Intensification of drying process of shiitake mushroom (*Lentinula edodes*) using combined methods of dehydration

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Abstract

Introduction. This study evaluated kinetics and value of swelling coefficient of cultivated shiitake mushrooms depending on different regimes of combined infrared and convective dehydration methods.

Materials and methods. Fresh cultivated shiitake mushrooms were sorted by shape, maturity, and size. The kinetics of the process was studied during convective two-stage drying (100 ºC+60 ºC) and combined infrared radiation and convective dehydration (100 W+60 ºC) drying.

Results and discussion. The drying of shiitake mushrooms at a heat carrier temperature of 60 °C takes 156 min. and using the two-stage convective method at 100/60 °C takes 97 min. When using the combined infrared radiation and convective dehydration method (100 W+60 ºC) the drying process takes 110 min. The use of the combined method (100 W+60 ºC) and two-stage (100 ºC/60 ºC) reduces the duration of drying by 1.4–1.6 times compared to the traditional mode of 60 ºC.

The efficiency of these processes is confirmed by a change in the Rebinder number, which depends on the heat carrier temperature and moisture content. During the period of changing the moisture content in shiitake mushrooms from 84 to 10%, the value of the Rebinder number is minimal. When the content of moisture in mushrooms reaches 10%, the Rebinder number increases sharply, which means that most of the energy is spent on heating of the material that leads to an increase in energy consumption for the process and a deterioration in the quality of the drying product. The determination of rehydration properties of mushrooms confirmed the high quality of the dried product.

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

Conclusions. The difference between the duration of drying processes using combined infrared-convective (100 W + 60 ºC) method and two-stage (100 ºC/60 ºC) method is 0.5%. It was shown that these two modes are the most effective to dry shiitake mushrooms.

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Introduction

Due to the high respiratory rate and moisture content close to 90%, cultivated shiitake mushrooms are vulnerable to microbial spoilage and deterioration in quality including texture, appearance, nutrients, and favor (Subramaniam et al., 2021; Yang et al., 2019). To extend the shelf life of mushrooms, thermal dehydration (drying), which prevents such spoilage as enzymatic darkening and microbial growth by reducing water activity, could be applied (Hu et al., 2021; Mierzwa et al., 2023). Drying significantly prolongs the shelf life of mushrooms, and dry mushrooms could be safely stored under proper conditions (Tian et al., 2016).

Turchyna et al. (2019) suggested that 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 heat carrier should be at least 180 °C, but less than 200 °C. 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.

The main modern methods of processing cultivated mushrooms were described by Avdieieva et al. (2021). The obtained results of the research by the spray method, which are presented in this paper, show that they have a favorable effect on the kinetics and content of nutrients, but lead to undesirable color changes and the use of β-cyclodextrin is not functional.

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

Argyropoulos et al. (2010) studied the convective drying of shiitake, the degree of redhydration, equilibrium moisture and color change. 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 et al. (2019) 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. Microwave drying distributes energy unevenly creating problems associated with uneven heating (Zhang et al., 2013). Vacuum drying is especially suitable for heat sensitive products. However, the low heat transfer rate in vacuum drying causes an extended drying time (Zhang et al., 2006).

Another shiitake drying method that has been investigated is microwave vacuum drying (MVD) and microwave vacuum drying combined with infrared radiation (MVD+IR) (Kantrong et al., 2014). The application of infrared radiation in 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 (Kantrong et al., 2014).

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 it can be seen from Figure 1.

