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RESEARCH PAPER

Influence of Different Drying Techniques on Selected Physicochemical and Bioactive Properties of Mushroom Powders

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Abstract

In the present study, the effect of different drying techniques on the mushroom powders were comparatively investigated. Mushroom purees were dried by refractance window drying (RW), oven drying (OD), vacuum drying (VD) and freeze drying (FD) techniques both in their original form and as foams. For foam mat drying (FM) experiments the puree samples were foamed with carboxymethyl cellulose (CMC) and whey protein (WP) with the ratio (1:1) that formed the maximum stable foam. The dried mushrooms were ground to obtain mushroom powder. Some chemical and physical properties of the mushroom powders were determined. Total phenolics content (TPC) of the mushroom powders were determined in the ranges of 0.545-1.293 g GAE 100 g^{-1} dry matter (dm). The highest TPC was determined for the sample dried by VD while the lowest TPC was determined for the sample dried by FM-FD. The L*, chroma and hue angle values of the samples obtained from the FM experiments were higher than those obtained from the three different drying methods (OD, RW and VD) directly applied to the mushroom purees. It was determined that the browning index of the samples especially those subjected to FM was significantly lower than that of the other samples (OD, RW and VD). The study reveals that the FM method generally reduced the drying time in all drying techniques.

1. Introduction

Mushroom is a saprophyte macroscopic fungus from the primitive plant class that has been consumed as food since ancient times (Kotwaliwale et al., 2007). Cultivated *Agaricus bisporus* L. (white cap mushroom, button mushroom) is a round mushroom with a diameter of 5-10 cm with white or brownish caps. These mushrooms are preferred by the consumers and widely cultivated since they are rich in flavour compounds, nutrients, particularly protein and fibre (Kalac, 2013; Manzi et al., 2001; Pei et al., 2014; Zhang et al., 2001).

Mushrooms are highly perishable foods due to the absence of a protective cuticle, their high moisture content and their high respiratory rate. It is well known that the shelf life of fresh mushrooms in desirable quality is not more than a few days under room condition. After harvesting, colour, texture and odour changed rapidly, and the quality of the fresh mushroom began to deteriorate by the effect of enzyme activities such as protease and polyphenol oxidase (Celen et al., 2010; Giri and Prasad, 2007; Giri and Prasad, 2009; Pei et al., 2014).

Mushrooms are mostly sold as fresh in food markets, but they are also processed into different products such as canned, dried, frozen and pickled mushrooms in food industry. However, drying is the most commonly used process in the food industry because it is easy to apply and economical (Arıcı and Mengeş, 2012). High in protein, fibre, vitamins and bioactive constituents such as polysaccharides

and antioxidants, edible mushrooms are a valuable resource for the development of innovative food products. The addition of mushroom powder helps to improve texture, stability and nutritional quality, meeting the growing consumer demand for health-conscious and environmentally sustainable food options (De et al., 2025).

In the food industry, different types of drying processes have been used to dry of many fresh products as whole, sliced or pureed forms. Foam mat drying (FM) is a method in which the liquid forms of foods are converted into a stable foamy structure with various foaming agents and then the drying process is carried out. This method decreases the drying time and allows the food components to dry with less heat exposure. The first step of this process is stable foam formation. In the formation of this foam structure, gums, proteins and various emulsifiers are used as foaming agents. The main reason for the short drying time in the process of drying food in the form of foam is that the water evaporates quickly due to the large surface area of the foam created (Kadam and Balasubramanian, 2011; Sangamithra et al., 2015). Refractance window drying (RW) is a film drying technique used for liquid and semi-liquid food materials such as herbal extract, fruit and vegetable purees, etc. In comparison to most of the other drying techniques, it has several advantages such as short processing time, low energy input and high product quality. In this drying technique, heat is transferred from the water bath to the products by conduction and radiation. This results in less change in the colour, quality characteristics and nutritional value of dried products (Abonyi et al., 2002; Bardakçi and Karacabey, 2024; Nindo et al., 2004; Nindo et al., 2006; Nindo and Tang, 2007; Tontul and Topuz, 2017).

