Effect of different drying methods on drying characteristics, colour and microstructure properties of mushroom

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Summary

In this study, the effects of microwave, convective and microwave-convective drying treatments on the drying parameters, colour and microstructure properties of mushroom samples were investigated. To select the best thin-layer drying models for the drying treatments, 9 mathematical models were fitted to the experimental data. Based on evaluation by statistical tests, the MIDILLI et al. model, the Diffusion Approach model, Logarithmic model, and WANG and SINGH model were found to be the best-fitting models to describe the drying behaviour of the mushroom samples. The shortest drying time was provided with microwave method at 500 W (35 min). However, the drying time was significantly reduced by combining microwave treatment with conventional drying. The drying time at microwave-convective power combination level of 90 W – 50 °C was by 33.8% shorter than drying by only microwave at a power of 90 W, and by 52.9% shorter than the drying by only convective treatment at a temperature of 50 °C. The colour values of the samples dried at 50 °C were closest to the fresh samples for all drying conditions. Scanning electron microscopy images revealed that a higher temperature or microwave power caused greater damage to the microstructure of the mushroom samples.

Keywords

microwave drying; thin layer; mushroom; colour; microstructure

Mushroom (*Agaricus bisporus*), which is consumed in many countries, is a popular and delicious product with high protein, vitamin, fibre, saccharide and mineral contents, while being and almost free of fat [1, 2]. It is also suitable for consumption by patients with diabetes or cardiac diseases, and offers various valuable biological effects, including antitumor, anti-aromatase, antimicrobial, immuno-modulatory, anti-inflammatory and antioxidant activities [3, 4]. Of all mushrooms produced around the world, 40–50% is consumed as fresh. After being harvested, mushrooms can be stored only for 1–7 days because of their high moisture (approximately 90%) and enzyme content [5, 6]. Furthermore, rapid loss of quality is observed throughout the storage process. Enzymatic browning, dehydration and reduction in protein and glucose contents are among the primary problems encountered, restricting consumption of fresh edible mushrooms [7, 8]. Due to these reasons, mushrooms are generally processed and canned, or offered for consumption in frozen or dried forms. The drying method is relatively more economical compared to other preservation methods, enabling the storage of dried mushrooms in airtight packages for more than 1 year [9]. Dried mushrooms can be used as a raw material for the instant soup and pizza industries, or as an auxiliary material for various sauce products and baby formulas, or processed to mushroom flour [10].

Various methods can be used to dry fruits and vegetables. Convective drying is the most commonly used method in the food industry because of the low costs of initial investment and of the operation, and because of the ease of controlling the process [11, 12]. However, the method damages both nutrition quality and texture, requires a long period of drying that causes discolouration, and has to be run under comparatively high temperatures [13]. On the other hand, the microwave drying method offers several advantages, such as high thermal conductivity to the interior of the material, short drying period and low energy consumption [14, 15], while it also has other shortcomings

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like irregular heating, possible textural damage and high investment costs [16, 17]. In recent years, combined microwave-convection systems have been utilized so that the problems to be dealt with are reduced in number, heat-sensitive products can be dried more easily and positive aspects of both methods are utilized in order to achieve good product quality and customer satisfaction [18].

The objective of this study was to determine the drying characteristics of mushroom samples dried using different drying methods, to select the most suitable of the thin-layer drying models, to investigate the colour differences between the fresh and dried products, and to analyse the effects of drying treatments on mushroom microstructure using scanning electron microscopy.

MATERIALS AND METHODS

Drying instruments and drying process

The fresh mushroom samples used in the tests were bought from a local market in Bursa, Turkey, and stored at a temperature of (4 ± 0.5) °C until completion of the experiments [19]. Prior to the drying processes, the mushroom samples were first sliced into cubes (0.7 cm^3) using a dicer (Börner, Wingene, Belgium) and dried in this form [20]. The initial moisture content of the samples was determined to be 9.10 $g\cdot g^{-1}$ (grams of water per gram of dry matter) on a dry basis (d.b.) by oven (ED115 Binder, Tuttlingen, Germany) drying at 105 °C for 24 h [21].

The drying experiments were performed using a microwave-convective oven (AMW 545, Whirlpool, Comerio, Italy) with the technical specifications of ~230 V, 50 Hz and 2800 W. A schematic diagram of the experimental microwave-convective drying system is shown in Fig. 1. Convective (50 °C and 75 °C), microwave (90 W, 160 W, 350 W and 500 W) and combined microwave-convective (90 W – 50 °C, 90 W – 75 °C, 160 W – 50 °C and 160 W – 75 °C) drying methods were conducted during the experiments. During the convective and combined microwave-convective drying experiments, the air velocity was 1 $m\cdot s^{-1}$. In the experiments, 200 g of samples [18] were placed inside the oven in the form of thin layers on a rotating glass plate with a diameter of 400 mm and dried. Moisture loss of the samples was recorded at 5 min intervals using a digital balance (Baster, Istanbul, Turkey) with 0.01 g precision; the balance was placed under the oven [19]. All drying processes were repeated 3 times and continued until the moisture content of the samples dropped down to 0.11 $g\cdot g^{-1}$ d.b.

Mathematical modeling of drying data

The moisture loss data were fitted to 9 mathematical models generally used for modeling of drying curves (Tab. 1). The moisture ratio (*MR*) and drying rates of mushroom samples during the drying experiments were calculated using the following equations [31, 32]:

$$MR = \frac{M_t - M_e}{M_0 - M_e} \quad (1)$$

where M_t is the moisture content at a specific time, M_0 is the initial moisture content, M_e is the equilibrium moisture content (expressed as grams of water per gram of dry matter). The values of M_e are relatively small compared with M_t or M_0. Therefore, the moisture ratio was simplified as [33]:

$$MR = \frac{M_t}{M_0} \quad (2)$$

Colour measurement

To measure colour values of fresh and dried products, a colorimeter MSEZ-4500L (HunterLab, Reston, Virginia, USA) was used. The L^* value was read between 0 and 100, where 0 corresponded to blackness and 100 to whiteness. Obviously, as the value went down, brightness decreased. The a^* value changed from (–) to (+), where (–) corresponded to green colour and (+) to red. In the case of the b^* value, (–) expresses blueness and (+) yellowness [34]. Colour mea-

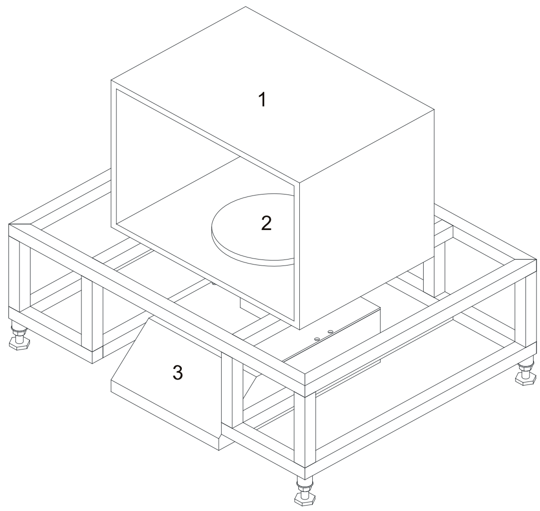

Fig. 1. Schematic diagram of experimental microwave-convective drying system.

