Pamukkale Univ Muh Bilim Derg, 29(5), 560-568, 2023

Pamukkale Üniversitesi Mühendislik Bilimleri Dergisi

Pamukkale University Journal of Engineering Sciences

Evaluation of high temperature-vacuum application periods during conventional drying of mushroom slices

Yüksek sıcaklık-vakum uygulama periyotlarının mantar dilimlerinin kurutulması üzerine etkisi

Betül GÜVENKAYA[1], *Sezin TUTA ŞİMŞEK*[1*], *Seda ÖZGEN*[1]

[1]Department of Food Engineering, Faculty of Engineering, Çankırı Karatekin University, Çankırı, Turkey.
betul.guvenkaya@gmail.com, sezintuta@karatekin.edu.tr, sozgen@karatekin.edu.tr

Received/Geliş Tarihi: 25.04.2022 Revision/Düzeltme Tarihi: 30.09.2022 doi: 10.5505/pajes.2022.98792
Accepted/Kabul Tarihi: 26.10.2022 Research Article/Araştırma Makalesi

Abstract

In the present study, a comparative study was conducted on drying characteristics, physicochemical (color, texture, rehydration ratio, total phenolic content, and antioxidant activity), and microstructural (SEM and XRD) properties of mushroom slices using conventional (control, 50°C at atmospheric pressure) and high temperature (75 °C-10 min)-vacuum treatments (-90 kPa) (HT-VT) at a different stage of conventional drying. HT-VT is carried out in the beginning (PRE), intermediate (MID70 and MID110), and final (POST) stages of hot air drying. HT-VT at low moisture content led to having similar drying and physicochemical properties to hot-air dried counterparts. MID and POST samples were more comparable with control, while PRE samples were completely different from control. According to SEM and XRD analyses, these differences can be associated with the decomposition of the cell wall and mannitol content within the tissue cells. PRE samples had a softer texture, darker color, and less rehydration ratio with the lowest total phenolic content and antioxidant activity among the others ($p<0.05$). The hardness, total color change, rehydration ratio, and total phenolic content of POST were similar ($p>0.05$) and the antioxidant activity was significantly different from the control ($p<0.05$). This study showed that drying duration can be shortened with desirable physicochemical properties by application combined high temperature and vacuum at lower moisture content levels.

Keywords: Vacuum, Mushroom, Drying.

Öz

Bu çalışmada geleneksel yöntem (kontrol, 50 °C, atmosferik basınç) ve farklı periyotlarda yüksek sıcaklık (75 °C-10 dk.) ve vakum (-90 kPa) uygulaması ile kurutulan mantar dilimlerinin kuruma karakteristikleri, fizikokimyasal (renk, tekstür, rehidrasyon oranı, toplam fenolik madde ve antioksidan içeriği) ve mikroyapısal özellikleri (SEM ve XRD) karşılaştırılmıştır. Yüksek sıcaklık -vakum uygulaması geleneksel kurutma öncesi (PRE), orta aşamaları (MID70-MID110) ve sonu (POST) uygulanmıştır. MID ve POST örneklerinin kurutma karakteristikleri ve fizikokimyasal özelliklerinin kontrolle benzer ve PRE örneklerinin kontrolden tamamen farklı olduğu görülmüştür. SEM ve XRD analizlerine göre bu farklılıklar mantar hücre duvarında olan bozulma ve hücre dokusunda bulunan mannitol içeriğindeki değişim ile ilişkilidir. PRE örnekleri diğer örneklerden daha yumuşak, daha koyu renkli, düşük rehidrasyon kapasitesine sahip ve toplam fenolik madde içeriğinin ve antioksidan aktivitesinin daha düşük olduğu görülmüştür ($p<0.05$). POST örneklerinin sertlik, toplam renk değişimi, rehidrasyon oranı ve toplam fenolik madde içeriği kontrolle benzer ($p>0.05$) ve antioksidan içeriği farklıdır ($p<0.05$). Bu çalışma yüksek sıcaklık-vakum uygulamasının düşük nem içeriğinde uygulanması ile kurutulmuş mantar dilimlerinin fizikokimyasal özellikleri etkilenmeden kuruma süresinin kısaltılabilme potansiyeli gösterilmiştir.

Anahtar kelimeler: Vakum, Mantar, Kurutma.

1 Introduction

Mushrooms are very popular around the world with their unique flavor, texture, and bioactive compounds; therefore it is used as an ingredient in many food formulations [1]. Mushroom (*Agaricus bisporus*) is highly perishable with a very short shelf-life. Drying is one of the preservation methods to store mushrooms and is applied to preserve approximately 5% of the fresh mushrooms. Conventional dried mushrooms have serious disadvantages such as losses of color, flavor, and nutrient value with reduction of bulk density and rehydration capacity due to high drying temperature and long time. These undesired properties restrict the usage of conventional drying to preserve mushrooms [2]. The application of an appropriate drying method is an important factor due to the very heat-sensitive properties of mushrooms. Conventional hot-air drying, freeze-drying, and vacuum drying methods are used in industrial dried mushroom production. Conventional hot-air drying is conducted at a low-temperature range, between 40°C and 70°C, and this leads to a long drying time with poor physical properties (3). Freeze-dried mushrooms have high-quality properties but long drying times and high operation costs limit its usage (4). Vacuum drying is a common method for the dehydration of heat-sensible foods. Ambient pressure is reduced during the vacuum drying; therefore this causes the reduction of both of boiling point of water and water vapor concentration. This provides the formation of a vapor pressure difference between the interior and the surface of the product. Simultaneous heat and mass transfer occur during the drying process. In vacuum drying, the convection effect is reduced, which causes limited heat transfer and a long drying time due to a decrease in the diffusion coefficient [5,6]. The highest drying time was obtained by vacuum drying among the drying techniques in cabinet moisture dryers, fluidized bed dryers, and microwave ovens (6). In the literature, vacuum is applied in different ways to enhance drying rates such as pulsed vacuum drying and explosion puffing drying. Pulsed vacuum drying (PVD) is novel and promising drying technology. In the

*Corresponding author/Yazışılan Yazar

literature, pulsed vacuum drying applications have been practiced for blueberry [7], lemon slices [8], rhizoma dioscoreae [9], and grape [10]. By PVD, the ambient pressure of the drying chamber is changed between vacuum pressure and atmospheric pressure at specific time intervals. Shortening drying time, inhibiting oxidative reactions, and reduction of degradation of heat-sensitive compounds are the main advantages of PVD. Using appropriate atmospheric and vacuum durations is an important factor to enhance the drying rate and physicochemical properties of mushrooms [11]. Explosion puffing drying is the other drying technique that is applied using a vacuum. In this technique, sudden temperature increase and sudden pressure decrease are applied at the intermediate stage of hot air drying which is called puffing [12]. Hot air drying is a pre-treatment method of explosion puffing drying to reduce the initial moisture content of food. To puff the sample low moisture content (25-50%) is required and generated steam amount in food during puffing depends on moisture content [13].