To our knowledge, only one study has reported the drying of *Pleurotus ostreatus* mushrooms using the RW technique (Timaná et al., 2024). However, to our best knowledge, there is no study on drying of mushroom (*Agaricus bisporus*) puree by RW and FM techniques to produce high quality mushroom powder. Therefore, this study aimed to determine the most appropriate drying technique for the mushroom purees obtained from small, deformed, irregularly shaped and broken mushrooms. The purees were dried using RW, oven drying (OD), vacuum drying (VD), and freeze drying (FD), through two different approaches: directly after preparation and in the form of a foamy structure. The products were compared on a number of quality characteristics related to mushroom powders.

2. Material and Methods

2.1. Materials

In the study, deformed mushroom (*Agaricus bisporus* L.) samples were obtained from a local producer in Antalya, Türkiye. The chemicals used in the analyses were purchased from either Sigma-Aldrich (Darmstadt, Germany) or Merck (Darmstadt, Germany). In addition, carboxymethyl cellulose and whey protein used for FM were purchased from local distributors.

2.2. Mushroom puree preparation

After washing with deionized water, the mushroom samples were blended for 3 min with a blender (Waring 51BL30 Laboratory blender, USA) until they were completely pureed. For FM experiments, the puree samples were foamed with carboxymethyl cellulose (CMC) and whey protein (WP) with the ratio (1:1) that formed the maximum stable foam determined by preliminary experiments. Preliminary tests showed that 1 g of CMC as a foaming agent and 1 g of WP powder (for 100 g of puree) provided the maximum stable foam structure. The mushroom puree was blended 3 min in a blender with CMC and WP in proportions determined by preliminary tests. For providing a spreadable structure, the puree samples were diluted with a certain amount of water that provided 6% final moisture content before blending. The mushroom purees were immediately dried using RW, OD, VD and FD methods, individually.

2.3. Drying of mushroom puree

The mushroom purees were dried with and without foam using RW, OD, VD and FD processes. The drying conditions were determined with some preliminary tests. In RW test, mushroom puree was spread as a thickness of 2 mm on the Mylar® plastic film in contact with circulating hot water maintained at 90°C. The drying unit was conditioned before the drying tests. The OD process was carried out in a tray dryer operated at 90°C air temperature and of 2 m s^{-1} air velocity. The mushroom purees were spread to a thickness of 2 mm on a glass plate (30×30 cm). The VD process was similarly carried out on the samples spread to a thickness of 2 mm on a 30×30 cm glass plate (30×30 cm) placed in a vacuum drying chamber operated at 60°C temperature and 0.001 mPa pressure.

For FD process, the mushroom purees were spread as a layer of 2 mm on steel trays and frozen at -80°C for 2 h in a freezer. The frozen samples were immediately placed in a freeze dryer (Operon FDU-7003, South Korea) operated at -70°C and 0.09-0.12 mm Hg absolute pressure. The drying treatments were maintained until the moisture content of the puree decreased below 8%. Drying times of mushroom purees detected in the experiments are given in Table 1. The dried samples were separately ground into a fine powder using a grinder (Sinbo SCM-2934) until they passed through a 35-mesh sieve. The obtained mushroom powders were stored in sealed glass jars at -18°C until the analyses.

Table 1. Drying times of the mushroom purees by different drying techniques.

Drying techniques	Time
Foam-mat-oven drying	75 min
Oven drying	94 min
Foam-mat refractance window drying	26 min
Refractance window drying	56 min
Foam-mat vacuum drying	120 min
Vacuum drying	180 min
Foam-mat freeze drying	48 h
Freeze drying	48 h

2.4. Mushroom powders analyses

2.4.1. Moisture content and water activity

The water activity of the samples was measured using a water activity meter (Aqualab 4TE: Decagon Devices, Pullman, WA) at 25°C. The moisture content was gravimetrically determined with a moisture analyzer (Kern DBS, Balingen, Germany) operated at 105°C until a constant weight.

2.4.2. Bulk and tapped density

To determine the bulk density (ρb) of the powders, 1 g of sample was weighed into a 25 mL graduated cylinder, and the volume was recorded. The tapped density (ρt) was calculated from also the weight/volume ratio, that 1 g of powder was transferred to 25 mL graduated cylinder, and then the graduated cylinder was tapped 30 times on a hard surface until there was no further change in volume (Beristain et al., 2001).

