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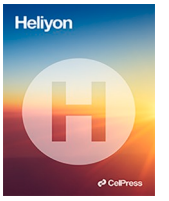

Research article

Oyster mushroom drying in tray dryer: Parameter optimization using response surface methodology, drying kinetics, and characterization

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ABSTRACT

In this study, the drying of oyster mushrooms (*P. ostreatus*) in a tray dryer was optimized. The parameters used to optimize the drying process were drying temperature, airspeed, mass loading, and moisture content. Its drying kinetics were investigated at the optimum drying parameters. A quadratic equation was obtained to predict the moisture content of mushrooms at the given drying temperature, airspeed, and mass loading, and it was validated against experimental results. A minimum moisture content (9.99 wt%) was obtained at the optimum conditions of 60 °C, 3 m/s airspeed, and mass loading of 200 g using a tray dryer. Proximate analysis, shelf-life analysis, inorganic elemental analysis, and functional group analysis were done as a characterization method for mushrooms after drying at the optimum drying conditions. About 27.8 wt% protein and 50.2 wt% carbohydrates were found in proximate results. Besides, potassium and sodium were the dominant elements as estimated by spectrophotometry analysis. The induction period (IP) of dried mushrooms at room temperature is 3520:47 (hour: minute) from the oxidation stability analysis, and the water activity of dried mushrooms was found to be 0.36. The drying kinetics of oyster mushrooms were studied at various temperatures (50–75 °C), optimum airspeed (3 m/s), and mass loading (200 g). The best-fit model describing the mushrooms drying kinetics was found to be Midilli et al., with the lowest RMSE (0.008749), X^2 (0.0014), and the highest R^2(0.9993) values. The kinetic triplet activation energy, effective diffusivity, and diffusivity constant (Ea, D_{eff}, D_0) for oyster mushrooms drying were determined and found to lay in the general range for foodstuffs. The value of D_{eff} results lies within the range of 10^{-8} to 10^{-12} m^2/s, with Ea of 15.32 kJ/mol and D_0 value 2.263 × 10^{-6} m^2/s.

1. Introduction

Mushrooms are the most important fungi and belong to a kingdom of Fungi different from plant and animal kingdoms [1]. The sporocarps of mushrooms, also known as the reproductive structures, are the fleshy, spore-bearing fruiting bodies of a fungus that are

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normally produced above ground on soil and its food source [2]. Human beings have recognized mushrooms for thousands of years now, and they were used as a diet in the old civilizations [3,4]. Black ear mushrooms (Auricularia) were first cultivated in China approximately a millennium ago and are now practiced all over the world [5].

Mushrooms possess various types of dietary supplements and are utilized as medicine in a variety of global ethnic cultures. Patients with high cholesterol and those with diabetes are advised to eat them since mushrooms are naturally low in sodium, fat, cholesterol, and calories [6]. They prevent heart attacks (cholesterol-lowering), cancer [7], and tumors, cure viral and bacterial infections, fungal diseases, and blood cholesterol, increase the body's capacity for self-healing, promote long life (anti-aging and vitality), boost immunity, lower stress levels, and ease mild anxiety and tenseness in the body [6,8]. Mushrooms contain high vitamins, minerals, and protein with low calorific value [9]. Due to its important content, mushrooms are commonly used as complementary food. Its protein has 60–70% digestibleness and incorporates all the essential amino acids that adults need, like lysine, rich in vitamins high in vitamins B12, C, D, and K, as well as minerals that contain elements like potassium, calcium, phosphorus, copper, and iron [10].

In order to preserve the most important content of mushrooms, it is necessary to apply some food preservation methods. Drying is the most common and promising for high moisture-contenting foods and other agricultural products [11]. Dried foods can be stored without deterioration for a prolonged period. Therefore, drying of foods like meat, mushrooms, pumpkin, fruits, etc. are carried out to maintain desired levels of nutritive properties for the longest conceivable period, transport and store easily, and make it suitable for handling [12]. The composition of food items determines the types of dryers that can be used for food preservation during drying. Mushrooms can be dried using a variety of methods, including tray drying, freeze drying, microwave drying, hoover drying, and sun drying. Most tray dryers use a hot air stream where moisture is evaporated from the item and is carried away by the airflow [13]. In a previous research, Zalewska reported that the mushrooms' shelf life was increased by a chemical method using solutions of sodium metabisulfite, ascorbic acid, citric acid, hydrogen peroxide, vitamin E, diacetyl, and rosemary extracts [14]. Lidhoo and Agrawal also studied the optimization of mushroom drying, considering temperature (45–95 °C) as an important parameter, and a temperature of 65 °C was observed as the optimum drying temperature [15].

Tarafdar et al. have recently studied the optimization of freeze-drying process parameters such as Pressure (0.04–0.1 mbar) and temperature ((−8)–(−2) °C) using response surface methodology (RSM) for button mushroom [16]. Their result showed that 7.28 mg/g of protein, 0.26 mg/g of ascorbic acid, and 8.6 mg/g of antioxidants were obtained at the optimum condition of 0.09 mbar for a temperature of −7.5 °C. There were studies about the drying and rehydration of mushrooms with a temperature range of 40–60 °C and 25–85 °C, respectively, and the best-dried mushrooms samples at 40 °C using air with a relative humidity of 75% for rehydration [17,18]. The effect of the drying technique on mushrooms and the final moisture content of mushrooms should be 10 wt% to make its important nutrients available after drying [19]. Hence, the moisture content is an important parameter for dried mushrooms for their longevity.

From the point of food processing and preservation, some works were studied with drying kinetics, nutritional value, and compositions of different grains and fruits, including mushrooms [20,21]. However, there was a lack of specific information on the drying kinetics study with optimization of the drying parameters of tray dryer and analysis of nutritional content for Ethiopian oyster mushroom drying. Several papers have been done and published on the hot-air drying process of fruits and vegetables. The investigation of optimum parameters and composition analysis of the dried oyster mushroom in a tray dryer with the optimum moisture level seems to have been obscured from the literature. Hence, the present study aimed to optimize the drying parameter and evaluate the drying kinetics model and kinetic triplet (E_a, D_{eff}, D_o) for Ethiopian oyster mushroom drying in a tray dryer. Further, important characteristics of dried mushrooms were investigated. This study generated new valuable scientific knowledge for the value of industrial production and mushroom harvesting companies.

2. Materials and methods

2.1. Materials

Raw material, an oyster mushroom (Pleurotus ostreatus) used for the present study, was collected from a mushroom harvesting company Located in Holeta, Ethiopia. Chemicals such as nitric acid (67% purity), sulfuric acid (98% purity), petroleum ether (analytical grade), hydrogen peroxide (32%), potassium sulfate (analytical grade), sodium hydroxide (analytical grade), copper sulfate (analytical grade) and hydrochloric acid (analytical grade) were used for AAS analysis, fat extraction, and protein content determination.

2.2. Methods

2.2.1. Sample preparation

Fresh Oyster mushrooms were collected and washed thoroughly with water to remove dust and impurities. Excess water was drained, and the mushrooms were patted dry with blotting paper. To increase drying efficiency, flat and spherical mushrooms were sliced into 26 × 13 × 26 mm rectangular pieces using a slicer and stored at 4 °C until further processing [22].