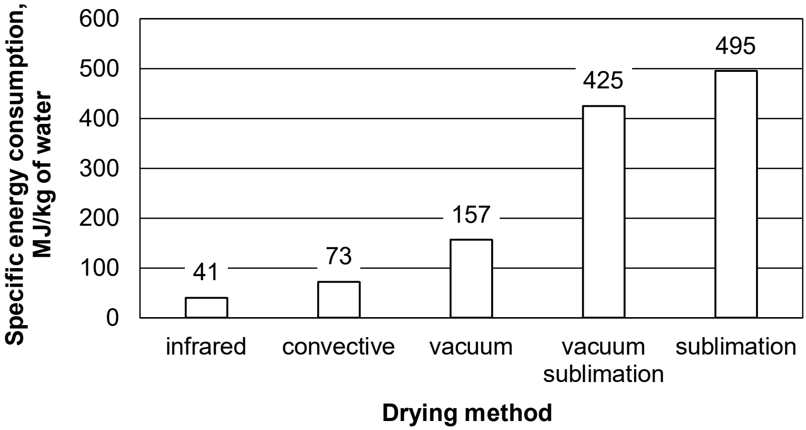

Figure 1. Specific energy consumption during drying of colloidal capillary-porous materials depending on the drying method

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 (Wu et al., 2019). 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 (Wu et al., 2019).

Previous studies (Petrova et al. 2018) have shown, that the problem of reducing energy consumption for the drying process remains relevant. Therefore, it is necessary to introduce modern energy-efficient heating technologies.

The aim of research was theoretical and experimental justification of the complex and effective processing of shiitake mushrooms taking into account the properties of the material and the development of energy-efficient drying modes due to combined and two-stage dehydration methods.

Materials and methods

Materials

Fresh shiitake mushrooms were sorted by shape, maturity, and size. All mushrooms were stored at a temperature of 4±0.5 ºC and a relative humidity 95% in a refrigerator before the experiment. The initial moisture was 86.4±1.4 %.

Methods

Research of drying kinetics

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

Figure 2 shows a diagram of an experimental convective drying installation. A change in a wide range of the speed of movement of the heat carrier and its temperature is achieved by adjusting the operation of the fan (3) on the control panel (5). The speed of the heat carrier 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) (Petrova et al., 2018).

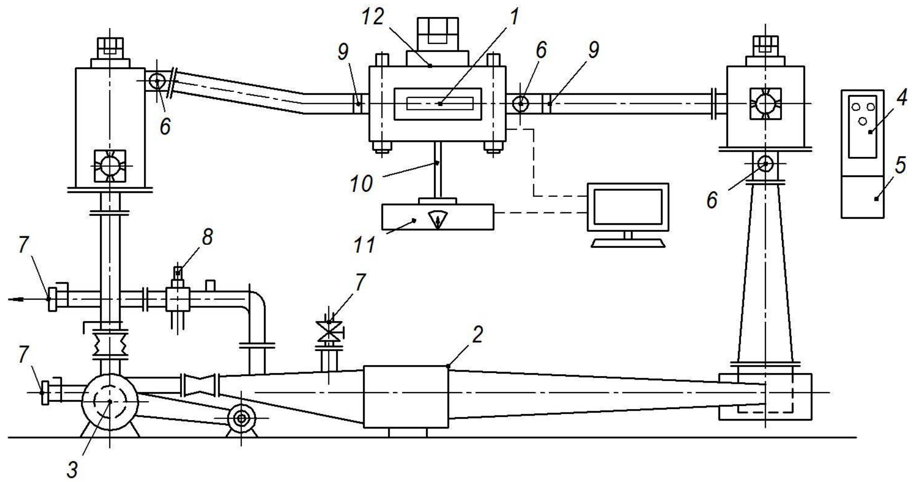

Figure 2. Scheme of the experimental convective drying installation:
1 – drying chamber; 2 – electric heaters; 3 – fan; 4 – thermostat; 5 – control panel; 6 – resistance thermometers; 7 – nozzles with valves; 8 – psychrometer; 9 – special grids; 10 – weight bar; 11 – scales, 12 – IR source (infrared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

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 heat carrier 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 (Petrova et al., 2018).

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 (Petrova et al., 2018).