In the light of this information, vacuum pressure periods affect final dried food quality and drying characteristics according to the moisture content of food. In this study, we demonstrate that high temperature-vacuum pressure can affect the drying characteristics and physicochemical properties of mushroom slices. To achieve better quality products, vacuum/atmospheric pressure application periods during drying are important. By understanding this phenomenon, the drying process, and physicochemical properties of mushrooms can be enhanced with moderate energy consumption. In this study, to determine this effect, the ambient pressure was reduced in different periods and this process was carried out at a temperature higher than the atmospheric drying temperature to accelerate the drying rate of mushroom slices. This process was conducted in a short time due to the heat sensitivity of the mushroom. The high temperature-vacuum application was investigated in terms of drying characteristics and physicochemical properties of the mushroom.

2 Materials and methods

2.1 Material

Mushroom (*Agaricus bisporus*) was supplied from local markets. Mushroom caps with 19.9±0.8 mm height and 38.3±2.0 mm width were used. Mushroom samples were cut into slices with a thickness of 5.0±0.5 mm after cleaning with a brush for removing impurities. Mushroom slices weighing 20.0±0.5 g were placed on a wire. The initial moisture content of mushroom slices was 92.2±1.2% (wet basis), which was measured by oven drying method at 105 °C until constant weight [14].

2.2 Drying experiments

Conventional drying: Mushroom slices were dried at atmospheric pressure (Absolute pressure was 101.3 kPa) in a fanned oven (Model MST-55, TEKLAB, Turkiye) at 50 ± 5 °C. The time in which the moisture content of mushroom slices was reduced by less than 10% was determined as conventional drying time [15].

High temperature-Vacuum treatment (HT-VT): The pressure reduction was conducted at four different stages during conventional drying. Vacuum treatments were applied at the beginning (pre-treatment), at two different intermediate stages (mid-treatments), and at the final stage (post-treatment) of drying. HT-VT was conducted in a vacuum oven (Model OV-11, Jeiotech, North Korea) coupled with a vacuum pump (Model MVP6, Woosung Vacuum Pump, Korea) at -90 kPa vacuum pressure ($P_{abs}=P_{atm}-P_{vacuum}$, P_{abs} = 11.3±5 kPa). HT-VT was applied in two stages high-temperature treatment at 75°C for 10 min at atmospheric pressure (P_{atm} =103.5 kPa) subsequently ambient pressure was reduced to -90 kPa and subsequently vacuum chamber was set to atmospheric pressure again. This process took 3.5 minutes in total. Vacuum pressure was set at-90 kPa to create a tunneling effect in the mushroom [8]. Mid-treatment periods were conducted according to the conventional drying curve, drying started to slow down at 70 min and a change in mushroom weights was observed that gradually decreased after 110 minutes (Table 1).

2.3 Determination of drying characteristics

2.3.1 Temperature profiles

Measurement of temperature of mushroom slices was carried out by thermocouples (36-gauge type-T thermocouples; Omega Engineering, Inc., Stamford, CT, USA) placed inside of slices. Time-temperature profiles during drying experiments were obtained at 1 s time intervals with a temperature measuring device (Model DT9805, Data Translation, Hungary).

2.3.2 Drying curves

Drying characteristics were determined by weighing mushroom samples at 10 min. intervals. Weight loss (WL) and moisture content (X) of mushroom samples were calculated by Equations 1 and 2.

The moisture content of mushrooms at any time was calculated according to Eq. 1.

$$X_t = \frac{W - L_s}{L_s} \quad (1)$$

Where X_t (g water/g dry matter), moisture content at different time intervals; W(g), wet solid mass of mushroom; L_s (g dry matter/g mushroom), dry matter content of mushroom. The drying rate of mushrooms was calculated by Eq 2., and free moisture content was calculated by Eq. 3.

$$\text{Drying rate} = \frac{X_t - X_{t+\Delta t}}{\Delta t} \quad (2)$$

$$X = X_t - X^* \quad (3)$$

Where X, free moisture content (g water/g dry matter) and X^*, final moisture content (g water/g dry matter).

2.4 Evaluation of dried mushroom samples

2.4.1 SEM analysis

The surface of dried mushroom slices was coated with Au/Pd after an adhesive application and images (5000x magnifications) were taken by scanning electron microscope (LEO, Model 440 VP Zeiss, Cambridge, England). This analysis was carried out in duplicate.

2.4.2 XRD analysis

Ground dried mushroom slices were compressed into the sample container and measurements were carried out using an X-ray diffraction device (Bruker AXS, Model D8 Advance, USA). XRD patterns were obtained between 10° and 40° diffraction angle (2θ) with 4°/min. scanning speed at room temperature. This analysis was carried out in duplicate.

2.4.3 Rehydration capacity

The rehydration capacity of dried mushroom slices was measured by immersing those samples in distilled water at room temperature. The ratio of mushroom slices in distilled water was 1:100 (w/w). Rehydrated samples were measured by taking out every 5 min during the first hour and then every 15 min. until a constant weight was obtained. Rehydrated samples were drained on a tissue for 1 min. The rehydration ratio was calculated according to Eq. 4.

$$\text{Rehydration ratio} = \frac{m_r - m_i}{m_i} \quad (4)$$

Where m_r, mass of rehydrated mushroom slices; m_i, initial mass of dried mushroom slices. Analyzes were conducted duplicate with 2 repeats.