2.4.3. Color analysis

The colors of the mushroom powders were recorded using a chromameter (CR 400; Konica Minolta Corp., Tokyo, Japan) in terms of 'L*' (degree of lightness to darkness), 'a*' (degree of redness to green) and 'b*' (degree of yellow to blue). The hue angle° and chroma values were calculated using Equation 1 and 2, respectively.

$$\text{Hue angle}^\circ = \frac{180}{\pi} \times arctan\frac{b*}{a*} \quad (1)$$

$$\text{Chroma} = \sqrt{a*^2 + b*^2} \quad (2)$$

where a* and b* are Hunter a *and b* values of the samples, respectively.

2.4.4. Total phenolics content (TPC)

The phenolic compounds from the sample were extracted following the procedure outlined by Dincer et al. (2012). One gram of the sample was mixed with 100 mL of 80% aqueous methanol and homogenized using an Ultraturrax (T 25, IKA Labortechnik, Germany). The extraction was conducted in a water bath (GFL 1092, Germany) maintained at 50°C, with continuous shaking at 150 rpm for 2 hours. After extraction, the mixture was allowed to cool to room temperature and then filtered through Whatman No. 42 filter paper. Total phenolic content (TPC) was determined according to the Folin–Ciocalteu method as described by Škerget et al. (2005). For this analysis, 0.5 mL of the extract was combined with 2.5 mL of Folin–Ciocalteu reagent (0.2 N) and 2 mL of sodium carbonate solution (75 g L^{-1}). The mixture was incubated at 50°C for 5 minutes and then cooled. Absorbance was measured at 760 nm using a UV-Vis spectrophotometer (Shimadzu UV-160A, Japan), with 80% aqueous methanol serving as the blank. Results were expressed as milligrams of gallic acid equivalents (GAE) per gram of dry sample (mg GAE g^{-1} dm).

2.4.5. Radical scavenging activity

The 1,1-diphenyl-2-picryl hydrazil (DPPH) radical scavenging method, as outlined by Fernandez-Leon et al. (2013), was used to evaluate the antioxidant capacity of the mushroom powder. For this purpose, 1 g of the sample was extracted with 100 mL of 80% aqueous methanol. The extraction process was performed in a water bath (GFL 1092, Germany) at 50°C with shaking at 150 rpm for a duration of 2 hours. After extraction, the obtained solution was diluted 1:200 with methanol in a centrifuge tube. Then, 50 µL of the diluted extract was added to 950 µL of DPPH solution, and the mixture was incubated at room temperature in the dark for 30 minutes. Absorbance readings were taken at 517 nm using pure methanol as a blank. The antioxidant activity was calculated and expressed as grams of Trolox equivalent antioxidant activity per gram of dry sample (g TEAA g^{-1} dm).

2.4.6. Phenolic composition

The determination of phenolic compounds in the samples was conducted according to the method described by Dincer et al. (2012). For extract preparation, 0.5 g of the sample was added to 50 mL of 80% aqueous methanol. The extraction process was performed in a water bath (GFL 1092, Germany) at 50°C for 2 hours with constant shaking at 150 rpm. After extraction, the solution was cooled to room temperature, diluted with methanol to a final volume of 200 mL, and filtered through a 0.45 µm nylon membrane filter. Analysis of phenolic compounds was carried out using high-

performance liquid chromatography (HPLC) (Shimadzu LC20 AD, Japan), with an injection volume of 20 µL. Separation was achieved using an AQ 5 C18 column (250 mm×4 mm, 5 µm) maintained at 25°C. The mobile phase consisted of solvent A (0.1% acetic acid in water, v/v) and solvent B (acetonitrile, 100%), with a flow rate of 0.8 mL/min. The gradient elution profile was programmed as follows: 100:0 (A:B) at 0 min, 95:5 at 2 min, 60:40 at 20 min, 20:80 at 22 min, 95:5 at 30 min, and 100:0 at 33 min. Phenolic compounds were identified and quantified using both spiking and external standard calibration techniques. Gallic acid and catechin were detected at 280 nm, while chlorogenic acid, caffeic acid, p-coumaric acid, and ferulic acid were monitored at 320 nm. The results were expressed as milligrams of compound per 100 grams of dry sample (mg 100 g^{-1} dm).