2.2.2. Drying of oyster mushrooms in a tray dryer

A computer-controlled tray dryer (CCTD/SCADA, Edibon, Spain) was used for drying the oyster mushroom samples under controlled conditions of hot air. The dryer has three main components. The drying chamber consisting of four trays with 270 mm × 240 mm dimension and made of stainless steel. an air supply unit (compressor that pumps air into the chamber) and an electrical heater

for heating the air flowing through the chamber. The full geometry and experimental setup of the tray dryer are presented in Fig. 1. On the tray, a known quantity of sample measured in grams (w_o) at various weights (50–500 g) was placed. The temperature and airspeed were adjusted between 20 and 80 °C and 0.5 and 5.5 m/s, respectively. Then the amount of moisture in the sample based on the weight change was calculated and continuously recorded as per Equation (1).

$$M_{DS}(wt\%) = \frac{W_{Mi} - W_{Mt}}{W_{Mi}} \times 100\% \tag{1}$$

where M_{DS} is the amount of moisture present in the dried sample (wt.%), W_{Mi} is the amount of moisture present in a fresh sample (g), and W_{Mt} is the amount of moisture removed at time t (g).

2.2.3. Design of experiment (DOE) for tray drying of oyster mushroom

The drying of oyster mushrooms is affected by the drying temperature, airspeed, mass loading, and type of dryer. Preliminary experiments were conducted using the following parameters: mass load (50–500 g), airspeed (1.5–5.5 m/s), and drying temperature (20–80 °C). The impact of each parameter on the final moisture content of the product has been studied separately. Based on preliminary findings, the upper and lower bounds for drying temperature, airspeed, and mass loading were established to construct an experimental matrix (Table 1) suitable for investigating the interaction effects of these parameters on oyster mushroom drying. The Box-Behnken Design (BBD) approach of response surface methodology (RSM) was applied to optimize the drying parameters for mushrooms. RSM–BBD was used for this study since full information can be obtained with a minimum number of experiments [23].

The total number of experiments (N) required for a given parameter was determined using Equation (2) [24].

$$N = 2k(k-1) + C \tag{2}$$

where k and C are the number of parameters, and the number of the center point respectively. Hence, the total number of combination experiments conducted for the present study was 16 experiments with a triplicate of experiments, and the average value was used as suggested by RSM-BBD. A model equation was obtained in the form of a quadratic equation (Equation (3)), and the model was statistically analyzed to check its significance for the mushroom drying process. Further, numerical optimization was performed for three parameters for minimization of moisture content in mushrooms through tray drying. The drying condition, which results in a minimum moisture content for the final product, was further used to study mushroom drying kinetics (Section 2.3).

$$\begin{aligned} Y = \beta + \alpha_1 X_1 + \alpha_2 X_2 + \alpha_3 X_3 + \alpha_4 X_4 + b_1 X_1 X_2 + b_2 X_1 X_3 + b_3 X_1 X_4 + b_4 X_2 X_3 + b_5 X_2 X_4 + b_6 X_3 X_4 \\ + c_1 {X_1}^2 + c_2 {X_2}^2 + c_3 {X_3}^2 + c_4 {X_4}^2 + \xi \end{aligned} \tag{3}$$

where Y is the response function, β is the intercept constant, α_1–α_4 are the main linear effects constant, b_1–b_4 are linear-linear coefficients, and c_1–c_4 are main quadratic effect coefficients, ξ is error and X_1–X_4 are the independent variables [25].

2.3. Drying kinetics

In order to study the drying characteristics of oyster mushrooms and temperature effect on the drying rate, drying experiments were done by taking optimum airspeed at 3 m/s and distributed mushrooms mass loading of 200 g. The temperature was varied from 50 to 75 °C with 5 °C intervals. This temperature range limitation was taken from the result of preliminary experiments. The remaining sample weight was noted in 15-min time intervals and used to investigate the drying rate of mushrooms [26]. The remaining moisture content in the sample versus time at different temperatures was plotted. Eight well-known thin-layer drying kinetics models were used to study the drying kinetic for mushroom drying (Table 2).

The dimensionless ratio of moisture content difference (MR) is defined by Equation (5) [31].

$$MR = \frac{m_t - m_e}{m_0 - m_e} \tag{5}$$

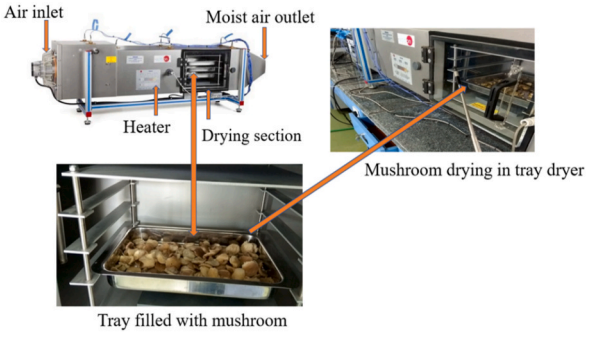

Fig. 1. Experimental procedures and setup of the tray drying of oyster mushroom.

Table 1
RSM-BBD experimental matrix for drying oyster mushrooms.

Drying parameters	Units	Labels	Low level	Middle	High level
Drying temperature	°C	T	50	60	70
Hot airspeed	m/s	V	2	3.5	5
Mass loading	g	W	100	200	300

Table 2
Various drying kinetics models proposed by several researchers for fruit sample.

Model name	Model	References
Newton or Lewis model	$MR = \exp(-kt)$	[12]
Page models	$MR = \exp(-kt^n)$	[27]
Modified page	$MR = \exp(-kt)^n$	[22]
Two exponentials	$MR = a\exp(-kt) + (1-a)\exp(-kt)$	[28]
Henderson and Pabis	$MR = a\exp(-kt)$	[29]
Logarithmic	$MR = a\exp(-kt) + c$	[28]
Midilli et al.	$MR = a\exp(-kt^n) + c$	[30]
Singh et al.	$MR = \exp(-kt) - akt$	[29]

where m_0, m_t, and m_e denote the initial moisture content, moisture content at a time (t), and equilibrium moisture content at infinite time, respectively.

Based on the experimental results for MR and drying time, the model parameters were determined using a MATLAB (*MATLAB R2018b*) non-linear regression method for each kinetics model. Using chi-square (X^2), the root means square error (RMSE), and the coefficient of determination (R^2), the experimental data fit to each of the chosen models was assessed. The best-fit kinetics model describing the drying kinetics of mushrooms was chosen with the lowest RMSE and X^2 values and the highest R^2 value.

Determining activation energy and effective moisture diffusivity: The drying of the sample takes place by liquid/vapor diffusion due to the difference in moisture concentrations. This involves a continuous mass and heat transfer toward the surface of the drying medium. The effective moisture diffusivity was defined by Fick's law of diffusion as given by Equation (6) [32].

$$\frac{dm_t}{dt} = \left(\Delta D_{eff} \times \Delta m_t\right) \tag{6}$$

where m_t is the local moisture content of the mushroom (wt.%), D_{eff} is effective moisture diffusivity (m^2/s), and t is the drying time (min).

Taking the assumptions as one-dimensional mass transfer in the sample by diffusion, negligible shrinkage or deformations of the sample while drying, constant drying air properties and constant thermal properties of the sample, and constant commodity density of the sample, the initial and boundary conditions were set to obtain the solution of Equation (6) and simplified to Equation (7) [33].