2.4.4 Water activity measurement

Dried mushroom slices were ground and water activity measurement was carried out by a water activity meter (AquaLab4, Meter, USA) at 25 °C. Triplicate analyzes were conducted.

2.4.5 Texture

Texture parameters were obtained using Texture Analyzer (TA-XT2i, Stable Micro Systems Ltd., Surrey, UK, 30 N load cell) with a cylindrical probe (P/36R). Pre-test speed, test speed, and post-test speed were 5 mm/s, 0.5 mm/s, and 10 mm/s, respectively and the compression ratio was 50%. Force-time curve was obtained and the highest peak value in this curve was identified as the hardness value of mushroom slices [16]. Eight different control and HT-V treated mushroom slices were analyzed for texture analysis.

2.4.6 Color

The colorimeter (Konica Minolta, Model CR400, Japan) was used to measure the color parameters of mushroom slices. The color parameters (L^*, a^*, b^*) were measured on five different points of mushroom slices. L^*, a^*, *and* b^* values indicate lightness (from 0 to 100), redness (from −120 to 120), and yellowness (from -120 to 120). Total color difference (ΔE) was calculated to analyze how much the color of mushroom slices differed from fresh mushroom slices using Eq. 5.

$$\Delta E = \sqrt{(L_0^* - L^*)^2 + (a_0^* - a^*)^2 + (b_0^* - b^*)^2} \quad (5)$$

Where L^*, a^*, b^* values are the mean of five color parameters of control and HT-V treated mushroom slices. L_0^*, a_0^*, b_0^* values were the mean color parameters of fresh mushrooms (L_0^* : 88.48, a_0^* : 1.71, b_0^* : 11.27).

2.4.7 Total phenolic content

Extract preparation with dried mushroom slices was carried out using methanol with the ratio of 1:50 (w/v, g mushroom slices: mL methanol). The cold maceration method was performed by stirrer at 200 rpm for 24h at room temperature. Subsequently, samples were filtered and the solvent was evaporated at 55 °C. Methanol was added to extract and filtered through a syringe filter (45 µm) to analyze total phenolic content and antioxidant analyzes.

Determination of total phenolic content was carried out using the Folin-Ciocalteu reagent. The mushroom extract was mixed with 150 µL Folin-Ciocalteu reagent and diluted with 2450 µL of distilled water and 300 µL of 20% sodium carbonate was added. TPC was measured at 725 nm using a spectrophotometer. Gallic acid was used (20-250 ppm) as a standard and the result was determined as mg gallic acid equivalent/g dried sample [17].

2.4.8 Antioxidant capacity

The antioxidant activity of dried mushroom slices was conducted by DPPH radical scavenging method. 150 µL of dried mushroom slices extract was added to 2850 µL of DPPH in methanol solution. The mixture was stood for 1 h in dark at room temperature. Antioxidant activity was measured at 515 nm using a spectrophotometer and calculated using Eq. 6.

$$\text{Inhibition (\%)} = \left(\frac{\text{Abs}_b - \text{Abs}_{dm}}{\text{Abs}_b}\right) \times 100 \quad (6)$$

Where Abs_b was the absorbance of blank at 515 nm and Abs_{dm} was the absorbance of dried mushroom slices at 515 nm [17].

2.5 Statistical analysis

Statistical comparison of rehydration ratio, hardness, color parameters, total phenolic compound, and antioxidant activity of dried mushroom slices was conducted by Fisher Pairwise Comparisons-Fisher least significant difference method (95% confidence, p=0.05) using Minitab®17.

3 Results & Discussion

3.1 Drying experiments

The conventional drying duration was determined as 210 min and the total atmospheric drying durations at 50 °C were 180 min for MID70, MID110, POST, and 170 min for PRE as shown in Table 1. Temperature profiles during drying experiments are shown in Figure 1(a).

A sudden temperature increase was observed during HT-VT periods. Increase in mushroom temperature during high temperature application was in order PRE (48.42 °C) < MID70 (56.90 °C) ≈ POST (56.20 °C) < MID110 (64.75 °C). The initial temperature of mushroom slices before HT-VT might be an important factor due to the decrease in the specific heat of water by increasing inner temperature. A less temperature increase was observed for PRE than for MID70 and MID110. The lowest moisture content during POST treatment may have reduced convection and enhanced conduction which is a slower heat transfer mechanism than convection. During drying, the mean temperature of mushroom slices was similar among Control and HT-VT samples (Table 1). The vacuum application after high-temperature treatment led to a decrease in temperature until ambient pressure reached 11.3 kPa (vacuum pressure was -90 kPa) and after that increased by reaching atmospheric pressure. After heat treatment at atmospheric pressure, vacuum treatment caused to decrease in temperature in order of PRE (20.67 °C) < POST (25.55 °C) < MID70 (29.02 °C) <MID110 (36.74 °C) and increased during come up to atmospheric pressure in order of PRE (35.79 °C) <POST (50.49 °C) <MID70 (54.82 °C) <MID110 (68.99 °C). At the beginning of the pressure reduction period in the vacuum oven, the mushroom temperature was higher which led to a sudden temperature decrease due to intense water evaporation and evaporative cooling. After the vacuum stage was completed boiling point of water increased and thermal energy was transferred to the product which resulted in a temperature increase in mushroom slices [18].

The drying curves of mushroom slices are presented in Figures 1(b) and (c). The drying rate versus moisture content is depicted in Figure 1(c). PRE samples had a higher drying rate compared to other samples. HT-VT led to increase in the drying rates of MID70 and MID110 and decrease for POST. Having crust and less water inside the material may have led to a decrease in the drying rate of POST. Thermal diffusion (free moisture evaporation due to temperature gradient) and liquid diffusion (water diffusion due to moisture content differences, capillary action) are dominant diffusion mechanisms during drying. The dominant diffusion mechanism is related to the moisture content of the material and affects drying rates [19]. According to this, different diffusion mechanisms were dominant according to moisture content during HT-VT. That was thermal diffusion and liquid diffusion during PRE and POST treatments, respectively. Both two mechanisms exist during HT-VT of MID70 and MID110, and more thermal diffusion may have been present in MID70 than liquid diffusion and vice versa for MID110 due to moisture content. Thermal diffusion enhanced during HT-VT of PRE, MID70, and MID110 caused accelerated drying rates. A change in mushroom temperature due to more thermal energy transfer during HT-VT may have promoted drying rates of MID70 and MID110. And more free moisture content may have accelerated the drying rate of pre-treated mushroom slices. During post-treatment, the limited moisture content may have led to a decrease in the drying rate.

