Food drying: a review on applications

Secagem de alimentos: uma revisão das candidaturas

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ABSTRACT
The growing global demand for food has required innovations in the techniques of processing and conservation of food raw materials. An alternative to expand food availability is to apply technologies aimed at preserving and increasing the durability of materials, in addition to significantly reducing waste. Currently, the food industry has stood out with the application of drying techniques for better conservation and marketing. This review presents studies carried out in the last decade on developments in new drying technologies, the improvement of techniques and their advantages and disadvantages. Thus, the aim is to show the relevance of this food processing technique and its advances regarding the techniques applied in food, given the complexity of the composition of food raw materials.

Keywords: Drying methods, Dehydration, Conservation, Quality.

RESUMO
A crescente procura global de alimentos tem exigido inovações nas técnicas de processamento e conservação de matérias-primas alimentares. Uma alternativa para expandir a disponibilidade de alimentos é aplicar tecnologias destinadas a preservar e aumentar a durabilidade dos materiais, para além de reduzir significativamente o desperdício. Actualmente, a indústria alimentar tem-se destacado com a aplicação de técnicas de secagem para melhor conservação e comercialização. Esta análise apresenta estudos realizados na última década sobre o desenvolvimento de novas tecnologias de
secagem, a melhoria das técnicas e as suas vantagens e desvantagens. Assim, o objectivo é mostrar a relevância desta técnica de processamento alimentar e os seus avanços no que diz respeito às técnicas aplicadas nos alimentos, dada a complexidade da composição das matérias primas alimentares.

**Palavras-chave:** Métodos de secagem, Desidratação, Conservação, Qualidade.

1 INTRODUCTION

Over the years with population growth, there is a need for expansion of the agricultural industry, in addition to the application of technologies aimed at offering food products. According to data from the Food and Agriculture Organization of the United Nations (FAO), by 2050 there will be a significant increase in the consumption of food (60%), energy (50%) and water (40%). These projections contribute for the food industry to pay attention to the amount of food needed to feed the population (1,2). In order to meet FAO estimates, it will be necessary to establish policies to increase agricultural yield and sustainable food production, in addition to preventing post-harvest losses and food waste (3).

An alternative to expand food production is through the application of technologies aimed at preserving and increasing the durability of food, as well as significantly reducing waste. Currently, the food industry has stood out with the application of drying techniques for better conservation and marketing. Drying has numerous advantages, such as: prolonging the shelf life of products and reducing problems of seasonality, packaging costs, storage, handling and transportation (4,5). The quality of dehydrated foods is influenced by the drying conditions and method. Therefore, high temperatures during food drying cause irreversible chemical and biological reactions, accompanied by various structural, physical and mechanical modifications (6).

The quality of dehydrated foods is influenced by the conditions and the drying method. Therefore, high temperatures during food drying cause irreversible chemical and biological reactions, accompanied by various structural, physical and mechanical modifications (7).

The thermal processes in the food sector usually involve energy transfer between the product being dehydrated and the air. These convective processes, such as drying, require large volumes and high speed of air, as well as low or high ambient temperature, which may increase energy demand and consumption (7).
Due to these factors, there have been increases in the number of studies focused on drying techniques and publications in several scientific journals in Brazil and worldwide. Considering the last 10 years, around 7,166 publications have been reported, among which unprecedented articles on food drying.

The present study brings the society scientific information about drying and its applications in the food industry, a scientific approach highlighting the importance, applications and understanding of the relevance of drying for the food industry and population demands. In this context, this review aimed to conduct a bibliographic survey on the drying techniques applied in food raw materials, with the purpose of assisting future research focused on drying.

2 MATERIAL AND METHODS

This study is an analytical bibliographic review about the drying techniques applied in food. The survey encompasses studies conducted in the last decade (2011 to 2020) and describes the evolution of techniques, their applications and limitations. Regarding the method of elaboration, the analyses were performed using articles that had as highlight the research terms “Food Drying”. It was defined as inclusion criterion of articles published between the years 2011 and 2020, in Portuguese and English. The articles of this review were consulted in databases indexed in the Capes journal platform such as the Web of Science and Science Direct databases. Data were collected from March to August 2020.

In terms of the amount of scientific research conducted on food drying, there is a clear tendency of increase in publications from various countries in all aspects and disciplines. In the period from 2000 to 2020, a total of 507,547 articles was revealed by searching for the term “Drying” through the Web of Science search tool. There was a total of 33,660 articles for the term “Food Drying”, which decreased to 30,199 when defining only unprecedented works in the form of article and to 10,398 when filtering by area categories in Food Science & Technology.

Figure 1 shows the number of papers as a function of the areas of scientific production and countries for the search term “Food Drying”.