At $t = 0, 0 < x < l, m_t = m_0$, no variations of moisture throughout the sample thickness

$t > 0, x = 0, \frac{dm_t}{dt} = 0$, mass transfer is symmetric to the center of the slab

$t > 0, x = l, m_t = m_0$, the moisture content reached at equilibrium with the drying medium.

$$MR = \frac{m_t - m_e}{m_0 - m_e} = \frac{8}{\pi^2}\sum_{n=0}^{\infty}\frac{1}{(2n+1)}\exp\left(-\frac{(2n+1)^2\pi^2 D_{eff}t}{4l^2}\right) \tag{7}$$

For thin-layer drying kinetics, long drying time (setting $n = 0$ and neglecting the high order terms) and assuming that m_e is negligible as compared to m_t and m_0, then Equation (7) was reduced to Equation (8) [12,34].

$$MR = \frac{m_t}{m_0} = \frac{8}{\pi^2}\exp\left(-\frac{\pi^2 D_{eff}t}{4l^2}\right) \tag{8}$$

Equation (8) was linearized and further simplified into a straight-line equation as given by Equation (9).

$$\ln(MR) = \ln\left(\frac{8}{\pi^2}\right) - \left(\frac{\pi^2 D_{eff}t}{4l^2}\right) \tag{9}$$

From the slope of the *ln (MR)* versus drying time, the D_{eff} for oyster mushrooms was calculated.

Activation Energy (E_a): The temperature dependence of the sample's effective moisture diffusivity can be presented by the Arrhenius relationship Equation (10) [28,35].

$$D_{eff} = D_0\exp\left(-\frac{E_a}{R}\frac{1}{T}\right) \tag{10}$$

where D_0 (m^2/s) is the Arrhenius constant, E_a (kJ/mol) is the activation energy, T(K) is the temperature of drying air, and R is the universal gas constant ($R = 0.008314\ kJ/mol.\ K$).

The above Equation (10) was converted to a straight-line equation as given by Equation (11), and *Ea* is determined from the slope of $ln(D_{eff})$ versus the $1/T$ *plot.*

$$\ln\left(D_{eff}\right) = \ln(D_0) - \frac{E_a}{R}\left(\frac{1}{T}\right) \tag{11}$$

2.4. Statistical analysis

All drying experiments were done in triplicate, and the mean values of the results were taken and processed using design expert software (*Design-Expert version 12*). The One-way analysis of variance (ANOVA) was done using response surface methodology (RSM), with p-values of <0.05 representing a significant level. Design expert (*design-expert 12*) and MATLAB were used to plot the graph. The design expert was used to plot the interaction effect of drying parameters and MATLAB to fit the experimental kinetics data with the selected different drying kinetics models. R^2, RSME, and X^2 were used to analyze and select the good fit drying kinetics models.

2.5. Characterization of dried mushroom mushrooms

Characterization methods such as proximate analysis, oxidation stability, water activity, inorganic elemental analysis with atomic absorption spectrometry (AAS), and Fourier transform infrared (FT-IR) were used to analyze the fresh and dried mushrooms obtained at optimum conditions. Moisture content, ash content, crude fiber, fat, protein, gross energy value, and total carbohydrate are the most widely used properties analyzed for food product characterization under proximate analysis. The analysis was carried out following the Association of Official Analytical Chemists (AOAC) standard [36].

2.5.1. Proximate parameter characterization

Moisture content: A 5 g sample in a crucible was dried at 105 °C ± 2 for 24 h in a drying Oven (700LT-*No. TD-1315, UK*). Then, the dried sample (w_d) was measured and subtracted from the initial weight of the sample (w_o) to calculate the moisture content (MC) of the sample, as given in Equation (12) [37,38].

$$MC(wt\%) = \frac{w_o - w_d}{w_o} \times 100 \tag{12}$$

where *MC* (wt.%) is moisture content, w_0 (g) and w_d (g) are the weight of the fresh sample and the weight of the dried sample after 24 h respectively.

Ash content: A 5 g sample was placed in a dried crucible and burned in the furnace (*MF 106, NUVE, Turkey*) at a temperature of 550 °C for 30 min [39]. Then, the ash content was calculated using Equation (13).

$$AC(wt\%) = \frac{w_a}{w_o} \times 100 \tag{13}$$

where w_a *(g)* is the weight of solid remaining (ash) after 30 min and w_o (g) is the sample weight taken.

Protein content: The protein content of both fresh and dried mushrooms was determined using and following a Kjeldahl method [40].

Crude fiber: The crude fiber content was determined using the AOAC method [36]. A sample of about 10 g was washed with petroleum ether to remove the fat present in the sample. The fat-free sample was soaked in 200 ml sulfuric acid (1.25% concentration) in a flask connected to the condenser and heated for 30 min. Then, the sample mixture was filtered before being washed with warm water, followed by socking in 200 ml caustic soda (1.25% concentration) and refluxed for 30 min. The sample was again filtered and washed with warm water and then 25 ml ethyl alcohol. The alcohol-washed sample mixture was dried in a drying oven at 100 °C for 8 h. The dried sample mixture was placed in muffle furnaces (*VELP SCIENTIFICA, S/N 384480, Italy*) using a dried crucible at 660 °C for 4 h. Finally, the residue sample (ash) was measured, and the percentage of crude fiber (*CF*) was determined with the given Equation (15).

$$CF(wt\%) = \frac{w_{ODS} - w_{RS}}{w_{IS}} \times 100 \tag{15}$$

where *CF* (wt.%) is the crude fiber content, w_{ODS} (g) is the weight of the oven-dried sample at 100 °C, w_{RS} (g) is the weight of the residue sample after burning at 660 °C, and w_{IS} (g) is the weight of the initial sample take for crude fiber content.

Crude Fat: The mushroom fat content was determined using the AOAC 2000 method. The procedure involves extracting the lipids with petroleum ether [41]. A sample (mushroom) of 6 g was placed in a thimble for extraction using Soxhlet extraction, and 150 ml of petroleum ether was used as a solvent. The extraction process was kept for 8 h at around the boiling point of the solvent. The solvent was removed from the extract mixture using a rotary evaporator, and the mass fat extract was measured using Equation (16) and used to estimate the fat yield.

$$FC(wt\%) = \frac{w_{FE}}{w_{IS}} \times 100 \tag{16}$$

where *FC* is the fat content, w_{FE} *(g)* is the weight of extracted fat, and w_{IS} *(g)* is the weight of the initial sample taken for fat content estimation.

Total carbohydrate and energy content: The proximate parameters such as ash, protein, fiber, and fat contents were used to determine the total carbohydrate (TC) and energy content (EC) according to Equation (17) and Equation (18) [32,42].

$$TC(wt\%) = 100 - (AC + PC + FC + CF) \tag{17}$$

$$EC(kcal\,/\,100g) = 4(PC + TC) + 9FC \tag{18}$$

2.5.2. Shelf life characterization

Oxidation stability: Oxidation stability analysis of the samples was conducted using the OXITEST reactor (*VELP SCIENTIFICA, S/N 363905, Italy*). The oxidation stability was used to determine the induction period (IP) of the sample at a given temperature. To estimate the IP, 10 g of sample were subjected to the reactor chambers, and the oxidation set was done at various temperatures (60, 70, 80, and 90 °C) at a pressure of 6 bars. Then, the oxygen pressure drop inside the oxidation chamber was recorded, and IP for each temperature was estimated by the least square method (LSM) using inbuilt software (Oxisoft) from the oxygen pressure and time plot. Finally, a linear plot of *ln(IP)* versus temperature (°C) was used to determine the IP of the sample at room temperature.

Water activity analysis: The water activity of the samples was measured by water activity meters (*AQUA LAB:* 4 TE*, Italy*) set at room temperature. The experiments were done in triplicate, and the average values were reported.

2.5.3. Atomic absorption spectroscopy (AAS) analysis

The inorganic elemental composition of the samples was analyzed by Atomic Absorption Spectrometry (*Agilent 4200MP-AAS; WI, USA*) following the AOAC method [36]. About 1 g of each sample was digested with a 1 M nitric acid solution and stirred for 30 min at 300 rpm using a hot plate, and the sample was filtered before use. Then, the concentration of the metals such as Na, Ca, Mg, K, Cu, and Zn were determined with the blank reference sample.