1 – microwave-convective drying chamber, 2 – rotating glass tray, 3 – balance.

Tab. 1. Thin-layer mathematical drying models applied to the drying curves of mushroom samples.

No	Model name	Model	References
1	Henderson and Pabis	$MR = a \exp(-kt)$	Westerman et al. [22]
2	Newton	$MR = \exp(-kt)$	Ayensu [23]
3	Page	$MR = \exp(-kt^n)$	Gupta et al. [24]
4	Logarithmic	$MR = a \exp(-kt) + c$	Togrul and Pehlivan [25]
5	Two Term	$MR = a \exp(-k_0t) + b \exp(-k_1t)$	Madamba et al. [26]
6	Two Term Exponential	$MR = a \exp(-kt) + (1 - a) \exp(-kat)$	Sharaf-Eldeen et al. [27]
7	Wang and Singh	$MR = 1 + at + bt^2$	Wang and Singh [28]
8	Diffusion Aapproach	$MR = a \exp(-kt) + (1 - a) \exp(-kbt)$	Yaldiz and Ertekin [29]
9	Midilli et al.	$MR = a \exp(-kt^n) + bt$	Midilli et al. [30]

MR – moisture ratio; *t* – time; *n* – number of constants; *a, b, c, k*, k_0, k_1 – model coefficients.

surements were conducted after the instrument had been calibrated in the illumination mode in line with the Stewart reflector plate [35]. Values were read from the exterior surfaces of the samples, measurements were repeated 3 times and mean values were calculated [36]. As the measured L^*, a^* and b^* values did not represent the colour conceptions of consumers, they were used to calculate the chroma (*C*) and hue angle (α) values, which pertain to the colour perception of consumers [37]. The *C* value, which covered redness and yellowness together and was described as the metric colour chroma, indicated colour saturation. It was high for vibrant colours and low for dull ones. The value α, which was a scale for colour tones, was described as a circle of colour where red, yellow, green and blue corresponded to the following angles, respectively: 0°, 90°, 180° and 270° [38]. As α was the expression of a^* and b^* in the form of an angle, it was reported that the best indication of a^* and b^* can be obtained through α [39]. Equations used to calculate *C* and α values are given as [40]:

$$C = \sqrt{(a^*)^2 + (b^*)^2} \tag{3}$$

$$\alpha = \tan^{-1}\left(\frac{b^*}{a^*}\right) \tag{4}$$

Microstructure analysis

A scanning electron microscope EVO 40 (Carl Zeiss, Oberkochen, Germany) was used to observe the effect of different drying methods on microstructure of mushroom samples. Particles extracted from the dried samples were vertically cut along the center of the pith and placed in the aluminium discs [41]. The samples were then coated with gold-palladium at a thickness of 40–50 nm under low vacuum (20 kV) using a coating device (SCD-005, Baltec, Wetzlar, Germany), and then microphotographs were taken [19].

Statistical analysis

The research was conducted using a randomized plots factorial experimental design. The results were analysed using MATLAB (MathWorks, Natick, Massachusetts, USA) and MINITAB (version 14; University of Texas, Austin, Texas, USA) programmes. Mean differences were tested for significance with a least significant difference (LSD) test at a 1% level of significance. In order to statistically find out the best model, the lowest reduced chi-squared (χ^2) and root mean square error (*RMSE*) values, and the highest coefficient of determination R^2 were selected [10, 42]. These statistical values are defined as follows:

$$\chi^2 = \frac{\sum_{i=1}^{N}\left(MR_{exp,i} - MR_{pre,i}\right)^2}{N - n} \tag{5}$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}\left(MR_{pre,i} - MR_{exp,i}\right)}{N}} \tag{6}$$

where $MR_{\mathrm{exp,i}}$ stands for the experimental moisture ratio in the test with number *i*, $MR_{\mathrm{pre,i}}$ stands for the estimated moisture ratio in the test with number *i*, N stands for the observation number, and *n* is the number of constants.

RESULTS AND DISCUSSION

Drying kinetics of dried mushrooms

Fig. 2 shows the moisture content versus drying time curves of mushroom samples under all drying conditions. As expected, increase in the temperature and microwave power level caused a significant decrease in the drying time (Fig. 2A–C). These results are similar to those reported by NAIK et al. [5], ARUMUGANATHAN et al. [10] and LEE and LEE [43] for the convective drying of mushroom, and by GIRI and PRASAD [19] for the microwave drying of mushroom samples. The experimental results indicated that the total drying time required to reach the final moisture content ranged from 160 min to 520 min for convective (50 °C and 75 °C), 35 min to 370 min for microwave (90, 160, 350 and 500 W), and 75 min to 245 min for microwave-convective drying (90 W – 50 °C, 90 W – 75 °C, 160 W – 50 °C

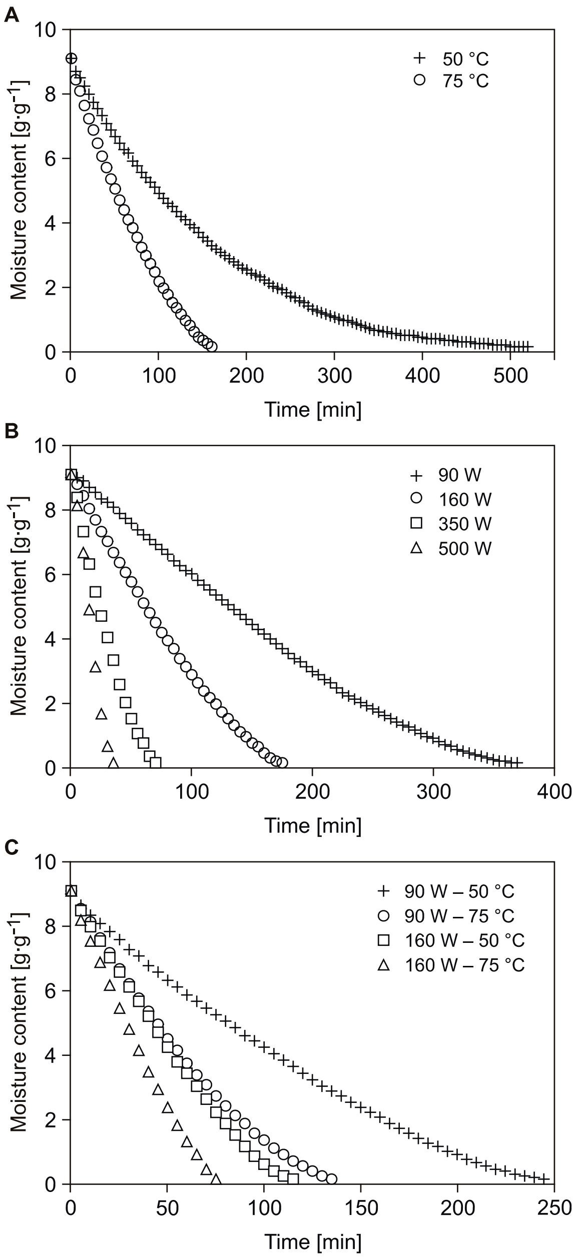

Fig. 2. Drying curves of mushroom samples at different conditions.

