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Efficiency and Energy Consumption Analysis of Infrared-Assisted Drying of Oyster Mushrooms

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ABSTRACT

The potential of infrared drying to enhance energy efficiency and condense drying periods has been increasingly recognized. The present study is centered on the application of infrared lamps to extend the shelf life of oyster mushrooms, a widely consumed species. The drying performance and energy consumption of these mushrooms were evaluated using a batch method, highlighting the influence of varying power levels (432 W, 504 W, and 624 W), drying air velocities (1.2 $m.s^{-1}$ and 1.5 $m.s^{-1}$), and mushroom weight (500 g and 750 g) on the drying process. Parameters including changes in water content, specific energy consumption (SEC; kWh. kg of $water^{-1}$), and drying energy efficiency (%) were meticulously observed. It was found that drying energy efficiency varied between 40.01 and 53.95%, while the SEC ranged from 2.81 to 3.58 kWh. kg of $water^{-1}$. The combination of 624 W power, 1.5 $m.s^{-1}$ of drying air velocity, and a mushroom weight of 750 g yielded the highest drying efficiency (53.95%) and the lowest SEC (2.81 kWh. kg of $water^{-1}$). Furthermore, the shortest drying time was observed when the conditions were adjusted to the highest power level (624 W), fastest air velocity (1.5 $m.s^{-1}$), and lowest sample weight (500 g). This study underscores the promise of infrared drying in optimizing the drying process of oyster mushrooms, with implications for broader applications in food preservation.

1. INTRODUCTION

Oyster mushrooms (Pleurotus ostreatus) are known for their white-hued appearance and hood shape, reminiscent of an oyster shell [1]. These mushrooms are rich in protein, carbohydrates, fats, vitamins, and minerals [2]. However, their high moisture content makes them prone to rapid decay, leading to an unpleasant odor, brownish color, and watery texture [3]. Consequently, these mushrooms have a limited shelf life, typically ranging from 1-2 days at room temperature to 2-3 days under controlled conditions [4-6].

To extend the shelf life of oyster mushrooms, various preservation methods have been explored, one of which involves drying the mushrooms [5, 7]. The drying process serves to remove most of the water content by employing heat energy, thus facilitating the equilibrium between the water content and the surrounding environment [8]. This not only reduces weight and volume, easing the process of transportation and storage [7], but also necessitates careful selection of the drying method, given the mushrooms' high sensitivity to temperature [6, 9-11].

Traditional sun drying is frequently employed by farmers, particularly in Indonesia [12, 13]. This method is simple and cost-effective, but it is marred by numerous drawbacks. These include dependence on weather conditions, prolonged drying times, and susceptibility to contamination from dust, insects, and dirt which ultimately lead to suboptimal, low-value end products [7, 13, 14].

Infrared (IR) drying, in contrast, is considered a more efficient method for enhancing the drying rate of agricultural products, using less energy than traditional drying methods [15].

This technique employs infrared radiation, produced by infrared lamps, to dry materials, making it a popular choice in food, pharmaceutical, and other industries [16-19]. Infrared radiation, falling within the electromagnetic spectrum between ordinary light and microwaves, can penetrate the surface layers of materials and cause water molecules within to vibrate and generate heat [20]. This radiation can be categorized into near-infrared (NIR) radiation (wavelengths from 0.78µm to 1.4µm), mid-infrared (MIR) radiation (wavelengths from 1.4µm to 3µm), and far-infrared (FIR) radiation (wavelengths from 3µm to 1000µm) [21].

The unique properties of infrared radiation make it ideal for drying materials with high dielectric values, such as water [22]. The volumetric nature of water means that when exposed to infrared radiation, the temperature increase originates within the material, moving outward. This is in contrast to conventional drying, where the heat primarily affects the surface of the material [23].

The advantages of infrared drying are manifold, including shorter processing times, increased energy efficiency, improved final product quality, and greater control over process parameters [18, 19, 24].

Furthermore, previous studies have revealed that infrared drying requires less energy and causes less damage or deformation to the material due to the lower drying temperature [6, 25].

However, it is worth noting that infrared drying is best suited for materials with relatively thin and homogeneous thickness, such as paper, cloth, or small food items. Materials with larger thickness or complex structure may necessitate alternative drying technologies for optimal results.