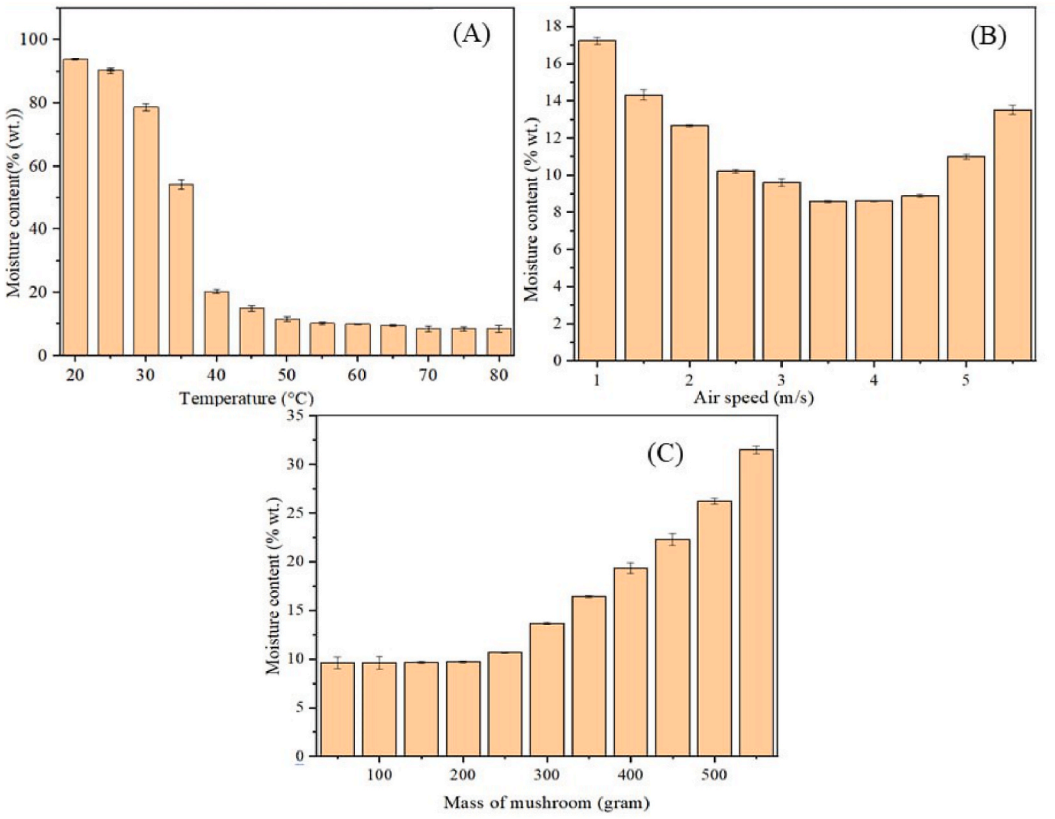

Fig. 2. Effect of (A) temperature, (B) airspeed, and (C) mass load at 60 °C temperature on moisture content removal.

2.5.4. Functional group analysis

The functional group present in the mushrooms (fresh and dried) was analyzed using a Fourier transform infrared (FTIR) (*Thermo Scientific iS50 ABX, WI, USA*) instrument equipped with an attenuated total reflection accessory, KBr beam splitter, and detector. Initially, the background was taken, and the samples were placed on the solid sample holder. Data was collected at 32 resolutions and 16 scans. The IR spectrum of scanning the sample was conducted in the range of 4000 and 400 cm^{-1} wavenumbers.

3. Results and discussion

3.1. Optimization of oyster mushroom drying using RSM-BBD

3.1.1. Effect of mushroom drying parameters in a tray dryer

The moisture content of fresh mushrooms was found to be within 80–93 wt%, depending upon the harvest time and environmental conditions. In order to prevent the mushroom from deteriorating, it has to be dried till the moisture content is reduced all the way down to 10 wt%. However, drying the mushroom below 10 wt% moisture content results in loss of important nutrients in the mushroom. In contrast, drying of the mushroom above 10 wt% moisture content leads to a short shelf life [43]. The tray drying process of mushrooms is mainly affected by temperature, airspeed, and mass load on the tray. Initially, raw oyster mushrooms contain 93.8 wt % moisture. Hence, the mushroom was dried to a moisture content of 10 wt% by varying drying air temperature from 40 to 80 °C, drying airspeed from 1 to 5.5 m/s, and mass load from 50 to 550 g (Fig. 2A–C).

The effect of temperature on moisture removal at an airspeed of 3 m/s for 8 h is shown in Fig. 2A. As can be seen from Fig. 2A, the moisture content decreases from 93.8 to 8.5 wt% as the drying temperature rises to 80 °C. As the drying temperature increases from 55 to 80 °C, the moisture content remains almost constant. The moisture content of the dried sample was greater than the target values of mushroom moisture content at a temperature of 40 °C (20.3 wt%) and lesser at a drying temperature of 80 °C (8.5 wt%). About 9.9 wt % moisture content was found at a drying temperature of 60 °C. However, further drying at higher temperatures may result in the degradation of food nutrients like proteins, vitamins, etc. [44]. Considering energy consumption for mushroom drying and targeted moisture content (10 wt%), a drying temperature range of 50–70 °C was taken for further investigation [45].

The effect of hot airspeed at a drying temperature of 60 °C for 8 h is presented in Fig. 2B. Fig. 2B depicts that the moisture content of mushroom slices rapidly reduced from 17.2 wt% to 8.6 wt% as the hot airspeed increased from 1 to 3.5 m/s. However, an increase in the airspeed beyond 3.5 m/s increases the moisture content of the mushroom to 13.5 wt%. This result may be attributed to shorter residence time for air-to-mass transfer. Furthermore, drying mushrooms at a very fast airspeed leads to inefficient moisture loss [46, 47]. Hence, airspeed between 2 and 5 m/s was considered for further investigation.

The effect of the mass of slice mushroom load at a hot airspeed of 3 m/s with 60 °C temperature is shown in Fig. 2C. From Fig. 2C, it is observed that the moisture content is almost constant (at 9.7 wt%) up to 250 g mass load. However, when the weight of the sliced mushroom increased, the change in moisture content was less as compared to the moisture content of a raw sample. This is so because of the mass transfer resistance due to low contact area (as overlapping of slice mushroom) for evaporation of moisture for larger mass load [48]. Therefore, a mass load of 300 g and below it, was taken for further investigation.

3.1.2. Model evaluation

Based on the effect of individual parameters, the lower and upper limits of temperature, hot airspeed, and mass load were set as 50 °C and 70 °C, 2 m/s and 5 m/s, and 100 g, 300 g, respectively. The result obtained was used for model analysis and presented in Table 3.

Based on the p-value (<0.05) of the pre-defined model, the quadratic model has been suggested as significant and selected for

Table 3
BBD experimental matrix of the three factors and their corresponding response.

