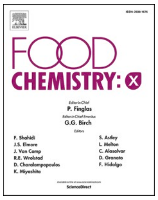
Food Chemistry: X 16 (2022) 100465

Contents lists available at ScienceDirect

Food Chemistry: X

journal homepage: www.sciencedirect.com/journal/food-chemistry-x



The role of emerging technologies in the dehydration of berries: Quality, bioactive compounds, and shelf life

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ARTICLE INFO

Keywords:
Dehydration technology
Drying method
Berry
Bioactive compounds
Phenolic compounds
Fruit quality

ABSTRACT

Berries are among the fruits with the highest nutritional and commercial value. This paper reviews the conventional and emerging dehydration methods most commonly used as postharvest treatment and discusses their efficacy in maintaining and/or improving the nutritional and functional qualities of dried berries. The characteristics of the conventional methods (*e.g.*, convective drying, freeze-drying, spray-drying, osmotic dehydration), their pre-treatments, their combination, and intermittent drying, as well as their potential disadvantages are discussed. The use of emerging dehydration techniques (*e.g.*, electromagnetic radiation drying, explosion puffing drying, heat pump drying, low-pressure superheated steam drying, microwave drying) allows to improve the quality of the dried berries compared to conventional techniques, in addition to reducing drying times, increasing drying speed and energy efficiency. Finally, the use of pre-treatments and the combination of technologies can enhance the quality of the final product as a result of the improvement in the effectiveness of the dehydration process.

Introduction

A “berry fruit” is commonly referred as a small fruit that can be eaten as a whole. On the other hand, from a botanical point of view it is defined as “a type of corpulent fruit in which the ovary of a single flower develops into an edible fleshy portion (*i.e.*, the pericarp)”. In both cases, berries are popular fruits commonly recognized as a great source of nutrients and bioactive compounds such as minerals, phenolic compounds (especially anthocyanins) and vitamins (D'Urso, Piacente, Pizza, & Montoro, 2017). Anthocyanins are pigments that belong to the flavonoid group, which are responsible for the red, purple, and blue colours that characterize several berries. In addition, these compounds are associated with beneficial health effects (Echegaray et al., 2020).

Fruits such as berries comprise essential nutrients necessary for healthy living, however, they are highly perishable (Bassey, Cheng, & Sun, 2021). In addition, their characteristics depend on various factors, including cultivation, geographic region, storage conditions, maturity and climate, among others. Indeed, these factors can modify the quality of the berries, their bioactive content and their antioxidant capacity (D'Urso et al., 2017). Therefore, adequate and advanced post-harvest processing technologies are required to minimize qualitative and quantitative post-harvest losses (fresh cut or processed product), which would avoid undesirable changes in weight, colour, texture, and aroma (Mencarelli & Bellincontro, 2020).

Drying is one of the oldest methods used to remove water for food preservation, as the lowest water potential (water activity) is achieved for food stability during storage. It is associated with a natural process, generally under open-air conditions. Therefore, today it has been

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https://doi.org/10.1016/j.fochx.2022.100465
Received 19 May 2022; Received in revised form 5 September 2022; Accepted 29 September 2022

substituted by other methods that carry out drying under controlled temperature and humidity conditions using sophisticated equipment (Roratto, Monteiro, Carciofi, & Laurindo, 2021). In this sense, dehydration is commonly used to reduce the water activity of fruits, which makes it possible to inhibit their subsequent deterioration (Roratto et al., 2021).

Water is the dominant component in fruits and vegetables and its removal prevents harmful microbial and physicochemical reactions, leading to a longer storage time (Ghellam et al., 2021). Therefore, dehydration technique allows to preserve the fruits and their juices, increasing their shelf-life while reducing their volume and weight, thus reducing the cost of packaging, storage and transport (Qi et al., 2021). As a result, the properties of flavor and texture are modified, obtaining new products in which their final quality is maintained or even improved. However, the temperatures used during dehydration could degrade bioactive compounds (*e.g.*, dietary polyphenols) present in berries, decreasing their quality (Arfaoui, 2021). The effects produced on the properties of the berries will depend on the dehydration method and the fruit species. This makes it necessary to profile the bioactive compounds of dried berries to know the benefits associated with their consumption (Bustos, Rocha-Parra, Sampedro, De Pascual-Teresa, & León, 2018). Bearing this in mind, the emergence of new dehydration techniques would provide advantages such as reduced drying times, higher energy efficiency, improved product quality, cost reduction and less environmental impact (Calín-Sánchez et al., 2020).

