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Influence of UV-B Pretreatments on Kinetics of Convective Hot Air Drying and Physical Parameters of Mushrooms (*Agaricus bisporus*)

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Abstract: The present study aimed to investigate the effects of ultraviolet-B (UV-B) pretreatments on selected physical properties (shrinkage, rehydration, color, texture) and drying kinetics and to model the drying kinetics of hot air dried mushrooms using several mathematical models, such as the Henderson–Pabis, logarithmic, two-term, Verma, Wang and Singh, Midilli, and modified Henderson–Pabis models. Results showed that the use of UV-B pretreatment before mushroom drying reduced shrinkage, color changes, firmness, and drying time and increased rehydration and the effective moisture diffusion coefficient. The amount of activation energy increased from 16.55 ± 1.3 kJ/mol (control sample) to 18.27 ± 2.2 kJ/mol (UV-B treated samples for 30 min), 19.72 ± 1.4 kJ/mol (UV-B treated samples for 60 min), and 21.9 ± 1.9 kJ/mol (UV-B treated samples for 90 min). However, increasing the drying temperature increased the shrinkage and firmness of samples. The modified Henderson–Pabis model with the highest correlation coefficient (R^2) and lowest root mean square error (RMSE) and chi-square (χ^2) showed the best fit for every drying curve, proving to be an excellent tool for the prediction of drying time.

Keywords: hot air assisted drying; UV light; modeling technique; mushroom; activation energy

1. Introduction

Champignon mushrooms (*Agaricus bisporus* (J.E. Lange) Imbach), also known as button mushrooms, are agricultural products that usually deteriorate in quality after harvest due to reduced moisture, shrinkage, discoloration, and softening of their texture. Therefore, various methods are used to store button mushrooms, the most common of which is drying [1,2]. Hot air drying is by far the most common method of drying, which includes simultaneous heat and mass transfer. In traditional drying methods, a high temperature or a long duration is used, which consumes a high amount of energy and is also time-consuming, leading to undesirable physical and chemical changes, such as changes in color, smell, and taste; it also reduces nutrients and causes shrinkage in the product. Thus, food quality can be maintained in a desirable manner by using other methods of drying or using pretreatment [3,4]. To date, many pretreatment methods have been used to shorten drying time and thus improve the quality of mushrooms, some of which include button mushroom immersion in osmotic solutions such as 7% w/w of sodium chloride [5], ultrasonic pretreatment [6], and infrared pretreatment [7]. Selecting the appropriate drying methods can improve the quality characteristics of dried fruits and reduce time and energy consumption during the drying process [3]. Today, ultraviolet light (UV) treatment is mainly

used to extend the shelf life of fruit and vegetables by reducing microbiota growth as well as enhancing their nutritional quality by positively affecting phytochemical values [8–10]. In recent years, the use of UV has been considered as a pretreatment in the drying process [11]. Generally, the UV radiation spectrum is divided into three regions, UV-C (wavelength 220 to 280 nm), UV-B (wavelength 280 to 320 nm), and UV-A (wavelength 320 to 400 nm). UV-B is the most energetic type of solar radiation that reaches the Earth's surface [12,13]. Braga et al. (2018) examined the use of UV lamps as a pretreatment in the drying process of mangoes and showed that UV pretreatment reduced the moisture content of the samples and increased the amounts of bioavailable vitamins in the samples. The high energy of the pulsed light treatment may have broken the bonds of the vitamins, changing them to their free and bioavailable form, thus resulting in a slightly higher content of vitamins in the treated dried product [11]. One of the most important aspects of any drying technology, especially for industrial processes, is the modeling of the drying process. The purpose of modeling is to choose the most appropriate method of drying, as well as to choose suitable operating conditions for the product. Knowledge of drying behavior is an important factor in designing, simulating, and optimizing the drying process [14,15]. Zhang et al. (2019) examined the effect of ultrasound as a pretreatment on the drying kinetics of button mushrooms. This study showed that the logarithmic model is the most suitable model for describing the drying process of mushrooms [16]. Since limited studies have been conducted on the use of UV-B pretreatment in mushroom drying, the aim of this study was to investigate the effect of UV-B pretreatment on drying kinetics and selected physical properties of dried button mushrooms by the hot air method.