Factor 1 A: temperature (°C)	Factor 2 B: airspeed (m/s)	Factor 3 C: mass loading (g)	Response 1: Moisture content (wt.%)	
			Actual	Predicted
50	3.5	100	17.3 ± 0.02	18.12
60	5	100	12.8 ± 0.1	12.70
70	3.5	300	16.6 ± 0.02	15.80
60	3.5	200	10.1 ± 0.01	9.67
50	2	200	26.5 ± 0.02	25.43
70	5	200	12.3 ± 0.02	13.37
50	3.5	300	22.5 ± 0.02	23.43
60	2	100	12.5 ± 0.04	12.71
60	3.5	200	8.8 ± 0.01	9.67
60	3.5	200	9.9 ± 0.02	9.67
70	2	200	10.2 ± 0.02	10.88
60	3.5	200	9.9 ± 0.01	9.67
60	5	300	16.8 ± 0.02	16.57
60	2	300	22.3 ± 0.03	22.44
50	5	200	17.8 ± 0.01	17.05
70	3.5	100	8.5 ± 0.02	7.52

drying mushrooms for moisture content prediction and optimization of the drying parameters during the drying of mushrooms. From ANOVA, the model is significant to explain the mushroom drying with a p-value of less than 0.0001 (Table 4). The Model F-value of 40.79 also implies the model is highly significant.

The value of prob > F less than 0.05 indicates model terms are significant. Hence, the terms A, B, C, AB, BC, A2, B2, and C2 are significant model terms, and the interaction factor AC is insignificant. The significance of terms are ordered as A (<0.0001) ≥ C (0.0001) > A^2 (0.0007) > B^2 (0.0008) > C^2 (0.0017) > AB (0.0027) > B (0.0095) > BC (0.0383). This indicates that temperature, hot airspeed, the mass of the sliced mushroom, the interaction of temperature with the weight of the sliced mushroom, and quadratic terms of hot airspeed significantly affect the drying process of the mushroom. The lack of fit with an F-value of 6.71 implies there is a 6.71% chance that this large lack of fit could occur due to noise. The model equation that correlates the response variable (moisture content) with the drying process variables in terms of coded factor is described in Equation (19). The actual and model-predicted values are compared in Fig. 3. The mushroom drying process was well explained by the model equation with an R^2 value of 0.98, which shows more than 98% of the experimental results are explained by the model.

$$MC(wt\%) = 9.67 - 4.56A - 1.47B + 3.40C + 2.72AB + 0.7425AC - 1.47BC + 3.56A^2 + 3.45B^2 + 2.99C \quad (19)$$

3.1.3. Interaction effect of parameters and parameter optimization

Fig. 4A–C presents the interaction effects parameters on the drying of mushrooms. Fig. 4A shows the response surface plots as a function of the interaction of temperature and airspeed while the mass loading was kept constant at 200 g. As drying temperature increases from 50 to 60 °C and airspeed increases from 2 to 3.3 m/s, the moisture content decreases from 25 to 8.4 wt%. Further, an increase in temperature to 70 °C and airspeed to 5 m/s caused the moisture content to increase slightly to 12.98 wt%. The decrement of moisture content with air temperature and speed is owing to heat and mass transfers between the heating medium and sample. However, at high airspeed, the contact time would be short, and moisture tends to increase.

Fig. 4B demonstrates the effect of the mass of load and temperature on the drying of mushrooms at a fixed airspeed of 3.5 m/s. It can be stated that the moisture content of the mushroom decreases as the mass load decreases, and the effect of the mass load is more sound than the effect of temperature. It seems that when more mass is loaded on the drying tray, the mass transfer would be impeded. This could impact the final moisture content of the mushroom [22].

The effect of airspeed and mass load on moisture removal of mushroom drying at a fixed drying air temperature of 60 °C is presented in Fig. 4C. As presented in Fig. 4C, the moisture content decreases from 22 to 9 wt% when the mass loading decreases from 300 to 180 g, and airspeed increases from 2 to 3.7 m/s. After that, there is a light increase in moisture content to 12 wt% as the mass load further decreases to 100 g and airspeed increases to 5 m/s. Fig. 4A–C shows that the drying parameters strongly affect the moisture removal of mushrooms in tray drying.

3.1.4. Optimization of process parameter of mushroom drying

RSM plays a crucial role in order to effectively explore the optimal values of process variables. The design of experiments based on the Box-Behnken response surface methodology with three factors (temperature, airspeed, and mass loading of slice mushrooms) were examined to identify the optimum condition of drying mushrooms in a tray dryer. The targeted moisture content and the three parameters were set in ranges between the lower and upper bounds, as shown in Table 5, and numerical optimization using RSM was used to obtain a targeted moisture content of 10 wt%. Based on the fitted and model numerical optimization using RSM, the optimum drying temperature, airspeed, and mass of the sliced mushroom are 59.81 °C, 2.96 m/s, and 200 g, respectively. This gives a moisture content of 9.99 wt%, at which the major component of the mushroom would be preserved, and the mushroom would have a longer shelf life [43]. Tran et al. determined in their research that a temperature of 70 °C is ideal for drying the oyster mushroom without considering the drying medium and amount of mushroom to be dried [12]. The mushroom sample dried at optimum condition was used for further characterization.

Table 4
RSM-BBD ANOVA results of response surface quadratic regression model.

Source	Sum of Squares	df	Mean Square	F-value	p-value	Remark
Model	450.42	9	50.05	40.79	0.0001	significant
A-temperature	166.17	1	166.17	135.42	<0.0001	
B-hot airspeed	17.26	1	17.26	14.06	0.0095	
C-mass	92.55	1	92.55	75.42	0.0001	
AB	29.54	1	29.54	24.07	0.0027	
AC	2.21	1	2.21	1.80	0.2286	
BC	8.58	1	8.58	7.00	0.0383	
A^2	50.80	1	50.80	41.40	0.0007	
B^2	47.64	1	47.64	38.83	0.0008	
C^2	35.67	1	35.67	29.07	0.0017	
Residual	7.36	6	1.23			
Lack of Fit	6.41	3	2.14	6.71	0.0761	not significant
Pure Error	0.9549	3	0.3183			
Cor Total	457.78	15				

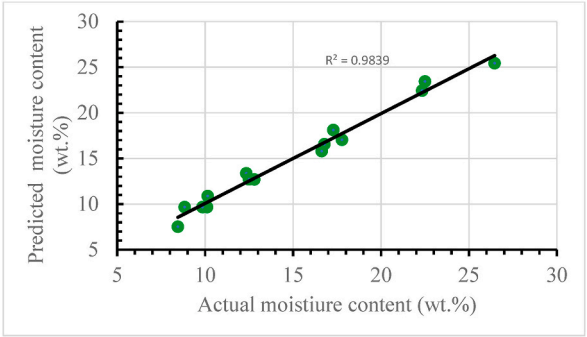

Fig. 3. Comparison of actual result with model-predicted moisture content of dried mushrooms.