A – drying at different convective temperatures, B – drying at different microwave power levels, C – drying at different microwave-convective combinations.
Moisture content is expressed in grams of water per gram of dry matter.

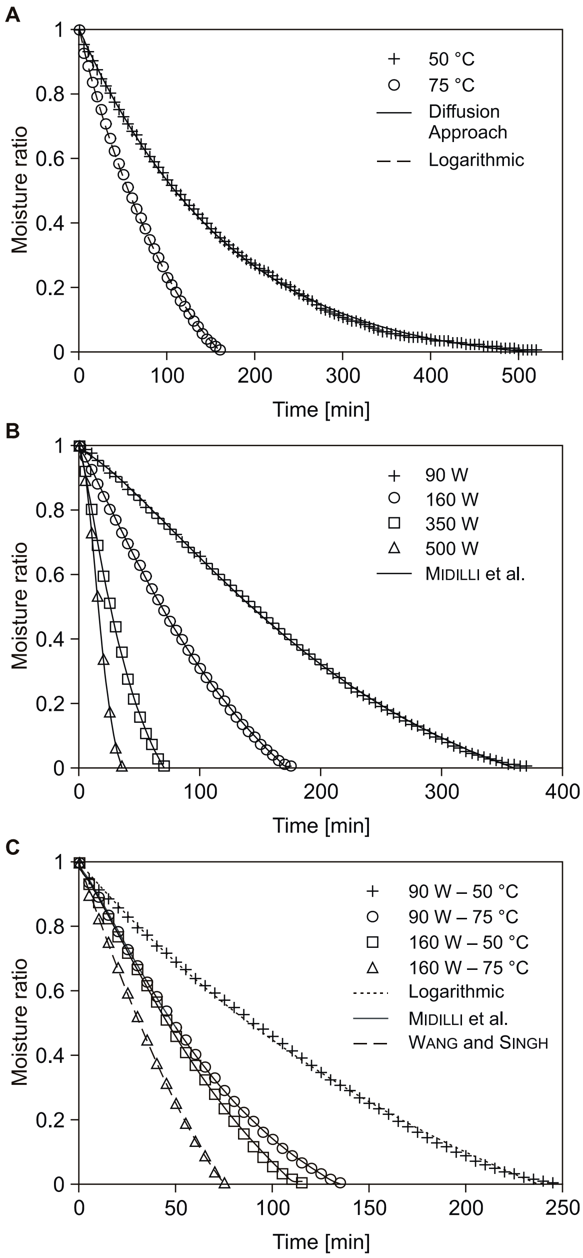

Fig. 3. A comparison of the experimental and theoretical moisture ratios predicted by the different models at specific drying times under selected drying conditions.

A – convective drying, B – microwave drying, C – microwave-convective combinations of drying.

Tab. 2. Estimated values of coefficients and statistical analyses obtained from various thin layer drying models for drying of mushroom samples at different temperatures.

No	50 °C				75 °C			
	Model coefficients	R^2	*RMSE*	χ^2	Model coefficients	R^2	*RMSE*	χ^2
1	$a = 1.034$ $k = 0.00699$	0.9941	0.0214	4.5108×10^{-4}	$a = 1.063$ $k = 0.01503$	0.9749	0.0474	23.9687×10^{-4}
2	$k = 0.00677$	0.9930	0.0232	5.2872×10^{-4}	$k = 0.01411$	0.9703	0.0515	28.1109×10^{-4}
3	$k = 0.003498$ $n = 1.127$	0.9976	0.0136	1.8323×10^{-4}	$k = 0.003896$ $n = 1.295$	0.9909	0.0285	8.7259×10^{-4}
4	$a = 1.062$ $k = 0.005912$ $c = -0.05937$	0.9989	0.0092	0.7833×10^{-4}	$a = 1.418$ $k = 0.007618$ $c = -0.4236$	0.9996	0.0057	0.2385×10^{-4}
5	$a = 20.79$ $k_0 = 0.006088$ $b = -19.81$ $k_1 = 0.006058$	0.9922	0.0245	5.8824×10^{-4}	$a = 21.91$ $k_0 = 0.003396$ $b = -20.97$ $k_1 = 0.003117$	0.9958	0.0194	3.6379×10^{-4}
6	$a = 1.621$ $k = 0.008538$	0.9979	0.0127	1.5895×10^{-4}	$a = 1.809$ $k = 0.02004$	0.9895	0.0306	10.1291×10^{-4}
7	$a = -0.004761$ $b = 0.00000572$	0.9885	0.0298	8.9853×10^{-4}	$a = -0.01024$ $b = 0.00002538$	0.9993	0.0081	0.6471×10^{-4}
8	$a = 3.126$ $k = 0.004516$ $b = 0.8327$	0.9993	0.0075	0.5076×10^{-4}	$a = 2.942$ $k = 0.00583$ $b = 0.5537$	0.9996	0.0060	0.3743×10^{-4}
9	$a = 0.9728$ $k = 0.003424$ $n = 1.117$ $b = -0.00005281$	0.9993	0.0076	0.5321×10^{-4}	$a = 0.9888$ $k = 0.008069$ $n = 1.051$ $b = -0.001191$	0.9996	0.0062	0.3972×10^{-4}

and 160 W – 75 °C). The longest and the shortest drying time were obtained at 500 W and 50 °C, respectively. It was found that mushroom samples dried at 90 W – 50 °C required by 33.8% less time than the microwave drying at 90 W, and by 52.9% less time than the convective drying at 50 °C. Similarly, the drying time was markedly reduced with all microwave-convective combination levels compared to the microwave or convective drying treatment alone. FUNEBO and OHLSSON [44] and ORSAT et al. [45] reported that the combined microwave-convective drying method ensured significant reductions in drying time for mushroom samples. WORKNEH et al. [46] found that combined microwave/hot air drying resulted reduced the drying time by 84% in comparison to conventional hot-air drying. Similar results were reported by various authors for drying of fruits and vegetables using microwave-convective techniques [47–49].