Figure 1

Figure 2 shows the number of publications over time from the search for topics that include in the search title, abstract, keywords and author.
In the last 10 years, there has been an increase in the number of publications and, of these, 888 (8.54 %) are concentrated in the United States, followed by China with 789 (7.58 %), Spain with 532 (5.12 %), and Brazil in fourth place with 528 (5.07 %) publications.

The bibliographic survey showed the significant proportion related to drying of food raw materials, development of new products and drying technique, using several sampling methods. In this context, the drying process has been commonly used to preserve food quality and prolong shelf life (8).

3 THEORETICAL REFERENCE

3.1 Types of drying

Sun drying in terraces with solar energy is the most traditional and simple method for drying food products. This dryer uses solar energy to add a significant amount of heat to the product and remove some of its water without affecting quality. It can be used in various situations, mainly in agriculture and industry, to preserve the quality of agricultural products (9).

However, this type of drying depends entirely on environmental conditions. In addition, the slowness of the process, the high labor requirement and the exposure to the external environment during the drying process limit its application (10). The longer time required for drying is associated with the need to use large open areas, which can compromise the sanitary conditions of the food with exposure to dust, soil, rain, various insects and animals roaming in the surroundings (8).

The combination of techniques is defined as hybrid drying technology and can be used as an innovative and energy-efficient alternative for the drying of food raw materials. Aimed at sustainability, the use of solar energy in hybrid drying technologies can significantly improve the cost-benefit ratio and energy efficiency of the entire system (11).

Artificial convective drying with hot air is one of the oldest and widely used methods (Table 1). In industries, more than 85% of dryers are convective type, although one of the disadvantages of these dryers is the high energy consumption (12).
Food drying by convection is a complex process, as it involves the simultaneous transfer of energy in the form of heat and mass (23). Convective drying is commonly accepted as a process in which the convective medium (usually air) heats the surface of food and this heat causes water evaporation. As a consequence, heat conduction and water diffusion occur in food (24).

There are several drying technologies that are applied to various temperature levels and drying principles (5). Techniques widely used around the world include convective drying, freeze-drying, spraying drying, ultrasound drying, microwave drying and high pressure drying (25).

However, disadvantages of these dehydration methods have been identified, such as high energy consumption and the possible loss of quality of the final product for hot air drying, as well as uneven drying or overheating for microwave drying, and high expenses with freeze-drying and hybrid drying (10).

Each drying method has its own characteristics and has advantages and limitations. The final products obtained with these methods may vary in terms of physical-chemical or nutritional properties and microstructure (26).

However, there is a growing demand for alternative, fast, energy-efficient and continuous drying methods by food companies and industries (27). Table 2 briefly presents the different drying techniques applied to food raw materials.

### Table 2

#### 3.2 ARTIFICIAL DRYING

##### 3.2.1 Freeze-drying

Alternative food drying processes, such as freeze-drying (lyophilization), have been proposed to improve energy efficiency (33). This technique consists of freezing the product, removing water by sublimation (water in the solid state passes directly from the solid state to the gaseous state), then the water is condensed and removed by thawing after the completion of the freeze-drying operation (49). The basic scheme of a freeze dryer is illustrated in Figure 3.

![Figure 3](image-url)

For foods with high quality and sensitive materials, usually the drying technique applied is freeze-drying, as it contributes to maintaining the functionality and quality of
the product (27,35). That is, it generates products with high quality characterized by a very low water content, good sensory and nutritional properties and good rehydration capacity (51).

Freeze-drying has long been known as the best drying method to preserve the original properties of dehydrated food. It favorably maintains the biological activity of food products, flavors and aromas, as well as better viability of cellular biological products (49).

However, freeze-drying is also known to be a more expensive drying method due to its complexity in operation and long drying time (35,49,51). In addition, freeze-drying requires minimal preparation time and does not require additional processing after drying (35).

### 3.2.2 Microwave drying

Microwave drying is a relatively recent technology that has been recommended and is spreading as an alternative, fast and effective drying technique to convective drying (40,51).

Microwave heating originates in the ability of materials to absorb microwave energy and convert it into heat, which is due to the presence of water and its dipolar nature. When an oscillating electric field is incident in water, permanently polarized dipolar molecules attempt to realign in the direction of the electric field. Due to the high frequency of the electric field, this realignment occurs one million times per second and causes internal friction between the molecules, resulting in the volumetric heating of the material (52).

In microwave drying, the time is reduced due to the rapid absorption of energy by water molecules, which accelerates water evaporation and results in high drying rates of food (12). Internal heat generation leads to an increase in internal temperature and vapor pressure, and both processes promote a flow of water towards the surface of the food and increase the drying rate (51). There are several factors that affect microwave heating and heat distribution, the main ones being dielectric properties and depth of penetration (52).