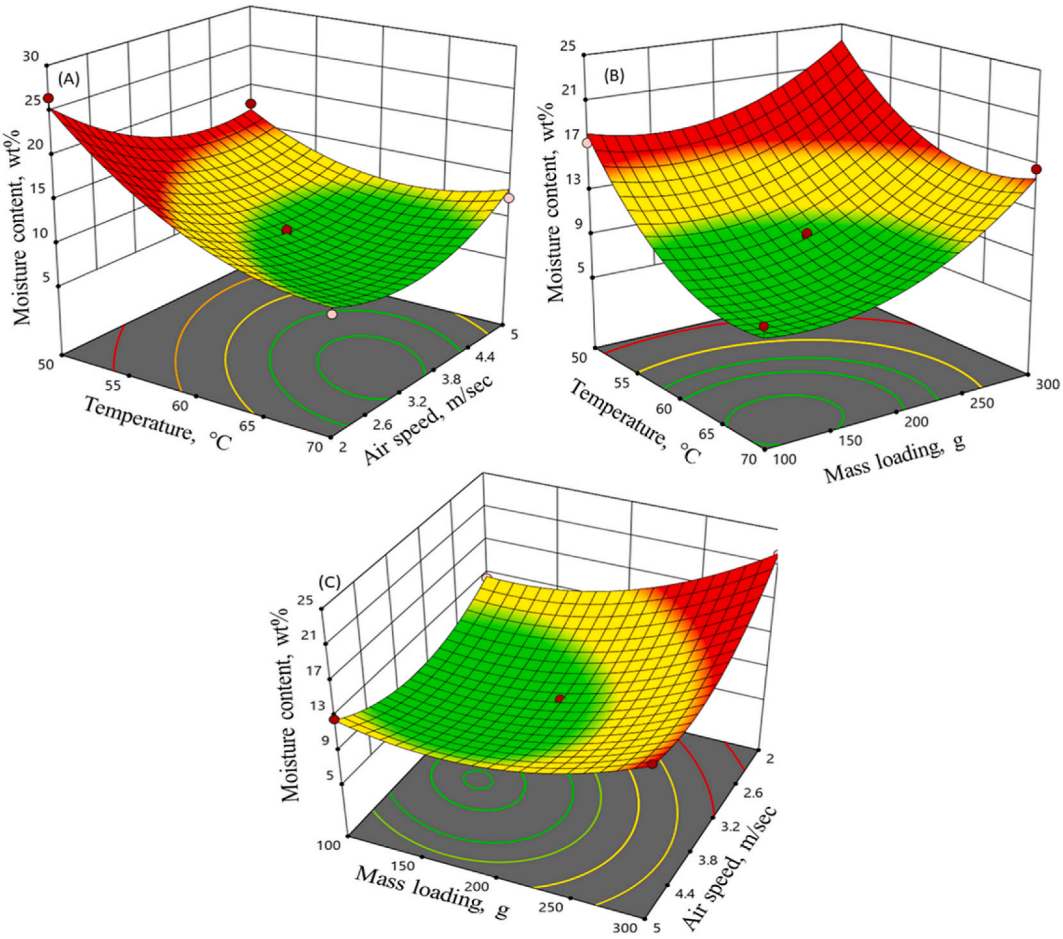

Fig. 4. Response surface plot for interaction effect for mushroom drying (A) effect of temperature and airspeed, (B) effect of temperature and mass loading, and (C) effect of airspeed and mass on the moisture content of mushroom.

3.2. Drying kinetics for mushroom drying

The drying curves of oyster mushroom drying in a tray dryer captured by the moisture content (MC) and moisture ratio (MR) (i.e. MC versus time and MR versus time) at different temperatures were presented in Fig. 5(A and B). As the curve demonstrates, the drying rate increases as the drying temperature changes from 50 to 70 °C (Fig. 5A). Particularly in the first 150 min, spurred a rapid loss of moisture, from 93 to around 30 wt% at higher temperatures. This indicates the falling rate period occurred from the beginning to the first 200 min and was followed by a constant rate period. In the plot of moisture ratio versus drying time, as shown in Fig. 5B, the MR

Table 5
Result validation for model and response at optimal drying condition.

Parameter and Response	Constraint	Optimum moisture content (wt.%)		Deviation
		Experimental	Model	
Temperature (°C)	[50,70]	59.81	60	0.19
Airspeed (m/s)	[2,5]	2.96	3	0.04
Slice mushroom weight (g)	[100,300]	200	200	0
Moisture content (wt.%)	10	9.99	10	0.01

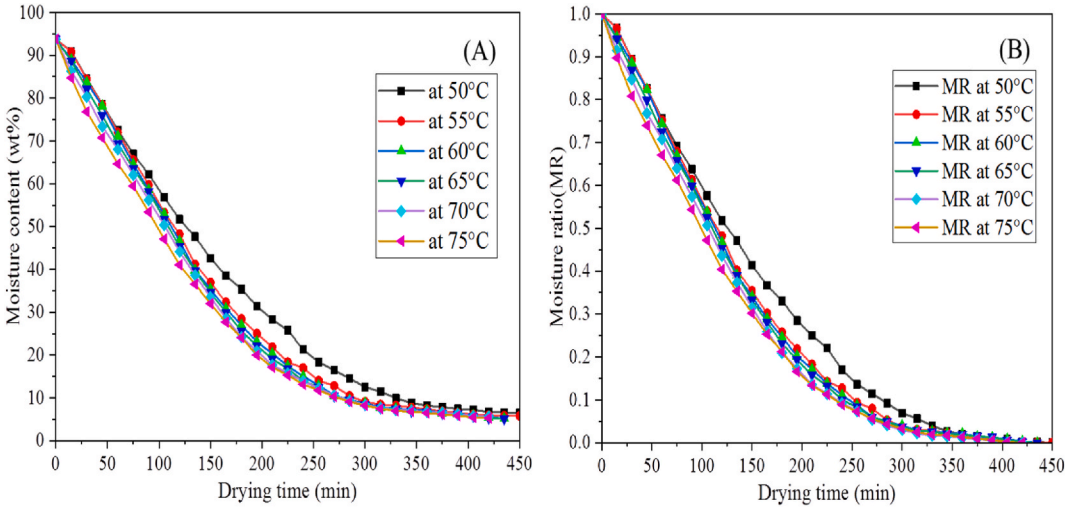

Fig. 5. Drying curves at various temperatures (A) variation of moisture content with time and (B) moisture ratio dependence on drying temperatures.

curves plummet faster at higher temperatures, highlighting the direct correlation between thermal boost and moisture removal. The effect of drying temperature on moisture removal is also related to drying time, and exceeding optimal duration would spoil important components of mushrooms [44].

As stated in Table 3, different mathematical drying kinetics models were examined to select the best-fitted models for mushroom drying at the optimum drying conditions. The models were formulated as a function of the moisture ratio and drying time. MATLAB nonlinear regression method was used to fit the generated data of moisture ratio and drying time. From the drying kinetics models at 60 °C, Midilli et al. is the best-fit drying kinetics model with $R^2 = 0.9993$, RSME = 0.008749, and $X^2 = 0.0014$. Moreover, the Midilli et al. thin layer drying kinetics model remains the best fit for all temperature ranges (50, 55, 65, 70, and 75 °C), as evidenced by the values of R^2, RSME, and X^2. The model parameters and coefficients of different drying kinetics are given in Table 6.

Different authors have shown that Midilli et al. is the best-fit drying model for mushroom drying [26,27,43]. So, Midilli et al. is the model selected for studying oyster mushroom drying rate. The time versus moisture ratio MATLAB non-linear curve fitting for the Midilli et al. kinetics model is shown in Fig. 6.

Effective moisture diffusivity and activation energy: The effect of temperature on the effective moisture diffusivity of mushrooms is presented in Fig. 7. In the drying process, effective moisture diffusivity is a measure of how all input parameters affect mass transfer. The value obtained at each temperature was in the range of 1.1071×10^{-8} to 6.982×10^{-9} m^2/s. A more or less result was obtained by

Table 6
Model parameters and goodness of fit for oyster mushroom drying kinetics.