2.4.7. Browning index

The mushroom powders were suspended in distilled water. Then, the suspensions were centrifuged at 10.000 × g for 10 min. A volume of 7 mL of the supernatant was mixed with 7 mL of aqueous methanol solution (95%) and the mixture was centrifuged under the same conditions for 10 min. The absorbance of the final supernatant was recorded at 420 nm (Gögüs et al., 2000).

2.4.8. Statistical analysis

The drying experiments and analyses were carried out in two replicates. The data were subjected to analysis of variance, and mean separation was performed according to the Duncan's multiple range test using SAS software (SAS Institute, Cary, NC, USA).

3. Results and Discussion

3.1. Moisture content and water activity

Moisture content and water activity of the mushroom powders produced by different dried methods are given in Table 2. The mushroom purees were dried with different drying techniques either as is (OD, RW, VD, and FD) or after foaming (FM-OD, FM-RW, FM-VD, FM-FD) until the final moisture content of 8%. The moisture contents of the mushroom powders were determined in the ranged of 5.62 g 100 g^{-1} to 8.4 g 100 g^{-1}. The water activity results of the mushroom powders produced by the drying techniques ranged between 0.18-0.24. Since food powders or additives are considered to be microbiologically and chemically stable with water activity and moisture content lower than 0.6 and 10 g 100 g^{-1} (Eroğlu et al., 2018), present results of water activity and moisture content of the mushroom powders are suitable for a stable product. Although every care was taken to produce mushroom powder with a target moisture content as close as possible to the drying methods used, inevitable variations occurred in the final moisture content due to the effects of temperature differences and environmental conditions until the product was removed from the dryer.

3.2. Bulk and tapped density

The bulk and tapped densities of the mushroom powders were measured in the ranges between 108.35-498.714 kg m^{-3} and 154.21-619.22 kg m^{-3}, respectively (Table 2). The densities are important parameters determining storage stability and flowing characteristics of powder products. The bulk and tapped densities of the RW-dried and oven dried mushroom powders were significantly ($p<0.05$) higher than the bulk and tapped densities of the other powders. On the contrary, the bulk and tapped densities of the mushroom powders produced from foam mat freeze-drying were determined in the lower ranges. In addition, it was determined that the bulk and tapped density values of the mushroom powders those subjected to FM was lower than that of the control samples (not foamed). The lower bulk density of freeze-dried mushroom powders is highly associated with big pore size of the particles evacuated by sublimation during the drying process (Koc et al., 2008).

3.3. Color analysis

The L*, a*, b*, hue angle and chroma values of the mushroom powder produced by the applied drying methods are given in Table 3.

Table 2.Some physicochemical properties of mushroom powders produced by different drying techniques.

Drying techniques	Moisture content (%)	Water activity	Bulk density (kg m^{-3})	Tapped density (kg m^{-3})
FM-OD	5.98±0.03^{cd}	0.19±0.01^{b}	383.92±0.20^{c}	463.30±2.91^{d}
OD	5.62±0.01^{d}	0.20±0.00^{b}	489.64±6.56^{a}	619.22±13.68^{a}
FM-RW	5.63±0.05^{d}	0.18±0.00^{b}	406.38±8.43^{c}	505.25±8.80^{c}
RW	6.73±0.02^{cd}	0.20±0.00^{b}	488.78±7.93^{a}	554.17±5.41^{b}
FM-VD	8.4±0.27^{a}	0.23±0.00^{a}	403.10±1.47^{c}	454.41±6.95^{d}
VD	6.95±0.03^{bc}	0.20±0.00^{b}	498.71±2.91^{b}	501.25±2.65^{c}
FM-FD	7.07±0.15^{bc}	0.24±0.00^{a}	108.35±4.99^{e}	154.21±5.67^{f}
FD	7.76±0.05^{ab}	0.24±0.00^{a}	135.23±0.80^{d}	220.74±7.09^{e}

The values are mean ± standard error. The values within a column with different superscript letters are significantly ($p<0.05$) different. Foam-mat hot air drying (FM-OD), Oven drying (OD),Foam-mat Refractance Window drying (FM-RW), Refractance Window drying (RW), Foam-mat vacuum drying (FM-VD), Vacuum drying (VD), Foam-mat freeze drying (FM-FD), Freeze drying (FD).