Fitting of drying curves

The results of the statistical analyses of the different models, including drying model coefficients and the comparison criteria used to evaluate the fitting quality, R^2, *RMSE* and χ^2, are presented in Tab. 2–4. The values of R^2, *RMSE* and χ^2 for all models ranged from 0.9097 to 0.9996, from 0.0057 to 0.1144, and from 0.2385×10^{-4} to 133.3442×10^{-4}, respectively. The models with same R^2 values were compared on the basis of *RMSE* and χ^2 parameters. Based on the statistical values, it was found that the drying characteristics of mushroom were best described by MIDILLI et al. model [30] (90, 160, 350, 500 W, 90 W – 75 °C and 160 W – 50 °C), Diffusion Approach model [29] (50 °C), Logarithmic model [25] (75 °C and 90 W – 50 °C), and by WANG and SINGH model [28] (160 W – 75 °C). GHADERI et al. [42] and ARTNASEAW et al. [50] reported that drying characteristics of mushroom were best described by MIDILLI et al. model [30]. On the other hand, XANTHOPOULOS et al. [51] found that the Logarithmic model [24] showed the best fit to experimental drying data of mushrooms. Diffusion Approach [29] and WANG and SINGH [28] models were also suggested by SACILIK et al. [52] and FARHANG et al. [53] to describe drying behaviour of different food products. Fig. 3 presents plots of the experimental moisture ratio values and those predicted by the most suitable models with drying at selected tem-

Tab. 3. Estimated values of coefficients and statistical analyses obtained from various thin layer drying models for drying of mushroom samples at different microwave powers.

No	90 W				160 W			
	Model coefficients	R^2	*RMSE*	χ^2	Model coefficients	R^2	*RMSE*	χ^2
1	$a = 1.129$ $k = 0.006533$	0.9617	0.0613	38.0012×10^{-4}	$a = 1.099$ $k = 0.01318$	0.9638	0.0588	34.2114×10^{-4}
2	$k = 0.005769$	0.9427	0.0750	56.3161×10^{-4}	$k = 0.01194$	0.9520	0.0678	45.4726×10^{-4}
3	$k = 0.0003664$ $n = 1.528$	0.9940	0.0242	5.9882×10^{-4}	$k = 0.001632$ $n = 1.443$	0.9911	0.0292	8.1545×10^{-4}
4	$a = 1.701$ $k = 0.002685$ $c = -0.6628$	0.9979	0.0144	2.0708×10^{-4}	$a = 1.732$ $k = 0.005183$ $c = -0.7171$	0.9992	0.0087	0.5827×10^{-4}
5	$a = 80.34$ $k_0 = 0.003755$ $b = -79.39$ $k_1 = 0.003736$	0.9327	0.0813	65.9209×10^{-4}	$a = 31.08$ $k_0 = 0.001532$ $b = -30.13$ $k_1 = 0.001346$	0.9933	0.0253	6.2336×10^{-4}
6	$a = 1.986$ $k = 0.00905$	0.9878	0.0346	12.1489×10^{-4}	$a = 1.923$ $k = 0.01817$	0.9865	0.0359	12.4355×10^{-4}
7	$a = -0.003972$ $b = 0.000003206$	0.9974	0.0159	2.4201×10^{-4}	$a = -0.008304$ $b = 0.00001439$	0.9994	0.0073	0.3648×10^{-4}
8	$a = 4.463$ $k = 0.001875$ $b = 0.6257$	0.9950	0.0222	4.7581×10^{-4}	$a = 3.92$ $k = 0.004176$ $b = 0.6006$	0.9975	0.0154	2.0428×10^{-4}
9	$a = 0.9882$ $k = 0.0007324$ $n = 1.347$ $b = -0.0003579$	0.9995	0.0070	0.4423×10^{-4}	$a = 0.9938$ $k = 0.003859$ $n = 1.169$ $b = -0.001186$	0.9995	0.0071	0.2808×10^{-4}

No	350 W				500 W			
	Model coefficients	R^2	*RMSE*	χ^2	Model coefficients	R^2	*RMSE*	χ^2
1	$a = 1.085$ $k = 0.03433$	0.9689	0.0581	34.3362×10^{-4}	$a = 1.107$ $k = 0.06051$	0.9143	0.1114	126.1757×10^{-4}
2	$k = 0.03163$	0.9612	0.0648	43.0468×10^{-4}	$k = 0.05481$	0.9097	0.1144	133.3442×10^{-4}
3	$k = 0.007099$ $n = 1.421$	0.9944	0.0246	6.0663×10^{-4}	$k = 0.003608$ $n = 1.923$	0.9966	0.0222	4.7912×10^{-4}
4	$a = 1.486$ $k = 0.01704$ $c = -0.4624$	0.9983	0.0137	1.8825×10^{-4}	$a = 2.923$ $k = 0.01321$ $c = -1.88$	0.9837	0.0486	22.8698×10^{-4}
5	$a = 13.8$ $k_0 = 0.007013$ $b = -12.86$ $k_1 = 0.005979$	0.9865	0.0383	15.1336×10^{-4}	$a = 6.956$ $k_0 = 0.008346$ $b = -5.931$ $k_1 = 0.003578$	0.9790	0.0552	29.6254×10^{-4}
6	$a = 1.926$ $k = 0.04785$	0.9910	0.0312	9.8364×10^{-4}	$a = 2.183$ $k = 0.09453$	0.9802	0.0535	28.8605×10^{-4}
7	$a = -0.02248$ $b = 0.0001164$	0.9988	0.0113	1.4107×10^{-4}	$a = -0.03402$ $b = 0.0001221$	0.9837	0.0486	23.2014×10^{-4}
8	$a = 3.682$ $k = 0.01125$ $b = 0.5897$	0.9977	0.0159	2.4540×10^{-4}	$a = 6.655$ $k = 0.02117$ $b = 0.8051$	0.9481	0.0867	64.2386×10^{-4}
9	$a = 0.9964$ $k = 0.007049$ $n = 0.933$ $b = -0.0001311$	0.9993	0.0087	0.7145×10^{-4}	$a = 1.001$ $k = 0.01208$ $n = 1.206$ $b = -0.001881$	0.9988	0.0135	1.2409×10^{-4}

Tab. 4. Estimated values of coefficients and statistical analyses obtained from various thin layer drying models for drying of mushroom samples at different microwave power and temperature combinations.

No	90 W – 50 °C				90 W – 75 °C			
	Model coefficients	R^2	*RMSE*	χ^2	Model coefficients	R^2	*RMSE*	χ^2
1	$a = 1.072$ $k = 0.00972$	0.9672	0.0540	29.0645×10^{-4}	$a = 1.087$ $k = 0.01805$	0.9712	0.0528	28.0830×10^{-4}
2	$k = 0.009041$	0.9610	0.0590	34.4205×10^{-4}	$k = 0.01657$	0.9624	0.0604	36.5545×10^{-4}
3	$k = 0.001718$ $n = 1.346$	0.9880	0.0327	10.7346×10^{-4}	$k = 0.003213$ $n = 1.391$	0.9941	0.0239	5.9404×10^{-4}
4	$a = 1.572$ $k = 0.004197$ $c = -0.5815$	0.9992	0.0086	0.6789×10^{-4}	$a = 1.467$ $k = 0.008982$ $c = -0.4498$	0.9989	0.0103	0.8673×10^{-4}
5	$a = 4.976$ $k_0 = 0.002278$ $b = -4.027$ $k_1 = 0.001379$	0.9971	0.0159	2.3496×10^{-4}	$a = 31.23$ $k_0 = 0.003508$ $b = -30.31$ $k_1 = 0.003282$	0.9845	0.0388	14.6517×10^{-4}
6	$a = 1.843$ $k = 0.0131$	0.9854	0.0361	12.9946×10^{-4}	$a = 1.897$ $k = 0.0247$	0.9912	0.0293	8.8303×10^{-4}
7	$a = -0.006434$ $b = 0.000009525$	0.9991	0.0088	0.7602×10^{-4}	$a = -0.01186$ $b = 0.00003291$	0.9996	0.0063	0.2592×10^{-4}
8	$a = 3.48$ $k = 0.00325$ $b = 0.564$	0.9991	0.0090	0.7495×10^{-4}	$a = 4.809$ $k = 0.005758$ $b = 0.6933$	0.9987	0.0111	0.9693×10^{-4}
9	$a = 0.9785$ $k = 0.003805$ $n = 1.097$ $b = -0.0008803$	0.9991	0.0088	0.7135×10^{-4}	$a = 0.9889$ $k = 0.005418$ $n = 1.208$ $b = -0.0009781$	0.9996	0.0059	0.2479×10^{-4}