2. Materials and Methods

2.1. Materials

Agaricus bisporus (button mushroom) specimens with initial humidity of 90% (wet weight bases) were purchased from Jolgeh dez Agricultural Company (Dezful, Iran). UV-B lamps (TL 20 W/12 RS SLV/25, Philips, Hamburg, Germany) were used for the UV-B pretreatment, which were placed in a small room measuring 15 × 35 × 65 cm and at a distance of 7 cm from the samples.

2.2. Drying

In order to investigate the effect of UV-B pretreatment time (30, 60, and 90 min) and the drying temperature (40, 50, and 60 °C) on the kinetics and qualitative characteristics of the control samples (no pretreatment) and samples with pretreatment of UV-B, around 50 g of each of the samples was placed in a cabinet dryer (Model X1, Behdooneh Co., Babolsar, Iran) equipped with an air controller and digital thermometer and hygrometer at a speed of 1.5 m/s until their moisture content reached 15%. The water activity (Novasina™ ms1-aw, Novasina, Pfaffikon, Switzerland) of all dried samples was in the range of 0.61–0.67. It should be noted that the control samples were specified at 40, 50, and 60 °C, in the form of C40, C50, and C60, and the samples treated with UV-B for 30, 60, and 90 min and at 40, 50, and 60 °C were specified in the form of U30-40, U30-50, U30-60, U60-40, U60-50, U60-60, U90-40, U90-50, and U90-60.

2.3. Shrinkage

The shrinkage of samples was investigated by measuring the sample volume change. Volume was estimated gravimetrically by displacement of toluene in a pycnometer, based on the method described by Yan et al. [14]. Distilled water was used to calibrate a flask. The volume of the flask was evaluated to be 48.91 mL. The density of toluene, which was determined by weighing the flask while full of

toluene, was found to be 874 kg/m³. The samples were weighed and then transferred into a flask filled with toluene. The volume of samples was calculated by the following Equation (1):

$$V = V_f - \frac{M_{t+s} - M_f - M}{P_s} \quad (1)$$

where V_f is the volume of the flask, M_{t+s} is the weight of the flask plus the sample and the solvent, M_f is the weight of the flask, and P_s is the density of toluene. Thus, the volume of the samples was measured before and after drying and the shrinkage of the samples was calculated using the Equation (2) [17]:

$$\%Sh = \left(1 - \frac{V}{V_0}\right) \times 100 \quad (2)$$

where V_0 is initial sample volume, V is dried sample volume, and Sh is Shrinkage (%).

2.4. Rehydration

Rehydration was performed using the Szadzińska (2018) method. For this purpose, the dried samples were immersed in distilled water at 100 °C (1:50 (*w/w*)) for 5 min. Then, the rate of water reabsorption by the samples was calculated using the following Equation (3) [18]:

$$Rehydration = \frac{M_1 - M_0}{M_0} \quad (3)$$

where M_0 and M_1 are sample weights (g) before and after the rehydration process, respectively.

2.5. Color

The color of the samples was measured with a colorimeter (CR-400, Konica Minolta, Osaka, Japan) using an illuminant D65 and 10° observer angle. The device was calibrated according to the manufacturer's instructions [19] before each measurement period using the white calibration standard tile ($L^* = 96.9$, $a^* = -0.04$, $b^* = 1.84$). Color data are provided as CIE $L^*a^*b^*$ coordinates, which define color in a three-dimensional space. L^* expresses the lightness, taking values within the range of 0 (black)–100 (white). a^* and b^* represent the green-red and the blue-yellow colors, respectively. a^* uses positive values for reddish colors and negative values for the greenish ones, whereas b^* uses positive values for yellowish colors and negative values for bluish ones [20]. All color analyses were run in ten replicates ($n = 10$). The total color changes (ΔE) were calculated using the following Equation (4) [21]:

$$\Delta E = \sqrt{\Delta L^2 + \Delta a^2 + \Delta b^2} \quad (4)$$

where ΔL ($L_A - L_0$), Δa ($a_A - a_0$), and Δb ($b_A - b_0$) indicate the mathematical differences measured in L^* , a^* , and b^* values of samples after (A) and before (0) drying.