Table 3. Effect of different drying techniques on color of the mushroom powders.

Drying techniques	L*	a*	b*	Hue angle	Chroma
FM-OD	38.75±0.31^{de}	5.94±0.11^{a}	11.62±0.04^{ef}	62.92±0.34^{ef}	13.05±0.08^{cd}
OD	39.36±0.04^{cd}	6.04±0.09^{a}	12.49±0.13^{de}	64.20±0.09^{de}	14.88±0.86^{bc}
FM-RW	43.79±0.01^{b}	6.06±0.04^{a}	13.72±0.11^{c}	66.18±0.03^{b}	15.02±0.10^{bc}
RW	37.56±0.19^{ef}	5.77±0.29^{ab}	11.13±0.52^{f}	62.62±0.06^{f}	12.53±0.61^{d}
FM-VD	40.14±0.43^{c}	5.75±0.00^{ab}	12.84±0.25^{cd}	65.89±0.42^{bc}	14.07±0.23^{cd}
VD	36.75±0.19^{f}	5.67±0.01^{ab}	11.79±0.28^{de}	64.48±0.35^{cd}	13.68±0.54^{cd}
FM-FD	51.39±0.44^{a}	5.23±0.16^{b}	16.09±0.11^{b}	71.81±0.62^{a}	16.94±0.05^{b}
FD	50.29±0.11^{a}	6.23±0.04^{a}	18.04±0.08^{a}	70.79±0.04^{a}	19.10±0.08^{a}

The values are mean ± standard error. The values within a column with different superscript letters are significantly ($p < 0.05$) different. Foam-mat hot air drying (FM-OD), Oven drying (OD),Foam-mat Refractance Window drying (FM-RW), Refractance Window drying (RW), Foam-mat vacuum drying (FM-VD), Vacuum drying (VD), Foam-mat freeze drying (FM-FD), Freeze drying (FD).

Table 4. Effect of different drying techniques on Total phenolics content, radical scavenging activity and browning index of the mushroom powders.

Drying techniques	Total phenolics content (g GAE 100 g^{-1} dm)	Radical scavenging activity (g TEAA 100 g^{-1} dm)	Browning index
FM-OD	0.78±0.01^{d}	0.84±0.00^{c}	77.05±1.94^{c}
OD	1.02±0.03^{b}	1.08±0.00^{a}	109.50±3.89^{a}
FM-RW	0.69±0.03^{e}	0.56±0.03^{e}	45.20±1.27^{e}
RW	0.70±0.01^{e}	0.92±0.01^{b}	73.30±0.28^{cd}
FM-VD	0.89±0.00^{c}	0.77±0.01^{d}	65.35±0.04^{d}
VD	1.29±0.01^{a}	1.06±0.03^{a}	90.60±0.14^{b}
FM-FD	0.55±0.02^{f}	0.62±0.01^{e}	43.65±0.11^{e}
FD	0.64±0.00^{e}	0.75±0.00^{d}	44.89±4.21^{e}

The values are mean ± standard error. The values within a column with different superscript letters are significantly ($p < 0.05$) different. Foam-mat hot air drying (FM-OD), Oven drying (OD),Foam-mat Refractance Window drying (FM-RW), Refractance Window drying (RW), Foam-mat vacuum drying (FM-VD), Vacuum drying (VD), Foam-mat freeze drying (FM-FD), Freeze drying (FD).

The mushroom powders obtained by the FM-FD and FD techniques had the highest L* and Hue angle values with no significant difference ($p > 0.05$) between each other's. The lowest Hue angle and chroma values among the samples were determined in the mushroom obtained by RW. In addition, the highest chroma value among the samples were determine in the mushroom obtained by the FD. In general, the L*, hue angle and chroma values of the samples obtained from the FD treatments were significantly higher than those obtained from the four different drying methods (OD, RW, VD and FD) applied directly to the purees. The reason for these colour differences can be associated with the shorter drying time of the FM process and/or the effect of the foaming agents used. The color results are mostly in agreement with a few previous studies performed on mushrooms similar in nature (Isik and Izlin, 2014; Lee et al., 2007; Qi et al., 2014).