Previous research on oyster mushroom drying has primarily focused on traditional methods, such as sunlight and vacuum drying [26, 27]. Although convective hot air drying has been explored [28], the potential of energy-efficient thermal energy sources that can reduce drying time and minimize energy consumption is yet to be fully realized. Therefore, the aim of this study is to assess the drying efficiency of an infrared dryer under different power levels and sample weights, and to evaluate the effects of air speed on the drying process. This study seeks to contribute to the existing literature by examining the potential of infrared drying as a more efficient, energy-saving method for preserving oyster mushrooms.

2. METHODOLOGY

2.1 Sample preparation

The material used for this research is oyster mushrooms obtained from traditional markets in South Tangerang. All drying experiments were conducted using oyster mushrooms. Prior to drying, the mushrooms were cleaned, halved, and sliced into strips measuring 0.007-0.01 m.

2.2 Experimental setup

The drying chamber was comprised of a glass enclosure with dimensions of 0.620 m x 0.490 m and a height of 0.460 m, as shown in Figure 1. The glass walls had a thickness of 0.05 m and were not insulated. The sample tray, which is made of wire mesh, is positioned parallel to the far-infrared heater.

Figure 2 depicts a schematic diagram of an experimental dryer that utilizes a far-infrared heat source. The far-infrared heaters have been constructed using carbon silicon (SiC) and are designed to operate at 220 volts, with a maximum power output of 1.3 kilowatts (kW).

This arrangement is commonly used in applications where materials need to be heated uniformly from below. The wire mesh allows for even heat distribution and airflow, ensuring that the samples receive consistent heating throughout the process and maintained a constant distance of 160 mm from the oyster mushroom samples throughout the duration of the experiments.

Figure 1. Infrared lamp-based dryer

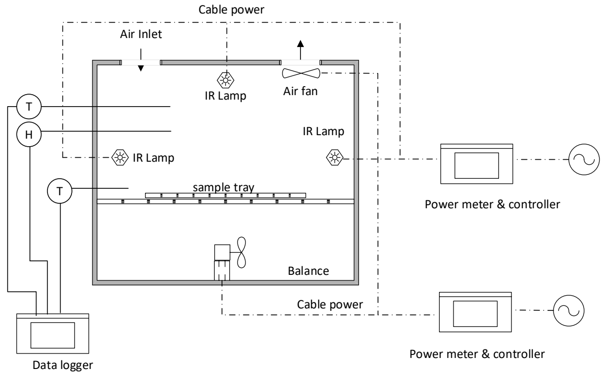

Figure 2. Scheme of infrared lamp-based dryer

This research is an experimental study with several variables, such as: Independent variables: infrared lamp power of 432 W, 504 W, 624 W, air flow rate of 1.2 $m.s^{-1}$, 1.5 $m.s^{-1}$, and the weight of the material being dried of 500 g, 750 g. The two various of air flow rates and three various power level selected refer to other IR drying research for agricultural product, such as longan fruit [29]; pineapple [30], mulberry leaf tea [31], strawberry [32].

Dependent variables: drying time, final moisture content, drying efficiency. Controlled variables: material heat temperature, drying chamber temperature, ambient temperature, mushroom weight, electric power consumption.

Each various variable conducted with three replicates for quality assurance in this experiment.

Test procedure for drying operation is as follows: the first, prepare the material to be dried by cutting the oyster mushrooms into pieces with a thickness of 0.005-0.01 m to make it easier to place them on the drying rack. Weigh the material and place it on the drying rack. After the material is dried, a sample of the dried material is weighed, which will be used as the observation material in the experiments. The next, checking all equipment for measurement and electrical equipment supporting the process. Further steps include operating the drying chamber by setting the lamp power and fan speed according to the pre-set variables. Every 10 minutes, measurements and recordings are conducted, including sample weighing, mushroom temperature, drying chamber temperature, electricity consumption, ambient temperature, and weighing the change in sample weight during the drying process. Further parameters are including changes in water content, energy efficiency (%) and specific energy consumption (SEC).

