Chapter 11

CONVECTIVE DRYING OF SHIITAKE MUSHROOMS WITH A FOCUS ON FUNCTIONALITY AND NATURALNESS

Petrova Zh. O., Samoilenko K. M.
DOI https://doi.org/10.30525/978-9934-26-445-0-11

INTRODACTION

Dry food products have a broad range of applications, including instant products, spices added to soups and sauces, muesli, and healthy snacks like fruit–vegetable bars or chips, which have gained popularity in recent times[1]. Convective drying is the most commonly used drying process due to several advantages, such as a simple apparatus and a well-known drying mechanism, which have led to its widespread use in the industry. On the contrary, hot airdrying is considered to be one of the most time– and energy-consuming techniques, as well as being destructive and causing a deterioration in the quality of the product[2].

An increasing demand for high-quality food products and limited energy consumption has led to the development of alternative and combined methods, as well as advancements in drying technology such as hybrid drying. To achieve green food processing, various techniques, such as microwaves and ultrasound, can be combined with hot air drying[3]. Therefore, we investigated traditional and hybrid methods of drying. The studied material is cultivated shiitake mushrooms *(Lentinula edodes)*[4].

---

[1] Tsotsas E., Mujumdar A.S., Modern Drying Technology. Wiley-VCH Verlag Weinheim, Germany, 2011. ISBN 978-3-527-31558-1.

[2] Mujumdar A.S. (Ed.) Handbook of Industrial Drying, 4th ed.; CRC Press Boca Raton, FL, USA, 2015, ISBN 9781466596665.

[3] Barba F.J., Roselló-Soto E., Marszałek K., Bursa´c Kovaˇcevi´c D., Režek Jambrak A., Lorenzo J.M., Chemat F., Putnik P. Green food processing: Concepts, strategies, and tools. In Green Food Processing Techniques. *Elsevier: Amsterdam, The Netherlands.* 2019, pp. 1–21, ISBN 9780128153536

[4] Yang X., Zhang Y., Kong Y., Zhao J. Sun Y., Huang M. Comparative analysis of taste compounds in shiitake mushrooms processed by hot air drying and freeze drying. *International Journal of Food Properties*. 2019, 22 (1), pp. 1100-1111, DOI: 10.1080/10942912.2019.1628777

Due to the high respiratory rate and humidity close to 90%, cultivated Shiitake mushrooms are vulnerable to microbial attack and deterioration of surface color[5].

One way to extend the shelf life of mushrooms is thermal dehydration (drying), which prevents most of the spoilage, for example enzymatic darkening, microbial growth, etc., by reducing water activity[6]. This significantly increases the shelf life of mushrooms after drying, which can then be safely stored under proper conditions [7].

The authors[8] suggested that in order to improve the structuring and moisture-conducting properties of the material during dehydration, the content of β-cyclodextrin in the mushroom suspension should be more than 10%, but less than 25%, and the temperature of the coolant should be at least 180 ºC, but less than 200 ºC. Due to this, greater strength and density of the dried particles is ensured and, thereby, the structural and mechanical characteristics of the powder are improved, and the increase in heat resistance of the material in combination with the achievement of the effect of microencapsulation of microparticles of thermolabile components of the mushroom during spray drying makes it possible to obtain high-quality mushroom powder.

Convective drying is considered to be a low-cost and easy-to-control method, so it is widely used for drying cultivated mushrooms[9].

Argyropoulos D. the convective drying of Shiitake was investigated, namely the mushroom cap in a thin layer at a temperature of 30 to 70 ° C, the degree of redhydration, equilibrium humidity and color change[10]. The higher

---

[5] Subramaniam Sh., Shunshun J., Zhang Zh., Pu J. Impact of post-harvest processing or thermal dehydration on physiochemical, nutritional and sensory quality of shiitake mushrooms. *Comprehensive Reviews in Food Science and Food Safety*. 2021. Vol. 20. pp. 2560–2595. DOI 10.1111/1541-4337.12738

[6] Hu L., Bi J., Jin X., Qiu Y. Study on the Rehydration Quality Improvement of shiitake Mushroom by Combined Drying Methods. *Foods*. 2021. Vol. 10. p. 769, https://doi.org/10.3390/foods10040769

[7] Tian Y., Zhao Y., Huang J., Zeng H., Zheng B. Effects of different drying methods on the product quality and volatile compounds of whole shiitake mushrooms. *Food Chemistry*. 2016. Vol. 197. pp. 714–722. https://doi.org/10.1016/j.foodchem.2015.11.029

[8] Турчина Т.Я., Жукотський Е.К., Костянець Л.О., Макаренко А.А. Моделювання впливу β-циклодекстрину

як структуруючої добавки на кінетику сушіння водної суспензії їстівного гриба шиїтаке. Наукові праці ОНАХТ, (2019), Vol. 83 (1), pp. 152-156.

[9] Chandrasekaran S., Ramanathan S., Basak T. Microwave food processing, *Food Research International*. 2013. Vol. 52 (1). pp. 243–261.

