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Comparative analysis of dehydration methods for apple fruit

Análise comparativa de métodos de desidratação do fruto maçã

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ABSTRACT

Fruit dehydration is a key option for food preservation, in order to increase shelf life and promote exportation. Numerous methods of dehydration have been developed in recent decades. The aim of the present work is to perform an assessment of the dehydration methods used more frequently with apple fruit, and subsequently, compare them as to the conditions of operation (temperature, speed of drying and drying time) and energy aspects (energy requirement and energetic efficiency). The comparative analysis shows that drying with microwave associated with a second method of drying has greater benefits in terms of quality of the final product. In addition, using the two methods it is possible to overcome the limitations of each one used individually. The microwave drying and microwave drying combined with vacuum present the lowest drying times, 0.87-h and 0.28-h, respectively, as opposed to traditional techniques (sun drying and solar drying). In terms of energy efficiency, it was found that among the methods analysed the higher rates were observed for the fluidized bed dryer (28.0-64.0%), microwave drying (79.0%) and drying by infrared radiation (30.0-60.0%). The infrared drying method appears to be the most efficient, presenting lower costs and providing greater benefits in terms of drying times, energy efficiency and, organoleptic and nutritional characteristics of the final product.

Keywords: dehydration, energetic efficiency, quality of the final product, time drying

RESUMO

A desidratação de frutos é uma opção chave para a conservação alimentar, permitindo aumentar o tempo de conservação e promovendo a exportação. Inúmeros métodos de desidratação foram desenvolvidos nas últimas décadas. O presente artigo tem como principal objetivo realizar uma avaliação técnica relativamente aos métodos mais utilizados na desidratação de frutos. Visa ainda comparar os métodos entre si quanto às condições de operação (temperatura, velocidade de secagem e tempo de secagem) e aspetos energéticos (requisito energético e eficiência energética). Da análise comparativa verificou-se que a secagem por microondas associada a outro método de secagem apresenta maiores benefícios em termos de qualidade do produto final superando-se as limitações de cada um. A secagem por microondas e a secagem por microondas combinado com vácuo são as técnicas que possuem os menores tempos de secagem, 0,87-h e 0,28-h, respetivamente, ao invés das técnicas tradicionais (secagem ao sol e secagem solar). De entre os métodos analisados constatou-se que os que possuem maiores taxas de eficiência energética são o secador de leito fluidizado (28,0-64,0%), secagem por microondas (79,0%), secagem por radiação infravermelha (30,0-60,0%). A secagem por infravermelhos revelou ser a técnica com menores custos, apresentando maiores vantagens ao nível de tempos de secagem, eficiência energética e características organoléticas e nutricionais no produto final.

Palavras-chave: desidratação de frutos, eficiência energética, qualidade do produto final, tempo de secagem

Introduction

The dehydration process is considered the oldest technique concerning food preservation. This technology consists in the removal of the majority of the food water, involving the simultaneous transfer of heat and mass (Lee *et al*., 2013; Silva *et al*., 2014). The use of drying processes in food becomes necessary in order to increase its shelf life, as the microorganisms are not able to develop and multiply in the absence of water (inactive for water amounts < 10%, in weight), nor are enzymes active without it (in amounts < 5%, in weight, in food) (Geankoplis, 2003). There are, also, other benefits associated with the dehydration food process, such as (Lewicki, 2006; Moses *et al*., 2014):

- reduction of food weight and volume, which permits and minimizes the storage and transport costs;

- easier manipulation of product;

- and higher diversification of products, producing food with distinct organoleptic characteristics.

Dehydration Methods for Apple Processing

The dehydration methods analyzed in the present work are the most used in apple dehydration, namely sun drying, solar drying, cabinet dryer, tunnel dryer, fluidized bed dryer, microwave drying, drying by microwave with vacuum and infrared drying, as described below.

Sun Drying

Sun drying is perhaps the oldest drying technique and it is also the most simple and economic. This technique requires no equipment, since the raw materials are simply arranged in fields, roofs or other flat surfaces, being steered frequently until dry (Rigit *et al*., 2013). This natural process requires ideal environmental conditions, which are achieved during the warmer months (Sharma *et al*., 2009; Bolea *et al*., 2012). This type of dehydration presents a problem to food safety for not being able to control the contact of insects and other vectors that transmit fruit pathogens.