The main advantage of the microwave is that it can heat all the material at the same time and eliminate enzymatic activity (38). The use of vacuum in drying improves the conservation of foods that are sensitive to heat and susceptible to changes in color, appearance, nutrient loss and vitamin content (11), in addition to obtaining higher drying rates and improving the quality of some food products (52).
However, a limitation of microwave heating is the accumulation of water on the surface of food (51). And excessive temperature at the ends or edges of food products results in burning and production of unpleasant flavors, especially during the final stages of drying (52). There are also limitations associated with microwave drying, such as irregular heating, limited microwave penetration depth and possible damage to texture when the product temperature is high (53).

Several food processing industries have already applied the microwave technique for drying food materials and, as a result, have achieved significant savings in energy costs and improved the sensory and nutritional attributes of the final products (11). Proper control of microwave power and combination with other drying methods should be carefully considered to overcome disadvantages (53).

3.2.3 Ultrasound drying

The use of ultrasound in food technology for processing, preservation and extraction is a system that has evolved to keep the development moving, as the thermal technologies, vacuum cooling, high-pressure processing and pulsed electric field have current limitations related to high costs of investment, total control of variables associated with process operation, lack of regulatory approval and, mainly, consumer acceptance, which have delayed a broader implementation of these technologies on an industrial scale(54). Ultrasound is one of the emerging technologies that have been developed to minimize processing, maximize quality and ensure the safety of food products (55). Ultrasound uses physical and chemical phenomena that are fundamentally different compared to those applied in conventional extraction, processing or preservation techniques (54).

High-intensity ultrasound uses frequencies between 18 and 100 kHz at intensities greater than 10 kW m$^{-2}$ [39], [55]. It refers to sound waves beyond the auditory frequency range (in general, $> 20$ kHz). When ultrasound passes through a liquid medium, the interaction between ultrasonic waves, the liquid and the dissolved gas originates a phenomenon known as acoustic cavitation (57).

High-power ultrasound modifies food properties, inducing mechanical, physical and chemical or biochemical changes through cavitation. By maximizing production and saving energy, power ultrasound is considered a green technology, with many promising applications in food processing, preservation and safety (55).
One of the main problems in the use of ultrasound in food processing is the modification in the functionality of food ingredients without chemical modification (57). On the other hand, ultrasound offers a net advantage in terms of productivity, yield and selectivity, with better processing time, improved quality and reduced chemical and physical risks, besides being ecological due to the low energy consumption (54).

3.2.4 Radio frequency

In recent times, the use of radio frequency heating has been widespread for agricultural products and food processing, such as for the control of insects in stored seeds and grains, meat thawing and drying of agricultural products (58,59).

Radio frequency heating is based on the principle of dielectric heating, thus allowing selective and volumetric heating with variable drying rate. Radio waves with lower frequency than microwaves are reported as suitable for drying, especially in the final stages of the process (6,58).

In radio frequency heating, waves have lengths ranging from 1.0 mm to about 100.0 km, with frequency from 3.0 kHz up to around 300.0 GHz; the penetration depth is comparatively higher than that of microwaves, which have lengths ranging from 1.0 mm to approximately 1.0 m, with frequencies between 300.0 MHz and 300.0 GHz (58).

The radio frequency heating technology has the disadvantage of uneven heating. Irregular temperature distribution can cause loss of quality or survival of insects or pathogens due to overheating or underheating in different parts of a food product (59,60).

3.2.5 Plasma technology

Cold plasma technology is an emerging non-thermal processing technique, which has stood out among researchers around the world and appeared as a new food processing technology (61,62).

Cold plasma technology was originally employed to improve the printing and adhering properties of polymers, increasing the surface energy of materials and a variety of domains of use in electronics, being commonly used in the treatment of textiles, glasses, paper and other products (62).

Plasma is the fourth state of materials, in addition to solid, liquid and gaseous states, and is generated by gas discharge (61). In general, plasma can be classified according to its temperature as thermal and non-thermal (63).
There are several types of non-thermal plasma that are used in different applications. This drying method has already been applied for gliding arc discharge used to degrade chemical contaminants in wastewater and for bacterial decontamination (61). Corona discharge plasma is exploited for microbial decontamination in food as well as dielectric barrier discharge plasma is applied for microbial decontamination of food products (64–66).

For applications in the food industry, non-thermal plasma induced by electrical discharges is of primary interest due to the relevant potential in low-temperature food processing (62). According to Chen et al. (61), plasma technology can be used as a new dehydration process that has potential for application in food, but further studies and research are needed to ratify its use and viability.