2.6. Texture

The texture characteristics of the samples were examined after drying using a Texture Analyzer (TA.XT. PLUS, Stable Micro Systems, Surrey, UK). In order to determine the firmness of the samples, a penetration test was performed using a 6 mm probe with a speed of 50 mm/min and a penetration depth of 2 mm. The force (in newtons) required for penetration by the probe was used to measure the firmness of the texture [3].

2.7. Mathematical Modeling

A moisture ratio was used during the drying process for modeling the drying kinetics. The moisture ratio was calculated according to the initial moisture, equilibrium moisture, and moisture of the samples at each drying time with the Equation (5) [22]:

$$MR = \frac{M_t - M_e}{M_0 - M_e} \quad (5)$$

In the above equation, MR is the moisture ratio, M_t is moisture uptake at a given time, M_e is the equilibrium moisture, and M_0 is the initial moisture of the sample. Drying curves were fitted to different drying models, as shown in Table 1.

Table 1. Mathematical models given by various authors for the drying curves.

Model Name	Model Equation	References
Henderson–Pabis	$MR = a \exp(-k t)$	[23]
Logarithmic	$MR = a \exp(-k t) + c$	[24]
Two-term	$MR = a \exp(-k_0 t) + b \exp(-k_1 t)$	[25]
Verma	$MR = a \exp(-k t) + (1 - a) \exp(-g t)$	[24]
Wang and Singh	$MR = 1 + a t + b t^2$	[24]
Midilli et al.	$MR = a \exp(-k t^n) + b t$	[25]
Modified Henderson–Pabis	$MR = a \exp(-k t) + b \exp(-g t) + c \exp(-h t)$	[23]

A data fit on drying models was performed using MATLAB software (R2016a, The Math Works Inc., Natick, MA, USA). The correlation coefficient (R^2), root mean square error (RMSE), and chi-square (χ^2) were used to select the best model [26] with the following Equations (6)–(8):

$$R^2 = \frac{\sum (O_{pre} - \sigma)^2}{\sum (O_{exp} - \sigma)^2} \quad (6)$$

$$RMSE = \sqrt{\frac{\sum (O_{exp} - O_{pre})^2}{k}} \quad (7)$$

$$\chi^2 = \sum \frac{(O_{pre} - O_{exp})^2}{k - m} \quad (8)$$

In that k is in the number of experimental data, m is the number of model parameters, O_{exp} is the experimental value of moisture content, O_{pre} is the prediction value of moisture content, and σ is the mean value of moisture content.

2.8. Determination of Effective Moisture Diffusion Coefficient

The Fick equation was used in order to evaluate the moisture diffusion coefficient using the following Equation (9) [27]:

$$MR = \frac{8}{\pi^2} \sum_{n=1}^{\infty} \frac{1}{(2n+1)^2} \exp\left(-\frac{(2n+1)^2 \pi^2 D_{eff} t}{4L_0^2}\right) \quad (9)$$

where M_0 is the moisture content in kg water/kg dry matter at the beginning of the drying. M_t is moisture content in kg water/kg dry matter at time t . M_e is moisture content in kg water/kg dry matter when equilibrium was reached. D_{eff} is diffusion coefficient (m^2/s); t is time (s), and L_0 is half the thickness (m). n is the number of terms taken into consideration.