[10] Argyropoulos D., Khan M., Müller J. Effect of drying temperature and pre-treatment on color and textural changes during convective air drying of Boletus edulis mushroom. *17th International Drying Symposium (IDS 2010)*. 2010. pp. 1404-1409

the drying temperature, the shorter the process duration[11]. The time required to reduce the moisture of the sample was much shorter for the 70 ° C – 190 min mode and too long for the 30 ° C – 1400 min mode. Slight darkening (yellowness) was observed already at 50 ° C, which was expressed more with higher temperatures of 60 and 70 ° C. After drying, the degree of rehydration was determined – all samples could not absorb the same amount that they had in fresh form. Samples dried at 30 °C indicate slightly greater rehydration capacity compared to material dried at higher temperatures.

Yang Xiao determined the content of free amino acids by sublimation and convective methods of research, which showed that the total content of free amino acids in convective drying samples treated at 60°C was the highest. That is, the sublimation method partially destroys amino acids[12].

Microwave drying distributes energy unevenly creating problems associated with uneven heating[13]. Vacuum drying is especially suitable for heat sensitive products. However, the low heat transfer rate in vacuum drying causes an extended drying time[14].

Despite the large number of previous studies, scientific interest in the process of dehydration of cultivated Shiitake mushrooms remains relevant, since the disadvantage of the main considered methods is the high cost, as can be seen from fig. 1. The highest level of the specific energy consumption indicator was registered during drying by sublimation (496.1 MJ/kg of water) and the combined vacuum-sublimation method (425 MJ/kg of water) in comparison with other drying methods[15].

The reason for the high energy consumption of sublimation (which is the main disadvantage of this method) is that the process usually uses electric heating plates to provide the heat needed to sublimate the ice, with low thermal conductivity. With freeze drying, the basic energy required to remove 1 kg of water is almost twice as high as with conventional drying.

---

[11] Argyropoulos D., Müller J. Convective drying and desorption isotherms of Shiitake (Lentinula edodes) mushroom. *Agricultural and Food Sciences*. (2013). Available at https://opus.unihohenheim.de/volltexte/2013/782/pdf/Argyropoulos_2011c.pdf

[12] Xiao Ya., Zhang Y., Kong Y., Zhao J., Sun Y., Huang M. Comparative analysis of taste compounds in shiitake mushrooms processed by hot air drying and freeze drying. *International Journal of Food Properties.* 2019. Vol. 22 (1). pp. 1100-1111, DOI: 10.1080/10942912.2019.1628777

[13] Zhang N., Chen H., Zhang Y., Ma L., Xu X. Comparative studies on chemical parameters and antioxidant properties of stipes and caps of shiitake mushroom as affected by different drying methods. *Journal of the Science Of Food and Agricultural*. 2013. Vol. 93 (12). pp. 3107-3113 https://doi.org/10.1002/jsfa.6151

[14] Zhang M., Tang J., Mujumdar A.S., Wang S. Trends in microwave-related drying of fruits and vegetables. *Trends in Food Science & Technology*. 2006. Vol. 17 (10). pp. 524-534

[15] Wu X., Zhang M., Bhandari B. A Novel Infrared Freeze Drying (IRFD) Technology to Lower the Energy Consumption and Keep the Quality of Cordyceps Militaris. *Innovative Food Science and Emerging Technologies*. 2019. Vol. 54. pp. 34-42.

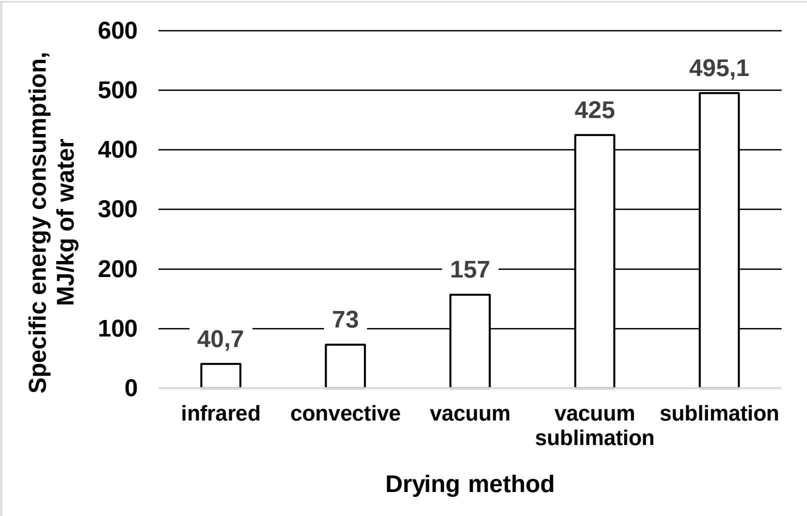

Fig. 1. Specific energy consumption during drying of colloidal capillary-porous materials depending on the method

The research aims to improve the availability and shelf life of mushrooms. The changes that were taken into account during the study were the temperature of the heat carrier and material, speed and duration of drying. Previous studies have shown the need to intensify the drying process while maintaining the high quality of the final product by using a combined energy supply, due to the fact that the given traditional methods of drying, the material temperature of which does not exceed 60 ºC, are long-term and amount to more than 150 min, and at the same time, the energy consumption increases costs.

The purpose of the research is theoretical and experimental justification of the complex and effective processing of Shiitake mushrooms, research on heat and mass transfer taking into account the properties of the material and the development of energy-efficient drying modes due to combined and two-stage dehydration methods.