These facts reinforce the study of dehydration methods with the aim of determining the best conditions to maintain the dried fruits properties compared with their fresh counterpart. In addition, the dehydration effects on polyphenols and antioxidant properties have not been consistently evaluated (Bustos et al., 2018). Therefore, selecting the best dehydration conditions to enhance berries quality is critical to produce dried fruits that can be used by food industry to meet consumer demand.

This review addresses the main dehydration techniques used in berries, presenting the most common and emerging dehydration methods, as well as their combination. In addition, a discussion of the methods in terms of their impact on overall quality, bioactive compounds, and shelf-life of the final dried product is also provided. The search for scientific studies that fitted in the scope of the present review was carried out in the Scopus database. 'Berries' and 'dehydration' were used as the main keywords, selecting those published between '2017' and '2021'. This approach generated 106 results from which 31 were selected. Additionally, another bibliographic research was conducted on the references related to "dried berries in foods", which confirmed that it is a novel topic since only a few articles have been published since 2017.

Dehydration methods

Various terms, drying, dehydration and withering, have been used interchangeably to refer to water loss. However, there are peculiarities between them that it is necessary to note. As already discussed, drying is the process of intense water loss from berries after harvest and is usually carried out outdoors; dehydration is a process of water loss under controlled conditions; and finally, withering is the result of a long dehydration process in which water loss and berry senescence stresses occur (Mencarelli & Bellincontro, 2020). In present review, only process developed under controlled conditions will be discussed.

In the last two decades, a scientific and industrial development has been observed in the methods used for berries dehydration (from conventional to emerging techniques and their combination). Therefore, the mechanisms, advantages, disadvantages, cost benefits and practical applications of the most important conventional (convective drying, freeze-drying, intermittent drying, osmotic dehydration and spray drying), and emerging drying techniques (electromagnetic radiation, explosion puffing, heat pump, low-pressure superheated steam) studied in the last years (Table 1), and their combination will be reviewed in this section.

Conventional methods

Regarding conventional dehydration mechanisms, convective (hot air) and vacuum are the main technologies used. Berry dehydration is based on the exchange of heat and mass between the medium and the fruit, where the driving force for moisture diffusion is the generated temperature-humidity gradient. The drying rate of fruit subjected to dehydration can be divided into five stages: (i) preheat stage, (ii) constant rate, (iii) first period of falling rate, (iv) second period of falling rate, and (v) period of equilibrium drying rate (Fig. 1) (Sun, Zhang, & Mujumdar, 2019).

Convective drying

Convective drying dehydration is a simple and cheap hot air-drying technique used as a method of dehydrating fruits. It is usually classified in three different methods: hot air drying (berry directly exposed to hot air), convective multi-flash drying (heat transfer is promoted by the wide difference between the temperature of the berries and the hot air), and fluidized bed drying (hot air is conducted to the drying belt at a controlled rate). The berries are directly exposed to hot air to transfer heat from the surface to the interior of the fruit, promoting moisture exchange between the product and the hot air flowing through the drying chamber (Bustos et al., 2018; Onwude et al., 2017). The relative humidity (RH) of the hot air is key in the drying process since it conditions both heat and mass transfer process, and therefore the fruit quality (Zhang, Yang, Mujumdar, Ju, & Xiao, 2021). In this regard, a low RH is associated with lower vapor pressure of air and higher mass transfer rate, which increases drying but a crust can be generated on the surface of the material (Darıcı & Şen, 2015). On the contrary, a high RH decreases the ability to absorb moisture from the environment, resulting in an improved pore network of materials but increases drying time (Zlatanović, Komatina, & Antonijević, 2013).