2.9. Activation Energy

The Arrhenius equation was used to calculate the activation energy using the Equation (10) [23]:

$$D_{eff} = D_0 \exp\left(\frac{-E_a}{RT}\right) \quad (10)$$

where E_a is energy of activation (KJ/mol), R is the universal gas constant (8.3 KJ/mol K), T is absolute air temperature (K), and D_0 is the exponential factor of the Arrhenius equation (m^2/s).

2.10. Statistical Analysis

Experiments were evaluated based on a completely randomized design with three replications. The Duncan multiple range test was utilized to compare the means and investigate the effects of treatments. During all stages of statistical analysis, SPSS 19 was used to analyze the data. For all statistical analyses, significance was established at the 5% level.

3. Results and Discussion

3.1. Shrinkage

As observed in Table 2, using UV-B pretreatment before drying the mushrooms had a significant effect on reducing the shrinkage of the samples, and increasing the drying temperature increased the amount of shrinkage in the samples (Table 2). The highest shrinkage was related to the C60 sample and the lowest shrinkage was related to the U90-40 sample (Figure 1). Some of the most important factors affecting the rate of shrinkage of the samples are the temperature and the intensity of drying (process time) [28]. The use of UV-B pretreatment reduced the drying time and thus reduced the shrinkage in the samples. However, by increasing the temperature in the hot air method, the heat transferred to the inside of the product increases and the amount of moisture in the product decreases, and, as a result, shrinkage also increases due to the tension stresses that occur in the cellular structure [29]. Our findings were consistent with those of other researchers [28–31].

Table 2. Effect of ultraviolet-B (UV-B) pretreatments on selected physical properties (shrinkage, rehydration, color, texture) of hot air dried mushrooms.

Sample	Shrinkage (%)	Firmness (N)	ΔE	Rehydration
C40	63.81 ± 0.10 ^{ab}	2.22 ± 0.01 ^{cde}	14.9 ± 1.43 ^{bc}	2.08 ± 0.05 ^{bc}
C50	64.40 ± 0.21 ^{ab}	2.25 ± 0.04 ^{ab}	16.3 ± 2.14 ^{ab}	1.78 ± 0.06 ^{cd}
C60	64.52 ± 0.12 ^a	2.30 ± 0.04 ^a	18.9 ± 2.11 ^a	1.58 ± 0.04 ^d
U30-40	62.93 ± 0.12 ^{abc}	2.23 ± 0.01 ^{bcd}	11.98 ± 1.10 ^{de}	2.28 ± 0.06 ^b
U30-50	63.43 ± 0.23 ^{abc}	2.24 ± 0.02 ^{bc}	14.07 ± 1.81 ^{bcd}	1.85 ± 0.02 ^{cd}
U30-60	63.77 ± 0.22 ^{ab}	2.27 ± 0.02 ^{ab}	15.01 ± 1.43 ^b	1.63 ± 0.01 ^d
U60-40	61.94 ± 0.33 ^{bcd}	2.18 ± 0.01 ^{def}	9.47 ± 1.72 ^{de}	2.38 ± 0.02 ^b
U60-50	62.92 ± 0.22 ^{abc}	2.23 ± 0.03 ^{bc}	9.85 ± 1.17 ^{ef}	2.10 ± 0.04 ^{bc}
U60-60	62.87 ± 0.25 ^{abc}	2.26 ± 0.01 ^{ab}	12.18 ± 1.36 ^{cde}	2.07 ± 0.09 ^{bc}
U90-40	56.26 ± 0.13 ^e	2.16 ± 0.02 ^f	6.78 ± 1.34 ^g	3.08 ± 0.07 ^a
U90-50	59.10 ± 0.21 ^{ed}	2.15 ± 0.01 ^f	7.40 ± 1.73 ^{fg}	2.46 ± 0.06 ^b
U90-60	60.8 ± 0.1 ^{cd}	2.17 ± 0.01 ^{ef}	7.49 ± 1.52 ^{fg}	2.31 ± 0.10 ^b

The same letters in columns means no statistical differences were found between samples ($p < 0.05$) according to Duncan's multiple range test.