Table 1. Drying conditions.

	Control	PRE	MID70	MID110	POST
Drying definition	50 °C	HT-VT + 50 °C	50 °C+HT-VT+ 50 °C	50 °C+HT-VT+50 °C	50 °C + HT-VT
HT-VT period	-	Before drying at 50 °C in atmospheric pressure.	Drying started at 50 °C and HT-V was applied after 70 min. and continued at 50 °C.	Drying started at 50 °C and HT-V was applied after 110 min. and continued at 50 °C.	Drying started at 50 °C and HT-VT was applied after 180 min. and drying was completed.
Total Drying time	210 min.	183.5 min.	193.5 min.	193.5 min.	193.5 min.
Mean temperature during drying	41.76±6.11 °C	41.20±3.63 °C	40.86±8.10 °C	42.46±8.55 °C	39.51±5.66 °C

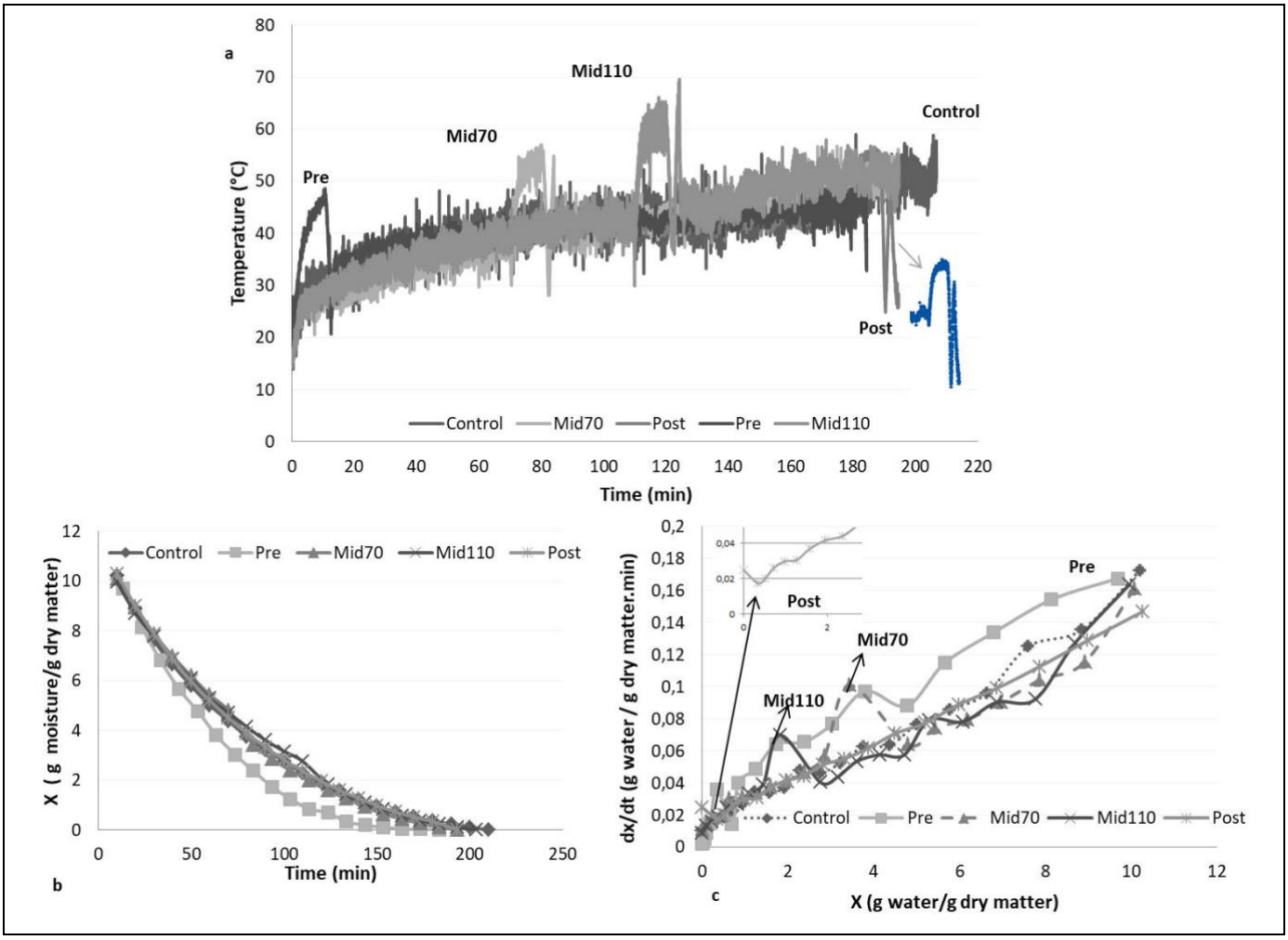

Figure 1. Temperature profiles. (a): and drying curves. (b)-(c): During drying experiments.

3.2 Characterization of dried mushroom slices

3.2.1 Microstructure of mushroom slices

SEM images of mushroom slices are shown in Figure 2. The intercellular spaces of Control and PRE were larger than MID70, MID110, and POST. High temperature and pressure change at the beginning of the drying process was considered to damage the cell wall and decrease cell wall strength as seen in PRE. HT-VT at lower moisture content may have led to a decrease in intercellular spaces of MID70, MID110, and POST. The POST differentiated from the Control by shrunk of tissue cells and junctions between cells.