Solar Drying

The solar drying technique is a modification of the previous one (Sharma *et al*., 2009). The evolution of this method enabled the reduction of drying times to 1-3 days compared with the previous one (Bolea *et al*., 2012). There are several types of solar dryers, namely direct and indirect. In the first one, the solar radiation is absorbed directly by the samples, which is the most effective way of converting solar radiation into useful heat for drying. In the latter, the food is not exposed directly to solar radiation (Janjai and Bala, 2012), but instead the solar rays are collected inside a specially designed unit, which contains an adequate ventilation system for the removal of moisture from the air. The equipment consists of a transparent panel located above the manifold or camera, which is painted black to absorb the solar rays and contains a series of trays, where the prepared fruit samples are placed uniformly (Sharma *et al*., 2009). The drying air flows through the solar collector where it is heated up. The temperature inside the unit is 10^0C to 30^0C higher than outside, which results in shorter drying times (Bolea *et al*., 2012).

Cabinet Dryer

The cabinet dryer, also known as tray dryer, is composed of an isolated cabin with perforated trays, each one with a depth of 2 to 6 cm. In this type of dryer, the food is placed in the trays evenly, forming a thin layer with a thickness between 10 and 100 mm (Fellows, 2000).

In this procedure, approximately 10% to 20% of the air flowing over the surface of the trays is fresh air, while the remaining results from its own recirculation (Brennan, 2006).

Tunnel Dryer

In a tunnel dryer, the fruits are placed in trays or carts that are constantly on the move through a tunnel, in which a current of air passes over the surface of each tray. Typically, the tunnel has a length of 20 m and a circular or rectangular cross-section of 2 m x 2 m, with a capacity of 5000 kg of food (Brennan, 2006; Jayaraman and Gupta, 2006).

Fluidized Bed Dryer

Dehydration employing a fluidized bed dryer occurs by convection and, therefore, the warm air moves through the bed causing the food to become suspended and vigorously agitated (fluidized), exposing the maximum area for drying (Brennan, 2006; Randel *et al*., 2013).

This type of dryer is compact and allows a good control over the drying conditions and speeds. The fluidization depends on the characteristics of the particles, in particularly the size, density and viscosity (Cohen and Yang, 1995).

Microwave Drying

The dehydration by microwave is caused by differences in vapour pressures between the interior and the surface of the food, which creates a driving force for the transfer of moisture (Feng *et al*., 2012). The dehydration occurs between a range of 915 MHz and 2450 GHz and the wavelengths vary between 1 mm and 1 m (Moses *et al*., 2014). The most important feature of this method is the volumetric heating, which means that food can absorb microwave energy directly or internally, being converted into heat. The heat generated during this process is a result of the interaction between the electromagnetic field and food. The heat is uniformly distributed over the entire food, leading to higher speeds of heating when compared with conventional methods (Zhang *et al*., 2006).

The polarity of water molecules allows them to vibrate under the action of an alternated electric field. Considering that 50 to 97% of food is made of water, the use of electromagnetic waves for dehydration of food presents itself as a valuable alternative (Nijhuis *et al*., 1998; Vadivambal and Jayas, 2007).

Drying By Microwave Combined With Vacuum

Drying by microwave combined with vacuum application is an alternative technique that has been used in fruit dehydration in order to improve drying times and the quality of the final product. When compared with drying methods employing microwave energy only, the conjunction of both methods leads to products with higher quality, due not only to the lack of oxygen on a dry environment but also to the reduction of adverse reactions in foods (Motevalli, 2013). The use of vacuum on such systems confers advantages to the dielectric heating, and consequently the drying of the samples can be performed at lower temperatures than applying exclusively microwave drying (Drouzas and Shurbert, 1996; Siavash *et al*., 2013).

Infrared Drying

Another way of shortening the drying time is to apply heat by infrared radiation. This method is nowadays considered as an effective alternative for food dehydration, especially suitable for drying thin layers with large exposed surfaces, achieving energy efficiencies in the range of 80-90% (Ratti and Mujumdar, 2006).

The infrared radiation is transferred from a heating element to the surface of the product, without heating the surrounding air. The radiation is target to the exposed product, penetrating it, and subsequently being converted into sensitive heat. During the product drying process and due to a decrease in its water content, the absorbance ability of the dry material decreases while its reflectivity increases the transmissibility (Kumar *et al*., 2005; Nowat *et al*., 2004).

Here we analyse the most widely used dehydration methods with possible applications for apple fruit. In addition, we present a comparative analysis between conventional methods (drying in the sun, solar drying, cabinet dryer, tunnel dryer and fluidized bed dryer) and alternative methods that have been the subject of increasing interest area of food dehydration. This comparative analysis assesses mainly the operating conditions, drying times and energy efficiencies.