2.3 Calculation

2.3.1 Change in moisture content

The change of moisture content in the oyster mushroom can be calculated as follows:

$$\Delta X = \frac{m_i - m_t}{m_i} \quad (1)$$

One method to calculate the rate of change in moisture content is by measuring the decrease of moisture content over a period of time.

$$M_t = -k.\ t \quad (2)$$

2.3.2 Drying efficiency

Drying efficiency can be determined by dividing the energy needed to evaporate the water from the material by the energy that enters the dryer [33]. Calculating the amount of energy needed for the drying process. The sensible heat of the material (Q_s) is the amount of heat used to heat the material.

$$Q_s = m_k C_p (T_t - T_i) \tag{3}$$

$$m_k = m(1 - x_i) \tag{4}$$

The sensible heat of water (Q_w) refers to the heat needed to increase the temperature of the water present in the material.

$$Q_w = m_a C_a (T_p - T_o) \tag{5}$$

$$m_a = m - m_k \tag{6}$$

The latent heat of evaporation of water (Q_{fg}) is the amount of heat used to evaporate the water of the material.

$$Q_{fg} = m_w . h_{fg} \tag{7}$$

$$m_w = m_i - m_o \tag{8}$$

$$m_o = \frac{m_k}{1 - x_f} \tag{9}$$

$$Q_t = Q_s + Q_w + Q_{fg} \tag{10}$$

Drying eficiency can be calculated as follows:

$$\eta = \frac{Q_t}{Q_p} . 100\% \tag{11}$$

$$Q_p = P.t \tag{12}$$

2.3.3 Specific energy consumption

The assessment of energy consumption in the drying process utilizing an infrared lamp dryer involves calculating the amount of the cumulative energy utilized by the infrared lamp and fan, which is subsequently divided by the total quantity of water evaporated [25, 34-36].

$$SEC = \frac{Q_t}{m_w} \tag{13}$$

3. RESULT AND DISCUSSION

3.1 Rate of change in moisture content

Change moisture content is one of the chemical properties of a material that indicates the amount of water contained in the food. Water is the most abundant component in oyster mushrooms [37].

The speed of moisture reduction in IR (infrared) lamp drying is influenced by several factors, such as drying temperature, radiation intensity, and the characteristics of the dried material. The higher the drying temperature, radiation intensity, and the lower the initial moisture content of the material being dried, the faster the moisture reduction rate will be. However, it should be noted that excessive parameter settings may affect the quality of the product. Therefore, careful parameter adjustment is necessary to achieve optimal drying efficiency and good product quality.

The effect of lamp power, drying air velocity, and the weight of the dried material on the reduction of moisture content can vary depending on the characteristics of the material being dried and the drying parameters used. However, in general, the higher the lamp power and drying air velocity, the faster the reduction of moisture content. On the other hand, the larger the weight of the dried material, the slower the reduction of moisture content tends to be. However, it should be noted that too rapid reduction of moisture content can affect the quality of the resulting product, so proper and accurate adjustment of drying parameters remains crucial to achieve optimal drying efficiency and good product quality.

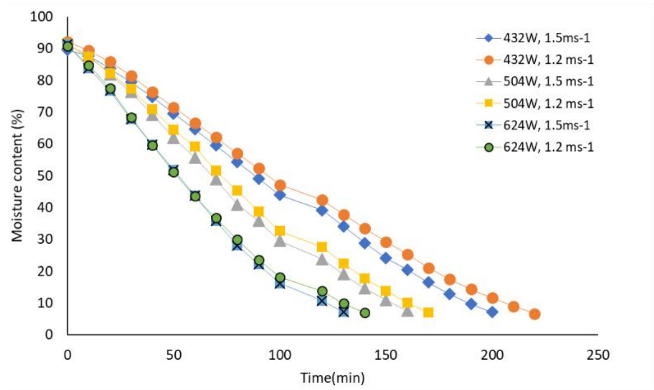

Figure 3. Variation of moisture content over time of different power levels with 500 gr of mushrooms

