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THE USE OF REDUCED PRESSURE IN METHODS OF DRYING FOOD®

Zastosowanie obniżonego ciśnienia w metodach suszenia żywności®

Key words: vacuum drying, freeze-drying, microwave-vacuum drying, fruit, vegetables.

Currently, in addition to the attractive appearance of dried plant materials, the nutritional and health-promoting value also determine their choice by consumers. Appropriate drying methods and parameters play a key role in shaping the properties of the product with the desired quality characteristics. The article shows the beneficial aspects of drying with the use of reduced pressure, especially with microwave assistance. Despite the difficulties in selecting drying conditions for various raw materials, the use of reduced pressure and microwaves allows to obtain the desired quality of droughts and significantly shorten the drying time, which is also important in sustainable food production.

Słowa kluczowe: suszenie próżniowe, liofilizacja, suszenie mikrofalowo-próżniowe, owoce, warzywa.

Obecnie oprócz atrakcyjnego wyglądu suszonych surowców roślinnych, także wartość odżywcza i prozdrowotna decydują o ich wyborze przez konsumentów. Odpowiednie metody i parametry suszenia odgrywają kluczową rolę w kształtowaniu właściwości produktu o pożądanych cechach jakościowych. W artykule wykazano korzystne aspekty suszenia z zastosowaniem obniżonego ciśnienia, zwłaszcza ze wspomaganiem mikrofalowym. Pomimo trudności w doborze warunków suszenia dla różnych surowców, zastosowanie tej metody pozwala otrzymać susze o pożądanej jakości i znacząco skrócić czas suszenia, co jest ważne również w zrównoważonej produkcji żywności.

INTRODUCTION

Due to the seasonality of harvesting many raw materials and the limited availability in the fresh state, it is necessary to process fruit and vegetables to make them available to consumers all year round. It is especially recommended to process raw materials with a delicate and unstable structure. Dried fruit and vegetables are attractive to consumers, including as snacks or as components of many products, as they are rich in nutrients and health-promoting substances such as carbohydrates, amino acids, vitamins, minerals, and dietary fiber. They are also sensory attractive. Crunchiness, taste, and aroma are especially appreciated [20, 38, 48].

Drying is one of the most popular and oldest methods of food processing and preservation. It consists in supplying the heat needed to evaporate the water, thus reducing its content in the dried material. The low water content (water activity < 0.6) of these products means that they can be stored for a long time. Limiting the availability of water contributes to inhibiting the development of harmful microflora and ensuring microbiological stability, as well as slowing down the rate of chemical reactions and physical changes in dried food [26, 48]. As a result of the removal of water, the mass and volume of the obtained dried material are significantly reduced compared to the raw material, which reduces the costs of transport and storage. This process also allows the utilization of plant raw materials in periods of production surplus [8].

The methods and conditions of drying determine the physicochemical properties, especially in terms of shaping the sensory features, as well as the chemical composition and nutritional value [38]. The processing of fruit and vegetables is expected to be gentle, resulting in attractive, high-quality products that could be an alternative to many of the less valuable snacks on the market.

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The physicochemical properties and the quality of the dried product determine the two most important closely related factors. The first is the type and quality of the processed raw material, the second is the process conditions. The drying process is influenced by changes in the material, and at the same time, the process parameters determine the degree of changes taking place in the drought [47]. Apart from changes in the nutritional value and health-promoting value of dried products, one of the most important features influenced by the process conditions is the color of the dried material, which is a direct indicator of the quality of the drought. During drying, pigment degradation (eg. chlorophylls, anthocyanins, carotenoids) and browning may occur due to both enzymatic and non-enzymatic reactions [54, 59]. Pre-osmotic dehydration in fruit juices or concentrates in combination with innovative drying methods allows for eliminating color changes and even enriching with bio-components (natural antioxidants, organic acids, vitamins, etc.) and thus increase the attractiveness of the obtained droughts [36]. Therefore, to obtain high-quality dried material, it is necessary to select an appropriate method and drying conditions. The most important parameters are the temperature, time of the process, and the flow rate of the drying agent. Currently, drying methods using reduced pressure deserve special attention. The most important advantage of these techniques is the possibility of creating low-temperature conditions, which, in addition to increasing the efficiency of the process and saving energy, compared to other techniques, has a very positive effect on the quality of the product. Many interesting design solutions with the use of reduced pressure include vacuum (VD), microwave-vacuum (MVD), and freeze-drying (FD) dryers. Depending on the type of dryer, especially within the MVD system, the selection of drying conditions is more complex. In addition to temperature and time, microwave pressure and power (possibly frequency) are important, as well as food composition and dielectric properties.