1. Methods.

Research of drying kinetics and study of rehydration properties

The study of the drying kinetics of cultivated Shiitake mushrooms was carried out on an improved experimental stand, which consists of the following main parts: a drying chamber, a heating system and a fan supply of the coolant to the drying chamber, insulated air ducts, scales, speed regulators and resistance thermometers.

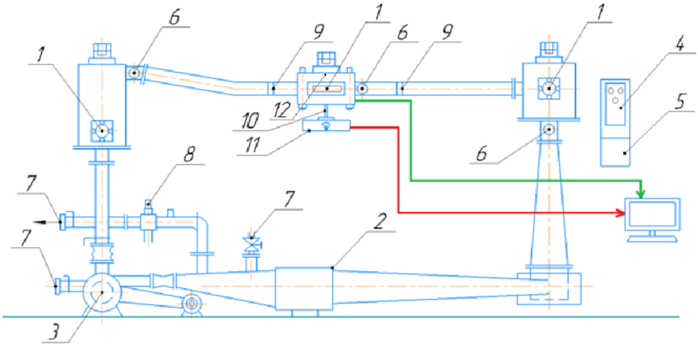

Fig. 2. Scheme of the experimental convective drying stand:
1 – drying chamber; 2 – electric heaters; 3 – fan;
4 – thermostat; 5 – control panel; 6 – resistance thermometers;
7 – nozzles with valves; 8 – psychrometer; 9 – special grids;
10 – weight bar; 11 – scales, 12 – IR source (infrared radiation)

Figure 2 shows a diagram of an experimental convective drying stand. A change in a wide range of the speed of movement of the coolant and its temperature is achieved by adjusting the operation of the fan (3) on the control panel (5). The speed of the coolant is changed by changing the air supply by the centrifugal fan (3) using a frequency converter with manual adjustment (5). The ratio between exhaust and fresh air can be adjusted with the help of dampers on the nozzles (7)[16].

Sliced Shiitake mushrooms are placed in a mesh basket, which is placed on the scales (11) in the drying chamber (1). The camera has a transparent glass, through which you can observe the state of the material during the drying process. In particular, it is possible to note the moment when the color of the sample changes due to the influence of the coolant modes, the shrinkage process and change the mode if necessary. A block of infrared lamps is installed in the chamber with the ability to adjust the heat flow from 0 to 3800 W/m^2 (12). The power of the lamps is changed by a rheostat type regulator.

Like the entire drying process, heat transfer is a non-stationary process. Another feature of this process is that (as indicated above) it is complicated by the transfer of matter (moisture), as it is due to the movement of heat. These

[16] Петрова Ж.О., Снєжкін Ю.Ф. Енергоефективні теплотехнології переробки функціональної сировини.Монографія. Наукова думка. 2018. 187 с. ISBN 978-966-00-1620-0.

features are reflected in the values of thermophysical parameters and their relationship.

Experiments on the study of drying kinetics were carried out at the rate of the coolant v = 3 m/s (the rate was chosen based on the condition of more efficient drying of the same material in existing modern dryers); at a heat carrier temperature of 60 ºC, 100 ºC, 100/60 ºC and infrared radiation of 100 W when drying on a convective stand; as well as the combined method of 100 W + 60 °C (infrared-convective). Dehydration processes continued up to a residual moisture content of 5.0% and within 60-160 minutes.

In connection with the automatic collection of information on the experimental convective drying stand, the temperature recording error does not exceed ± 1 °C and mass ± 5 mg.

The studied samples of dried mushrooms were prepared in the form of a plate (25x10x3 mm) and powder with a dispersion of less than 0.5 mm. The coefficient of swelling was determined by the method described in the paper[17]. The essence of the method is that the material under study is weighed in prepared containers and filled with water (45 °C) in a ratio of 1:10. A certain period of time is maintained – 30 min, the liquid is drained, and the recovered sample is weighed and the swelling coefficient is calculated. The swelling is estimated by the coefficient of swelling C_{swell}, which shows the relative increase in mass of the product after swelling and determines the ability to restore the initial properties of the material upon dehydration. The coefficient of swelling is calculated according to the formula:

$$C_{swell} = \frac{G_2}{G_1}$$

where C_{swell} – the coefficient of swelling; G_1 and G_2 – mass of material before and after swelling, respectively, g.

2. Experimental studies of heat and mass transfer during drying of cultivated Shiitake mushrooms

Avdieieva L obtained research results by the spray drying method of mushrooms has a beneficial effect on the kinetics and content of nutrients, but leads to undesirable color changes and the use of β-cyclodextrin is not functional[18].

Another Shiitake drying method that has been investigated is microwave vacuum drying (MVD) and microwave vacuum drying combined with infrared radiation (MVD+IR). The application of infrared radiation in

[17] Снєжкін Ю.Ф., Петрова Ж.О. Тепломасообмінні процеси під час одержання каротиновмісних порошків. Монографія. Академперіодика. 2007. 160 с. ISBN 978-966-360-076-5.