3.4. Total phenolics content

Total phenolics content of the mushroom powder obtained from the drying methods are given in Table 4. The TPC of the mushroom powders were determined in the ranges of 0.55-1.29 g GAE 100 g^{-1} dm, the difference in the TPC results are significantly ($p<0.05$) different from each other. The highest TPC were determined for the sample dried by VD while the lowest TPC was determined for the sample dried by FD. The TPC content of the mushroom powders has been interpreted as highly associated with the drying temperature and time. Indeed, the highest drying temperature and the longest drying time in the drying experiments resulted in more or less high content of TPC, as determined in several previous studies of a similar nature. (Papagiannopoulos et al., 2004; Soontharapirakkul and Kotpat, 2023). Yim et al. (2010) reported TPC of mushroom (*Pleurotus ostreatus*) extract was determined as 798.55 mg GAE 100 g^{-1}. Another study on drying of *P. ostreatus* mushrooms reported that TPC of the mushroom dried by forced air OD, FD and RW changed between 4.62 and 6.82 mg GAE g^{-1} (Timaná et al., 2024). Total phenolics content of the mushrooms dried by freeze and cabinet drying was determined to range between 17.06 and 20.30 mg GAE g^{-1} as well (Shams et al., 2022). The TPC results of a study were found to be between 1.6 and 3.2 mg GAE 100 g^{-1} dm. The results of the current study is generally in agreement with the reviewed results for the mushrooms dried by different drying methods (Tepsongkroh et al., 2019).

3.5. Radical scavenging activity

The radical scavenging activity of the mushroom powders produced by the drying techniques was determined in the ranges of 0.56-1.08 g TEAA 100 g^{-1} dm. The difference in the radical scavenging activity of the samples was significant ($p < 0.05$) (Table 4). The highest radical scavenging activity was determined for the sample dried by OD while the lowest radical scavenging activity was determined for the sample dried by FM-RW. These results are consistent with the findings

Table 5. Phenolic composition of the mushroom powders dried by different drying techniques (mg 100 g^{-1} dm).

Drying techniques	Gallic acid	Catechin	Ferulic acid	ρ-coumaric acid	Caffeic acid	Chlorogenic acid
FM-OD	31.98 ± 0.58^{d}	0.29±0.01^{c}	1.78±0.11^{bc}	0.01±0.00	0.02±0.00	0.09±0.00^{cd}
OD	51.94 ± 0.07^{b}	0.50±0.00^{a}	1.45±0.06^{de}	0.01±0.00	0.02±0.00	0.25±0.01^{a}
FM-RW	25.66±0.44^{e}	0.18±0.01^{d}	1.35±0.02^{de}	n.d	0.01±0.00	0.04±0.00^{e}
RW	40.12±0.09^{c}	0.30±0.01^{b}	1.20±0.02^{e}	n.d	0.01±0.00	0.09±0.00^{cd}
FM-VD	39.11±1.21^{c}	0.14±0.00^{e}	1.82±0.00^{bc}	0.01±0.00	0.02±0.00	0.12±0.01^{c}
VD	58.57±1.27^{a}	0.31±0.00^{b}	4.26±0.06^{a}	0.02±0.00	0.02±0.00	0.17±0.00^{b}
FM-FD	17.77±0.10^{f}	0.21±0.01^{c}	1.57±0.09^{cd}	0.03±0.00	0.01±0.00	0.03±0.00^{e}
FD	15.44±0.18^{f}	0.25±0.00^{c}	1.93±0.03^{b}	0.01±0.00	0.01±0.00	0.07±0.00^{de}

The values are mean ± standard error. The values within a column with different superscript letters are significantly ($p < 0.05$) different. Foam-mat hot air drying (FM-OD), Oven drying (OD), Foam-mat Refractance Window drying (FM-RW), Refractance Window drying (RW), Foam-mat vacuum drying (FM-VD), Vacuum drying (VD), Foam-mat freeze drying (FM-FD), Freeze drying (FD).

of an earlier study (Tepsongkroh et al., 2019). The high radical scavenging activity of the mushroom powder dried by VD can be associated with high concentration of phenolic compounds. It is also related to be amount of brown pigments, low L* values, and melonoidins, which is formed from carbonyl and amine reaction and reported to be responsible for high antioxidant activity (Madrau et al., 2009; Tepsongkroh et al., 2019). The phenolic content of mushroom powders dried by the vacuum drying method was determined to be high and it is expected that these samples have higher antioxidant activity. In addition, the browning index of these samples is also high. It is known that antioxidants are formed as a result of non-enzymatic browning reactions (Quintero Ruiz et al., 2014).