Assessment of conventional and emerging methods for apple dehydration

A preliminary review was carried out on the numerous drying techniques and further work was performed with selected conventional methods and methods recently emerging in the field of fruit dehydration. In terms of conventional and more recent methods, the different parameters were obtained from scientific and technical literature devoted exclusively to the drying process, particularly experimental activities focused on fruits and mushrooms, since these have a moisture content similar to apple fruit (80-90 %).

The technical analysis of the different methods used in fruit dehydration allows an accurate comparison between them (Table 1 and 2). In addition to the technical parameters analyzed (Table 1), the advantages and limitations that each method presents (Table 2) allow the evaluation of the different dehydration technologies. Of extreme importance concerning the parameters referred are the operating conditions (drying temperature and drying speed), the duration of drying and the maximum capacity of evaporation, the latter two depending on the operating conditions used in each method. Another criterion for differentiation of apple fruit dehydration methods are the energy costs, which include the energy consumption and the rate of energy efficiency (Table 1).

The definition of drying times is based on Mujumdar (2000), which consider low times as less than one minute; average drying times between 1 and 60 minutes, while long times are considered those above 60 minutes. Taking this into account, we can conclude that the drying technologies that have shorter drying times are microwave drying and microwave combined with vacuum drying. The fluidized bed dryer and infrared drying have average drying times, with values close to 60 minutes. The residence times of sun drying methodologies, solar drying, cabinet dryer and tunnel dryer are considered long, since they are higher than 60 minutes. The traditional methods (sun and solar drying) imply higher times, since these depend on weather conditions and these are not always optimum for the process.

The maximum capacity of evaporation is the amount of water that is removed per hour and, therefore, the dryer with greater capacity of water evaporation is the tunnel type (Table 1). For this reason, this method can be adjusted for large-scale applications (Jayaraman and Gupta, 2006), as opposed to the cabinet and microwave dryers that have less evaporation capacity (55-75 kg/h and 0.13 kg/h, respectively) and therefore are more appropriate for small scale use (Fellows, 2000; Zhang *et al.*, 2006).

Table 1 - Operating conditions, drying times and energetic parameters.

Dehydration methods	Temperature (ºC)	Air Velocity (m/s)	Drying time (h)	Maximum evaporation capacity (kg/h)	Specific Energy Consumption (MJ/kg_{water})	Energetic efficiency (%)	References
Sun Drying	30	-	96 – 120	-	-	-	(Bolea *et al.*, 2012; Sharma *et al.*, 2009)
Solar Drying	30	-	24 -72	-	-	-	(Bolea *et al.*, 2012; Sharma *et al.*, 2009; Mujumdar, 2000)
Cabinet Dryer	50 – 75	0.50 – 5.0	10 -60	55 -75	8 –16	14 -28	(Brennan, 2006; Bureau of Energy Efficiency and Indian Renewable Energy Development Agency, 2006; Fellows, 2000; Mujumdar, 2000)
Tunnel Dryer	50 – 75	2.50 – 6.0	0.50 – 6	5000	6 – 16	14 -38	(Brennan, 2006; Bureau of Energy Efficiency and Indian Renewable Energy Development Agency, 2006; Fellows, 2000; Mujumdar, 2000)
Fluidized Bed Dryer	-	0.20 – 5.0	1	910	3 – 8.5	28 – 64	(Bureau of Energy Efficiency and Indian Renewable Energy Development Agency, 2006; Chua and Chou, 2003; Fellows, 2000; Mujumdar, 2000)
Microwave Drying (260 W)	-	-	0.87	0.13	4.5 ± 0.21	79	(Motevali *et al.*, 2011; Siavash *et al.*, 2013)
Drying By Microwave Combined With Vacuum (260 W and 200 mbar)	-	-	0.28	-	3.66 ± 0.25	57	(Motevali *et al.*, 2011; Siavash *et al.*, 2013)
Infrared Drying (intensity of radiation 0,49 W/cm²)	-	1,0	1,13	-	76	30 – 60	(Nowat and Piotr, 2004; Samadi and Loghmanieh, 2013)

According to Table 1, the optimum temperature of operation of the sun and solar drying method is 30 ^{0}C or higher, meaning it can only be achieved in the summer, on days in which solar radiation is high. As opposed to these, the cabinet and tunnel dryers use the same range of temperatures, 50-75 ºC, when used for apple dehydration, which results in faster drying times.