Experiments on the study of drying kinetics were carried out at the rate of the heat carrier 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 ºC/60 ºC and infrared radiation of 100 W when drying on a convective installation; 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 installation, the temperature recording error does not exceed ± 1 °C and mass ± 5 mg.

Study of rehydration properties

The samples of dried mushrooms were prepared in the form of a strip (25×10×3 mm) and powder with a dispersion of less than 0.5 mm. The coefficient of swelling was determined by the method described in (Sniezhkin et al., 2007). 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.

Results and discussion

Heat and mass transfer during drying of shiitake mushrooms

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 °C /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.

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 melanoidin reactions, the destruction of vitamins and other undesirable processes, although at the same time the shortest duration of the process (Gou P. et al., 2005). 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 °C/60 °C and a material temperature of 60 °C.

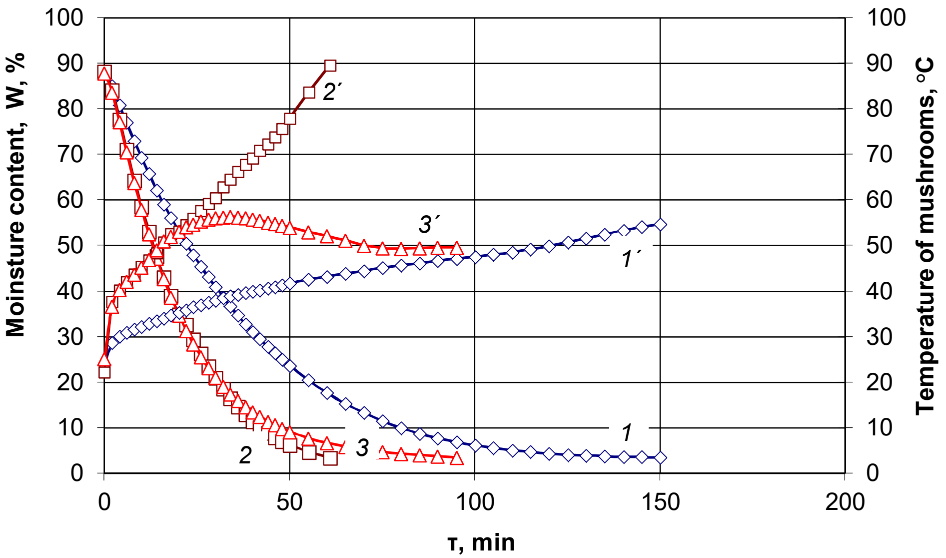

Figure 3. Changes in the moisture content and temperature of shiitake mushrooms.
1, 2, 3 – moisture; 1', 2', 3' – temperature;
δ (material thickness) = 10 mm, v (heat carrier speed)= 3 m/s,
d (moisture content of the air) = 10 g/kg dry air:
Temperatures of the heat carrier:
1, 1' – 60 °C; 2, 2' – 100 °C; 3, 3’ – 100 °C /60 °C