Thin-layer drying models	Coefficients					Statistical values		
	a	b	c	k	n	R^2	RMSE	X^2
Lewis or Newtons	–	–	–	0.008239	–	0.9804	0.0435	0.028
Page Models	–	–	–	0.001745	1.31	0.9985	0.01225	0.0024
Modified page	–	–	–	−0.0668	−0.123	0.9804	0.04427	0.0020
Two-term exponentials	0.1304	0.9459	–	0.008813	–	0.9858	0.03829	0.0085
Henderson's and Pabis	1.076	–	–	0.008812	–	0.9858	0.0376	0.0022
Logarithmic	1.123	–	−0.07926	0.007186	–	0.9945	0.02387	0.0195
Midilli et al.	0.989	−0.01303	–	0.001546	1.322	0.9993	0.008749	0.0014
Singh et al.	0.02528	–	–	0.007291	–	0.9914	0.02932	0.057

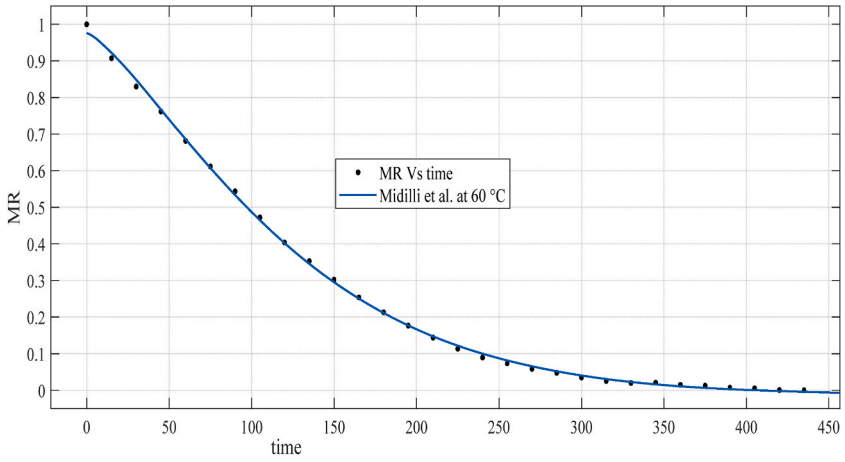

Fig. 6. The Midilli et al. MATLAB curve fitting of non-linear regression at 60 °C.

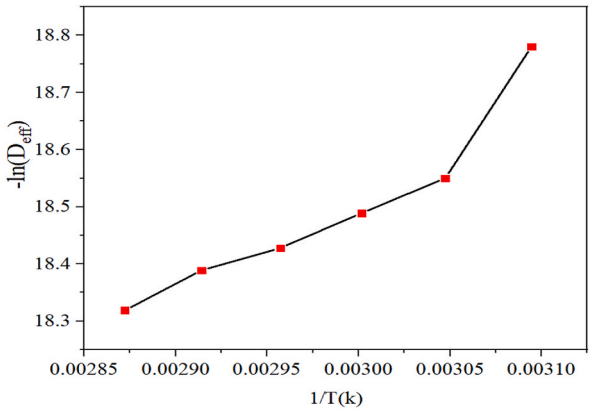

Fig. 7. Relationship between effective moisture diffusivity and reciprocal absolute temperature.

Tran et al. [12]. However, their studies are not at the optimal drying temperature and do not consider the effect of other drying parameters. As is known, the effective moisture diffusivity increases as the drying temperature increases. The value of D_{eff} lies within the general range of 10^{-8} to 10^{-12} m^2/s for most food materials [22,49]. The activation energy calculated from the slope of *ln* (D_{eff}) versus the reciprocal of temperatures (*1/T(K)*), as shown in Fig. 8, was found to be 15.32 kJ/mol with Arrhenius constant (D_0) value of 2.263×10^{-6} m^2/s. This result indicated that the energy consumption in the range of temperature studied in the drying of mushrooms falls within the typical range of 12–110 kJ/mol for food materials [22,50].

3.3. Characterizations of dried mushrooms

3.3.1. Proximate composition analysis

The proximate composition of fresh and mushroom dried at optimal drying conditions on a dry basis is given in Table 7. The result of moisture content after drying and the fresh mushrooms shows a big difference, 93.8 wt% and 9.5 wt%, respectively. This indicates that fresh mushroom is a highly moist food item. Almost similar results were obtained in previous studies [20,51]. The highest content of mushrooms was total carbohydrate (51.0 wt% in fresh mushrooms and 50.2 wt% in dried mushrooms). The protein content of mushrooms also changes from 29.5 wt% in fresh mushrooms to 27.8 wt% in dried ones. The difference between the protein contents of fresh and dried mushrooms was not that much more (1.7 wt%). This difference might be owing to the loss of nitrogen while grinding the dried mushroom and the digestion process, as dried products are not equally digested with humid products. An insignificant change was observed in the ash content (8.8 wt% in fresh and 8.6 wt% in dried mushroom) and crude fat content (2.0 wt% in fresh and 1.9 wt% in dried mushroom) between the dried mushroom and fresh mushroom. This shows that the all-inorganic components of the mushroom were kept while drying.

Crude fat is a sign of the lipid fraction related to the food. Therefore, it determines the triglycerides, phospholipids, waxes, sphingolipid steroids, terpenes, and fat-soluble vitamins [41]. The fat content found in oyster mushrooms was very small in quantity. This indicates that the oyster mushroom species had fewer lipids content in nature. The crude fibers in dried mushrooms (11.5 wt%)

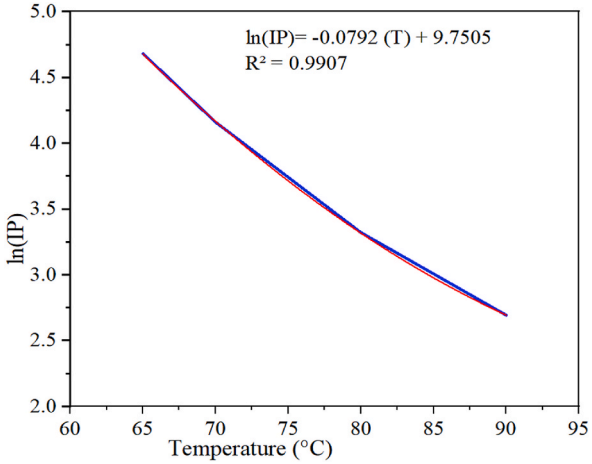

Fig. 8. The relationship between the induction period and temperatures.

Table 7
Proximate analysis of fresh mushroom and dried mushroom.

Proximate parameters	Fresh mushroom[#]	Dried mushroom at optimal condition[#]	*Calocybe gambosa* *	*Pleurotus ostreatus*[##]	*Fresh Pleurotus Ostreatus* [###]
Moisture content (wt.%)	94 ± 1	9.5 ± 0.5	91 ± 1	4.8 ± 0.6	91 ± 2
Ash content (wt.%)	8.8 ± 0.4	8.6 ± 0.6	14 ± 1	6.6 ± 0.5	8 ± 1
Fat content (wt.%)	1.9 ± 0.1	1.9 ± 0.06	0.8 ± 0.1	1.5 ± 0.1	2.6 ± 0.5
Protein content (wt.%)	29.5 ± 0.5	28 ± 1	16.4 ± 0.2	30.5 ± 0.4	18 ± 3
Crude fiber (wt.%)	8.7 ± 0.4	11.5 ± 0.7	ND	8.2 ± 0.8	14.3 ± 0.7
Total carbohydrate (wt.%)	51.0 ± 0.9	50.2 ± 0.8	70 ± 1	52.0 ± 0.3	71 ± 3
Gross Energy value (kcal/100 g)	368 ± 3	329 ± 2	401 ± 4	ND	ND

#present study, *Fresh mushroom (*Calocybe gambosa*) [52], [##]Dried mushroom (*Pleurotus ostreatus*) [53], [###]Fresh mushroom (Pleurotus ostreatus) [54], ND: not determined.

showed a little difference from that of the fresh mushrooms (8.7 wt%). The small change in this crude fiber might have resulted from the interaction difference of the solvent with dried and fresh mushrooms. The slight difference observed in the dried mushroom would be due to the difference in moisture content, as it is known that the moisture content of the mushroom depends on harvested time and other factors such as humidity, temperature, and storage conditions. Also, there will be composition differences from one species of mushroom to another. As a result, the drying of mushrooms to the optimum moisture content did not affect the important compositions (protein, carbohydrate, and gross energy value) except the moisture content. These results have an agreement with the previous studies on mushrooms [55].