In terms of energy expenses, several authors have focused on different dehydration methods mainly microwave based methods and infrared radiation techniques (Siavash *et al*., 2013); Samadi and Loghmanieh, 2013). The dehydration methods using microwave and microwave combined with vacuum are more economic when comparing with the conventional methods, due to their reduced drying times.

Specifically, in a recent report concerning both methods the authors used sliced mushrooms and during the process of drying these were weighed on a precision scale (Siavash *et al*. 2013). The drying was completed when the samples reached a moisture content of 6 - 7% (wet basis). The drying by microwave was performed at 4 power levels (130, 260, 380 and 450 W), on the other hand the drying performed by microwave combined with vacuum used 4 levels of power for the microwave and 4 vacuum pressure values (200, 400, 600 and 800 mbar). For this experimental activity a vacuum pump Kawake airvac Jp-120h and a microwave AEG Micromat 725 with rated power of 1200 W, frequency of 2450 MHz and an inner chamber with the following dimensions: 230 x 320 x 360 mm, were used. Comparing these two methods, the author concluded that the combination of microwave drying with vacuum application presents a lower drying time. On the other hand, the use of solely microwave for drying processes requires less energy rates, which can be explained by the simultaneous use of vacuum and microwave power in the latter method.

Regarding infrared radiation drying, the determination of energy consumption was achieved by Samadi and Loghmanieh (2013). Apples were previously kept in a cooling chamber at a temperature of 4±1 ^oC, and afterwards sliced with approximately 5 mm thickness. The initial moisture content of the fresh fruit used was approximately 82± 0.5% (wet basis). The dehydration was performed in an infrared dryer, which consists of two parts: (1) a camera of infrared radiation and (2) an air duct. The camera of infrared radiation is located above the air duct. This dehydrator uses infrared lamps and samples are placed in the centre of the shelf, located on top of a digital scale. During the drying process the samples of sliced apple were weighed directly on the digital scale in intervals of 30 seconds. Both the intensity of infrared radiation and the air velocity were measured using an intensity meter and an anemometer, respectively. The experimental activity was performed at an intensity of infrared radiation of 0.22 W/cm^2, and 0.31 W/cm^2 and 0.49 W/cm^2, with an air velocity of 1 m/s. However, table 1 only presents data related to an intensity of infrared radiation of 0.49 W/cm^2, as this one represents less time, lower energy consumption and lower drying times. In general, as reported by these authors, this technology presents a high specific energy consumption, which can be related to the air velocity used and depends on the distance between the infrared energy transmitters and the irradiated surface. In theory, infrared drying can achieve an energy efficiency in the range of 80-90% (Ratti and Mujumdar, 2006; Nowat and Piotr, 2004), although such results were not observed in the studies of Samadi and Loghmanieh (2013).

Considering the conventional methods (cabinet, tunnel and fluidized bed dryer) the one which has a lower consumption of energy and, therefore, a higher rate of energy efficiency, is the fluidized bed dryer, which can be explained by the smaller residence times.

According to Table 2, the methods that are simpler and on the other hand imply reduced initial investment are the sun drying and solar drying processes. However, the more traditional method (sun drying) is not appropriate for apple fruit drying due to the high possibility of microbial contamination arising from the fact that this method consists of an open air method. This risk is an impediment to the certification of dehydrated products by sun drying, since it does not fulfil the requirements of Hygiene and Food Safety. The solar drying replaced the previous method (Rigit *et al*., 2013), since it is based on the same concept though it is carried out in a closed system (tunnel or cabinet), consequently reducing the possibility of contamination. For these reasons, the solar drying appears as a more efficient method, leading to smaller drying times. Both the sun and solar drying techniques depend on the weather conditions and therefore, there is great difficulty in controlling the drying environment, leading to long residence times.

Table 2 - Advantages and limitations of the methods of dehydration for apple fruit.