No	160 W – 50 °C				160 W – 75 °C			
	Model coefficients	R^2	*RMSE*	χ^2	Model coefficients	R^2	*RMSE*	χ^2
1	$a = 1.093$ $k = 0.01973$	0.9558	0.0667	44.6654×10^{-4}	$a = 1.08$ $k = 0.02856$	0.9559	0.0673	45.7623×10^{-4}
2	$k = 0.01799$	0.9460	0.0738	54.4554×10^{-4}	$k = 0.02634$	0.9492	0.0722	52.4126×10^{-4}
3	$k = 0.002442$ $n = 1.489$	0.9893	0.0328	11.0493×10^{-4}	$k = 0.004631$ $n = 1.472$	0.9889	0.0337	11.9640×10^{-4}
4	$a = 1.911$ $k = 0.006779$ $c = -0.9023$	0.9982	0.0134	1.5647×10^{-4}	$a = 2.065$ $k = 0.008967$ $c = -1.062$	0.9992	0.0093	0.6677×10^{-4}
5	$a = 16.03$ $k_0 = 0.001425$ $b = -15.08$ $k_1 = 0.0008522$	0.9920	0.0283	7.7286×10^{-4}	$a = 5.06$ $k_0 = 0.004889$ $b = -4.088$ $k_1 = 0.001991$	0.9975	0.0161	2.1914×10^{-4}
6	$a = 1.943$ $k = 0.02763$	0.9832	0.0412	17.2715×10^{-4}	$a = 1.931$ $k = 0.04036$	0.9834	0.0413	17.6706×10^{-4}
7	$a = -0.0123$ $b = 0.00002977$	0.9987	0.0114	1.0831×10^{-4}	$a = -0.01795$ $b = 0.00006084$	0.9995	0.0075	0.4282×10^{-4}
8	$a = 4.424$ $k = 0.005155$ $b = 0.5582$	0.9978	0.0149	1.8862×10^{-4}	$a = 11.35$ $k = 0.01088$ $b = 0.9025$	0.9854	0.0388	35.9772×10^{-4}
9	$a = 0.9896$ $k = 0.009192$ $n = 1.155$ $b = -0.003461$	0.9993	0.0083	0.5838×10^{-4}	$a = 1.017$ $k = 0.01152$ $n = 1.035$ $b = -0.0000013$	0.9987	0.0104	1.1773×10^{-4}

peratures and microwave power treatments. As can be seen from Fig. 3A–C, results obtained from the most appropriate models are quite close to the experimental results. Thus, the MIDILLI et al. model [30], Diffusion Approach model [29], Logarithmic model [25] and WANG and SINGH model [28] were satisfactory in describing the thin-layer drying behaviour of mushroom samples under the experimental conditions investigated.

Colour analysis

The results of the colour measurements of the fresh and dried mushroom samples are presented in Tab. 5. In general, while the L^* value of the fresh sample decreased, the a^* and b^* values increased with increasing temperature and/or microwave power. The overall colour parameters of mushroom samples were more influenced by the microwave drying method. The lowest L^* (41.667), and the highest a^* (8.197) and b^* (20.123) values were obtained at 500 W. Best colour parameters, that were closest to those of fresh mushroom samples, were obtained for samples dried at 50 °C. SOTO et al. [54] and NOUR et al. [55] reported that colour values of dried mushroom samples were a critical quality parameters to the acceptance of final product, products with high L^* values being preferred by consumers. Furthermore, a decrease in L^* value as the microwave power or temperature increased was reported by FUNEBO and OHLSSON [44] for apple, and ORSAT et al. [45] for various products.

The values C and α were affected ($p < 0.01$) in comparison to fresh mushroom samples. Additionally, the higher C and lower α values recorded for all dried samples compared with the fresh mushroom clearly indicated that more browning occurred [56]. Non-enzymatic Maillard reaction that occurs between proteins or amino acids and reducing saccharides during heating may be responsible for the formation of brown compounds [57]. KOTWALIWALE et al. [58] noted that the increased darkening of mushroom samples dried at high temperatures could be attributed to the negative influence of high temperature on mushroom pigments. KUROZAWA et al. [59] determined that with increasing temperature, while L^* value decreased, C value increased in mushroom samples dried at various temperatures (40 °C, 60 °C and 80 °C).

Microstructural changes

Fig. 4 shows scanning electron microscope images of the microstructure of mushroom samples dried by convective, microwave and combined microwave-convective drying methods. As can be seen in the microscopic images, the increased temperature and/or microwave power caused microstructural damage and destroyed the cell walls of dried samples. In the case of convective drying, samples dried at 75 °C had more irregular pore structure with smooth surface than that of the mushrooms dried 50 °C. As for drying of samples with the microwave drying method, the tissues of

Tab. 5. Colour values of fresh and dried mushrooms at different drying methods.

Drying method	Colour parameters				
	L^*	a^*	b^*	Chroma	Hue angle
Fresh	87.133 ± 0.474^{a}	2.103 ± 0.119^{j}	17.417 ± 0.568^{d}	17.543 ± 0.578^{h}	83.160 ± 0.162^{a}
Convective drying					
50 °C	68.013 ± 0.021^{b}	3.580 ± 0.010^{i}	17.870 ± 0.285^{d}	18.225 ± 0.279^{g}	78.710 ± 0.195^{b}
75 °C	50.387 ± 0.785^{f}	4.587 ± 0.137^{h}	19.113 ± 0.500^{b}	19.656 ± 0.510^{cde}	76.544 ± 0.279^{c}
Microwave drying					
90 W	60.467 ± 0.091^{c}	4.617 ± 0.012^{gh}	18.483 ± 0.012^{c}	19.051 ± 0.013^{f}	76.014 ± 0.030^{d}
160 W	53.290 ± 0.053^{d}	4.753 ± 0.015^{f}	18.717 ± 0.006^{bc}	19.311 ± 0.007^{ef}	75.789 ± 0.043^{d}
350 W	43.400 ± 0.251^{i}	6.640 ± 0.017^{e}	19.033 ± 0.025^{bc}	20.158 ± 0.019^{bc}	70.804 ± 0.069^{e}
500 W	41.667 ± 0.421^{j}	8.197 ± 0.032^{a}	20.123 ± 0.055^{a}	21.729 ± 0.063^{a}	67.872 ± 0.024^{i}
Microwave-convective drying					
90 W – 50 °C	51.513 ± 0.437^{e}	4.720 ± 0.020^{fg}	18.813 ± 0.110^{bc}	19.396 ± 0.111^{def}	75.954 ± 0.036^{d}
90 W – 75 °C	46.250 ± 0.030^{g}	7.113 ± 0.006^{c}	18.527 ± 0.006^{c}	19.845 ± 0.007^{bcde}	69.031 ± 0.014^{g}
160 W – 50 °C	46.143 ± 0.182^{g}	7.510 ± 0.046^{b}	18.790 ± 0.079^{bc}	20.235 ± 0.091^{b}	68.249 ± 0.040^{h}
160 W – 75 °C	44.377 ± 0.091^{h}	6.940 ± 0.027^{d}	18.630 ± 0.010^{bc}	19.881 ± 0.007^{bcd}	69.604 ± 0.079^{f}