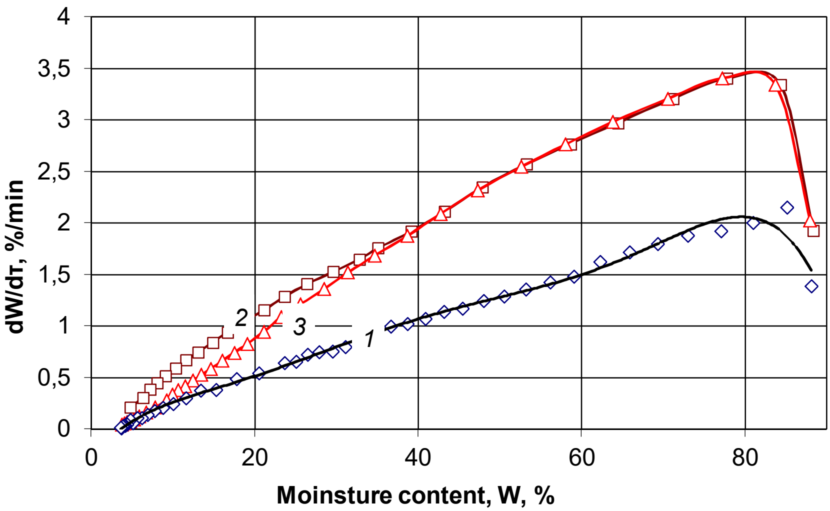

Figure 4. Change in drying rate of shiitake mushrooms.
1, 2, 3 – moisture; 1', 2', 3’ – temperature
δ (material thickness) = 10 mm, v (heat carrier speed)= 3 m/s,
d (moisture content of the air) = 10 g/kg dry air:
Temperatures of the heat carrier:
1, 1' – 60 °C; 2, 2' – 100 °C; 3, 3’ – 100 °C /60 °C

The drying rate curves (Figure 4) show, that the drying rate is 3.5%/min both at a heat carrier temperature of 100 °C and at 100 °C /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 °C/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 (Figure 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 installation), as shown in Figure 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 installation 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 Figure 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).

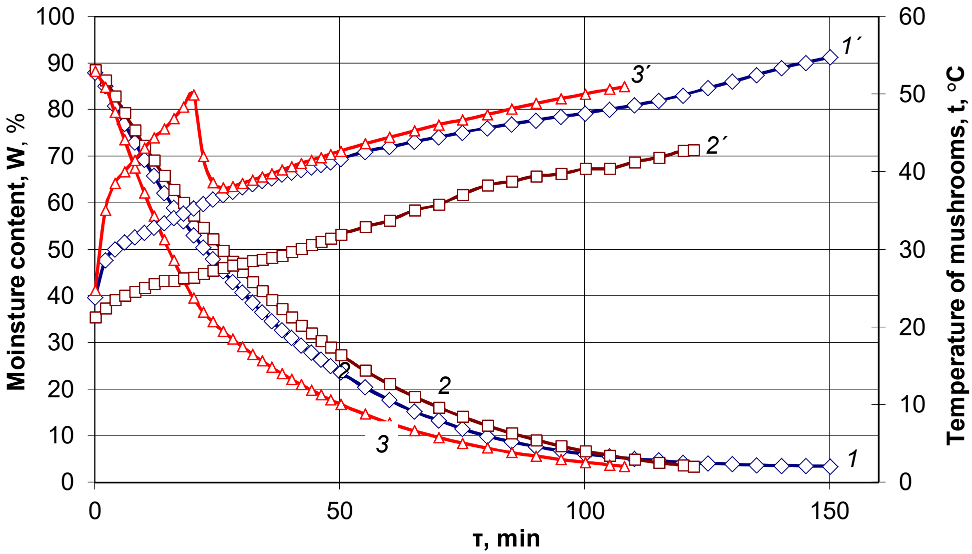

Figure 5. Change in moisture content of shiitake mushrooms during convective drying and IR (infrared radiation when drying on a convective installation).
1, 2, 3 – moisture; 1', 2', 3' – temperature;
δ (material thickness) = 10 mm, v (heat carrier speed) = 3 m/s,
d (moisture content of the air) =10 g/kg of dry air:
1, 1' – 60 °C; 2, 2' – 100W (at 20 °C); 3, 3' – 100 W+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 (Figure 6).