Dehydration Method	Advantages	Disadvantages	References
Sun Drying	- Simple and economic.	- Requires large areas; -Process that requires optimum environmental conditions; - Difficulty in controling atmospheric conditions; - microbial contamination; - Long drying times.	(Cohen and Yang, 1995; Fellows, 2000; Sharma *et al*., 2009)
Solar Drying	- Simple and economic; - Reduction of microbial contamination in comparison with the sun drying.	- Process that requires optimum environmental conditions, 30 °C temperature and low humidity; - Weak controls due to atmospheric conditions; - Albeit minor in relation to the drying in the sun, their drying times are large; - Production of low quality in fruit; - Non-uniform drying in products.	(Bolea *et al*., 2012; Janjai *et al*., 2012)
Cabinet Dryer	- Uniform distribution of drying air along the tray; - Low maintenance cost; - Flexible in operations with different foods.	- Use in small production scale or on a pilot scale; - Low level control of food production with more quality; - Long drying times.	(Brennan, 2006; Fellows, 2000)
Tunnel Dryer	- Flexibility for the large scale; - Possibility of air circulation being done in parallel, counter flow or flow, depending on the characteristics of the product.	- It was replaced by fluidized bed dryer by present better results.	(Brennan, 2006; Jayaraman and Gupta, 2006)
Fluidized Bed Dryer	- High energy efficiency; - Reduction of operating costs; - Production of better quality in the final product.	- Limited range size (it is more efficient on smaller dimension products).	(Brennan, 2006; Cohen and Yang, 1995; Jayaraman and Gupta, 2006)
Microwave Drying (260 W)	- Short drying times; - Energy saving; - Can be combined with other methods of drying, optimising the dehydration process; - Flexibility in dehydration of various types of food; - Produces better quality in products.	- Lack of heating uniformity; - The rapid transfer of earth may cause damage to the texture of the food; - At the end of the drying process by microwave is difficult to control the temperature and high temperatures at the ends of the products may lead to overheating and irreversible drying; - Sensory changes the level of colour and flavour; - Difficulty in dehydration of foods in large sizes.	(Motevalli, 2013; Mujumdar, 2000; Zhang *et al*., 2006)

Table 2 - Continuation

Dehydration Method	Advantages	Disadvantages	References
Drying By Microwave Combined With Vacuum (260 W and 200 mbar)	- The quality of the product is higher when compared with a dehydrated product only with the method that uses microwave energy.	- High initial costs.	(Drouzas *et al*., 1999; Motevalli, 2013; Zhang *et al*., 2006)
Infrared Drying (intensity of radiation 0.49 W/cm^2)	- Short drying times and low-cost technology; - Uniform Heating of the product; - The infrared radiation is economic; - Low deterioration of the product; - Easily adapted to more conventional dryers.	- Potential fire risks; - Essentially the surfaces of products are dried.	(Ratti and Mujumdar, 2006; Nowat and Piotr, 2004; Samadi and Loghmanieh, 2013)

Comparing the conventional methods (cabinet dryer, tunnel dryer and fluidized bed dryer), the fluidized bed dryer is the one that presents more economical benefits as well as better quality of the final product. The cabinet dryer, despite having a uniform air circulation along the shelves and presenting low maintenance costs, is merely used on a small scale and the final product is of reduced quality. Concerning the dryer tunnel, although it is flexible on a large-scale for various types of products, it is being replaced by the fluidized bed dryer as the latter has a high efficiency, low operating costs and presents final products with better quality.

Despite being used in a wide range of products and presenting final products with high quality, the microwave drying technique has not yet been properly introduced at the industrial level, due to several reasons among which the lack of a uniform heating, the high initial investment needed and the insufficient penetration of heat when used in large dimension fruits (Zhang *et al*., 2006). To overcome these limitations, microwave drying has been combined with other methods, in particular vacuum drying. Such conjunction of methods enables final products with higher quality due to the lack of oxygen in dry environment and the reduction of adverse reactions in the fruits (Motevalli, 2013). Furthermore, the combination of these two drying methods leads to a high efficiency, despite the high initial costs.

From all the methods presented and excluding the sun and solar drying, the infrared drying process is the most efficient technology in economic terms due to its small drying times and due to the fact that the infrared radiation is more economic than the dielectric and microwave energies. If on the one hand this type of radiation has a long lifetime, on the other hand it requires very little maintenance. Additionally, this type of dryer can be easily adapted to more conventional dryers (Ratti and Mujumdar, 2006).

Conclusions

Food dehydration has been the subject of several studies and is nowadays considered as a vital technique in the food and industrial sectors.

Among the different methodologies of dehydration analysed, the one that reaches lower drying times is the microwave combined with vacuum displaying higher rates of energy efficiency and lower consumption of specific energy. The main limitation of this method is the high initial investment; compensated later by the low energy costs, by high quality products (good retention of organoleptic and nutritional characteristics) and by the reduced need of maintenance.

Drying by using direct sunlight leads to longer drying times and also high risks of microbial contamination by failing to comply with the sanitary conditions. Thus this type of traditional drying is not appropriate for the apple fruit dehydration. It should be noted that, among the various dehydration technologies studied for the apple fruit, infrared drying presents itself as a low cost technique with great benefits in terms of the final product, and displaying good results in terms of drying times and energy efficiency.

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