In fresh fruits converge bound moisture and unbounded moisture. In the first case, the liquid solution is held in the structure of the solid matrix, whereas in the second is represented by free water. Many conventional methods use hot air (convection drying) to enhance heat transfer between the air of low relative humidity and the fruit, which makes complex processes coexist during thermal drying. Although during the process an evaporation takes place on the surface, it is also necessary to vaporize bounded water since only after the period of falling rate the process allows to obtain a safe dried product (Calín-Sánchez et al., 2020). The safety would be guaranteed by the characteristics of the dried fruit, which generally include low water activity (<0.600), high sugar content (38 to 66 %), low pH (<4.5), and antimicrobial phenolic compounds (Bourdoux, Li, Rajkovic, Devlieghere, & Uyttendaele, 2016; Jayeola, Farber, & Kathariou, 2022). On the other hand, in some soft berries, a deformation and fissuration (drying quality decrease) may occur due to the high moisture content and high vapor pressure generated within the fruit. Moreover, if the evaporation from the surface of the berry is too slow, it can happen that the moisture inside the material barely diffuses outwards. This would cause a decrease in the drying speed, and even the ripening and the appearance of mould.

Convective drying is commonly used for solid fruits and pomace processing (functional ingredients production). Among the advantages of convective dehydration are its easy operation, low cost and simple design, while extending the shelf-life of the dehydrated product. However, this method also has some disadvantages related to inlet gas characteristics (high temperature, relative humidity) and long drying times, which result in the formation of crust on the product surface, degradation of heat-sensitive compounds, enzymatic and non-enzymatic browning reactions, off-flavor generation, visible shrinkage (due to mechanical stress), and consequently low rehydration capacity and nutritional quality (Zielinska, Zielinska, & Markowski, 2018). In this regard, Bustos et al. (2018) observed that the application of prolonged times (50 °C for 48 h) or high drying temperatures (130 °C for 2 h)

Table 1
Conventional and emerging dehydration methods comparison: mechanisms, advantages, disadvantages, cost benefits and practical application.

Methods	Mechanism	Advantages	Disadvantages	Cost benefits *vs* practical application (PA)
Conventional				
Convective drying	Hot air [1]	Easy operation and simple design [1]	Long drying times [2] with high temperatures [4] Berries with superficial crust, loss of bioactive compounds, undesirable chemical reactions, off-flavour, shrinkage, and low rehydration [2]	Low cost [1] PA: solid fruits and pomace [2]
Spray-drying	Hot gas [3]	Single step process [3] Product with similar size and shape and long shelf-life [4]	High temperatures reached result in loss of bioactive compounds, and wall depositions (due to sugars and acids) in products	High size and high installation cost [5] PA: Powder production, combined with ultrasound extraction can obtain high quality products [3]
Freeze-drying	Low pressure (vacuum) and temperature with microwave [6][9]	High rehydration rateHigh quality products (bioactive compounds and vitamins retention) with similar original colour and flavour [7][9]	Long drying time and requires pre-treatment (freezing) [8]	High cost (equipment and energy): one of the most expensive [5][7][8], cost up to 8-fold higher than conventional hot air [10] PA: products with higher quality and final price [7]
Osmotic dehydration	Hypertonic solution [11]	No thermal treatment with high properties preservation [11]	High moisture in final product and berries chemical composition modification (depends on solution utilized) [11]	Low cost (energy and equipment) PA: all berries, juices quality improvement [11]
Emerging				
Heat pump drying	Hot air [9]	Reduce energy, time, and temperature demand by heat recovering while dehumidify the air [9]	Thermal treatment (depends on settings) with loss of bioactive compounds (phenolics content) [12] Longer drying time depending on product properties [13] and can affect product quality [14]	Low energy consumption [12]PA: high quality products when combined with other methods (*e.g.* vacuum-microwave), useful for sensitive berries [9]
Electromagnetic radiation drying	Microwave (MW) [15]Infrared (IR) [16]Radio frequency (RF) [17]Refractance window (RW) : conduction, convection, and radiation [18]	MW: high quality products (similar to freeze-drying with lower drying time), high energy efficiency [15]IR: quick and effective moisture reduction, simple equipment (compared to conventional) , energy efficient [16] RF: maintain the quality of the product [17] RW: energy efficient, decrease drying time maintaining the quality of fruits, low temperature and low oxidation [8][18]	MW: thermal treatment (bioactive compounds degradation) [15], chestnut, penetration, reflection, and refraction effect [8] IR: thermal treatment, products with low rehydration capacity [16] RF: thermal migration and corner effect [17] RW: low capacity to operate [18]	MW: low cost (compared to conventional); PA: industrial application in berries [15] IR: low-cost product [20], PA: can be the most appropriate to be combined with conventional methods [16] RF: considerably high cost to installation [21], PA: alternative to convective method [17] RW: Low cost to installation and operation, PA: useful for heat-sensitive berries [18]
Explosion puffing drying	Steam or gas, and vacuum [19][24]	Saves energy and time when used as intermediate stage of dehydration [19] or with pre-treatments [24]	Thermal treatment can affect bioactive compounds content, antioxidant activity and sensorial properties of berries [19][24]	Cheaper alternative to freeze-drying PA: improve dehydration when used as intermediate staged of convective drying or freeze-drying [19]
Low-pressure superheated drying	Steam and vacuum [5] [8]	Energy efficient, better-quality product due to low temperature and low oxygen [5] [8]	Few information available [8][22] [23] and complex method [5]	Low cost: can reduce 50 % of energy consumption (compared to low temperature conventional methods) [8] PA: combined with solar or vacuum methods can improve the performance of the system and the products quality [8]. However, applications are limited, and more studies are necessary to recommend the suitable conditions for this drying technique [8][22][23]