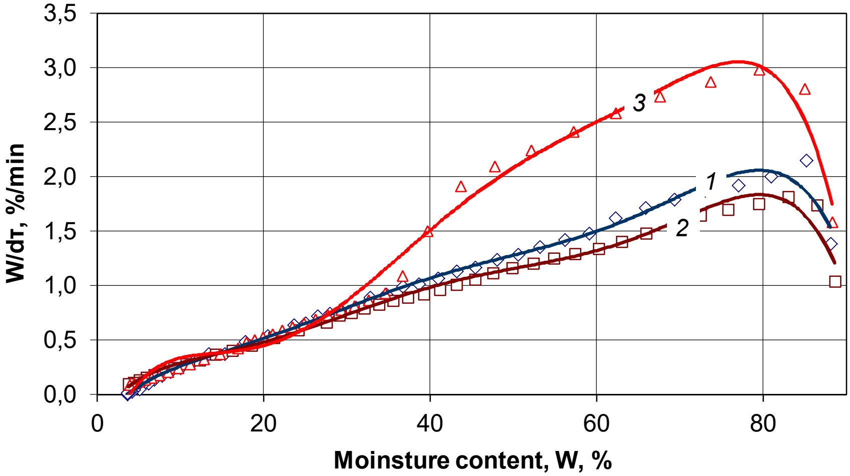

Figure 6. Influence of heat carrier temperature during convection and IR on drying rate of shiitake mushrooms.
δ (material thickness) = 10 mm, v (heat carrier speed) = 3 m/s,
d (moisture content of the air) =10 g/kg dry air:
1 – 60 °C; 2 – 100 W (at 20 °C); 3 – 100 W+60 °C

A comparative characterization of the change in moisture content of cultivated shiitake mushrooms (Figure 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.

Curve 2, 2' (Figure 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 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 is 3.5%/min (Figure 8).

These two modes are the most effective, the difference in drying 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 (Figure 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.

For comparison, the duration of drying shiitake mushrooms, which was described by Argyropoulos et al. (2010), was 190 min at 70 °C, and 1400 min at 30 °C. The duration of the combined drying method described in the present study was 110 minutes and using the two-stage method it was 97 minutes.

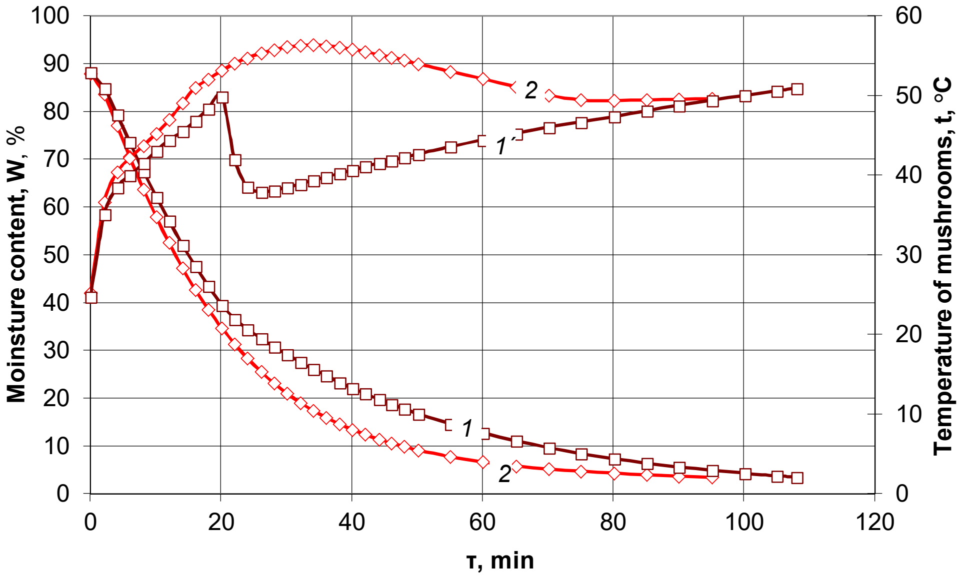

Figure 7. Comparative characteristics of changes in moisture content of shiitake mushrooms in effective drying modes.
1, 2 – moisture; 1', 2’ – temperature;
δ (material thickness) = 10 mm, v (heat carrier speed) = 3 m/s,
d (moisture content of the air) =10 g/kg dry air:
1, 1’ – 100 W+60 °C; 2, 2’ – 100 °C /60 °C