In many publications, the influence of the application of different pressure, the drying time of food on the properties of the obtained dried material, was analyzed, e.g. from strawberries [10, 51], calabash and quince [29, 30], beetroot [42], sweet cherry [62], bamboo [43], sohiong (Prunus nepalensis) fruit [17], papaya [15], pomegranate skins [56], and also green malt [5].

The aim of the article is to review the current state of knowledge on the use of food drying methods using reduced pressure, with particular emphasis on freeze-drying, vacuum, and microwave-vacuum drying.

DRYING MECHANISM AT DIFFERENT PRESSURE

The use of different pressure in the drying process is primarily related to the possibility of effective drying of food at a moderate temperature, allowing the preservation of thermolabile ingredients. Compared to atmospheric pressure, the use of reduced pressure for drying food results in a lower boiling point of water, and thus the phase transformation necessary to ensure the drying of the material [60]. The lower the pressure value, the lower the boiling point of the water in the drying material. Moreover, the presence of dissolved substances in the water contained in the material may increase the boiling point [60]. Is observed that at the beginning of drying, the temperature of the material is close to the boiling point of water at the corresponding pressure value. In the course of the process, as the moisture decreases, the surface temperature of the material increases. At the end of drying, when a significant part of the water has evaporated, the temperature of the material increases [19].

Ciurzyńska et al. [10] presented the effect of applying different pressure during vacuum drying on the rehydration properties of dried strawberries. Vacuum drying carried out at a lower pressure of 4 kPa resulted in obtaining a product with greater rehydration capacity compared to the dried material obtained at a pressure of 16 kPa. After rehydration, the dried samples were characterized by higher water content and a greater weight gain. This is explained by greater damage to the structure of the material at higher pressure during drying. Observations were also carried out on the influence of abrupt pressure change on the quality of dried material. Two variants were used, consisting in reducing and increasing the pressure value. The step change in pressure from 16 to 4 kPa resulted in the improvement of the rehydration capacity of the dried material, which results from the increase in its porosity. However, when the pressure was changed from 4 to 16 kPa the obtained dried material had a lower water absorption capacity [10]. Wu et al. [64] investigated the effect of different pressure during vacuum drying on the amount of drying shrinkage of eggplant. With increasing pressure in the drying chamber, the material shrinkage increased. This phenomenon results from the pressure imbalance between the inside of the dried material and the outside environment, which causes stresses leading to shrinkage. As a result of the application of the reduced pressure, a much smaller pressure difference between the inside of the dried material and the external environment was observed than in the case of drying under atmospheric pressure [64].

In food processing, microwaves used in the frequency range 915 MHz – 3 GHz are easily absorbed by water, fat, and sugars contained in food [7, 25]. At this frequency range, variable movement of polar molecules is generated, and their inversion 2450 times in 1 s. This is due to the action of microwaves and electrodynamic forces causing rotation and positioning of the dipoles, depending on the variable electric field, causing the rotation of the charges and the constant movement of the dipoles. The result is intermolecular rubbing leading to the release of thermal energy in the entire material [30]. Thus, as a result of stimulating the material particles with microwaves, energy is generated in the entire volume of the material. There is also the phenomenon of electroosmosis causing the flow of a stream of liquid water to the surface, which facilitates evaporation.