a–j – values with different superscript letters in the same column differ significantly ($p < 0.01$).

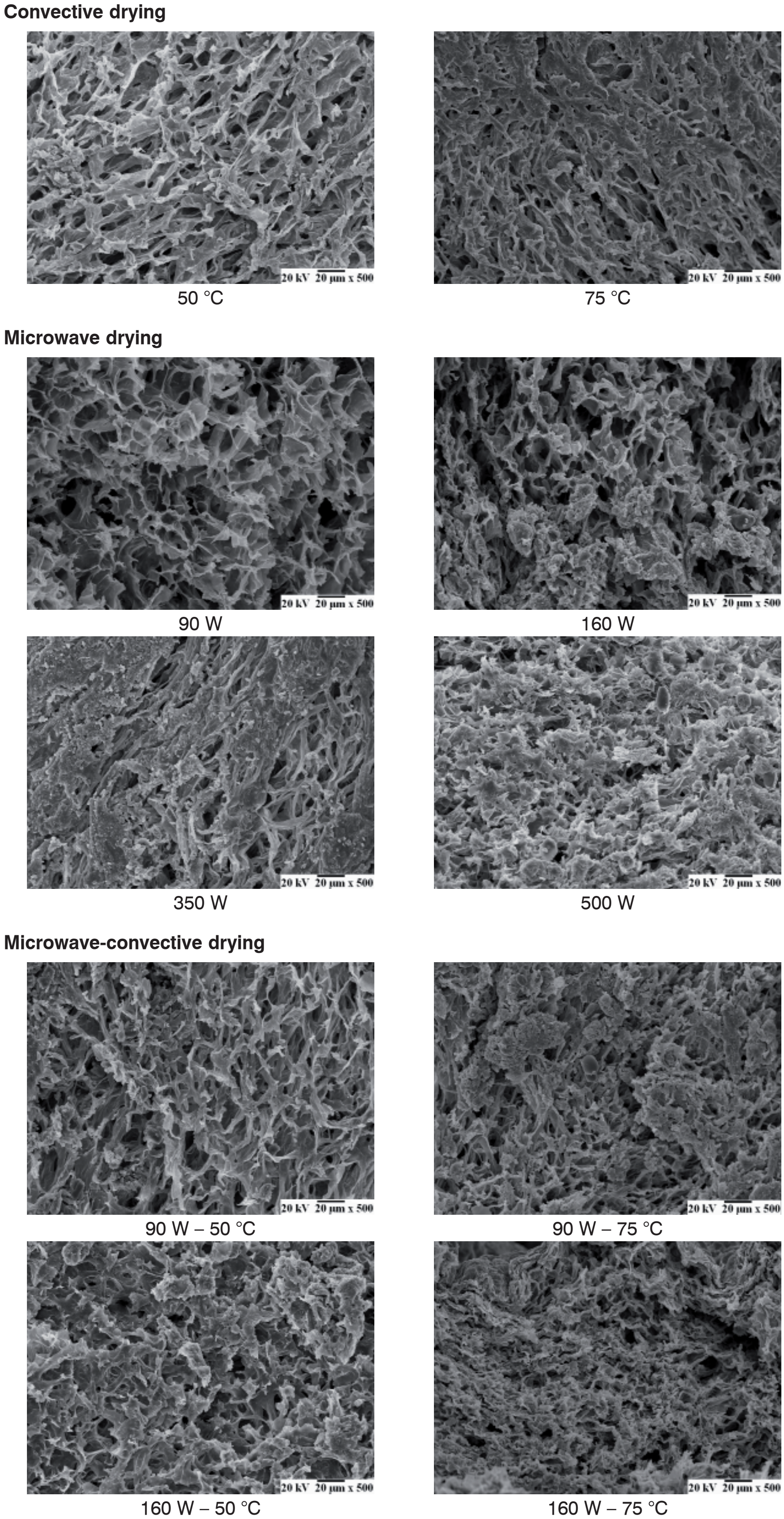

Fig. 4. Scanning electron microscope images of dried mushroom samples.

mushrooms dried at 90 W and 160 W were found damaged less, with a more homogeneous structure than that of the samples dried at 350 W and 500 W. Due to the shorter drying time, diffusion and evaporation rates of water from the inside to the surface were higher [19] for mushrooms dried at 350 W and 500 W, followed by formation of non-homogenous structure with severe shrinkage in some parts, as compared to samples dried at 90 W and 160 W. Furthermore, the temperature and/or microwave power increment at combined microwave-convective drying resulted in more tissue shrinkage and collapse. Giri and Prasad using the convective drying method determined severe shrinkage and collapse in the tissues of mushroom samples dried at a 60 °C [19]. Rodríguez and Lombraña [60] reported that the microstructures of mushrooms dried by a combined microwave convective drying method exhibited a more homogenous distribution and were damaged less than mushrooms dried by only microwave drying method. Witrowa-Rajchert and Rzaca [61] observed that convective and combined microwave-convective drying methods caused significant changes and damage in microstructures of apple samples. However, this effect was higher in samples dried using the microwave-convective drying method. Additionally, they reported that the higher temperatures caused more damage to the dried samples.

CONCLUSIONS

In the present study, the effect of different drying methods on the drying kinetics, colour and microstructure of mushroom samples were investigated. Additionally, the experimental moisture loss data were fitted to 9 thin-layer drying models. The shortest drying time was obtained with the microwave method at 500 W. However, the combined microwave-convective method provided the greatest time savings in comparison to microwave or convective drying alone. Among the used thin layer drying models, Midilli et al. model [30], Diffusion Approach model [29], Logarithmic model [25] and Wang and Singh model [28] provided the best representation of the experimental data. The convective treatment at 50 °C yielded the best product colour values, which were closest to the L^*, a^*, b^* C and α values of the fresh sample. The scanning electron microscopy images revealed that high drying temperature or microwave power caused deformation in the microstructure of the mushroom samples.