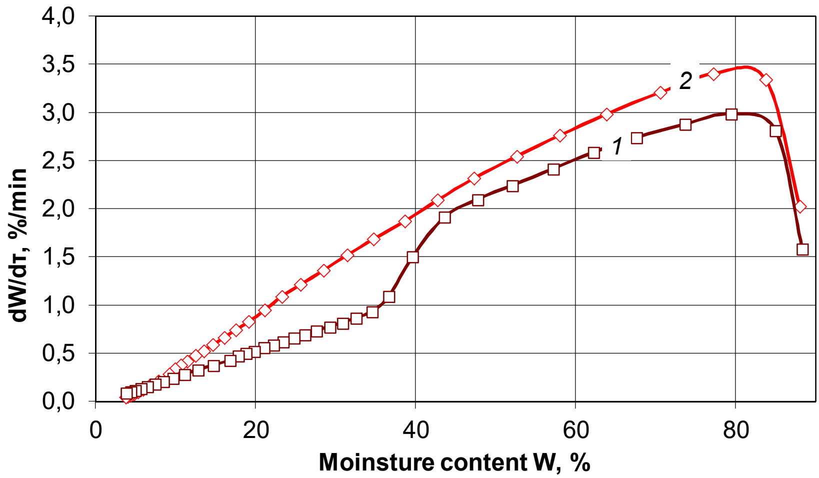

Figure 8. Comparative characteristics of drying rate of shiitake mushrooms in effective drying modes.
δ (material thickness) = 10 mm, v (heat carrier speed) = 3 m/s,
d (moisture content of the air) = 10 g/kg dry air:
1 – 100 W+60 °C; 2 – 100 °C /60 °C

Mierzwa et al. (2023) showed, that the duration of the process decreases with the use of hybrid drying. This effect was also found when drying leafy cabbage using microwave drying (Lichtenthaler et al., 2001) and hybrid microwave-convective drying of onion pieces (Maftoonazad et al., 2022). Our use of the hybrid infrared-convective method in drying Shiitake mushrooms in this work also confirmed these studies.

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 (Petrova et al., 2018):

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

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 moisture over an infinitesimally small period of time is called the temperature coefficient of drying.

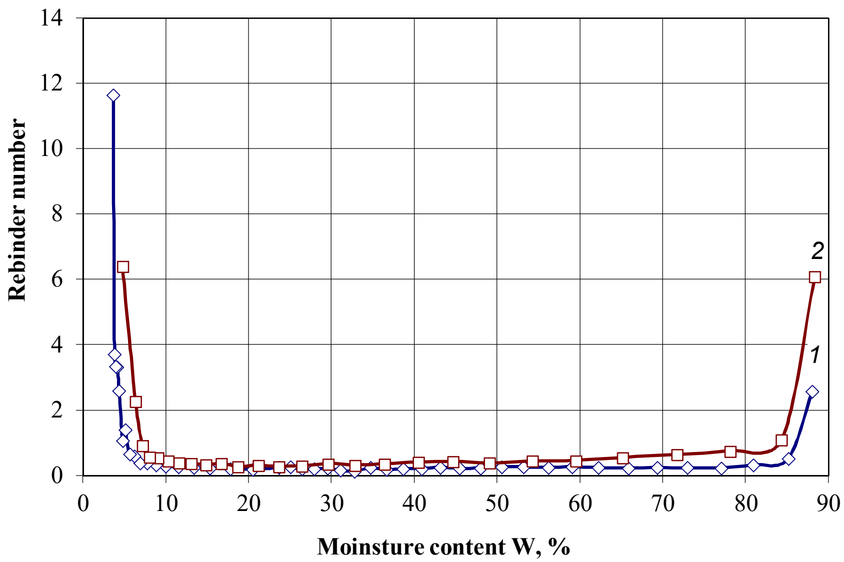

Figure 9. Change in Rebinder's number depending on heat carrier temperature.
δ (material thickness) = 10 mm, v (heat carrier speed) = 3 m/s,
d (moisture content of the air) =10 g/kg dry air:
1 – 60 °C; 2 – 100 °C

In Figure 9 it is shown the change in the Rebinder number 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.