[18] Avdieieva L., Zhukotskyi E., Dekusha H., Ivanov S. Analysis of the existing methods and specific features of drying shiitake mushroom. *Food science and technology.*(2021. Vol. 15 (3). pp. 94-107. DOI: https://doi.org/10.15673/fst.v15i3.2118

combination with microwave vacuum drying significantly improved the color of dried Shiitake samples, as well as the rehydration coefficient and texture of rehydrated samples, reduced drying time and specific energy consumption compared to microwave-vacuum drying. The optimal conditions for drying Shiitake mushrooms were drying in MVD+IR mode at 267 W MW in combination with 200 W IR under operating pressure at 18.66 kPa[19].

After considering previous studies, it was interesting to investigate the hybrid method of drying cultivated shiitake mushrooms by infrared-convective 100 W+ 60 °C in comparison with convective 60 °C and stepwise 100/60 °C.

Figure 3 shows the drying curves of changes in the average (integral) moisture content of material W over time and temperature curves. The heat carrier temperature is 60 °C, 100 °C and two-stage 100/60 °C. Due to the small thickness of the material and the high intensity of evaporation, the analysis of all curves indicates the absence of the first drying period. Dehydration occurs in the second period. The change in moisture content (curve 1) of Shiitake mushrooms at a heat carrier temperature of 60 °C occurs within 156 minutes. At the same time, as can be seen from the temperature curve 1', the material heats up evenly during the entire drying period and only at the end the temperature of the material is 55 °C.

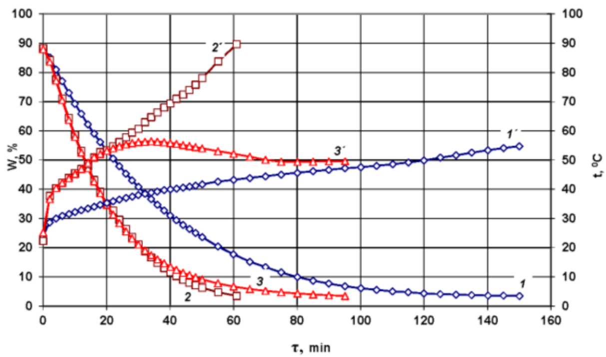

Рис. 3. Changes in the moisture content of cultivated Shiitake mushrooms at different temperatures of the coolant δ (material thickness) = 10 mm, v = 3 m/s,
d (moisture content of the air) = 10 g/kg dry air:
1.1' – 60°C; 2.2' – 100°C; 3.3' – 100/60°C

---

[19] Kantrong H., Tansakul A., Mittal GS. Drying characteristics and quality of shiitake mushroom undergoing microwave-vacuum drying and microwave-vacuum combined with infrared drying. *Journal of food science and technology.* 2014. Vol. 51 (12). pp. 3594–3608. DOI 10.1007/s13197-012-0888-4.

Moisture content change curve 2 shows that the process intensifies at a heat carrier temperature of 100 °C and lasts only 60 minutes. Temperature curve 2' indicates intense heating of the material and at 55 minutes of the process, the temperature of the material rises sharply and is 90 °C for 60 minutes. This leads to the denaturation of proteins, the formation of melanoid reactions, the destruction of vitamins and other undesirable processes, although at the same time the shortest duration of the process. Based on these studies, it is advisable at the beginning of the process, when the moisture content of the mushrooms is high, to increase the temperature of the heat carrier to 100 °C, without leading to high heating of the material. The curves of changes in moisture content 3 and temperature 3' show, that after 20 minutes the material temperature is 50 °C and it is advisable to reduce the heat carrier temperature to 60 °C. In this case, the process slows down a bit and its duration is 97 min, which is much longer. than the mode heat carrier of 100 °C (curve 2.2'), but much less, than at a temperature of 60 °C (curve 1.1'). Based on these data, the drying study should be carried out in a two-stage mode at a heat carrier temperature of 100/60 °C and a material temperature of 60 °C.

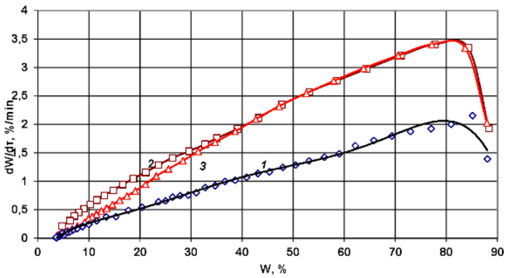

Fig. 4. Change in drying rate of cultivated Shiitake mushrooms at different temperatures of heat carrier δ (material thickness) = 10 mm, v = 3 m/s, d (moisture content of the air) =10 g/kg of dry air: 1 – 60°C; 2 – 100°C; 3 – 100/60°C

The drying rate curves (Fig. 4) show, that the drying rate is 3.5 %/min both at a heat carrier temperature of 100 °C and at 100/60 °C (curves 2.3). A temperature of 60 °C (curve 1) slows down the drying rate. The drying rate curve of the two-stage mode (curve 3), as well as the graph of the change in moisture content shows, that increases the drying rate compared to 60 ºC (curve 1). As can be seen from figures 2–3, with the two-stage mode of 100/60 °C, the drying process lasts 1.6 years faster, compared to the mode of 60 °C, and the drying rate is also higher and is 3.5%/min (Fig. 4).

We investigated the change in the moisture content of cultivated Shiitake mushrooms during convective drying and IR (infrared radiation when drying on a convective stand), as shown in Fig. 5. The graph shows the comparative characteristics of the convective mode 60°C (curves 1.1'), the drying mode with infrared radiation when drying on a convective stand with an ambient temperature of 20 °C (hereinafter IR) – 100 W (curves 2.2') and the combined (infrared-convective) mode 100 W+60°C (curves 3.3').