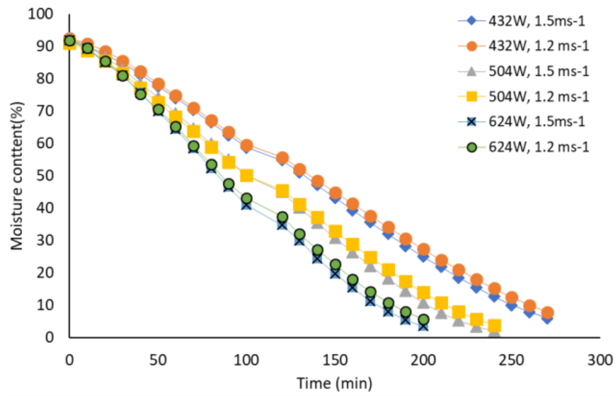

Figure 4. Variation of moisture content overtime of different power level with 750 gr mushrooms

Changes in moisture content obtained in drying oyster mushrooms with various differences in power levels, drying air speed and the weight of the dried mushrooms can be seen in Figures 3 and 4.

Table 1. Value of k (drying constant) of 500 g and 750 g mushrooms

Level Power (P), Fan Velocity ($m.s^{-1}$)	**k (min^{-1})**	
	500 g	**750 g**
(432 W;1.5 $m.s^{-1}$)	0.434	0.339
(432 W;1.2 $m.s^{-1}$)	0.406	0.328
(504 W;1.5 $m.s^{-1}$)	0.550	0.419
(504 W;1.2 $m.s^{-1}$)	0.519	0.390
(624 W;1.5 $m.s^{-1}$)	0.682	0.482
(624 W;1.2 $m.s^{-1}$)	0.626	0.464

Note: k=drying constant

From Figures 3 and 4, it can be observed that there is a correlation between the change in moisture content (M_t) and time (t) for various power levels, fan speeds, and mushroom weights. It was found that for a mushroom weight of 500 g, a power level of 624 W and a fan velocity of 1.5 m.s^{-1} resulted in the fastest decrease in moisture content. Within 130 minutes, a moisture content value of 7.1% was achieved. A higher power level leads to a larger temperature increase, resulting in significant water evaporation. Thus, a higher lamp power level leads to a faster drying process. Similarly, a higher drying air speed results in a faster drying process.

Table 1 describes the values of the drying constant (k) with various variables such as power level, fan velocity, and weight of the mushroom. It can be observed that the dryer with the highest power level (624 W), highest fan velocity (1.5 m.s^{-1}), and mushroom weight of 500 g obtained the highest value of k, which is 0.682 min^{-1}. The greater the power level, the greater the amount of heat energy produced, this occurs because the friction between water molecules is greater, resulting in a faster evaporation process and a faster decrease in the water content of the dried material. The higher the fan speed, the faster the transfer of water vapor from the drying chamber. For a higher mushroom weight, a smaller k value will be obtained due to the increase in the weight of the mushrooms, resulting in a thicker layer of material on the tray, causing the evaporation process to be slower and the drying process to be slower as well [38]. Increasing the velocity of the drying air can also accelerate the transfer of water vapor from the material to the surrounding atmosphere [22].

3.2 Specific energy consumption

Dryer energy consumption is a crucial technical information that is essential for the optimal design and cost-effective operation of energy-efficient drying systems. In order to assess the energy performance of dryers, its thermal efficiency and specific energy consumption (SEC) are taken into consideration. SEC in the drying process (MJ.kg^{-1}) refers to the amount of energy required to remove 1 kg of water from the moist product [39].

Specific energy consumption (SEC) is the amount of incoming energy required for the drying process [40].

Therefore, the power of the lamps, the weight of the material being dried, and the drying air velocity all affect the SEC value. The power level of the IR lamps used in the drying process will affect the SEC value. The greater the power level of the lamps used, the more energy is required to operate them, which increases the SEC value. The weight of the material being dried also affects the SEC value. The greater the weight of the material that needs to be dried, the more energy is required to dry it. Therefore, the greater the weight of the material being dried, the higher the SEC value. Drying air velocity also affects the SEC value. The higher the velocity of the drying air, the more energy is required to produce the air, which results in a higher SEC value.

In order to minimize the SEC (Specific Energy Consumption) value, several measures can be used. These measures involve optimizing the utilization of lamp power, optimizing the load of the material undergoing drying, and optimizing the velocity of the drying air. By implementing these actions, the SEC value can be reduced.