3.2. Texture

According to the obtained data from Table 2, the use of UV-B pretreatment reduces the fracture force of the pretreated samples compared to the control samples. The probable reason for this occurrence is that applying pretreatment reduces the drying time and destroys the cell walls in the sample texture, which, as a result, softens the texture. Although this hypothesis has not yet been clearly proven,

it can be proven by impedance measurement of the tissue. In addition, with increasing temperature, the fracture force of the cell walls increased. The highest fracture force of the cell walls in control and pretreated samples was observed at 60 °C, and the lowest fracture force rate was observed at 40 °C (Table 2). The reason for this is that, with increasing drying temperature, the moisture removal rate from the samples increases and the surface hardness of the samples increases. The phenomenon of surface hardening of samples increases with the increasing temperature and results in the hardening of the surface of the dried samples, which, in turn, increases the fracture force of the samples [30].

Figure 1. Image of a raw mushroom before drying (A); a mushroom dried without pretreatment at 60 °C (B), and a mushroom pretreated with UV-B (90 min) and dried at 40 °C (C).

3.3. Color

The results showed that the highest rate of color change during the drying process was related to the control samples (no pretreatment process). After applying UV-B pretreatment, the color change of the samples was reduced when compared to the control samples (Table 2). One of the reasons for the decrease in the color change of the pretreated samples compared to the control samples is that the application of the pretreatment reduced the drying time, which, in turn, caused the product to be in contact with hot air for a shorter time, resulting in reduced enzymatic and non-enzymatic browning reactions in the samples [30]. However, as the temperature increased, the color change of the samples also increased due to the increased decomposition of pigments and the enzymatic and non-enzymatic browning reactions that increase with increasing temperature [32].

3.4. Rehydration

Rehydration can be a criterion for assessing the damage caused by drying or pre-drying treatments. The rate of rehydration is significantly affected by the texture characteristics of the product and the low rehydration rate indicates the collapse of the internal structure of the sample [33]. Based on the obtained findings, using UV-B pretreatment increased the rate of water rehydration by the samples (Table 2). Since UV-B waves are absorbed only by the surface of the samples, there is a probability of an increase in the diameter of the pores in the cell wall, without side effects on the capillary tubes inside the samples. In control samples (without UV-B pretreatment), the lack of surface pores creates more pressure on the capillary tubes and, as a result, the rate of rehydration by the samples is reduced [34]. However, as the temperature increased, the rate of rehydration by the samples decreased, which is probably due to the destruction of the orifice and capillary pores in the structure of the product (Table 2) [4]. The use of scanning electron microscopy is recommended in order to further investigate the effect of the process on the pore size. In general, the data from Table 2 indicate that the use of UV-B pretreatment reduced shrinkage, color changes, and firmness and, on the other hand, increased the rehydration of the dried samples, while the U90-40 treatment had the greatest effect on these characteristics.

3.5. Effects of Pretreatment and Air Temperature on Moisture Ratio

As depicted in Figure 2 (the general trend was similar for all three temperatures), the use of UV-B pretreatment before drying reduced the drying time of the mushroom. Applying UV-B pretreatment increases the diameter of the pores in the cell wall without exerting side effects on the capillary tubes inside the sample. As a result, the moisture removal of the product increased, thus decreasing the drying time of the mushrooms. In the control sample, due to the removal of moisture from the surface of the product and the phenomenon of shrinkage, the capillary tubes on the surface of the product were almost blocked. This blockage is intensified due to water outflow, which, in turn, reduces the moisture removal of the product and increases the drying time of the samples [34]. In addition, the drying time of the mushrooms decreased as the temperature increased (Figure 3). As the temperature rises, the destruction of the membrane layers also increases and the texture of the product is further damaged, which is followed by the removal of more moisture. In addition, the increase in temperature, along with the increase in the molecular movement, causes more water molecules to come out of the product, which reduces the drying time [25].