[1] Bustos et al. (2018), [2] Zielinska et al. (2018), [3] Gagneten et al. (2019), [4] Qi et al. (2021), [5] Calín-Sánchez et al. (2020), [6] Zielinska et al. (2018), [7] Quispe-Fuentes et al. (2018), [8] Sun et al. (2019), [9] Figiel and Michalska (2017), [10] Téllez-Pérez et al. (2020), [11] Ghellam et al. (2021), [12] Xiong et al. (2021), [13] Tajudin, Tasirin, Ang, Rosli, & Lim (2019), [14] Taşeri et al. (2018), [15] Kumar & Karim (2019), [16] Moses et al. (2014), [17] Jiang et al. (2019), [18] Raghavi et al. (2018), [19] Chen et al. (2017), [20] Boudhrioua, Bahloul, Ben Slimen, & Kechaou (2009), [21] Marra, Zhang, & Lyng (2009), [22] Sehrawat, Nema, & Kaur (2018), [23] Kongsoontornkijkul, Ekwongsupasarn, Chiewchan, & Devahastin (2006), [24] Zou, Teng, Huang, Dai, & Wei (2013).

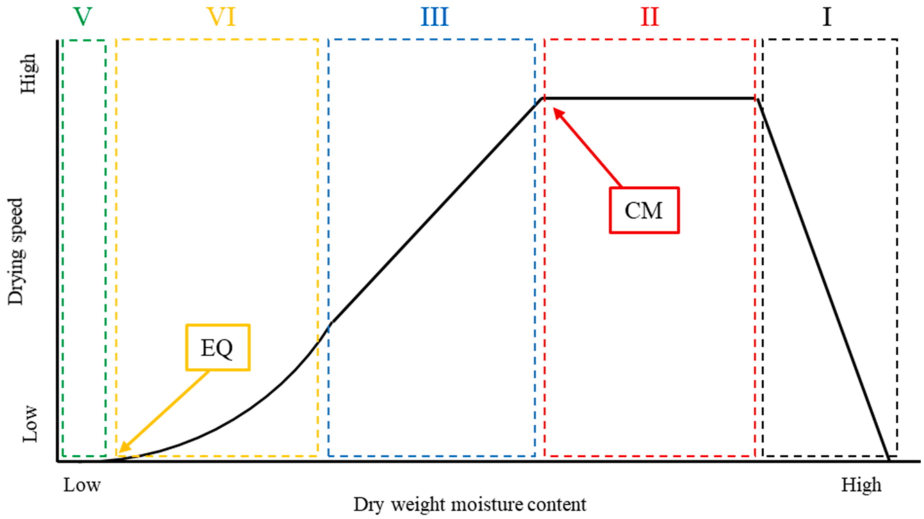

Fig. 1. Five stages of the drying speed during dehydration. I: pre-heat; II: constant rate; III: first falling rate; IV: second falling rate; V: equilibrium drying rate. CM: Critical moisture content. EQ: Equilibrium of moisture content.

resulted in a greater degradation of the quality of raspberry, boysenberry, redcurrants and blackcurrants. On the contrary, intermediate drying conditions (65 °C for 20 h) allowed to preserve the color, the polyphenol content, and the antioxidant activity of the berries. Some research claims that the effect of exposure time would be more noticeable than that caused by temperature. This would be due to the volume reduction and porosity increase that occur during drying, which would be responsible for the degradation of the antioxidants (Méndez-Lagunas, Rodríguez-Ramírez, Cruz-Gracida, Sandoval-Torres, & Barriada-Bernal, 2017). This was observed when convective drying was applied on strawberry (*Fragaria ananassa*), showing a 74.7 % loss of antioxidant activity at 50 °C/360 min *vs* 66.2 % when 60 °C/300 min was used. The same effect was observed in color with higher values of the colour change (ΔE) in samples subjected to prolonged temperature exposure (9.3 *vs* 5.3 at 50 °C/360 min and 60 °C/300 min, respectively). In the same way, Chen et al. (2021) found that the combination of high temperatures/low times (50 °C for 5 days *vs* 40 °C for 12 days and 30 °C for 30 days) favoured the accumulation of glucose, fructose and total soluble sugars and the contents of citric acid, lactic acid, malic acid, tartaric acid, and gallic acid and its derivatives in grape berries.

Therefore, for many years, studies have focused on improving convective drying, combining it with other processes, or replacing it with other methods (Kumar & Karim, 2019; Onwude et al., 2017).

Vacuum drying