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REFERENCES

1. Walde, S. G. – Velu, V. – Jyothirmayi, T. – Math, R. G.: Effects of pretreatments and drying methods on dehydration of mushroom. Journal of Food Engineering, *74*, 2006, pp. 108–115.
2. Gençcelep, H.: The effect of using dried mushroom (*Agaricus bisporus*) on lipid oxidation and color properties of Sucuk. Journal of Food Biochemistry, *36*, 2012, pp. 587–594.
3. Nan-yi, L. – Wei-ming, C. – Qun-li, J. – Qiao-ping, Q. – Fu-lai, R.: Molecular cloning and expression of polyphenoloxidase genes from the mushroom, *Agaricus bisporus*. Agricultural Sciences in China, *10*, 2011, pp. 185–194.
4. Tian, Y. – Zeng, H. – Xu, Z. – Zheng, B. – Lin, Y. – Gan, C. – Lo, Y. M.: Ultrasonic-assisted extraction and antioxidant activity of polysaccharides recovered from white button mushroom (*Agaricus bisporus*). Carbohydrate Polymers, *88*, 2012, pp. 522–529.
5. Naik, S. – Ramachandra, M. – Rajashekharappa, K. S. – Tulasidas, T. N. – Murali, K. – Mallesha, B. C.: Drying of Oyster mushroom (*Pleurotus florida*) in different dryers. Journal of Dairying, Foods and Home Sciences, *25*, 2006, pp. 79–86.
6. Jiang, T.: Effect of alginate coating on physicochemical and sensory qualities of button mushrooms (*Agaricus bisporus*) under a high oxygen modified atmosphere. Postharvest Biology and Technology, *76*, 2013, pp. 91–97.
7. Sommer, I. – Schwartz, H. – Solar, S. – Sontag, G.: Effect of gamma-irradiation on flavour 50-nucleotides, tyrosine, and phenylalanine in mushrooms (*Agaricus bisporus*). Food Chemistry, *123*, 2010, pp. 171–174.
8. Jiang, T. – Zheng, X. – Li, J. – Jing, G. – Cai, L. – Ying, T.: Integrated application of nitric oxide and modified atmosphere packaging to improve quality retention of button mushroom (*Agaricus bisporus*). Food Chemistry, *126*, 2011, pp. 1693–1699.
9. Rama, V. – John, P. J.: Effects of methods of drying and pretreatments on quality of dehydrated mushroom. Indian Food Packer, *54*, 2000, Issue 5, pp. 59–64.
10. Arumuganathan, T. – Manikantan, M. R. – Rai, R. D. – Anandakumar, S. – Khare, V.: Mathematical modeling of drying kinetics of milky mushroom in a fluidized bed dryer. International Agrophysics, *23*, 2009, pp. 1–7.
11. Mundada, M. – Hathan, B. S. – Maske, S.: Convective dehydration kinetics of osmotically pretreated pomegranate arils. Biosystems Engineering, *107*, 2010, pp. 307–316.
12. Hiranvarachat, B. – Devahastin, S. – Chiewchan, N.: Effects of acid pretreatments on some physicochemi-

cal properties of carrot undergoing hot air drying. Food and Bioproducts Processing, *89*, 2011, pp. 116–127.
13. Figiel, A.: Drying kinetics and quality of beetroots dehydrated by combination of convective and vacuum-microwave methods. Journal of Food Engineering, *98*, 2010, pp. 461–470.
14. Maskan, M.: Microwave/air and microwave finish drying of banana. Journal of Food Engineering, *44*, 2000, pp. 71–78.
15. Wang, J. – Xi, Y. S. – Yu, Y.: Microwave drying characteristics of potato and the effect of different microwave powers on the dried quality of potato. European Food Research and Technology, *219*, 2004, pp. 500–506.
16. Zhang, M. – Tang, J. – Mujumdar, A. – Wang, S.: Trends in microwave related drying of fruits and vegetables. Trends in Food Science and Technology, *17*, 2006, pp. 524–534.
17. Motevali, A. – Minaei, S. – Khoshtaghaza, M. H. – Amirnejat, H.: Comparison of energy consumption and specific energy requirements of different methods for drying mushroom slices. Energy, *36*, 2011, pp. 6433–6441.
18. Zecchi, B. – Clavijo, L. – Garreiro, J. M. – Gerla, P.: Modeling and minimizing process time of combined convective and vacuum drying of mushrooms and parsley. Journal of Food Engineering, *104*, 2011, pp. 49–55.
19. Giri, S. K. – Prasad, S.: Drying kinetics and rehydration characteristics of microwave-vacuum and convective hot-air dried mushrooms. Journal of Food Engineering, *78*, 2007, pp. 512–521.
20. Oikonomopoulou, V. P. – Krokida, M. K.: Structural properties of dried potatoes, mushrooms, and strawberries as a function of freeze-drying pressure. Drying Technology, *30*, 2012, pp. 351–361.
21. Cao, W. – Nishiyama, Y. – Koide, S.: Thin-layer drying of maitake mushroom analysed with a simplified model. Biosystems Engineering, *85*, 2003, pp. 331–337.
22. Westerman, P. W. – White, G. M. – Ross, I. J.: Relative humidity effect on the high temperature drying of shelled corn. Transactions of the ASAE, *16*, 1973, pp. 1136–1139.
23. Ayensu, A.: Dehydration of food crops using a solar dryer with convective heat flow. Solar Energy, *59*, 1997, pp. 121–126.
24. Gupta, P. – Ahmet, J. – Shivhare, U. S. – Raghavan, G. S. V.: Drying characteristics of red chilli. Drying Technology, *20*, 2002, pp. 1975–1987.
25. Togrul, I. T – Pehlivan, D.: Mathematical modelling of solar drying of apricots in thin layers. Journal of Food Engineering, *55*, 2002, pp. 209–216.
26. Madamba, P. S. – Driscoll, R. H. – Buckle, K. A.: The thin-layer drying characteristics of garlic slices. Journal of Food Engineering, *29*, 1996, pp. 75–97.
27. Sharaf-Eldeen, Y. I. – Blaisdell, J. L. – Hamdy, M. Y.: A model for ear corn drying. Transactions of the ASAE, *5*, 1980, pp. 1261–1265.
28. Wang, C. Y. – Singh, R. P.: Use of variable equilibrium moisture content in modeling rice drying. Transactions of the American Society of Agricultural Engineers, *11*, 1978, pp. 668–672.
29. Yaldiz, O. – Ertekin, C.: Thin layer solar drying of some vegetables. Drying Technology, *19*, 2001, pp. 583–596.
30. Midilli, A. – Kucuk, H. – Yapar, Z.: A new model for single-layer drying. Drying Technology, *20*, 2002, pp. 1503–1513.
31. Doymaz, I.: Thin-layer drying behaviour of mint leaves. Journal of Food Engineering, *74*, 2006, pp. 370–375.
32. Therdthai, N. – Zhou, W.: Characterization of microwave vacuum drying and hot air drying of mint leaves (*Mentha cordifolia* Opiz ex Fresen). Journal of Food Engineering, *91*, 2009, pp. 482–489.
33. Xiao, H. W. – Pang, C. L. – Wang, L. H. – Bai, J. W. – Yang, W. X. – Gao, Z. J.: Drying kinetics and quality of Monukka seedless grapes dried in an air-impingement jet dryer. Biosystems Engineering, *105*, 2010, pp. 233–240.
34. Köse, B. – Erentürk, S.: Drying characteristics of mistletoe (*Viscum album* L.) in convective and UV combined convective type dryers. Industrial Crops and Products, *32*, 2010, pp. 394–399.
35. Odjo, S. – Malumba, P. – Dossou, J. – Janas, S. – Béra, F.: Influence of drying and hydrothermal treatment of corn on the denaturation of salt-soluble proteins and color parameters. Journal of Food Engineering, *109*, 2012, pp. 561–570.
36. Cheng, W. M. – Raghavan, G. S. V. – Ngadi, M. – Wang, N.: Microwave power control strategies on the drying process II. Phase-controlled and cycle-controlled microwave/air drying. Journal of Food Engineering, *76*, 2006, pp. 195–201.
37. McGuire, R. G.: Reporting of objective color measurements. HortScience, *27*, 1992, pp. 1254–1255.
38. Luo, M. R.: Applying colour science in colour design. Optics and Laser Technology, *38*, 2006, pp. 392–398.
39. Voss, H. D.: Relating colorimeter measurement of plant color to the royal horticultural society colour chart. HortScience, *27*, 1992, pp. 129–145.
40. Karaaslan, S. N. – Tunçer, I. K.: Development of a drying model for combined microwave-fan-assisted convection drying of spinach. Biosystems Engineering, *100*, 2008, pp. 44–52.
41. Bondaruk, J. – Markowski, M. – Błaszczak, W.: Effect of drying conditions on the quality of vacuum-microwave dried potato cubes. Journal of Food Engineering, *81*, 2007, pp. 306–312.
42. Ghaderi, A. – Abbasi, S. – Motevali, A. – Minaei, S.: Comparison of mathematical models and artificial neural networks for prediction of drying kinetics of mushroom in microwave–vacuum drier. Chemical Industry and Chemical Engineering Quarterly, *18*, 2012, pp. 283–293.
43. Lee, J. H. – Lee, M. J.: Effect of drying method on the moisture sorption isotherms for *Inonotus obliquus* mushroom. LWT–Food Science and Technology, *41*, 2008, pp. 1478–1484.
44. Funebo, T. – Ohlsson, T.: Microwave-assisted air dehydration of apple and mushroom. Journal of Food Engineering, *38*, 1998, pp. 353–367.

