

ADVANCED FRUIT DRYING TECHNOLOGIES

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Summary. Drying is a process aimed i.a. at extending the shelf life of food products. Depending on the possibilities, needs and raw material, different drying techniques are used. This study aims to discuss promising and still developed fruit drying methods. Commonly used convection drying and freeze drying offering the highest quality products were acknowledged as the reference methods. Following drying methods: superheated steam drying, supercritical fluids drying, electrohydrodynamic drying, microwave vacuum drying and drying through controlled pressure drop are described. The impact of these drying methods on the product quality, process efficiency and economy was described.

Key words: SSD, SCF, EHD, MVD, DIC, PEF, novel drying

INTRODUCTION

Drying is a process that involves removing water from the raw material utilising a phase transformation, to a level that stops the development of microbiota, while slowing or limiting chemical, biochemical and physical processes [Vega-Gálvez et al. 2011]. Drying of food products enables their safe storage for a long time, minimises weight loss during storage and significantly reduces transport costs [Sagar and Kumar 2010].

The quality of a dehydrated food product is most often determined by the following features and issues: preservation of flavours, preservation of heat and oxygen-sensitive nutrients, product browning, rehydration capacity, uniform quality as well as appearance and texture [Zhang et al. 2017]. Therefore, drying should take place in the shortest possible time, causing the least stress for the tissue, with minimal deformation of the product, without inducing chemical or biochemical reactions. From an industrial point of view, the process should require small financial outlays, be fast and energy-efficient. Commonly used drying methods implement only a few of these postulates at the same time, hence research focus on the use of modern pre-treatment methods together with combined drying methods [Vega-Gálvez et al. 2011].

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REFERENCE METHODS

Convective drying (CD)

In food processing, several drying methods are used. One of the most common methods is convection (convective, air, hot air) drying. The reasons for the popularity of this method are independence from climatic and weather conditions and the high cost of alternative techniques. Removal of water by this method requires long-term maintenance of elevated temperature combined with forced airflow. The material obtained in this way differs from the raw product in terms of colour, taste, smell, and above all texture [Ciużyńska et al. 2012]. Convection drying significantly affects the quality of the product. High temperature, long-term contact with oxygen catalyses a number of chemical and biochemical reactions that can cause, among others changes in colour, taste, aroma and nutritional value [Kowalski and Mierzwa 2013]. Other negative effects include significant shrinkage and deformation – this results in the deterioration of the appearance of the product and hinders its rehydration [Contreras et al. 2008, Arslan and Özcan 2011]. Adverse biochemical changes caused by drying include, among others loss of vitamins and enzymes, degradation of pigments. Observed physical changes include contraction, reduced or increased porosity, limited ability to bind water and damage at the cellular level [Witrowa-Rajchert and Lewicki 2006]. The obtained product varies in quality, which is why attempts are made to reduce the negative effects of drying, among others by increasing the resistance of cells and their compounds to high temperatures and shortening drying time [Lewicki and Porzecka-Pawlak 2005].

Freeze drying (FD)

Freeze drying (sublimation drying lyophilization) allows obtaining dried foods that exceed the features and parameters of products produced by other techniques. In food technology, it is often the reference method for maintaining high quality. It is used for perishable, high water content, easily damaged, special purpose and luxury products. Deep freezing of the raw material, followed by heating under reduced pressure makes this method energy-intensive and expensive [Donsi et al. 2001]. Therefore, attempts are being made to modify this process in order to shorten or simplify it [Ciużyńska et al. 2012, Pei et al. 2014]. Drying is carried out under conditions of reduced pressure so that the resulting product is porous, the tissues are uncontracted, minimal loss of taste and aroma is observed. The low temperature of the process and the lack of water in the liquid state means that non-enzymatic browning reactions, protein denaturation or enzymatic reactions are inhibited [Liapis and Bruttini 2015].

METHODS FOR OBTAINING HIGH QUALITY DRIED FRUIT

Drying with superheated steam under normal (SSD) and reduced pressure (LPSSD) conditions

Saturated water vapour is formed when water reaches a boiling point and all water molecules are converted into gas. Further heating it under constant pressure converts it into superheated steam. The superheated steam introduced into the drying chamber trans-

fers heat to the product, while the water removed from the raw material becomes part of the drying medium. Utilised steam can be removed, recycled or condensed, so the heat can be recovered [Sehrawat et al. 2016]. Drying with overheated steam is characterised by low energy consumption, the possibility of reusing the heating medium and reducing the severity of the oxidation reaction in the raw material. After reaching the inversion temperature, it is also possible to obtain a higher drying rate than for convection drying [Jangam and Mujumdar 2015]. An important feature of this technology is the fact that commonly used convection dryers can be easily adapted for drying using superheated steam [Tatemoto et al. 2007]. Numerous studies have shown the possibility of using SSD, among others drying of apples [Elustondo et al. 2001] and coconut slices [Sook Yun et al. 2015] can be highlighted.