As can be seen from fig. 5, the duration of drying with IR (curves 2.2') is 122 min, which is 19 % faster, than with the convective mode of 60 °C. Curve 3.3' shows combined drying – at the beginning of the process, two types of heat carrier were supplied simultaneously (IR 100 W and convective 60 °C).

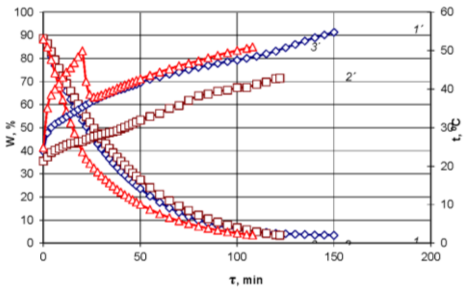

Рис. 5. Change in the moisture content of cultivated shiitake mushrooms during convective drying and IR (infrared radiation when drying on a convective stand) δ (material thickness) = 10 mm, v = 3 m/s, d (moisture content of the air) =10 g/kg of dry air: 1.1' – 60°C; 2.2' – 100W (at 20°C); 3.3' – 100W+60°C

When the tested sample reached a temperature of 50 °C at the 20th minute of the experiment, one of the heat carriers (IR 100 W) was turned off. At the same time, a sharp drop in the temperature of the material to 39 °C with subsequent gradual heating is observed. Combined drying (curves 3.3') lasts 110 minutes, and at the same time, the drying process is intensified by 1.4 times compared to the 60 °C mode. The drying rate at the convective mode of 60 °C is 2.0 %/min, at IR 100 W – 1.8 %/min, at the combined 100 W + 60 °C it is the highest – 3 %/min (Fig. 6).

A comparative characterization of the change in moisture content of cultivated Shiitake mushrooms (Fig. 7) was carried out in the combined infrared-convective 100 W + 60°C (curve 1.1') and two-stage 100/60°C (curve 2.2') drying regimes. The use of an IR lamp at the beginning of the process made it possible to reduce the drying time, as indicated above.

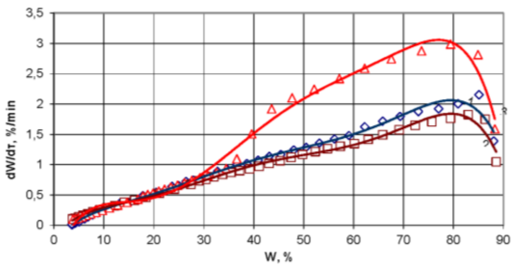

Fig. 6. The influence of heat carrier temperature during convection and IR on the drying rate of Shiitake mushrooms. δ (material thickness) = 10 mm, v = 3 m/s,
d (moisture content of the air) =10 g/kg dry air:
1 – 60°C; 2 – 100 W (at 20°C); 3 – 100W+60°C

Curve 2.2' (Fig. 7) shows the characteristics of two-stage drying in comparison with combined drying, which shows that at the beginning of the process, the heat carrier temperature was 100 °C, then when the material temperature reached 50 °C (for about 20 min), the the heat carrier temperature was reduced up to 60 °C, however, the material temperature continues to increase by inertia to 55 °C, since the decrease heat carrier temperature occurs after a certain period of time gradually. Further, the temperature of the material begins to gradually decrease from 35 min to reach 48 °C at 75 min, and then increases to 50 °C. The drying rate for the combined method is 3%/min and for the stepwise method 3.5%/min (Fig. 8).

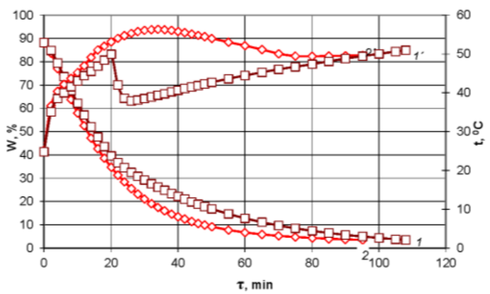

Fig. 7. Comparative characteristics of changes in the moisture content of cultivated mushrooms Shiitake in effective drying modes δ (material thickness) = 10 mm, v = 3 m/s, d (moisture content of the air) =10 g/kg dry air:
1.1' – 100W+60°C; 2.2' –100/60°C

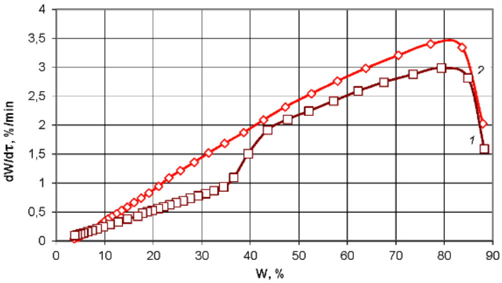

Fig. 8. Comparative characteristics of the drying rate of cultivated of Shiitake mushrooms in effective drying modes δ (material thickness) = 10 mm, v = 3 m/s, d (moisture content of the air) =10 g/kg dry air: 1 – 100W+60°C; 2 – 100/60°C

These two modes are the most effective, the difference in time between them is 8–10 min and the difference in drying rate is 0.5%/min with an advantage for the two-stage mode (Fig. 8). This happens, because the temperature of the material during drying by the combined method drops to 40 °C, and with two-stage drying – to 50 °C.