Using microwave drying in an atmosphere of reduced pressure, the energy generated by the electromagnetic field causes accelerated movement of water molecules, and the force caused by the reduced pressure causes water molecules to quickly migrate from the material to the surface and evaporate. On the other hand, the vacuum system in the chamber reduces the concentration of water vapor and lowers the boiling point of water inside the chamber, thus enabling drying of the products at a lower temperature than at atmospheric pressure [25]. In addition to reduced process time and energy efficiency, the operation of microwaves and reduced pressure can improve the formation of the desired structure of the dried products. According to Anli [2], a vacuum helps evacuate water as gas molecules pass through the pores of the material; increasing the surface for mass transfer and phase transition at a lower temperature, which is extremely beneficial in drying heat-sensitive foods. Many studies show that obtaining an appropriate MVD drying effect depends on the type of raw material and the selection of drying conditions. It is often quite difficult because the individual parameters are related to each other. Process conditions are controlled by various parameters such as microwave power, pressure, temperature, as well as degree of moisture loss, as well as food composition, and dielectric properties, ie the ability to absorb and convert electrical energy into heat [25, 53], making the process complicated. The dielectric properties are important because in foods with a high dielectric loss and moisture content, the dipolar rotation in water molecules and the conversion of electromagnetic energy into heat energy increases. In materials with a low loss coefficient, called "transparent" to microwaves, microwaves do not generate heat, they tend to pass without absorption [25]. Moreover, depending on the food matrix, the effect of microwaves is related to the physical phenomenon of absorption and reflection of electromagnetic radiation, which is referred to as the resonant cavity [16, 25]. This is one of the most important issues that should be investigated because a properly designed resonance cavity can improve the distribution and homogeneity of the electromagnetic field.

As a design solution, MVD drying systems include static, rotating systems, with more than one wave generator (magnetron) and with different designs of vacuum chambers [25]. For food, mainly rotating systems are used to obtain an even distribution of radiation.

LOW-PRESSURE DRYING METHODS

Freeze-drying (FD)

Freeze-drying is the removal of water from previously frozen material by sublimation, i.e. a direct transition from solid (ice) to vapor, omitting the liquid phase. The process can take place under atmospheric pressure, but reduced pressure (below 200 Pa) is used more often [21, 34]. To ensure the proper course of drying, it is necessary to supply the heat of sublimation which is the sum of the heat of vaporization of water and the latent heat of melting ice, but without the possibility of defrosting the material, and maintaining pressure difference through the discharge of water vapor. The high quality of the dried products obtained with this method is conditioned by factors such as low temperature and the lack of oxygen. Freeze-drying allows for maintaining the shape and structure of the dried tissue. Particularly valuable are the features of drought, such as high nutritional value, natural color, intense taste, and aroma, as well as crunchiness, porosity, and the ability to rehydrate [38].

Freeze-drying is a complex process. In the first stage, the raw material is frozen, most often at a temperature of -20 to -40ºC [38]. The speed of freezing is important. Because the faster this process takes place, the smaller ice crystals are formed and the structure of the material is not damaged. The process of freezing the raw material, which precedes the freeze-drying stage, may take place under atmospheric pressure or be self- freezing as a result of lowering the pressure in the drying chamber. The latter method is usually used in freeze dryers on an industrial scale [34]. In the next stage, the phenomenon of ice sublimation occurs, which usually takes place under reduced pressure, 60–70 Pa, and lasts from 12 to 24 hours. At this stage, it is important to constantly supply the right amount of heat, as well as remove water vapor by freezing it on the cold walls of an ice condenser between the vacuum pump and the drying chamber [27, 34]. The process temperature at this stage plays an important role in shaping the structure of the lyophilized products. The use of too high a temperature may defrost the dried material, and thus the breakdown of the dry structure [11]. The first stage of drying continues until no more ice is deposited on the surface of the condenser. In the second phase of drying, non-freeze bound water is removed from the material by desorption. This stage takes place under conditions of increased temperature and reduced pressure. Its purpose is to dry the product to the desired humidity [22]. The final stage of drying significantly affects the quality of the dried material. Because, as a result of the increased temperature, there is a risk of losing many valuable thermolabile food ingredients at this stage. Therefore, this process in the case of products containing ingredients sensitive to high temperature is carried out in the temperature range of 10–35ºC, and in products with higher thermal resistance at temperatures above 50ºC. The pre-drying stage is considered complete when the dried products reach a humidity of approx. 2% and all water vapor present in the dried material is evaporated [27]. The course of lyophilization and the quality of the obtained products depend on factors such as the type of raw material (composition, humidity, maturity), the rate of freezing the raw material and the heat flux supply to the system, process parameters (temperature, pressure, time) and the method of storing lyophilisates [22, 33].