Vacuum drying is an appropriate drying method for fruits that are sensitive to heat and that deteriorate rapidly due to high temperature and oxidation. The absence of oxygen during the dehydration processes, the application of subatmospheric pressures and the low drying temperatures results in a low-moisture and high-quality product (López et al., 2017; Quispe-Fuentes et al., 2019). The choice of appropriate dehydration parameters (*e.g.*, temperature, residual pressure, and heat flow rate) determines the efficiency of this drying technique. The evaluation of vacuum drying on wild-growing berries (*i.e.*, blackberry, raspberry, red currant, and strawberry) under different conditions showed that the increase in temperature reduces the drying time but worsens the quality characteristics of the dried berries. On the contrary, an increase in the residual pressure prolongs the duration of the vacuum drying (Ermolaev, 2018).

Compared with convection, vacuum drying dehydration has advantages including higher drying speed, and the possibility of using a lower drying temperature and a low-oxygen environment (Akdaş & Başlar, 2015). In addition, phenolic and volatile compounds, and vitamins can be better retained from the fresh berries (Sun et al., 2019). Some studies have evaluated the effect of vacuum drying conditions on dried product quality. Quispe-Fuentes et al. (2019) studied the impact of vacuum drying temperature on phenolic and antioxidant compounds of maqui (*Aristotelia chilensis* [Mol] Stuntz) berry. The samples were drying in a vacuum drying oven at 40–80 °C under 150 mbar. As expected, the increase in temperature decreased a_w in the fruit (0.482–0.387 when temperatures of 40 and 80 °C were applied, respectively), which ensured that the product was microbiologically stable ($<$0.600). Regarding polyphenols, the use of 80 °C allowed to preserve the contents of total phenolic content (TPC) (36.49 *vs* 23.16 mg GAE/g d.m. when temperatures of 80 and 40 °C were applied, respectively), total flavonoid content (TFC) (21.09 *vs* 16.82 mg QE/g d.m. at 80 and 40 °C, respectively), and total anthocyanin content (TAC) (11.57 *vs* 10.20 delphinidin-3-glucoside equivalent/g d.m. at 80 and 40 °C, respectively). This trend was also observed in the antioxidant activity measured by DPPH assay (220.26 *vs* 195.60 μmol TE/g d.m. at 80 and 40 °C, respectively). In the case of ORAC, the highest capacity was observed in the samples dried at 60 °C (454.02 μmol TE/g d.m.). Within phenolic compounds profile, ellagic acid, ferulic acid, gallic acid, myricetin, protocatechuic acid, and quercetin were identified. In general, the application of temperatures higher than 60 °C favoured the degradation of these compounds.