The duration of drying Shiitake mushrooms, which was described in the article (Argyropoulos et al., 2010), is 190 min at 70 °C, and 1400 min at 30 °C. The duration of the combined drying method presented by us is 110 minutes, and with the two-stage method – 97 minutes.

3. Heat and moisture exchange in the case of drying Shiitake mushrooms

One of the main characteristics of the kinetics of the dehydration process is the Rebinder number (Rb) – a drying optimization criterion that determines the ratio of the amount of heat spent on heating the material and on the evaporation of significant moisture in an infinitesimally small period of time:

$$Rb = b\frac{\bar{c}}{r} = \frac{\bar{c}}{r}\left(\frac{d\bar{t}}{dW}\right)$$

where Rb – Rebinder number,

$b\frac{c}{r}$ – integral characteristic of the kinetics of the drying process,

$\frac{d\bar{t}}{dW}$ – the change in the average temperature of the material being dried per unit of change in its average humidity over an infinitesimally small period of time is called the temperature coefficient of drying.

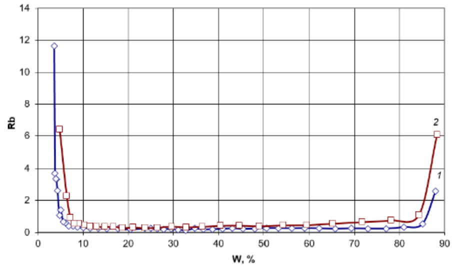

Fig. 9. Change in Rebinder's number Rb depending on the heat carrier temperature at δ (material thickness) = 10 mm, v = 3 m/s, d (moisture content of the air) =10 g/kg dry air: 1 – 60 °C; 2 – 100 °C

In fig. 9 shows the change in the Rebinder number *Rb* depending on the heat carrier temperature. At the beginning of the drying process to a moisture content of 84%, the material is heated with a decrease in its moisture content, while the Rb number decreases.

During the period of change in humidity of cultivated shiitake mushrooms from 84–10% to Rebinder's number *Rb* is minimal. At this time, most of the heat is spent on removing moisture from the material. After the moisture content point of 12–10%, the Rebinder number *Rb* increases sharply, which means that most of the heat is spent on heating the material, which leads to additional energy costs for the process and deterioration of the quality of the dried material. The nature of the change in Rebinder's number *Rb* proves the effectiveness of the introduction of two-stage drying regimes.

The value of the Rebinder number *Rb* depends on the temperature coefficient of drying, the specific heat capacity of the wet material and the specific heat of evaporation, and, accordingly, on the form of moisture connection with the material. Therefore, it makes no sense to maintain a high temperature of the coolant in the last period of the dehydration process.

In researches was also concluded, that hybrid processes such as convective drying with microwave or in combination with microwave and ultrasound are more energy efficient, than the convective method and ultrasonic convection. These findings are consistent with previous studies of microwave convective drying of kale[20] and a hybrid microwave hot air drying of onion slices[21].

[20] Lichtenthaler H.K., Buschmann C. Chlorophylls and Carotenoids: Measurement and Characterization by UV-VIS Spectroscopy. *Curr. Protoc. Food Anal. Chem.* 2001. 1. F4.3.1–F4.3.8.

[21] Maftoonazad N., Dehghani M.R., Ramaswamy H.S. Hybrid microwave-hot air tunnel drying of onion slices: Drying kinetics, energy efficiency, product rehydration, color, and flavor characteristics. *Dry. Technol*. 2022. Vol. 40. pp. 966–986.

4. Research of quality characteristics (swelling coefficient) of Shiitake mushrooms after drying

For dried agricultural products, rehydration characteristics are often used as an index of structural quality. These characteristics largely depend on the drying conditions used.

In fig. 10 shows the dependence of the swelling coefficient on the drying modes. The material was studied in the form of a plate (Fig. 11, *b*), which was dried on an experimental stand at different temperature regimes of the coolant. Samples in the form of powder were also obtained from them (Fig. 11, *c*).

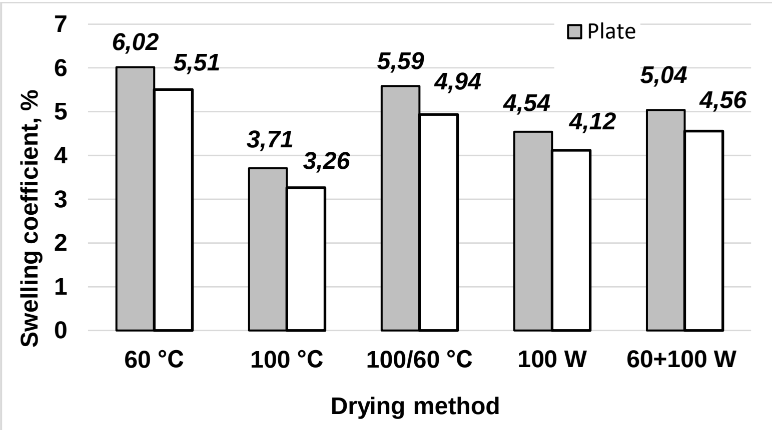

Fig. 10. Dependence of the swelling coefficient on the modes of convective drying at the heat carrier temperature 60 °C, 100 °C, 100/60 °C; with IR radiation 100 W and with the combined infrared-convective method 60/100 W

The highest value of the swelling coefficient C_{swell} – 6.02% – is for the sample (piece) dried at the temperature of the heat carrier 60 ºC. At a temperature of 100 ºC, C_{swell} decreases by 40% and is the lowest.