4 FINAL CONSIDERATIONS

This review surveyed the main drying methods applied to food raw materials. The approach included aspects related to the fundamentals of the methods, impacts on the properties of raw materials, advantages and disadvantages in application. The production of dehydrated, dried or powdered foods is an increasingly important industrial area due to the high stability and ease of handling of these products. However, the process used to obtain them should consider the maintenance of the nutritional and sensory quality of the raw materials. Thus, there are several studies and techniques investigated, but there is still no consensus as to the best technique to be applied, given the complexity and diversity of food raw materials.

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AUTHORS’ CONTRIBUTION

Francileni Pompeu Gomes: data collection, data analysis and interpretation, performing the analysis, drafting the article.
Osvaldo Resende: conception or design of the work, critical revision, final approval of the version to be published.
Elisabete Piancó de Sousa: data analysis and interpretation, conception or design of the work, critical revision.


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### TABLE

Table 1: Types of hot-air dryers applied to food

<table>
<thead>
<tr>
<th>DRYING METHOD</th>
<th>DRYING CONDITIONS</th>
<th>FOOD</th>
<th>REFERENCES</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tunnel dryer</td>
<td>Temperature 50, 60, 70; 80 °C; Time 330–470 min</td>
<td>Potato slices</td>
<td>(13)</td>
</tr>
<tr>
<td>Microwaves</td>
<td>Temperature 60 °C; Time 80, 15 and 10 min; Powers 300, 1500 and 2700 W</td>
<td>Sweet potato</td>
<td>(14)</td>
</tr>
<tr>
<td>Spray dryer</td>
<td>Input and output 165 °C and 65 °C. Capacity 1 l/h</td>
<td>Sugar-protein solutions</td>
<td>(15)</td>
</tr>
<tr>
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<td>Input and output 120 °C and 91 °C; Feed flow rate of 0.60 m³/min</td>
<td>Propolis solution</td>
<td>(16)</td>
</tr>
<tr>
<td>Convective tray dryer</td>
<td>Temperature 50, 60 and 70 °C; Air flow speeds 2.0 and 3.5 ms⁻¹</td>
<td>Passion fruit peel</td>
<td>(17)</td>
</tr>
<tr>
<td></td>
<td>Temperatures of 50, 60, 70, 80, 100 and 110 °C;</td>
<td>Pineapple slices</td>
<td>(18)</td>
</tr>
<tr>
<td>Convective dryer</td>
<td>Temperature 50, 60 and 70 °C; Air flow speeds 6.7 and 10.15 m s⁻¹; Slice thickness 1, 1.5 and 2 cm</td>
<td>Fresh pumpkin</td>
<td>(19)</td>
</tr>
<tr>
<td>Electric ultrasound-assisted convective dryer</td>
<td>Air temperatures 40, 50, 60, 70 and 80 ± 1.2 °C; Air speeds 1.2 and 3 m s⁻¹; Ultrasound power 0, 6.2, 12.3, 18 kW m⁻³</td>
<td>Fresh leaves of Garden Thymes (Thymus vulgaris L.)</td>
<td>(20)</td>
</tr>
<tr>
<td>Spouted bed dryer</td>
<td>Temperature 80, 90 and 100 °C; Air speed 0.30 to 0.35 m s⁻¹; Flow rate of 0.2 kg paste kg⁻¹ h⁻1</td>
<td>Vegetable paste (pumpkin, potato, onion, carrot, cabbage and tomato)</td>
<td>(21)</td>
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<tr>
<td>Atmospheric double drum dryer</td>
<td>Internally steam-heated drums 379.2 ± 7 kPa producing a temperature of 152 ± 2 °C</td>
<td>Frozen mango puree</td>
<td>(22)</td>
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<tr>
<td>DRYING METHOD</td>
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<tr>
<td>Fluidized bed</td>
<td>Wheat</td>
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<td>Millet</td>
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<td>Soybean</td>
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<td>Carrot</td>
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<td></td>
<td>Wheat germ</td>
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<td>Electro-osmosis</td>
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<tr>
<td>Atmospheric freeze-drying</td>
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<td>Freeze-drying</td>
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<td>Orange pulp</td>
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<td>Yam</td>
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<td>Microwave</td>
<td>Apple</td>
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<td>Kiwi slices</td>
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<td>Chrysanthemum</td>
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<td>Yam</td>
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<td>Mint leaf</td>
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<td>Cherry</td>
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<td>Cold plasma</td>
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<td>Spray Drying</td>
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<td><em>N. sativa</em> oil</td>
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<td>Rosemary extract</td>
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<tr>
<td>Convective drying</td>
<td>Jambu</td>
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<td>Tomato</td>
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FIGURE

Figure 1: Number of publications by area of knowledge and by place of production. Source: Web of Science.

Figure 2: Number of publications over the last 10 years. Source: Web of Science.

Figure 3: Basic illustrative scheme of a freeze dryer. Source: Adapted from Tonon, R.V.; Baroni, A.F.; Hubinger (50).