Despite many positive aspects, freeze-drying has certain disadvantages. First of all, it is a time-consuming and cost-intensive process, as the cost of freeze-drying is 4 to 8 times greater than that of convection drying [55, 63]. The high costs of the process are related to the long duration of the process, reaching even 72 hours. Moreover, the porous structure of the lyophilisates promotes oxidation processes, therefore these products should be packed without contact with oxygen and moisture [58].

Vacuum drying (VD)

Vacuum drying is characterized by a faster drying rate, resulting from a lower boiling point of water in the product under reduced pressure than at atmospheric pressure [26]. Compared to drying techniques in which the material is in direct contact with a drying agent, e.g. a stream of hot air, heat during vacuum drying is transferred by conduction through the contact of the material with the heated surface of the dryer shelf. Unlike convection drying, it is carried out at a lower temperature and with limited oxygen access, which results in the high quality of the dried material [44, 49]. Changes in color, taste, smell, and shape are limited, as well as the degradation of nutrients and health-promoting ingredients [3]. The changes in the color of carrots dried under reduced pressure were about 21% lower than during convection drying [23]. Another positive feature of this method is energy saving [3]. It is an economical and environmentally friendly method. The use of low temperatures makes it possible to use this method to dry fruits and vegetables which contain thermolabile compounds [26]. To increase the efficiency of drying under reduced pressure they are combined with microwaves [26, 58].

Microwave-vacuum drying (MVD)

Microwave-vacuum drying is a relatively new and effective technology for drying food, which allows for obtaining high-quality dried products. There are three periods of drying with the MVD method. First, the drying rate is increased in a short time, with the product reaching the boiling point of water due to the efficient transfer of microwave energy. In the constant rate step, free water is removed from the material at a constant rate. The temperature of the product during this period is relatively stable. The evaporation of the water at a constant rate can be carried out to a lower moisture level than with conventional drying. This extension of the area of constant drying rate allows for the reduction of the time of the conducted process. The final stage is a period of slowing down of the drying rate, during which the drying rate is reduced due to the removal of bound water. This step is often the longest for conventional methods as well. The use of microwave-vacuum drying allows to shorten its duration, not only due to the loss of moisture in the permanent drying period but also the evaporation of water "in situ", i.e. "in place", therefore it is faster than the diffusion of liquid water occurring during traditional drying [6, 60].