The change in moisture content occurs from 84% to 10%, as seen in Figure 9. During the period of change in moisture of cultivated shiitake mushrooms from 84-10% to Rebinder number is minimal. At this time, most of the heat is spent on removing moisture from the material (Petrova et al, 2018). After the moisture content point of 12–10 %, the Rebinder number increases sharply, which means that most of the heat is spent on heating the material that leads to additional energy costs for the process and deterioration of the quality of the dried material. The change in Reminder number proves the effectiveness of the introduction of two-stage drying regimes.

The value of the Rebinder number depends on the temperature coefficient of drying, the specific heat capacity of the wet material, the specific heat of evaporation, and, accordingly, on the form of moisture connection with the material (Petrova et al., 2018). Therefore, it makes no sense to maintain a high temperature of the heat carrier in the last period of the dehydration process.

Mierzwa et al. (2023) found 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 (Lichtenthaler et al., 2001) and a hybrid microwave hot air drying of onion slices (Maftoonazad et al., 2022).

Quality characteristics (swelling coefficient) of dried shiitake mushrooms

For dried agricultural products, rehydration characteristics are often used as an index of structural quality. These characteristics largely depend on the drying conditions used (Sniezhkin et al., 2007). In Figure 10 the dependence of the swelling coefficient on the drying modes is shown.

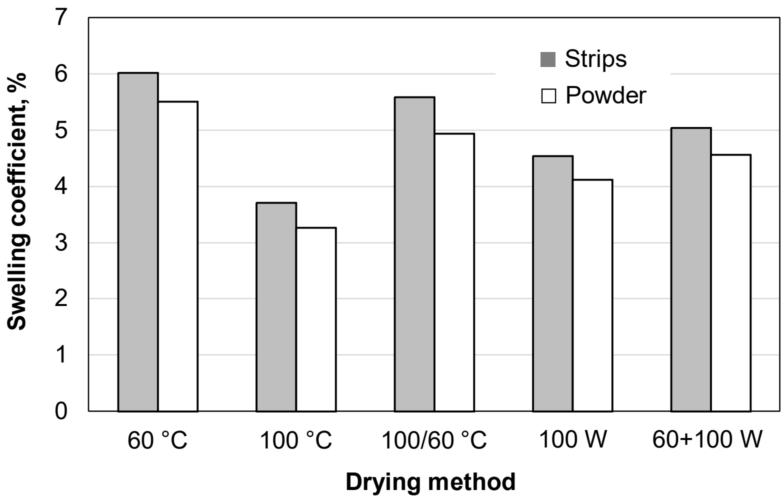

Figure 10. Dependence of the swelling coefficient on the modes of convective drying at the heat carrier temperature 60 °C, 100 °C, 100 °C /60 °C; with IR radiation 100 W and with the combined infrared-convective method 60 °C/100 W

The shiitaki (Fig, 11a) was studied in the form of dry strips (Figure 11b) or in the form of a powder (Figure 11c).

a

b

c

Figure 11. Shiitake mushrooms:
a – fresh; b – dried in form strips; c – dried in form of a powder.

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. 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 of the cultivated shiitake mushrooms were determined: two-stage 100 °C/60 °C and combined (infrared-convective) 100 W + 60 °C.
2. Using of proposed methods allow to reduce the duration of drying for shiitake mushrooms by 1.4–1.6 times compared to the 60 ºC mode, which is the key to the light color of the dry product.
3. The change in Rebinder 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 (strips or powder) has maximum value in the combined 100 Вт+60 °C and two-stage 100 °C/60 °C modes are 7 and 11%.

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