Figure 5 shows the relationship between power level, fan velocity, and specific energy consumption (SEC). The lowest SEC value is achieved with the highest power level and highest airspeed, while the highest SEC value is obtained with the lowest power level and lowest airspeed. The SEC values generated vary between 2.81 kWh. kg of water^{-1} and 3.58 kWh. kg of water^{-1}. Previous research on food materials using an IR dryer has reported SEC values ranging from 0.91 1 to 250 kWh. kg water^{-1} [15]. For slide mushrooms, the SEC values range from 2.87 kWh. kg of water^{-1} to 5.36 kWh.kg of water^{-1} [25].

The effect of power level, fan velocity, and mushroom weight on SEC can be analyzed statistically using regression analysis with *Microsoft Excel*. The results of the statistical analysis are presented in Tables 2, 3, and 4.

Table 2. Model summary regression of SEC

Regression Statistic	
Mutiple R	0.955
R Square	0.913
Adjusted R Square	0.880
Standard Error	0.073
Observations	12

Table 3. Anova value of SEC

	df	SS	MS	F	Significance F
Regression	3	0.448	0.149	27.878	0.00014
Residual	8	0.043	0.005		
Total	11	0.491			

Table 4. Regression statistics of SEC

Parameter	Coefficients	Standard Error	t Stat	P-Value
Intercept	5.258	0.259	20.309	3.61E-08
P (X_1)	-0.001	0.0003	-5.306	0.001
v (X_2)	-0.386	0.141	-2.740	0.025
w (X_3)	-0.001	0.0002	-6.927	0.0001

Tables 2, 3, and 4 present the results of the statistical analysis. Based on the analysis, the line equation is $y=-0.001x_1-0.386x_2-0.001x_3+5.258$, where y=SEC (kWh. kg of water^{-1}), x_1=power level (W), x_2=fan velocity (m.s^{-1}), and x_3=weight of mushrooms (g).

The significance *F* value is 0.00014 (less than 5%), indicating that the independent variables (power level, fan speed, mushroom weight) have a significant effect on the SEC value. Therefore, the regression model can be used to predict the fixed variable (SEC). The *P* value of each independent variable is 0.001 (less than 5%), 0.025 (less than 5%), and 0.0001 (less than 5%). This indicates that each independent variable has a significant effect on the SEC value when analyzed individually.

Based on the coefficients table, fan velocity (v) has the greatest effect in decreasing SEC by 0.386 kWh. kg of water^{-1}, followed by power level (P) with an effect of 0.00141, while the weight of the mushrooms has the least effect at 0.001. The coefficient of determination (R^2) is 0.91, indicating that the three independent variables (P, v, w) collectively affect the SEC by 91.27%, while the remaining 8.73% can be influenced by other variables not included in the study.

3.3 Efficiency energy

This research examines the impact of three variables on the efficiency of infrared lamp drying: lamp power, drying air velocity, and weight of the material being dried. Lamp power in infrared drying has a significant influence on drying energy efficiency. The higher the IR lamp power, the more energy is required to generate the heat needed to dry the material. However, using an IR lamp power that is too low can result in insufficient heat to dry the material. Therefore, selecting an appropriate lamp power is crucial for improving drying energy efficiency.

The weight of material being dried also affects the efficiency of infrared drying. The more material there is to dry, the more energy is needed to dry it all. Therefore, it is necessary to adjust the amount of material being dried to the drying capacity to maintain energy efficiency.

Drying air velocity also plays a role in infrared drying efficiency. Higher air velocity requires more energy to produce the desired dry air. However, fast-moving air on the surface of the material reduces drying time by removing moisture from the surface. Therefore, adjusting the drying air velocity according to the material being dried and the drying capacity is essential to maintain energy efficiency. Proper selection of lamp power, adjustment of material quantity according to the drying capacity, and adaptation of drying air velocity to the material and capacity can enhance infrared drying energy efficiency.