The SSD method is not optimal for drying products sensitive to heat and oxygen. Therefore, a method of drying by superheated steam under reduced pressure (LPSSD) was developed [Zhang et al. 2017]. The effectiveness of such a modified method in maintaining the physical and chemical properties “as it was demonstrated” of products for cabbage [Phungamngoen et al. 2013], bananas [Nimmol et al. 2007] and mangosteen skins [Suvarnakuta et al. 2011].

Supercritical fluid drying (SCF)

Supercritical fluids (SCF) have been used in the food industry as extraction solvents since the early 1980s [Bourdoux et al. 2016]. Carbon dioxide (scCO_2) is most often used to process food with supercritical fluids because it is recognised as a safe solvent (GRAS) [Raventós et al. 2002].

The drying process using scCO_2 is a process of extracting water that dissolves in scCO_2 [Benali and Boumghar 2015]. The disadvantage of this process is the low water solubility in scCO_2 , which can be increased by adding a co-solvent. In the study carried out by Brown et al. [2008] [Brown et al. 2008] the effect of ethanol addition to scCO_2 and temperature on the carrot drying process was investigated. Samples obtained by convective drying were used as the reference method. It was found that carrots obtained in pure scCO_2 had less shrinkage, and dried samples with the addition of ethanol were less compressed, which means that they had better rehydration properties.

Electrohydrodynamic drying (EHD)

The most commonly used drying technologies are based on conduction, radiation or convection. An example of non-thermal drying of food products is electrostatic treatment [Zhang et al. 2017]. Corona discharge ionizes the air components, which are created the ionic wind, enables removing water from the raw material. The possibility of using this method for drying has been proven rapeseed [Basiry and Esehaghbeygi 2010], tomatoes [Esehaghbeygi and Basiry 2011] and Goji berries [Yang and Ding 2016]. Two key features speak for the potential further development of this method. Compared to convective drying and freeze drying, EHD dryers have a simpler design and consume less energy. The EHD method is a non-thermal technique that lowers the temperature of the raw material during water removal. This is due to fast evaporative cooling

as well as reduced entropy of the system caused by the orientation of the particles in the electric field [Zhang et al. 2017].

Shortening the drying time, reducing energy consumption or improving the quality of the product is also possible using several different methods. These methods are used in tandem (in series) or together (in parallel). Two or more drying methods are used simultaneously in parallel drying. Series (tandem) drying involves the use of several successive different pre-treatment or drying methods [Zhang et al. 2017].

Convective drying assisted by microwave vacuum drying (C-MVD)

Convective drying assisted by microwave-vacuum drying is one of the combined methods, the aim of which is to improve the quality of the obtained product. The process is two-stage, the first stage is convective drying, which aims to reduce the water content, and the next stage is microwave-vacuum drying, which aims, among others obtaining increased (or recovery) product volume the “puffing” effect [Zielinska et al. 2013].

The microwave energy is delivered over the entire volume of the tissue and is absorbed by the water molecules, which causes their rapid heating and evaporation. Drying in vacuum conditions allows water to be removed at low temperature. Eliminating the presence of oxygen during the process reduces the number of autooxidation reactions, which is why the colour and taste of dried fruit during drying does not deteriorate. Drying time is shorter, drying efficiency increases, and the obtained product is characterised by higher quality and practically homogeneous humidity [Bórquez et al. 2010, Zielinska et al. 2013].

This method has been developed for drying of medium-sized pieces of fruit and plants that rehydrate quickly, at a cost comparable to drying with hot air. In industrial practice, the process consists of the following phases: pre-drying, puffing, and subsequent drying until the desired humidity is reached. Pre-drying is to reduce the water content in the tissue so that too much volume of vapour released does not damage the fruit tissue. Puffing improves porosity and accelerates further drying, eliminating the need for control diffusion drying. This method minimises the unfavourable hardening of the dried surface layer, which enables drying larger pieces of fruit, and also reduces browning of the drought. Better rehydrating properties of the dried by these method materials in comparison to air dried samples have been confirmed experimentally [Jayaraman and Gupta 2015]. Thanks to this method, it is possible to obtain a product with properties similar or superior to products obtained by the sublimation method. Promising results were obtained by combining this method with osmotic pre-treatment [Cieurzyńska et al. 2012].

Drying assisted by immediate controlled pressure drop (DIC)

Immediate controlled pressure drop (DIC) is a finishing treatment method that can be combined with other drying technology. It is based on thermo-mechanical transformation caused by a sharp drop in pressure, which leads to the expansion of the dried material [Alonzo-Macias et al. 2014].