XRD spectrums of dried mushroom slices were shown in Figure 3. XRD spectrums of MID110 and POST were comparable with Control while some differences were observed for PRE and MID70. Mannitol and galactose are the main crystalline structures of mushrooms [20]. Mannitol is responsible for the firmness and volume of mushrooms due to its osmotic function. Food processes such as drying, freezing, and boiling affect the mannitol content of mushrooms [21]. As stated in Popescu et al. [20], peaks at around 10°, 20°, and 45° related to the mannitol content of mushrooms. Peak heights of 10°, 22°, and 36° reduced for HT-VT mushroom slices, and the lowest peak height was observed for PRE. One of the peaks of two-headed peaks at 25° and 45° disappeared for Pre and Mid70-HT-VT mushroom slices. PRE had the most affected pattern and this was compatible with the SEM image of Pre samples. The thinner connections between tissue cells of PRE (white arrows in Figure 2) than the other mushroom slices may have been linked to osmotic pressure loss due to mannitol content. HT-VT caused more cell wall damage compared to completely hot air drying at 50°C. The higher moisture content of mushroom slices of PRE, MID70 than Control, MID110, and POST during HT-V treatments may have caused more disruption of tissue cells. Protein denaturation leads to affect the rehydration capacity of protein-rich foods and the change in the protein structure harms cell wall strength. Protein denaturation occurs between 49.8 °C and 76.1 °C [22]. In our study, the hot air drying temperature was 50 °C and the temperature reached upper than this value during high-temperature treatment. The temperature of mushroom slices reached to maximum≈48 °C during high-temperature treatment of PRE Figure 1(a), but more cell damage occurred in this sample. This can be interpreted as vacuum treatment leading to more cell damage than temperature. MID70 and MID110 had a higher temperature than 49.8 °C, high-temperature treatment at lower moisture content may not have allowed for structural change of cells due to cell wall stabilization.

3.2.2 Rehydration ratio

The water absorption ability of dried samples depends on rehydration capability and relates to the pore size of dried samples [23]. Rehydration ratio values of Control and HT-VT mushroom slices are shown in Table 2. Control had the highest rehydration ratio and MID70, MID110, and POST had statistically similar rehydration ratios ($p>0.05$). A statistically significant rehydration ratio was observed between PRE, which had the lowest rehydration value, and Control, MID70, and POST ($p<0.05$). In contrast to Xu et al. [16], who demonstrated high temperature pre-drying improved the rehydration ratio of air-dried shiitake mushroom, in our study PRE had the lowest rehydration rate due to vacuum application after high-temperature application.

Rehydration ratio changes over time of Control and HT-VT samples are shown in Figure 4. The rehydration curves demonstrated that the high water absorption rate at the initial stage declined with time. Trends of rehydration curves were similar with Giri and Prasad [5]. At the beginning of rehydration, rapid water absorption occurs through capillaries and cavities near the surface; and then intercellular pores and free capillaries absorb water slowly in the final stage [24]. Although the final rehydration values of Control and MID70, MID110, and POST were statistically similar, rehydration ratio changes with time were different. Change in rehydration value of Control and POST overlapped after 40 min immersion in water. At the beginning of immersion, the POST samples absorbed the water more slowly than the control.

Figure 2. Images and SEM images (x5000 magnification) of mushroom slices (dashed line-white arrow: intercellular spaces, white arrow: link between tissue cells).

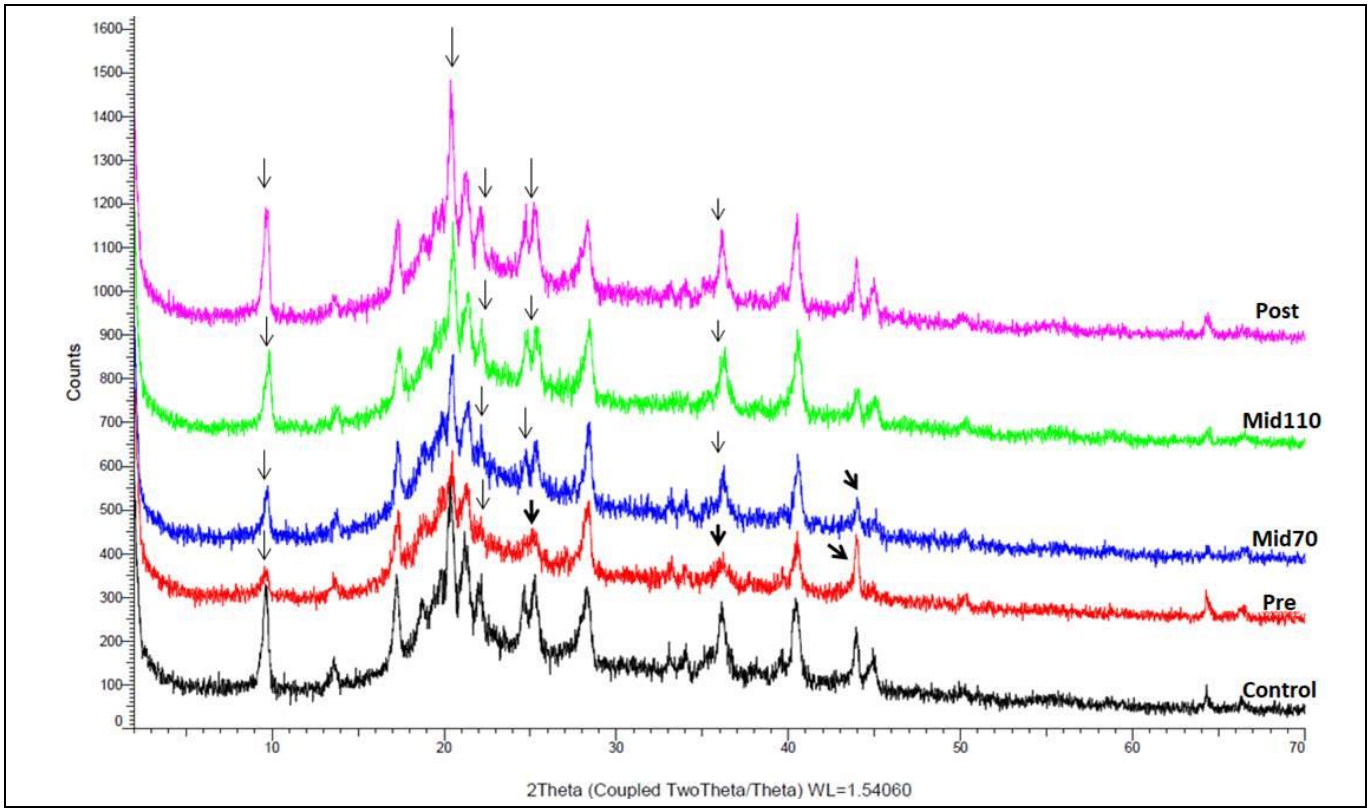

Figure 3. XRD spectrums of dried mushroom slices.

