitake mushroom after drying and the associated energy consumption.

Conclusions

This study systematically evaluated the effects of constant and step-down MW power strategies on the drying kinetics, physical quality, and energy efficiency of Shiitake mushrooms. The use of higher MW power significantly reduced drying time. Constant MW power of 450 W, the drying time was reduced by half compared to using 100 W, achieving a final moisture content of 10% (d.b.) in 25 minutes. MW drying demonstrated superior moisture removal rates of up to 18.92% (d.b.)/min, which is higher than the rates achieved with HA drying. Additionally, step-down MW drying was found to better preserve color, resulting in higher lightness and minimizing non-enzymatic browning. However, Constant MW power drying at 450 W caused some discoloration due to Maillard reactions and led to greater shrinkage compared to step-down methods. On the other hand, constant MW power drying resulted in higher rehydration ratios. Step-down MW drying method, which involves drying at MW 450 W for 10 minutes then MW 200 W minimized specific energy consumption to 18.89 MJ/kg_{water evaporated}. While constant drying at 450 W optimized drying time, it consumed more energy than the step-down methods. Constant MW power drying outperformed the step-down protocol in terms of shorter drying time, but it required careful power modulation to avoid degrading product quality. For industrial applications, it is recommended to use the step-down MW power drying method at MW 450 W for 10 minutes then MW 200 W, to balance energy efficiency, drying time, and product quality. Although constant drying at 450 W may be suitable for time-sensitive operations, it could compromise color and physical appearance. Future research should focus on exploring hybrid MW-vacuum systems and conducting microstructure analysis to further optimize drying parameters.

Acknowledgements

The authors would like to thank Faculty of Science at Chandrakasem Rajabhat University and Faculty of Science and Technology at Rajamangala University of Technology Phra Nakhon for their support in providing research tools and facilities.

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