Figure 6 depicts the relationship between power level, air velocity, and drying efficiency. Low power levels and airspeeds result in low efficiency values. Conversely, the highest power level and air speed result in the highest efficiency value. The greater the power level, the more electromagnetic energy is absorbed by the material. This energy causes friction between molecules in oyster mushrooms, especially for water molecules since water is the dominant element. This friction increases the temperature in the oyster mushroom cells and causes the water to evaporate. The resulting drying energy efficiency ranges from 40.01%-53.95%. In general, the energy efficiency of drying ranges from 20-60% [41].

The effect of power level, fan velocity, and mushroom weight on efficiency can be analyzed statistically using the regression method in *Microsoft Excel*. The results of the statistical analysis are shown in Tables 5-7.

Tables 5-7 show the results of the statistical analysis. From the statistical analysis, the line obtained the equation $y=0.002x_1+6.485x_2-0.032x_3+6.966$ where y=efficiency (%), x_1=power level (W), x_2=fan velocity (m.s^{-1}) and x_3=mushroom weight (g). Significance F is 5.0311×10^{-5} (less than 5%), which means that the independent variables (power level, fan speed, mushroom weight) have significant effect on the efficiency value, so the current regression model can be used to predict the fixed variable (efficiency). For the P value of each independent variable, which are 0.001 (less than 5%), 0.014 (less than 5%), 1.2×10^{-6} (less than 5%) are partially acquired significant effect on the value of efficiency.

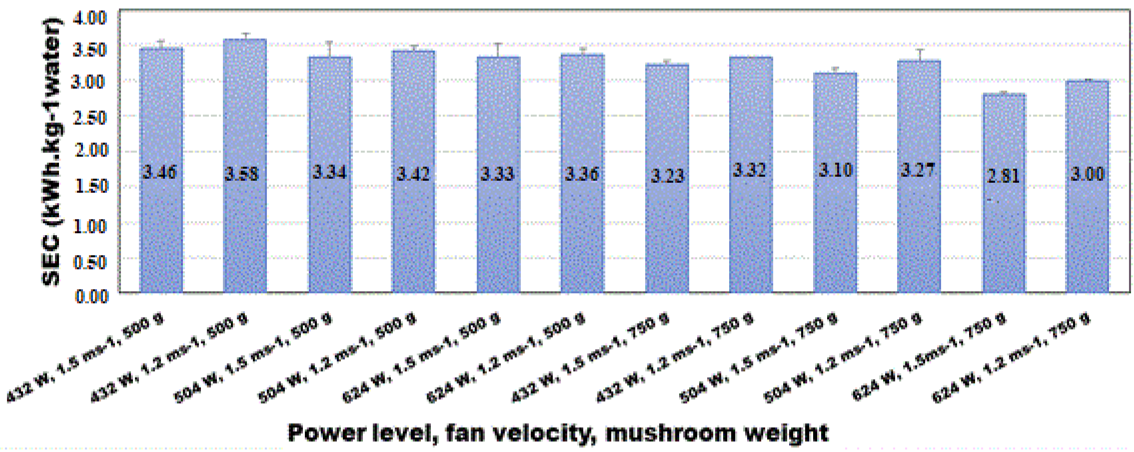

Figure 5. Relationship graph between power level, fan speed and SEC with 500 g and 750 g mushrooms