Sharma and Prasad [61] proved that drying garlic using this MVD method allowed to shorten the drying time by about 80% compared to convection drying. A comprehensive review article by González-Cavieres et al. [25] presents a lot of information about MVD, including the fact that it allows shortening the drying time by 70-90% compared to the methods of hot air drying and freeze-drying. The combination of reduced pressure and the effect of microwaves increases the drying efficiency and the possibility of producing attractive products with favorable properties and requires a lower energy demand [12, 18, 38]. The reduced pressure contributes to a relatively quick mass transfer and the microwave effect of a quick heat transfer in the entire volume of the dried material. As a result of the phase change of water to steam, an internal pressure gradient is created within the material, which causes the water to flow from the inside to the surface and then to the outside of the material. The phase transformation of water into a gas state increases the volume of the material, and the action of the reduced pressure accelerates its removal from the sample, creating the "puffing" effect. Under these conditions, a stable structure is created, also resulting from the amorphous transformation of tissue components [24, 38]. This allows obtaining a product with much lower drying shrinkage or its elimination, and with better rehydration properties than in convection drying. Such a product may be light and porous, similar to that of a freeze-dried one, but is usually harder. Moreover, many of these dried products are less sensitive to moisture than lyophilisates. The intensity of this phenomenon depends on many factors. The type of dried material is of great importance, especially its initial moisture content, but also the content of food ingredients that affect the amorphous transformation and drying conditions, such as microwave power, vacuum level, and drying time. It has been shown that the product with the "puffing" effect is obtained with higher microwave power and lower pressure [32, 35, 46]. Dai et al. [15] for various thicknesses of papaya slices (3–12 mm), tested the microwave power density in the range of 6–12 W/g, temperatures in the range of 50–70°C, and vacuum degree in relative pressure in the range from 75 to 90 kPa. The optimal technological parameters were established at a microwave power density of 10 W / g, a vacuum degree of 90 kPa, a drying temperature of approx. 55°C, and a slice thickness of 6 mm.

One of the most important disadvantages of microwave drying is the uneven heating of the material, resulting e.g. from the inhomogeneous distribution of the electromagnetic field inside the drying chamber and the inhomogeneous distribution of moisture in the material. This may cause some parts of the dried food to burn. Uniform drying can be achieved through a properly constructed microwave chamber, installation of wave mixers, a rotating drum, or temperature control with power modulation. Setting the dried material in constant motion averages the effect of the electromagnetic field on each part of the dried material, and as a result, more homogeneous heating [45]. Moreover, the moisture content may not be the same in different parts of the final product. In order to improve the process, it is recommended to combine microwave-vacuum drying with preliminary convection drying [38].

EFFECT OF SELECTED PARAMETERS ON MICROWAVE-VACUUM DRYING

In the case of microwave-vacuum drying, the microwave power, temperature, pressure, and process time have a significant impact on the process and the quality of the obtained dried products. The influence of microwave power on microwave-vacuum drying has been the subject of research by many researchers. Jałoszyński et al. [30]confirmed that with the increase in microwave power the duration of the process is shortened. Drying quince fruit using the lowest microwave power, 240 W, took the longest and lasted 51 minutes. After increasing the power to 360 W, the drying time was reduced to 39 minutes. In the case of the highest microwave power of 480 W, the process took 27 minutes. The doubling of the power reduced the processing time by 47%. The maximum material temperatures during drying depending on the power of the applied microwaves were also examined. The rapid increase in the temperature of the samples was observed in the first 3 minutes of the process. The authors confirmed the effect of increasing the microwave power on increasing the maximum temperature of the dried material. In the fruit dried at the lowest power (240 W), their temperature was 55°C. Increasing the microwave power to the level of 360 and 480 W increased the maximum material temperature to 70 and 77°C, respectively. A clear temperature stabilization was observed at the final drying stage at all three levels of microwave operation. A significant effect of the microwave power on the final drying shrinkage of the product was also observed. The highest volume shrinkage occurred when using the lowest microwave power, it was at the level of 75%. Increasing the microwave power to 360 and 480 W limited the drying shrinkage to 68 and 62%, respectively. The study showed no significant effect of the microwave power used on the antioxidant activity and the total polyphenol content in the final product. However, slightly higher values of these determinants were observed in the case of using the highest microwave power [30].

In studies conducted by Lech et al. [40], it was shown that higher microwave power increased the drying rate of beetroot slices, which resulted in a shorter process duration. The longest time was observed at a microwave power of 120 W; it was 104 minutes. With a power of 480 W, drying was the shortest to 16 minutes. Moreover, the dried obtained as a result of drying with the use of higher microwave power was characterized by a higher maximum temperature. The lowest temperature (81°C) was achieved by the dried material obtained with the use of 120 W, and the highest (138°C) was achieved by the material dried at 480 W [40]. Too high microwave power may cause a local temperature increase in the material and its local burning.