Figure 2. Effect of UV-B pretreatment on moisture ratio (MR) $\pm$ SD with drying time of samples at 50 °C (the bars smaller than the point on the graph are not shown).

Figure 3. The effect of temperature on moisture ratio (MR) $\pm$ SD with drying time of treated samples exposed to UV-B for 60 min (the bars smaller than the point on the graph are not shown).

3.6. Modeling of Drying Curves

In order to model the drying kinetics of treated and control mushrooms, different models were compared in terms of R^2 , RMSE, and χ^2 . Ultimately, the modified Henderson–Pabis model had the highest R^2 and the lowest RMSE and χ^2 and was therefore selected as the best model. Thus, the modified Henderson–Pabis model had the best fit with the experimental data at all drying temperatures. The statistical results of this model are presented in Table S1 as a supplementary file.

3.7. Determination of Effective Diffusivities

The values of the effective diffusion coefficient during drying and energy activation of the samples can be seen in Table 3. There was an increase in the effective diffusion coefficient of moisture with increasing temperature and application of UV-B pretreatment (Table 3). The effective diffusion coefficient of moisture for the control sample at 40–60 °C was 2.43×10^{-9} to 3.2×10^{-9} (mm^2/s). As the temperature increases, the molecular motion and surface tension of the water also increases, which leads to an increase in the effective diffusion coefficient of moisture in the samples [35]. In addition, the use of UV-B pretreatment reduces the blockage and shrinkage of the cell wall due to the increase in the diameter of the cellular orifice, and this too increases the effective diffusion coefficient of moisture [34].

Table 3. Values of effective diffusivity obtained for mushrooms under different drying conditions.

Temperature (°C)	Effective Diffusivity (m^2/s)			
	Control	U30	U60	U90
40	2.43×10^{-9}	2.56×10^{-9}	2.71×10^{-9}	2.78×10^{-9}
50	2.74×10^{-9}	2.76×10^{-9}	2.87×10^{-9}	2.92×10^{-9}
60	3.2×10^{-9}	3.25×10^{-9}	3.32×10^{-9}	3.39×10^{-9}

3.8. Determination of Activation Energy

It is essential to have knowledge of activation energy as a tool for designing and modeling mass transfer in food processes such as drying. Activation energy indicates temperature sensitivity and emission capability [24]. Based on the obtained findings, the amount of activation energy increased with the application of UV-B pretreatment from 16.55 ± 1.3 (control sample) to 18.27 ± 2.2 kJ/mol (UV-B treated samples for 30 min), 19.72 ± 1.4 kJ/mol (UV-B treated samples for 60 min), and 21.9 ± 1.9 kJ/mol (UV-B treated samples for 90 min). The probable reason for this is that the use of UV-B pretreatment has increased the diameter of the cellular orifice in the sample texture, as well as increasing the effective diffusion coefficient of moisture, leading to the increase in the activation energy [36].

4. Conclusions

The effect of UV-B pretreatments on drying rate and physical properties (shrinkage, rehydration, color, texture) were evaluated. In the falling-rate period of the drying of mushrooms, the diffusion mechanism controlled the moisture movement. UV-B pretreatments and drying air temperature affected the drying rate and time. The drying rate increased with increasing UV-B pretreatment and drying air temperature. The modified Henderson–Pabis model can be used to model the kinetics of drying the control and treated mushrooms. These findings indicate that the shrinkage, color change, and firmness of the product, which are considered to be undesirable quality parameters in dried mushrooms, are reduced by using the UV-B pretreatment before drying. Therefore, the use of UV-B is recommended as a suitable pretreatment in drying mushrooms. However, further tests such as sensory evaluation are suggested for future studies in order to make a final decision as to the effectiveness of UV-B pretreatments in the drying process of mushrooms.

Supplementary Materials: The following are available online at <http://www.mdpi.com/2077-0472/10/9/371/s1>, Table S1: Statistical results and coefficients of models of mushrooms under different drying conditions.

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