When drying mushrooms under infrared radiation with a lamp power of 100 W – C_{swell} is 25% less. With effective two-stage and combined modes by 7–11% and 5–7 %, respectively. That is, these two modes are not only energy efficient, but also preserve the physical properties of the material as much as possible.

As can be seen from Figure 10, the coefficient of swelling C_{swell} of the samples that were presented in the form of a piece, for each mode, is 9–12% more meaning, than for the samples in the form of powders.

Fig. 11. Appearance of Shiitake in fresh form (*a*), in dried form - plate (*b*), powder (*c*)

In our opinion, in a piece, the structural skeleton is not physically disturbed, and in the powdery state, the skeleton of the material is already disturbed, which becomes finely dispersed. During the experiment, dry substances are released from the powder into the water, so the weight and recoverability are lower, and in a plate they remain unchanged.

CONCLUSIONS

1. The most effective modes of drying cultivated shiitake mushrooms were determined – two-stage 100/60 °C and combined (infrared-convective) 100 W + 60 °C.
2. The drying time for cultivated shiitake mushrooms is reduced by 1.4-1.6 times compared to the 60 ºC regime, due to which almost no oxidation of the mushrooms occurs, which is the key to the light color of the dry product.
3. The nature of the change in Rebinder's number depending on the temperature of the heat carrier proves the effectiveness of the introduction of stepwise drying modes.
4. The coefficient of swelling for each mode and form of samples (plates, powder), the maximum value of which in the combined and two-stage mode is 7 and 11%.

SUMMARY

This study evaluated different regimes of combined infrared and convective dehydration methods on the kinetics and swelling coefficient of cultivated Shiitake mushrooms.

Fresh cultivated shiitake mushrooms were purchased from one batch in a Kyiv supermarket chain from the "Kingdom of Mushrooms" trademark. Mushrooms were sorted by shape, maturity and size. The kinetics of drying was investigated by convective two-stage 100/60 ºC and combined 100 W+60 ºC methods on an experimental research stand developed at the Institute of Engineering Thermophysics of NAS of Ukraine. The qualitative characteristics of dried mushrooms were investigated by the rehydration method.

The study of the effect of combined methods of infrared radiation and convective dehydration on the kinetics and swelling coefficient of cultivated Shiitake mushrooms was successful in determining the optimal conditions for drying and preserving products.

The change in moisture content of Shiitake mushrooms at a coolant temperature of 60 °C takes 156 minutes, and with the two-stage method of 100/60 °C (convective) it takes 97 minutes. When using the combined method of 100 W + 60 ºC, the humidity changes in 110 minutes. The use of the combined method of 100 W + 60 ºC and two-stage 100/60 ºC reduces the drying time by 1.4–1.6 times compared to the traditional mode of 60 ºC.

The efficiency of these processes is confirmed by the definition of a change in the Rebinder number, which depends on the coolant temperature and moisture content. During the period of changing the humidity of cultivated shiitake mushrooms from 84-10%, the value of the Rebinder number Rb is minimal. After 10% moisture of the material, the Rebinder number increases sharply, which means that most of the telpot is spent on heating the material, which leads to an increase in energy consumption for the process and a deterioration in the quality of the material. The determination of rehydration properties confirmed the high quality of the samples under these modes, which retain the physical properties of the material.

The study provides valuable information on the optimization of drying processes, contributing to the production of high-quality dried mushrooms with increased nutritional value.

The difference between the duration of drying processes combined infrared-convective 100 W + 60 ºC and two-stage 100/60 ºC is 0.5%. Therefore, these two modes are the most effective and can be recommended for use.

Bibliography

1. Tsotsas E., Mujumdar A.S. Modern Drying Technology. Wiley-VCH Verlag Weinheim, Germany, 2011. ISBN 978-3-527-31558-1.
2. Mujumdar A.S. (Ed.) Handbook of Industrial Drying, 4th ed.; CRC Press Boca Raton, FL, USA, 2015, ISBN 9781466596665.
3. Barba F.J., Roselló-Soto E., Marszałek K., Bursa´c Kovaˇcevi´c D., Režek Jambrak A., Lorenzo J.M., Chemat F., Putnik P. Green food processing: Concepts, strategies, and tools. In Green Food Processing Techniques. *Elsevier: Amsterdam, The Netherlands.* 2019, pp. 1–21, ISBN 9780128153536.
4. Yang X., Zhang Y., Kong Y., Zhao J. Sun Y., Huang M. Comparative analysis of taste compounds in shiitake mushrooms processed by hot air drying and freeze drying. *International Journal of Food Properties*. 2019, 22 (1), pp. 1100-1111, DOI: 10.1080/10942912.2019.1628777

5. Subramaniam Sh., Shunshun J., Zhang Zh., Pu J. Impact of post-harvest processing or thermal dehydration on physiochemical, nutritional and sensory quality of shiitake mushrooms. *Comprehensive Reviews in Food Science and Food Safety*. 2021. Vol. 20. pp. 2560–2595. DOI 10.1111/1541-4337.12738.