The negative effect of fixing the material by drying is the loss of heat-sensitive compounds. In the studies by Lech et al. [40] it was confirmed that the bioactive potential of dried beetroots was reduced in terms of the content of polyphenols and antioxidant activity in relation to fresh material. However, increasing the microwave power had a positive effect on both the content of polyphenols and the antioxidant activity, which was explained by a significant reduction in the drying time of the material. On the other hand, in beetroot samples subjected to initial osmotic dehydration in chokeberry juice, the increase in microwave power resulted in a significant reduction in the total content of polyphenols and antioxidant activity. This was explained by the fact that the initial osmotic dehydration increased the maximum temperature of the dried material [40].

In the case of solutions using rotary systems during microwave-vacuum drying, the rotational speed of the drum is an important parameter influencing the structure of the material. It is a variable that can prevent uneven temperature distribution during drying, as well as irreversible changes caused by electric arcs, i.e. the accumulation of excess moisture from the product on the walls of the resonance cavity or in the vacuum chamber. The research on drying pork showed that despite the use of the different rotational speeds of the drum in the range from 9 to 11 rpm, it was not possible to obtain a product without visible damage to the structure of muscle fibers. When selecting the rotational speed of the drum, an important element is to pay attention to the composition of the food undergoing drying [25], because higher rotation speeds may contribute to the formation of damage in the structure due to the collision of pieces of material, as well as the accumulation of sugars on the surface of the product, causing sticking or sticking to the walls dryers.

Effect of convective drying and osmotic pre-treatment

Initial reduction of the material moisture content by convection drying or during osmotic dehydration with slight changes in structure is a favorable method of preparing the material for drying using the microwave-vacuum method. In the studies by Kowalska et al. [35] already at the stage of pre-treatment with the use of sucrose solution or with the addition of 5% concentrated chokeberry juice, strawberries were characterized by no shrinkage and were distinguished by an attractive appearance. Fruits subjected to MVD drying underwent the puffing effect much more easily than the samples not subjected to this osmotic treatment. On the other hand, the opposite tendencies were observed during the drying of strawberries by the freeze-drying method; fruits were most easily dried without pretreatment. Also in the studies by Piotrowski et al. [50] it was shown that preliminary osmotic dehydration resulted in obtaining significantly higher values of water activity of freeze-dried strawberries as compared to the dried strawberries without preliminary drainage. Moreover, in the case of strawberries obtained by the hybrid method, the water activity after storage decreased. For the lyophilized samples, an inverse relationship was obtained [35]. Kowalska et al. [37] showed that the use of convection drying at 50°C in the first stage, and then microwave-vacuum drying (microwave power 400 W, pressure 3.5 kPa) contributed to the production of high-quality products in terms of the preservation of many polyphenolic compounds.

EFFECT OF THE APPLICATION OF DRYING UNDER LOW-PRESSURE CONDITIONS ON THE PROPERTIES OF DRIED PRODUCTS

The use of various methods of drying fruit and vegetables in an atmosphere of reduced pressure has a significant and varied impact on the physicochemical properties, analyzed with both instrumental and sensory methods, as well as the nutritional and health-promoting value. Low pressure reduces the phase transition temperature of the water, therefore water from the material can be removed under milder conditions than under atmospheric pressure. This method of conducting the process may reduce overheating of the material and the loss of thermolabile components. Drying without air access is also beneficial [1, 29]. The main advantage of freeze-drying is obtaining a product with properties similar to the raw material in terms of nutritional value and sensory values. However, both freeze-drying and microwave-vacuum drying allow for the removal of significant amounts of water, up to 95–99%, but the lyophilisates are more delicate, crunchy, and highly hygroscopic, and those dried by the MVD method are harder and less hygroscopic [38]. On the other hand, their crispness and hygroscopicity make it difficult to pack, store and transport them [9, 21]. The low temperature of the FD process allows for the preservation of natural food ingredients, e.g. vitamins, dyes, but the short drying time using the MVD method at a higher temperature may result in obtaining similar or higher contents of some ingredients, e.g. polyphenolic compounds [35, 38]. Taking into account the possibilities related to the lower energy demand in the MVD method, in the next part of the article, the properties of droughts obtained with this method will be discussed in more detail.