3.6. Browning index

Browning index values of the mushroom powder obtained by the different drying methods are given in Table 4. The results, determined in the ranges of 43.65-109.50, showed a significant difference ($p < 0.05$) between each other. These results are generally in agreement with the findings of a previous study (Timaná et al., 2024). For instance, browning index of mushroom powders was determined between 13.34-69.50 (Zhang et al., 2021). In another study performed with different mushrooms dried by microwave, cabinet and vacuum drying reported that browning index values varied between 29.252 and 84.348 (Siti-Nuramira et al., 2022). The reason for the differences in browning index values between these studies and the current study is the difference in dried mushroom type and drying method. It was determined that the highest browning index belonged to the powders obtained by oven drying method. The differences in the browning index can be related to depending on the drying time and temperature. However, in RW, which is carried out at the same temperature and in a shorter time than OD, the browning index was found to be much lower due to the high drying speed and the short completion time of the process. The lowest browning index was determined in samples obtained by FD, which is not a thermal process. It was determined that the browning index of the mushroom powders, especially those subjected to FM was significantly lower than that of the control samples. It is known that non-enzymatic browning reactions occur through the sugar-amine reaction under the influence of heat. The browning index data obtained increased with high temperatures and long processing times in parallel with this information. The browning index values determined can be explained mostly by non-enzymatic browning reactions (Cernîşev, 2010).

3.7. Phenolic composition

The results of identified phenolic compounds (gallic acid, catechin, ferulic acid, ρ-coumaric acid, caffeic acid, and chlorogenic acid) of the mushroom powders obtained by different drying methods are given in Table 5. Concentration of the individual phenolic compounds in the samples were calculated as mg 100 g^{-1} dm using their calibration curves prepared with standards solutions at different concentrations. The gallic acid, catechin, ferulic acid, ρ-coumaric acid, caffeic acid, and chlorogenic acid of the mushroom powders were determined in the ranges of 15.44-58.57, 0.14-0.50, 1.20-4.26, 0.01-0.03, 0.01-0.02 and 0.03-0.25 mg 100 g^{-1} dm, respectively. Results reflected that the principle phenolic compounds, such as gallic acid, ferulic acid and catechin, were determined to be the highest amount in the samples dried by VD. This can also be associated with combination of the higher drying temperature and longer drying time.The results are generally consistent with the phenolic compounds found in several previous studies conducted on different mushroom species (Palacios et al., 2011). The gallic acid and ferulic acid were determined in the highest amount in the samples dried by VD, while catechin and chlorogenic acid amounts were determined in samples dried by OD, p-coumaric acid was determined in samples dried by FM-FD, and caffeic acid was determined in samples dried by VD and FM-VD.

4. Conclusion

In this study, mushroom purees were dried using the refractance window drying and foam mat refractance window drying for the first time. In order to increase the stability of the bioactive compounds of the mushrooms and to prolong the shelf life of the product, the mushroom purees were comparatively dried by different drying techniques, such as oven drying, vacuum drying and freeze drying, both in the form of foam and directly as is in the form of puree. Various quality characteristics of the dried mushroom powders were tested. The obtained results showed that FD techniques had superior physical characteristics whereas the dried mushroom obtained by RW and VD drying techniques had marked phenolic content thereby higher antiradical scavenging activities. It was specifically found that the colour properties of the products obtained by the FM-RW and FM-FD method gave the best results, and the browning index gave the lowest results. Considering the shortest drying time of FM-RW process which also provides some superior colour and other quality properties in the dried mushroom powders, it can be selected as more practical, preferable and sustainable method. The mushroom powders can be preferably used in a variety of food formulations including soups, sauces, snacks, seasoning blends, and functional foods. Additionally, the high retention of bioactive compounds and improved shelf stability make these powders suitable for nutraceutical products, dietary supplements, and health-oriented food innovations. Overall, the study provides a foundation for the development of energy-efficient and quality-preserving drying processes that can be readily integrated into industrial-scale production.

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