3.3.2. Shelf-life characteristics

Shelf life and the stability of food items are extremely dependent on the water content since they directly affect the rate of food deterioration reactions [14]. Mushrooms are exceedingly perishable after harvesting because of their excessive breathing charge and their sensitive epidermal structure. Therefore, its storage time should be determined before packing. The oxidation stability analysis of the sample shows that the dried mushroom induction period (IP) and temperature have a linear relationship (Fig. 8). The IP of dried mushrooms at 20 °C and 25 °C was found to be 3520.99 h and 2369.66 h, respectively, from the regression equation. From the plot of IP versus temperature, it is possible to conclude that as the temperature increases, the IP becomes smaller, which implies a shorter shelf

Table 8
Mineral composition of fresh and dried mushrooms.

Type of metals	Composition value (mg/g)	
	Fresh Mushroom	Dried mushroom
Magnesium (Mg)	5.9 ± 0.2	5.0 ± 0.2
Calcium (Ca)	8.7 ± 0.1	8.4 ± 0.2
Sodium (Na)	12.7 ± 0.2	12.5 ± 0.1
Potassium (K)	10.2 ± 0.3	9.8 ± 0.3
Copper (Cu)	3.0 ± 0.1	2.3 ± 0.01
Zinc (Zn)	2.6 ± 0.1	1.9 ± 0.04

life of the sample.

The water activity (a_w) is another way to estimate the shelf-life that indicates how capable the water present can take part in a chemical reaction. The lower the a_w results, the longer the storage time [56]. The result of water activity of the dried mushroom at 20 °C was found to be 0.36, and the result was much less than that of fresh mushroom water activity (0.97). Hence, the dried mushroom would be less exposed to microorganism formations and could stay for a longer period without deterioration.

3.3.3. Atomic absorption spectroscopy (AAS) analysis

The basic metals (Magnesium, Calcium, Sodium, potassium, Copper, and Zinc) of fresh and dried mushrooms were analyzed and shown in Table 8. The result obtained from AAS showed that potassium and sodium metal concentrations in mushrooms are high and account for 10.2 mg/g, 9.8 mg/g in a fresh sample, 9.7 mg/g, and 9.5 mg/g in a dried mushroom. In a previous study [57], claimed that potassium is the highest value (38.86–47.39 mg/g) in five edible mushroom species. The amount of calcium present in mushrooms (8.7 mg/g in fresh, 8.4 mg/g in dried) is higher compared to other metals such as magnesium (5.9 mg/g in fresh and 5.0 mg/g in dried mushroom), copper, and zinc. The lowest metal components of mushrooms were found to be Copper (2.97 mg/g, 2.302 mg/g) and zinc (2.607 mg/g, 1.949 mg/g). Similar results were reported for oyster mushroom (*Pleurotus ostreatus*) mineral analysis from the works of Ogundele et al. [58].

3.3.4. Functional group analysis

FTIR of both dried mushrooms and fresh mushrooms was analyzed to determine a qualitative functional group analysis, which is shown in Fig. 9. The spectra of samples (dried mushroom and fresh mushroom) were similar, with a slight difference in the intensity of the peaks. The spectra observed in the samples indicate inorganic phosphate, amides, aliphatic, amino acid, and methyl groups in protein, carbohydrate, aliphatic hydrocarbons, phenolic, and water. The broad peaks at 3273 cm^{-1} (dried mushroom) and 3274 cm^{-1} (fresh mushroom) may be attributed to the N–H stretching vibration of the amide in protein. On the other hand, such a peak may appear due to the O–H stretching vibration in phenol or H_2O, as indicated in the proximate analyses [59]. However, the functional group OH-bond is more intense in the fresh mushroom. This may be due to water molecule removal during the drying of mushroom samples. The amino acid functional group was also observed at a wavenumber of around 1635 cm^{-1}. This also shows aromatic ring deformation in amino and amide groups. The peak at around 1500 cm^{-1} showed the N–H bending vibration and C–N stretching vibration of the amide II region in protein. Furthermore, the C–O stretching vibration due to the carbohydrate compound present in the samples resulted in a peak at around 1030 cm^{-1}. The peaks at 2922, 1635, 1543, and 1387 cm^{-1} regions resembled hydrogen bond stretching [60], CH-stretching and $–CH_2$ group stabilized, carboxylate (carboxylic acid salt), C=N stretching absorption for open-chain compounds, $–CH_3$ deformation absorption band splitting, respectively [61].

4. Conclusions

The drying of the oyster mushroom and drying process parameters were optimized using RSM-BBD, and 60 °C drying temperature, 3 m/s airspeed, and 200 g mass loading were found to be the optimal drying conditions. Using a tray dryer, the moisture content of the mushroom sample was decreased from 94 to 10 wt percent at these ideal drying conditions. The dried mushroom contains a biochemical composition of protein (27.8 wt%), carbohydrates (50.2 wt%), fat (1.9 wt%), and crude fibers (11.5 wt%) with a calorific value of 329.0 kcal/100 g. The basic inorganic elements of oyster mushrooms, such as potassium, sodium, magnesium, calcium, copper, and zinc, were analyzed, and potassium and sodium content were higher than in other mushrooms. The optimum moisture content of oyster mushrooms that have a long shelf life is 10 wt% with induction period and water activity of five months and 0.36, respectively. Moreover, the Midilli et al. kinetic model was found to be the best-fit model for oyster mushroom drying based on the

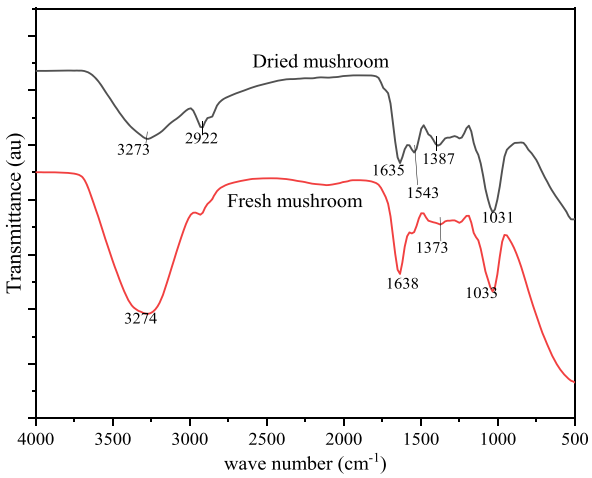

Fig. 9. FTIR results of Fresh and dried mushroom.

drying kinetics analysis. Furthermore, the activation energy and moisture diffusivity were also obtained within a range of food materials (12–110 kJ/mol) and ($10^{-8} - 10^{-12}$ m^2/s) respectively. Drying mushrooms to a moisture content of 10 wt% does not change the basic composition and important nutrients of mushrooms as well as the functional group of mushrooms. The model suggested by the experiment design well predicted the experimental results with a p-value less than 0.0001. Optimization of drying parameters, including the thickness of the slice mushroom and moisture desorption isotherm models for oyster mushrooms, will be the suggested further studies that have not yet been studied.

Data availability statement

The data used to support the findings of this study are all included in this article.

CRediT authorship contribution statement

Talbachew Tadesse Nadew: Writing – original draft, Validation, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Ali Shemsedin Reshad:** Writing – review & editing, Visualization, Supervision. **Tsegaye Sissay Tedla:** Writing – review & editing, Visualization, Validation, Software, Methodology.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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