Jałoszyński et al. [28] observed in microwave and vacuum dried rosehips an almost 3 times higher degree of vitamin C preservation compared to convection dried material. Cui et al. [12] proved that, compared to freeze-drying, the use of microwave-vacuum drying at a similar level allowed to maintain the content of carotenoids in carrot slices and chlorophyll in chives. In the studies of Chong et al. [6], it was shown that microwave-vacuum drying allows for maintaining high antioxidant activity, polyphenol content, and attractive appearance of dried apples. Cranberries dried using this method at low microwave power turned out to be a good alternative to convective dried products in terms of color and the content of bioactive ingredients, such as polyphenols and flavonoids [65]. Similarly, MVD-dried carrot slices proved to be better in terms of beta-carotene content, vitamin C, delicate texture, and rehydration properties, compared to samples prepared by the convection method [41]. Calín-Sánchez et al. [4], examining the influence of the drying method on changes in the sensory characteristics of fruit, found that microwave-vacuum drying of chokeberry allows to obtain a high-quality product, e.g. in terms of porosity, but low hardness and bulk density, and relatively low intensity of sour taste, bitterness and astringency.

The shape change (shrinkage) and increasing the hardness of the material have a negative impact on the acceptability of dried food snacks [14]. One of the most important problems during drying is the so-called drying shrinkage, which is influenced by the structure and composition of the raw material as well as the conditions and method of drying. The shrinkage determines the quality of the dried material, because it determines its texture, limits the wettability and the ability for water adsorption, and therefore has a negative impact on the rehydration and hygroscopic properties of the product. The increasing moisture gradient in the dried material causes internal stresses and structural damage, which result, among others, from reducing the diameter of capillaries through which water flows. The gradual increase in the concentration of soluble components in the plant tissue results in the stiffening of its cell walls and the change in the properties of the material from viscoelastic to brittleness. The porosity and density of the material are closely related to the phenomenon of shrinkage; higher porosity, i.e. lower product density, conditions the occurrence of lower drying shrinkage. The products dried by the microwave-vacuum method are characterized by the high porosity of the structure, which in turn contributes to higher values of rehydration coefficients [1]. Jałoszyński et al. [31] observed a significant influence of the drying method and process parameters on the drying shrinkage of the scorzonera root. The highest shrinkage occurred in the case of traditional drying, it was 91%. Microwave-vacuum drying significantly reduced material shrinkage. Depending on the microwave power used, the shrinkage was in the range of 52–74%, with the lowest value occurring at the highest microwave power, and the highest at the lowest microwave power. Monteiro et al. [44] presented the influence of various drying methods on the rehydration of dried pumpkins. During rehydration at 25°C, the product of microwave-vacuum drying was characterized by a higher moisture content after rehydration than that obtained by lyophilization and convection. When using a higher temperature (80°C), microwave-vacuum dried samples showed lower values of the rehydration coefficient compared to lyophilisates, but higher than in the case of convection droughts.