45. Orsat, V. – Yang, W. – Changrue, V. – Raghavan, G. S. V.: Microwave-assisted drying of biomaterials. Food and Bioproducts Processing, *85*, 2007, pp. 255–263.
46. Workneh, T. S. – Raghavan, V. – Gariepy, Y.: Microwave assisted hot air ventilation drying of tomato slices. In: International Conference on Food Engineering and Biotechnology, 28–30 September 2011, Singapore. IPCBEE, Vol. 9, IACSIT Press, 2011, pp. 150–161. Available at <http://www.ipcbee.com/vol9/29-B10005.pdf>
47. Sharma, G. P. – Prasad, S. – Chahar, V. K.: Moisture transport in garlic cloves undergoing microwave-convective drying. Food and Bioproducts Processing, *87*, 2009, pp. 11–16.
48. Diaz, G. R. – Martinez-Monzo, J. – Fito, P. – Chiralt, A.: Modelling of dehydration-rehydration of orange slices in combined microwave air drying. Innovative Food Science and Emerging Technologies, *4*, 2003, pp. 203–209.
49. Dev, S. R. S. – Geetha, P. – Orsat, V. – Gariépy, Y. – Raghavan, G. S. V.: Effects of microwave-assisted hot air drying and conventional hot air drying on the drying kinetics, color, rehydration, and volatiles of *Moringa oleifera*. Drying Technology, *29*, 2011, pp. 1452–1458.
50. Artnaseaw, A. – Theerakulpisut, S. – Benjapiyaporn, C.: Drying characteristics of Shiitake mushroom and Jinda chili during vacuum heat pump drying. Food and Bioproducts Processing, *88*, 2010, pp. 105–114.
51. Xanthopoulos, G. – Lambrinos, G. – Manolopoulou, H.: Evaluation of thin-layer models for Mushroom (*Agaricus bisporus*) drying. Drying Technology, *25*, 2007, pp. 1471–1481.
52. Sacilik, K. – Keskin, R. – Elicin, A. K.: Mathematical modelling of solar tunnel drying of thin layer organic tomato. Journal of Food Engineering, *73*, 2006, pp. 231–238.
53. Farhang, A. – Hosinpour, A. – Darvishi, H. – Khoshtaghaza, M. H. – Hashtjin, T. T.: Accelerated drying of alfalfa (*Medicago sativa* L.) by microwave dryer. Global Veterinaria, *5*, 2010, pp. 158–163.
54. Soto, M. G. – Camacho, R. O. – López, O. P.: Effect of pretreatment and drying on the quality of oyster mushrooms (*Pleurotus ostreatus*). Drying Technology, *19*, 2001, pp. 661–672.
55. Nour, V. – Trandafir, I. – Ionica, M. E.: Effects of pre-treatments and drying temperatures on the quality of dried button mushrooms. South-Western Journal of Horticulture, Biology and Environment, *2*, 2011, pp. 15–24.
56. Pathare, B. P. – Opara, U. L. – Al-Said, F. A.: Colour measurement and analysis in fresh and processed foods: A review. Food and Bioprocess Technology, *6*, 2013, pp. 36–60.
57. Nguyen, M. L. – Schwartz, S. J.: Lycopene: Chemical and biological properties. Food Technology, *53*, 1999, pp. 38–45.
58. Kotwaliwale, N. – Bakane, P. – Verma, A.: Changes in textural and optical properties of oyster mushroom during hot air drying. Journal of Food Engineering, *78*, 2007, pp. 1207–1211.
59. Kurozawa, L. E. – Azoubel, P. M. – Murr, F. E. X. – Park, K. J.: Drying kinetic of fresh and osmotically dehydrated mushroom (*Agaricus blazei*). Journal of Food Process Engineering, *35*, 2012, pp. 295–313.
60. Rodríguez, R. – Lombraña, J. I.: Analysis of microwave drying variants and their effect on the quality of the dehydrated product. In: 2nd Mercosur Congress on Chemical Engineering, 4th Mercosur Congress on Process Systems Engineering, 14–19 August 2005, Rio de Janeiro, Brasil. Rio de Janeiro : Enpromer, 2005, pp. 1287–1296. Available at <http://www.enpromer2005.eq.ufrj.br/nukleo/pdfs/1287_1287_microwave_drying_reviewed2_.pdf>
61. Witrowa-Rajchert, D. – Rzaca, M.: Effect of drying method on the microstructure and physical properties of dried apples. Drying Technology, *27*, 2009, pp. 903–909.

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