Similar results were observed by López et al. (2017) in murta (*Ugni molinae* T.) berries subjected to vacuum drying at different temperatures. The application of vacuum drying also allowed to obtain a safety product ($a_w < 0.500$). A different behaviour was observed between free and bound TPC and TFC. In general, vacuum drying reduced the content of fresh TPC and TFC compared to the content observed in fresh murta berries. The highest free contents in dried berries were found at 90 °C (2373.21 mg GAE/g d.m. and 854.3 mg QE/g d.m. for TPC and TFC, respectively). On the contrary, dried samples had higher bound flavonoid contents than those found in fresh samples. A similar trend was observed in bound TPC when the samples were dried below 60 °C. This could be due to alterations in their chemical structures or their possible combination with other compounds (*e.g.*, proteins) (Qu, Pan, & Ma, 2010). In contrast to the results obtained by other authors, the increase in temperature decreased significantly the antioxidant activity probably due to the degradation of phenolic compounds. In contrast, β-carotene contents increased with drying temperature.

The combination of vacuum drying with other technologies, such as freeze-drying and microwave drying, allows to reduce drying time and improve drying efficiency (Zielinska & Michalska, 2016). In this regard, Roratto et al. (2021) recently developed an hybrid-solar-vacuum dryer as an innovative and clean technology to fruits and vegetables dehydration.

Spray drying

This method is usually applied for liquids (juices) to powder production and microencapsulation. It is a single-step processing operation, which uses hot drying gas (usually air) as drying agent. Berry extract is swiftly evaporated because it is quickly atomized into droplets due to the high pressure reached in the atomization chamber and the small nozzle where it comes out of the equipment. As a result, a powder with good solubility and dispersibility is obtained (Gagneten et al., 2019). Moreover, the dried fruit obtained has a high-quality since it has a similar size and shape which, together with low values of a_w and water content, and high values of glass transition temperatures (T_g), allows it to have a long shelf-life. On the other hand, this technique has some disadvantages related on one hand to the use of high temperatures, which could cause the loss of bioactive compounds; and on the other hand, depositions on the wall are produced due to the existence of low molecular weight sugars and organic acids in the juice, which remains one of the main problems of this drying method (Qi et al., 2021). In addition, the equipment has a high size and high installation cost (Calín-Sánchez et al., 2020).

Therefore, with the aim of developing berry powders rich in bioactive compounds and with desirable physical properties, Gagneten et al. (2019) suggested to apply a combined method, using ultrasound-assisted extraction as pre-treatment and spray-drying (operating conditions: inlet air temperature of 170 °C, flow rate 8 mL/min, air pressure 3.2 bar, and nozzle diameter 1.5 mm; carrier matrix: maltodextrin). The authors concluded that the combination of these techniques is a satisfactory procedure to obtain berries with a higher phytochemical content and with relatively good flow properties.

Freeze-drying

The freeze-drying, also known as lyophilization or cryodesiccation, is a relatively common vacuum drying technique for berry dehydration. In this case, berries are evaporated at low pressure and low temperature. In general, the process is divided into 3 stages, (1) *cooling stage*, in which the material is cooled to freezing point temperature. This step is very important since it determines the morphology and the size of the ice crystals, which could produce the cells disruption and the damage of the fruit microstructure, avoiding a correct freeze-drying; (2) *change stage*, where the phase change from liquid to solid occurs, producing the first ice nucleous formation and the growth of ice crystal; and finally, (3) *solidification stage*, in which the ice crystals grow reducing the availability of liquid water (Assegehegn, Brito-de la Fuente, Franco, & Gallegos, 2019). The advantages of freeze-drying are its ability to operate under high-vacuum conditions, the lower drying temperature, and the higher drying rate.