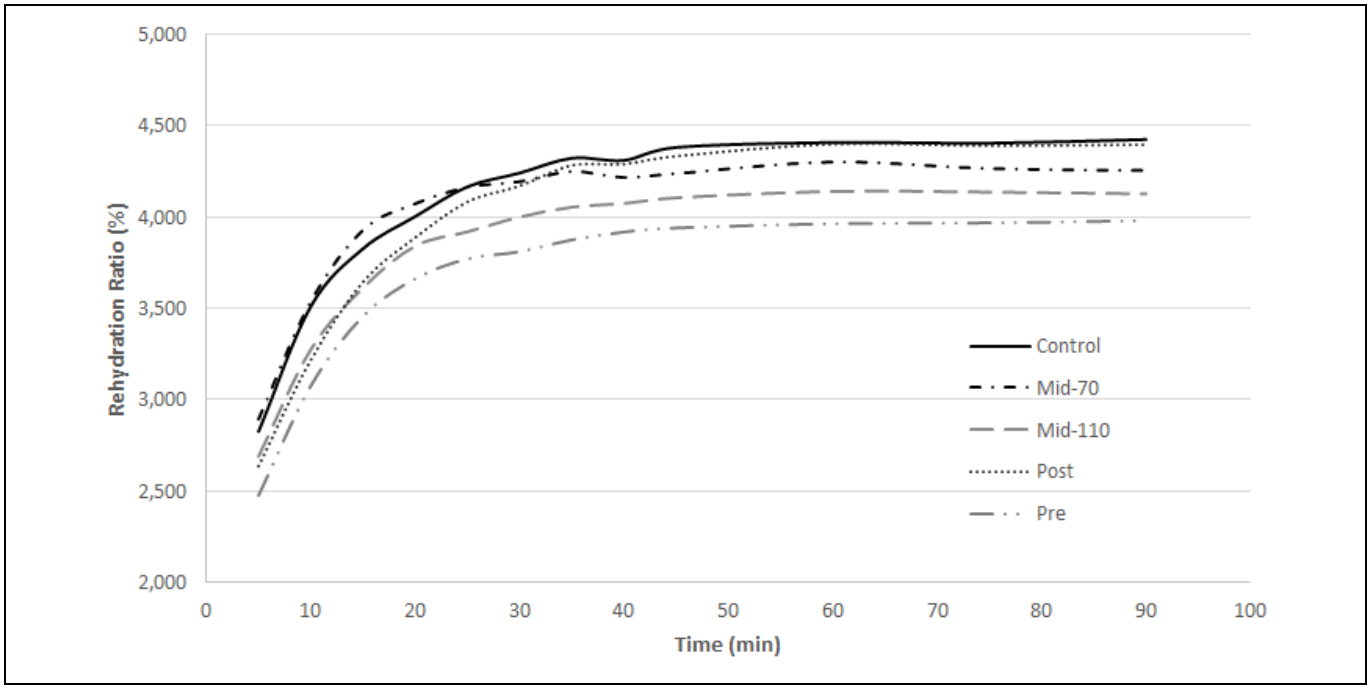

Figure 4. Rehydration ratio of dried mushroom samples.

This can be attributed to the shrunken structure of the surface of POST as seen in the SEM image (Figure 2) which made difficult the water absorption in the initial stage. The lowest rehydration ratio of PRE might be linked non-porous structure of the crust and the damage to the intercellular and capillary structure which caused to loss of water holding ability. Control and PRE had different rehydration ratio curves, although both had larger pore sizes compared to other mushroom slices, the turgor pressure loss and loss of cell integrity of those samples (as stated in SEM image in Figure 2 and XRD spectrum in Figure 3) due to exposing the higher temperature. Hence, the sudden change in mushroom temperature at the beginning of the drying process of PRE may not have allowed immersion of water as Control.

The beginning of rehydration of MID70 was similar to Control and differentiated and slowed down in the final stage. MID110 hydrated slower and the rehydration ratio was lower than Control. This might be interpreted as the internal structure of MID70 being more compact while the surface structure of MID70 is similar to the Control; MID110 was completely differentiated from Control.

3.2.3 Texture and color

The hardness of Control and HT-VT mushroom slices are depicted in Table 2. Statistically similar water activity values were obtained for all mushroom slices ($p>0.05$). The hardness of MID70 was the highest and that of PRE was the lowest. The differences in the hardness of mushroom slices were statistically different for MID70 compared to the control and other samples ($p<0.05$). Textural alteration forms by structural changes in the cell wall component of mushrooms. The lowest hardness of PRE may have been related to a decrease in turgor pressure and osmotic binding ability of cell walls due to the decomposition of fibrous material of tissue cells as stated in Qiu et al. [25]. The cell wall stabilization and hardening may have occurred due to HT-V application in the later stages of drying, causing to have the harder texture of Control, MID70, MID110, and POST.

The color parameters are depicted in Table 2 and the images of mushroom slices are shown in Figure 2. L^* and a^* values of PRE differed from the other HT-VT samples significantly ($p<0.05$) and the mean of L^* values was lower and that of a^* values was higher. Differences between b^* values of mushroom slices were statistically insignificant ($p>0.05$). The total color difference of Control was the lowest and statistically similar with MID110 and POST ($p>0.05$) and the highest ΔE was obtained PRE ($p<0.5$). The lighter color of control was possibly due to application of lower temperature during whole process as discussed in Siti-Nuramira et al. (26) for lighter color of air-cabinet dried mushroom. The higher the moisture content during the period of high-temperature application, the greater the darkening occurred in order of Pre>Mid70>Mid110>Post. In the images of mushroom slices, PRE and MID70 were darker than the others (Figure 2) and this is compatible with color parameter results. The free moisture content is directly related to the water activity and it is responsible for quality changes such as enzymatic, non-enzymatic activities, oxidation, and also microbial growth [27]. L^* values were related to enzymatic browning in general [28]. The more total color change and the higher L^* value of PRE may have been linked to more enzymatic browning reactions due to high moisture content during HT-VT. Non-enzymatic browning occurs at the later stages of drying and is slower than enzymatic browning [16]. That may have been the reason of the lighter color of mid and post-treated samples than pre-treated ones.