This method allows the structure to be preserved, reduces shrinkage while maintaining the nutritional value of the raw material [J. Yi et al. 2016]. Studies have shown that DIC can be used to obtain high-quality fruit chips from apples, peaches, strawberries and

nuts [Alonzo-Macias et al. 2014, Lyu et al. 2015, J. Yi et al. 2016, J.-Y. Yi et al. 2016]. The high water content of fruits and vegetables makes it necessary to use pre-drying before DIC.

In practice, the fruit is usually dried until it reaches a low water content, and then stored to equalize the moisture level in the raw material (MEP). This improves the quality of the final product and prevents bubbling during DIC. Maintaining proper water content is a driving force for material expansion, which is why in industrial conditions MEP is carried out by direct immersion or spraying with water or osmoactive solutions [Zhou et al. 2018].

PRE-TREATMENT

Pulsed electric field pre-treatment (PEF)

Pre-treatment before drying is aimed at reducing the energy consumption needed for the process, as well as maintaining the highest nutritional value characteristic of the raw material in the dried material. In the last two decades, a lot of attention has been devoted to non-thermal methods that affect the speed of drying because they can increase the permeability of cell membranes [Sagar and Kumar 2010, Betoret et al. 2015]. One such method is the pulsed electric field (PEF) [Jin et al. 2015]. This method is distinguished by operation on the entire volume of raw material, the possibility of continuous operation and short processing time [Odriozola-Serrano et al. 2013]. This process involves the operation of high-intensity electric field pulses of $1\text{--}10\text{ kV}\cdot\text{cm}^{-1}$, in the range from $20\ \mu\text{s}$ to 10 ms. This causes a temporary or permanent increase in the permeability of cell membranes, and thus reduces the mass transfer resistance [Wiktor et al. 2016]. As a result, it shortens the drying time, without adversely affecting the other physicochemical parameters [Lamanauskas et al. 2015].

In studies conducted by Lamanauskas et al. [2015], it has been proven that optimal PEF parameters can shorten the drying process of the fruit of the *Actinidia kolomikta* in a fluidised bed by 50% without loss of vitamin C. Jin et al. [2015] studied the impact of the PEF on the kinetics of the blueberry vacuum drying process. Depending on the temperature used, the PEF treatment reduced the duration of the process by 30–40%, and at the same time, there was no negative impact on the content of anthocyanins, vitamin C and dried antioxidant capacity.

Osmotic dehydration (OD)

Osmotic dehydration (OD) is a process in which water migrates through a semi-permeable membrane, from a lower concentration of solute to a higher concentration until the equilibrium is obtained. This reduces both the water activity and the water content of the material. This process allows both to increase the quality of dried material and has a positive effect on the economics of the process [Kowalski and Mierzwa 2013]. Dehydration often precedes various technological treatments because it does not stop the growth of microflora.

In the experiment performed by Bórquez et al. [2010], researchers dried dehydrated raspberries under lower pressure to enhance mass exchange process. They established that this type of pre-treatment can positively influence retention of vitamin C in the dried fruits. Moreover, osmotic dehydration increased the drying rate, and shortened the drying time.

RECAPITULATION

The review showed selected and currently promising fruit drying methods. Increasing energy prices and consumer expectations mean that the attention of scientists and industry will be focused on the development of methods that can meet both of these postulates. The presented conventional and unconventional methods present different ways to solve both of these challenges simultaneously.

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UDOSKONALONE METODY SUSZENIA OWOCÓW

Streszczenie. Suszenie to proces, którego głównym celem jest przedłużenie trwałości produktu. W zależności od możliwości, potrzeb i rodzaju suszonego materiału stosowane są różne techniki i parametry suszenia. Celem pracy była analiza obiecujących i dalej rozwijanych metod suszenia owoców. Jako punkt odniesienia wybrano dwie metody suszenia. Powszechnie stosowane suszenie konwekcyjne oferujące niedrogi produkt niskiej jakości oraz liofilizację umożliwiającą uzyskanie suszu wysokiej jakości uznano za metody referencyjne. W artykule opisano metody suszenia z zastosowaniem pary przegrzanej oraz płynów w stanie nadkrytycznym, a także techniki suszenia elektrohydrodynamicznego, mikrofalowo-próżniowego i kontrolowanego spadku ciśnienia. Dodatkowo uwzględniono metody obróbki wstępnej takie jak pulsacyjne pole elektryczne i odwadnianie osmotyczne. Opisano wpływ zastosowanych metod na jakość uzyskanego suszu, wydajność procesu oraz zawartość substancji termolabilnych.

Słowa kluczowe: suszenie parą przegrzaną, nadkrytyczne, elektrohydrodynamiczne, mikrofalowo-próżniowe, natychmiastowy kontrolowany spadek ciśnienia, pulsacyjne pole elektryczne