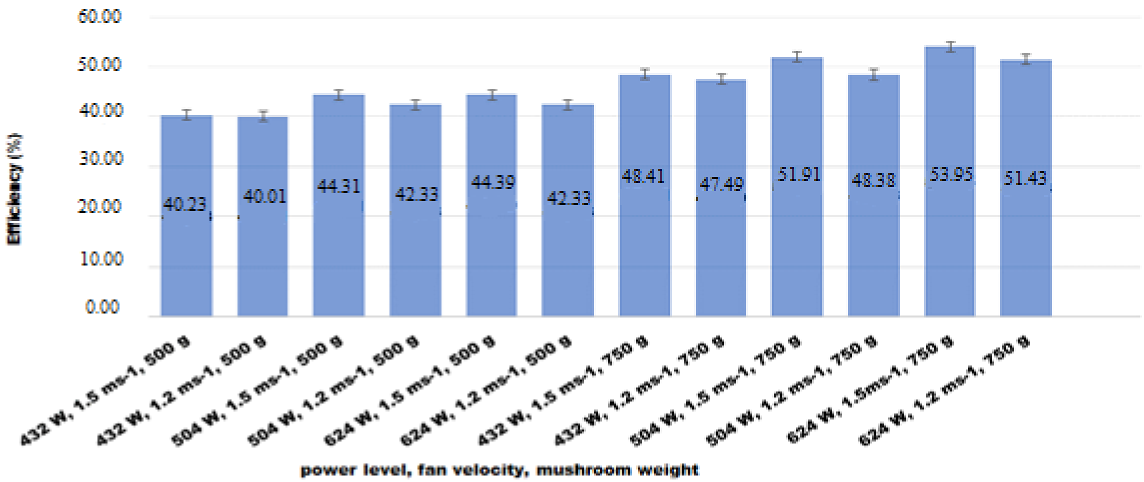

Figure 6. Relationship graph between power level, fan velocity and efficiency with a mushroom weight of 500 g and 750 g

From the coefficient table, fan velocity (v) has the greatest effect on the increase in efficiency of 6.485, the weight of the mushroom has the effect of 0.003, and the power level (P) has the least influence of 0.002. The coefficient of determination (R^2) result is 0.96, which means that the three independent variables (P, v, w) simultaneously affect the efficiency of 96.20%. The remaining 3.80% are influenced by other variables outside the three variables.

Table 5. Model summary regression of energy efficiency

Regression Statistics	
Multiple R	0.980837
R Square	0.962041
Adjusted R Square	0.947806
Standard Error	1.080085
Observations	12

Table 6. Anova value of energy efficiency

	df	SS	MS	F	Significance F
Regression	3	236.529	78.843	67.584	5.0311E-06
Residual	8	9.333	1.167		
Total	11	245.862			

Table 7. Regression statistics of energy efficiency

Parameter	Coefficients	Standard Error	t Stat	P-value
Intercept	6.966	3.820	1.824	0.106
P (X_1)	0.020	0.004	5.043	0.001
v (X_2)	6.485	2.079	3.120	0.014
w (X_3)	0.032	0.002	12.94	1.2004E-06

4. CONCLUSION

This work evaluated the drying performance of osyter mushroom using infrared drying method. Some various parameter that significantly affect the oyster mushroom drying process, including the power of the lamp, the drying air velocity, and the weight of the material were examined. These factors influence the energy efficiency of the drying process and the SEC during infrared drying.

Based on the research, the variation of 624 W lamp power, 1.5 m.s^{-1} air speed and 500 g mushroom weight has the highest rate of water content decrease, while the variation with 624 W lamp power, 1.5 m.s^{-1} air speed, and 500 g mushroom weight results in the highest drying energy efficiency of 53.95% and had a lower SEC of 2.81 kWh. kg of water^{-1}. Meanwhile, the variations in lamp power of 432 W, air speed of 1.2 m.s^{-1} and a mushroom weight of 500 g results in the lowest drying energy efficiency of 40.01% and had a higher SEC of 3.58 kWh. kg of water^{-1}.

The development of the SEC and drying efficiency models was based on first-order equations, which considered variables such as infrared power, sample mass, and air speed. The findings revealed a strong agreement between the predicted results and the actual data, as evidenced by the R^2 values of 0.91 and 0.96 obtained for the SEC model and drying efficiency, respectively.

On a laboratory scale, the infrared drying method for oyster mushroom can considerably increase drying efficiency and energy efficiency. Future research should prioritize the commercial application of these infrared drying technologies. However, additional research is required to determine the effects of infrared drying on the nutrient content of the product.

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NOMENCLATURE

SEC	specific energy consumption, kWh. kg of water^{-1}
P	power consumption of lamp and fan, W
C_p	specific heat of material, J. Kg^{-1}°C^{-1}
m	mass, kg
k	drying constant
Q	energy, J
h	enthalpy, kJ. kg^{-1}
t	time, s
T	temperature, ℃
x	ratio of moisture content

Greek symbols

η	drying efficiency, %

Subscripts

fg	latent
f	fluid
w	water
s	sample
o	mass dry matter portion
k	dry mass where the moisture content is 0%
i	initial mass of sample
t	mass of sample after t time
f	final
t	total drying energy
p	power consumption of fan and lamps