3.2.4 Total phenolic content and antioxidant activity

Total phenolic content (TPC) and antioxidant activity (AA) of mushroom slices are shown in Table 2. Mushrooms have secondary metabolites which are important for the human diet and phenolic compounds are one of the secondary metabolites and have antioxidant activity [1]. Control samples had the highest total phenolic content and antioxidant activity among all dried mushroom slices. Mirzaei-Baktash et al. [29] reported that hot air dried untreated mushroom samples had the highest TPC and AA values compared to pulsed electric field and ultrasound pre-treated counterparts. POST had the highest TPC and AA values among HT-V treated samples. The TPC of that was statistically comparable ($p>0.05$), while the antioxidant activity value of that was statistically different from Control ($p<0.05$). Pre HT-V treatment caused a decrease in TPC and AA, and those were statistically different from the other mushroom slices ($p<0.05$). The degradative enzymes such as polyphenol oxidase have the ability of phenolic compound degradation [28]. HT-V was practiced at high water activity content of mushroom slices during Pre HT-V treatment; this may have caused more activation of this enzyme and led to the lowest TPC due to the degradation of more phenolic compounds. Enzymes inactivated during HT-V application in the later stages of the drying process caused them to retain more phenolic compounds. Completion of enzyme inactivation may have led to more TPC and more AA of Control and POST.

4 Conclusions

In this study, the effect of the high temperature and vacuum application during the different periods of hot air drying was investigated in terms of drying characteristics, and physicochemical and microstructural properties of mushroom slices. Using HT-VT at the beginning of the drying process (PRE) led to enhance drying rates, but failed to obtain the desired final product quality. In the later intermediate (MID110) and at the final stages (POST), HT-VT had similar drying and physicochemical characteristics compared to control. The more enhancement of drying rate by HT-VT can be obtained after MID110 with several stages. This study revealed that the drying rate and physicochemical characteristics of mushrooms can be enhanced by the application of high temperatures with vacuum pulses in more than one period after the middle stages of drying. This output will be helpful for the practical application of pulsed vacuum drying to obtain better quality products with this process. In further studies, the optimization study will be conducted to understand the effect of different temperature degrees during atmospheric and vacuum pressure stages.

Table 2. The water activity, hardness, rehydration ratio, color parameters, TPC, and AA of dried mushroom slices (Same letters in horizontal lines of each measured parameter are statistically insignificant ($p>0.05$)).

	Control	PRE	MID70	MID110	POST
Water activity	0.359±0.025^{a}	0.335±0.064^{a}	0.330±0.047^{a}	0.373±0.005^{a}	0.315±0.031^{a}
Hardness (g)	1129.0±518.0^{a}	463.6±235.4^{b}	1408.0±525.0^{a}	972.0±408.0^{a}	1040.0±538.0^{a}
Rehydration Ratio	3.424±0.343^{a}	2.848±0.196^{b}	3.254±0.287^{a}	3.132±0.203^{ab}	3.396±0.070^{a}
L^*	65.80±4.25^{a}	48.63±6.06^{b}	58.83±3.29^{a}	60.33±2.62^{a}	63.71±6.07^{a}
a^*	2.42±0.91^{a}	5.20±0.28^{b}	3.96±0.48^{c}	3.68±0.36^{c}	3.42±0.55^{c}
b^*	14.99±1.09^{a}	16.07±3.51^{a}	17.44±1.19^{a}	16.11±1.41^{a}	16.33±1.00^{a}
ΔE	23.05±4.06^{a}	40.47±5.39^{b}	30.40±3.09^{c}	28.67±2.42^{ac}	25.41±5.75^{ac}
TPC (mg gallic acid/ g dried mushroom)	7.74±0.14^{a}	6.60±0.11^{b}	6.88±0.16^{c}	7.30±0.13^{d}	7.57±0.10^{a}
AA (% inhibition)	53.74±2.22^{a}	40.94±1.92^{b}	45.78±1.09^{c}	45.09±1.85^{c}	49.30±2.03^{d}

5 Acknowledgement

This work was supported by the Çankırı Karatekin University Project Administration Department (Project no: MF210621L07). X-Ray Diffraction (XRD) and Scanning Electron Microscopy (SEM) analyses were performed by in Afyon Kocatepe University, Technology Research and Application Center (TUAM).

6 Author contributions

Betül GÜVENKAYA in literature review, performing experiments and analyzes, collecting and processing data, assesment of obtained results; Sezin TUTA ŞİMŞEK in supervision of the experimental design, statistical analyzes, examination of the results, funding acquisition, writing and reviewing the manuscript; Seda ÖZGEN in conducting chemical analyzes, processing data, assesing and reviewing of results.

7 Ethics committee approval and conflict of interest

There is no need to obtain permission from the ethics committee for the article. We declare no conflict of interest.

8 References

[1] Cheung LM, Cheung PC, Ooi VE. "Antioxidant activity and total phenolics of edible mushroom extracts". *Food Chemistry*, 81(2), 249-255, 2003.

[2] Zhang KX, Pu YY, Sun DW. "Effective postharvest preservation methods for mushroom (*Agaricus Bisporus*): A Brief Review". *Biosystems and Food Engineering Research Review*, 22, 1-4, 2017.

[3] Peter M, Liu Z, Fang Y, Dou X, Awuah E, Soomro SA, Chen K. "Computational intelligence and mathematical modelling in chanterelle mushrooms' drying process under heat pump dryer". *Biosystems Engineering*, 212, 143-159, 2021.

[4] Zhang L, Zhang M, Mujumdar AS. "Development of flavor during drying and applications of edible mushrooms: A review". *Drying Technology*, 39(11), 1685-1703, 2021.

[5] Giri SK, Prasad S. "Drying kinetics and rehydration characteristics of microwave-vacuum and convective hot-air dried mushrooms". *Journal of Food Engineering*, 78(2), 512-521, 2007.

[6] Walde SG, Velu V, Jyothirmayi T, Math, RG. "Effects of pretreatments and drying methods on dehydration of mushroom". *Journal of Food Engineering*, 74(1), 108-115, 2006.