According to the research by Kowalska et al. [38] strawberries dried by MVD without pre-treatment were too soft. It was probably difficult to choose the right parameters to obtain a texture similar to that of freeze-dried samples. The authors concluded that there was probably not enough (there was not enough) an ingredient that would strengthen the structure of the dried fruit, such as sugar. As a result, the samples were unevenly dried, burnt in places, especially inside, and damp in places. However, the hardness of dried strawberries increased depending on the amount of concentrated chokeberry juice added (5 or 15%) to the sucrose solution (from 48.3 to 56.8 N). Conversely, freeze-dried samples were characterized by lower hardness but greater brittleness, and those after initial dehydration became more flexible and soft. Initial freeze-drying of the dehydrated osmotic fruits was difficult. The more stable and higher hardness of dried strawberries obtained by the method with pre-osmotic treatment should be explained by the difference in the mechanism of both methods of drying. In dehydrated and MVD-dried samples, a stable structure arises as a result of an amorphous transformation of plant tissue components. It was favored by factors such as temperature, increased content of carbohydrate components that had penetrated from the osmotic solution [57]. The fruit tissue filled with the osmotic substance has become more resistant to shape changes caused by the collapse of the cell walls. In the freeze-drying method, sublimation of ice occurs in the frozen material with a high sugar content, which may be difficult, e.g. due to the entrapment of water in a concentrated, highly viscous liquid phase. Also, too high lyophilization temperature may cause the collapse of the structure of the material, which may be associated with exceeding the critical temperature at which the glass transition took place [39]. Similarly, when the temperature is too low, the drying rate of the material is not fast and efficient enough [55]. In the studies by Prosapio et al. [52] it was shown that initial osmotic dehydration allowed to keep the structure of strawberries dried by freeze-drying, compared to non-osmotically dehydrated samples. It was also shown that samples with medium moisture content formed less ice, and the presence of sugar causes the formation of smaller crystals because under such conditions it promotes the nucleation process and not the growth of ice crystals.

Cui et al. [13] attempted to combine microwave-vacuum drying with freeze-drying in order to obtain dried carrots and apples. This hybrid drying system proved to be an excellent alternative in which high-quality dried samples were obtained. The combination of both drying techniques allowed for the preservation of a higher content of vitamin C and carotene in the dried material, as well as obtaining favorable color, texture, and rehydration properties. At the same time, despite the multi-stage nature of freeze-drying, the combination of both methods of drying allowed to shorten the drying time compared to freeze-drying.

CONCLUSIONS

Drying is important in food production in the era of developing production including the production of fruit and vegetable snacks (chips), which are more and more common on the market. common on the market. The choice of food processing methods, and especially the drying of plant raw materials, should respond to the growing awareness of consumers in terms of nutritional and health-promoting quality. Sensory qualities are also always important. In the case of snacks in the form of dried fruit or vegetables, crunchiness is important in addition to the outside appearance. The qualitative features of the obtained droughts are shaped by both the appropriately selected method and the parameters of the process itself. Drying methods using reduced pressure, especially with microwave support, often considered innovative, should be used more widely. They allow for obtaining high-quality dried products in terms of sensory features, nutritional value, and microbiological stability. These technological solutions are also important for energy savings, especially in sustainable production. Despite the difficulties in selecting the appropriate drying parameters, depending on the type of raw material, the use of reduced pressure and microwaves allows to significantly shorten the drying time and obtain products of the desired quality.

WNIOSKI

Suszarnictwo ma istotne znaczenie w produkcji żywności, w tym do wytwarzania coraz bardziej powszechnych na rynku przekąsek (chipsów) owocowych i warzywnych. Dobór metod przetwarzania żywności, a zwłaszcza suszenia surowców roślinnych, musi stanowić odpowiedź na wzrastającą świadomość konsumentów odnośnie jakości żywieniowej i prozdrowotnej. Zawsze ważne są również cechy sensoryczne. W przypadku przekąsek w postaci suszonych owoców lub warzyw oprócz wyglądu zewnętrznego, ważna jest chrupkość. Cechy jakościowe otrzymanych suszy kształtuje zarówno odpowiednio dobrana metoda, jak i parametry samego procesu. Metody suszenia z zastosowaniem obniżonego ciśnienia, zwłaszcza ze wspomaganiem mikrofalowym, często uznawane za innowacyjne, powinny być szerzej wykorzystywane. Pozwalają one uzyskać susze wysokiej jakości pod względem cech sensorycznych, wartości odżywczej i trwałości mikrobiologicznej. Te rozwiązania technologiczne ważne są również ze względu na oszczędności energetyczne, zwłaszcza w produkcji zrównoważonej. Mimo trudności w doborze odpowiednich parametrów suszenia, zależnie od rodzaju surowca, zastosowanie obniżonego ciśnienia i mikrofal pozwala znacząco skrócić czas suszenia i otrzymać susze o pożądanej jakości.

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