6. Hu L., Bi J., Jin X., Qiu Y. Study on the Rehydration Quality Improvement of shiitake Mushroom by Combined Drying Methods. *Foods*. 2021. Vol. 10. p. 769, https://doi.org/10.3390/foods10040769

7. Tian Y., Zhao Y., Huang J., Zeng H., Zheng B. Effects of different drying methods on the product quality and volatile compounds of whole shiitake mushrooms. *Food Chemistry*. 2016. Vol. 197. pp. 714–722. https://doi.org/10.1016/j.foodchem.2015.11.029

8. Турчина Т.Я., Жукотський Е.К., Костянець Л.О., Макаренко А.А. Моделювання впливу β-циклодекстрину як структуруючої добавки на кінетику сушіння водної суспензії їстівного гриба шиїтаке. Наукові праці ОНАХТ, (2019), Vol. 83 (1), pp. 152-156.

9. Chandrasekaran S., Ramanathan S., Basak T. Microwave food processing, *Food Research International*. 2013. Vol. 52 (1). pp. 243–261.

10. Argyropoulos D., Khan M., Müller J. Effect of drying temperature and pre-treatment on color and textural changes during convective air drying of Boletus edulis mushroom. *17th International Drying Symposium (IDS 2010)*. 2010. pp. 1404-1409.

11. Argyropoulos D., Müller J. Convective drying and desorption isotherms of Shiitake (Lentinula edodes) mushroom. *Agricultural and Food Sciences*. (2013). Available at https://opus.unihohenheim.de/volltexte/2013/782/pdf/Argyropoulos_2011c.pdf

12. Xiao Ya., Zhang Y., Kong Y., Zhao J., Sun Y., Huang M. Comparative analysis of taste compounds in shiitake mushrooms processed by hot air drying and freeze drying. *International Journal of Food Properties.* 2019. Vol. 22 (1). pp. 1100-1111, DOI: 10.1080/10942912.2019.1628777

13. Zhang N., Chen H., Zhang Y., Ma L., Xu X. Comparative studies on chemical parameters and antioxidant properties of stipes and caps of shiitake mushroom as affected by different drying methods. *Journal of the Science Of Food and Agricultural*. 2013. Vol. 93 (12). pp. 3107-3113 https://doi.org/10.1002/jsfa.6151

14. Zhang M., Tang J., Mujumdar A.S., Wang S. Trends in microwave-related drying of fruits and vegetables. *Trends in Food Science & Technology.* 2006. Vol. 17 (10). pp. 524-534.

15. Wu X., Zhang M., Bhandari B. A Novel Infrared Freeze Drying (IRFD) Technology to Lower the Energy Consumption and Keep the Quality of Cordyceps Militaris. *Innovative Food Science and Emerging Technologies.* 2019. Vol. 54. pp. 34-42.

16. Петрова Ж.О., Снєжкін Ю.Ф. Енергоефективні теплотехнології переробки функціональної сировини. Монографія. Наукова думка. 2018. 187 с. ISBN 978-966-00-1620-0

17. Снєжкін Ю.Ф., Петрова Ж.О. Тепломасообмінні процеси під час одержання каротиновмісних порошків. Монографія. Академперіодика. 2007. 160 с. ISBN 978-966-360-076-5.

18. Avdieieva L., Zhukotskyi E., Dekusha H., Ivanov S. Analysis of the existing methods and specific features of drying shiitake mushroom. *Food science and technology*.(2021. 15 (3). pp. 94-107. DOI: https://doi.org/10.15673/fst.v15i3.2118

19. Kantrong H., Tansakul A., Mittal GS. Drying characteristics and quality of shiitake mushroom undergoing microwave-vacuum drying and microwave-vacuum combined with infrared drying. *Journal of food science and technology*. 2014. Vol. 51 (12). pp. 3594–3608. DOI 10.1007/s13197-012-0888-4.

20. Lichtenthaler H.K., Buschmann C. Chlorophylls and Carotenoids: Measurement and Characterization by UV-VIS Spectroscopy. *Curr. Protoc. Food Anal. Chem.* 2001. 1. F4.3.1–F4.3.8.

21. Maftoonazad N., Dehghani M.R., Ramaswamy H.S. Hybrid microwave-hot air tunnel drying of onion slices: Drying kinetics, energy efficiency, product rehydration, color, and flavor characteristics. *Dry. Technol*. 2022. Vol. 40. pp. 966–986.

Information about the authors:
Petrova Zhanna Oleksandrivna,
Doctor of Technical Sciences, Professor,
Chief Researcher
Institute of Engineering Thermophysics of the National Academy of Sciences of Ukraine
2-a, Marii Kapnist str., Kyiv, 03057, Ukraine

Samoilenko Kateryna Mykolaivna,
Candidate of Technical Sciences, Senior Researcher
Institute of Engineering Thermophysics of the National Academy of Sciences of Ukraine
2-a, Marii Kapnist str., Kyiv, 03057, Ukraine