[7] Liu ZL, Xie L, Zielinska M, Pan Z, Wang J, Deng LZ, Wang H, Xiao HW. "Pulsed vacuum drying enhances drying of blueberry by altering micro, ultrastructure and water status and distribution". *LWT*, 142, 1-11, 2021.

[8] Wang J, Law CL, Nema PK, Zhao JH, Liu ZL, Deng LZ, Gao ZJ, Xiao HW. "Pulsed vacuum drying enhances drying kinetics and quality of lemon slices". *Journal of Food Engineering*, 224, 129-138, 2018.

[9] Xie Y, Gao Z, Liu Y, Xiao H. "Pulsed vacuum drying of rhizoma dioscoreae slices". *LWT*, 80, 237-249, 2017.

[10] Wang J, Mujumdar AS, Wang H, Fang XM, Xiao HW, Raghavan V. "Effect of drying method and cultivar on sensory attributes, textural profiles, and volatile characteristics of grape raisins". *Drying Technology*, 39(4), 495-506, 2021.

[11] Zhang W, Pan Z, Xiao H, Zheng Z, Chen C, Gao Z. "Pulsed vacuum drying (PVD) technology improves drying efficiency and quality of Poria cubes". *Drying Technology,* 36(8), 908-921, 2018.

[12] Zou K, Teng J, Huang L, Dai X, Wei B. "Effect of osmotic pretreatment on quality of mango chips by explosion puffing drying". *LWT*, 51(1), 253-259, 2013.

[13] Yi J, Zhou L, Bi J, Chen Q, Liu X, Wu X. "Influence of pre-drying treatments on physicochemical and organoleptic properties of explosion puff dried jackfruit chips". *Journal of Food Science and Technology*, 53(2), 1120-1129, 2016.

[14] Lin X, Xu JL, Sun DW. "Investigation of moisture content uniformity of microwave-vacuum dried mushroom (*Agaricus bisporus*) by NIR hyperspectral imaging". *LWT*, 109, 108-117, 2019.

[15] Li X, Zhang Y, Zhang Y, Liu Y, Gao Z, Zhu G, Mowafy S. "Relative humidity control during shiitake mushroom (*Lentinus edodes*) hot air drying based on appearance quality". *Journal of Food Engineering*, 315, 1-9, 2022.

[16] Xu L, Fang X, Wu W, Chen H, Mu H, Gao H. "Effects of high-temperature pre-drying on the quality of air-dried shiitake mushrooms (*Lentinula edodes*)". *Food Chemistry,* 285, 406-413, 2019.

[17] Thaipong K, Boonprakob U, Crosby K, Cisneros-Zevallos L, Byrne DH. "Comparison of ABTS, DPPH, FRAP, and ORAC assays for estimating antioxidant activity from guava fruit extracts". *Journal of Food Composition and Analysis*, 19(6-7), 669-675, 2006.

[18] Liu ZL, Xie L, Zielinska M, Pan Z, Deng LZ, Zhang JS, Xiao HW. "Improvement of drying efficiency and quality attributes of blueberries using innovative far-infrared radiation heating assisted pulsed vacuum drying (FIR-PVD)". *Innovative Food Science & Emerging Technologies*, 77, 1-11, 2022.

[19] Erbay Z, Icier F. "A review of thin layer drying of foods: theory, modeling, and experimental results". *Critical Reviews in Food Science and Nutrition,* 50(5), 441-464, 2010.

[20] Popescu ML, Costea T, Gird CE, Fierăscu I, Balaci TD, Fierăscu RC. "Antioxidant activity of romanian *Agaricus blazei Murrill* and *Agaricus bisporus* JE lange mushrooms". *Farmacia*, 65(3), 329-335, 2017.

[21] Kalač P. "A review of chemical composition and nutritional value of wild-growing and cultivated mushrooms". *Journal of the Science of Food and Agriculture*, 93(2), 209-218, 2013.

[22] Qiu Y, Bi J, Jin X, Wu X, Hu L, Chen L. "Investigation on the rehydration mechanism of freeze-dried and hot-air dried shiitake mushrooms from pores and cell wall fibrous material". *Food Chemistry*, 383, 1-9, 2022.

[23] Zhao Y, Bi J, Yi J, Njoroge DM, Peng J, Hou C. "Comparison of dynamic water distribution and microstructure formation of shiitake mushrooms during hot air and far infrared radiation drying by low-field nuclear magnetic resonance and scanning electron microscopy". *Journal of the Science of Food and Agriculture*, 99(6), 2826-2834, 2019.

[24] Cunningham SE, Mcminn WAM, Magee TRA, Richardson PS. "Experimental study of rehydration kinetics of potato cylinders". *Food and Bioproducts Processing*, 86(1), 15-24, 2008.

[25] Qiu Y, Bi J, Jin X, Hu L, Lyu J, Wu X. "An understanding of the changes in water holding capacity of rehydrated shiitake mushroom (*Lentinula edodes*) from cell wall, cell membrane and protein". *Food Chemistry,* 351, 1-9, 2021.

[26] Siti-Nuramira J, Farhana R, Nabil S, Jafari SM, Raseetha S. "Impact of drying methods on the quality of grey (*Pleurotus sajor caju*) and pink (*Pleurotus djamor*) oyster mushrooms". *Journal of Food Measurement and Characterization*, 16, 3331-3343, 2022.

[27] Zhang K, Pu YY, Sun DW. "Recent advances in quality preservation of postharvest mushrooms (*Agaricus bisporus*): A review". *Trends in Food Science & Technology,* 78, 72-82, 2018.

[28] Barimah J, Yanney P, Laryea D, Quarcoo C. "Effect of drying methods on phytochemicals, antioxidant activity and total phenolic content of dandelion leaves". *American Journal of Food and Nutrition*, 5(4), 136-141, 2017.

[29] Mirzaei-Baktash H, Hamdami N, Torabi P, Fallah-Joshaqani S, Dalvi-Isfahan M. "Impact of different pretreatments on drying kinetics and quality of button mushroom slices dried by hot-air or electrohydrodynamic drying". *LWT*, 155, 1-11, 2022.