Freeze-drying is one of the gentlest methods of dehydration that allows to obtain high-quality dried fruits, in which volatile compounds, bioactive compounds and vitamins are retained to a relatively high degree (Bustos et al., 2018; Figiel & Michalska, 2017; Quispe-Fuentes, Vega-Gálvez, & Aranda, 2018; Samoticha, Wojdyło, & Lech, 2016). Moreover, this technique allows minimal shrinkage and it is capable of maintaining the original colour and flavouring substances of the berries with a high rehydration rate, retaining the special taste of fresh berries. On the contrary, although freeze-drying is a good alternative for preserving labile and photooxidative compounds (*e.g.*, antioxidants), it requires high energy consumption and installation costs, pre-treatment stage (initial freezing), and vacuum equipment.

Recently, the combination with other innovative technologies or pre-treatments allows to overcome some of the processing challenges. Microwave-assisted freeze drying promotes a quick heating, since microwaves ensure the general heating of large parts of the product. This is due to microwaves penetrate deep into the fruit by electromagnetic radiation. These characteristics prevent or decrease oxidation damages, bioactive and volatile compounds degradation, shrinkage and displacement of soluble solids, and porous structure loss (Ozcelik, Heigl, Kulozik, & Ambros, 2019).

Osmotic dehydration

The osmotic dehydration method consists of immersing the fresh product in a hypertonic solution in order to transfer water from the food to the solution by osmotic pressure difference. This technique, which can be applied to all types of fruit, uses concentrate juices, polyols solutions, and salt (sodium chloride) and sugar solutions as the most common drying agent (Ghellam et al., 2021). In general, the type of osmotic solution and the process time are the most significant factors affecting mass exchange values during osmotic dehydration, while temperature is the least significant factor (Kowalska et al., 2017).

This method allows to preserve the physicochemical characteristics and sensory attributes. Osmotic treatment is effective in preventing and minimizing discoloration and flavour loss attributed to thermal damage and delayed enzymatic browning reactions. In this regard, it can even improve quality when used in concentrated juices. Furthermore, it is described as a tool that requires less energy consumption and operating costs. On the other hand, its disadvantages are related to the composition of the final product, in particular with the high moisture or sugar/salt content (if dehydrated with these solutions), which makes it sometimes difficult to predict the chemical composition of the final product (*e.g.*, concentrates juices) (Ghellam et al., 2021).

Zielinska and Markowski (2018) applied osmotic dehydration in cranberries (*Vaccinium oxycoccus* L.). As osmotic solution, a sucrose solution with a concentration of 65° Brix was used. Dehydration was carried out for 6 h at 21 °C with continuous stirring. Despite the application of this drying method increased dehydration and decreased impregnation, its combination with microwave-vacuum pretreatment improved the dehydration process, decreasing the resistance to mass transfer through the skin and the waxy layer of cranberries. Kowalska et al. (2017) evaluated the use of osmotic dehydration in strawberry fruits of *Honeoye* var., using sucrose as osmotic solution. Moreover, inulin and chokeberry *Aronia melanocarpa* juice concentrate were also studied as carrier of functional compounds. These osmotic substances were used as partial sucrose substitutes. All the solutions had a concentration of 50° Brix and were applied at 30–50 °C during 360 min. The use of inulin or chokeberry juice concentrate facilitated mass exchange. In the first case, inulin avoided the solid gain compared to sucrose (1.29 *vs* 1.48, for normalized solids content in osmotically dehydrated strawberries using inulin and sucrose, respectively). This might be due to the fact that inulin is characterized by a lower ability to penetrate tissues. On the other hand, the use of juice concentrate increased the polyphenols content and therefore, the antioxidant activity of dehydrated strawberries.

Emerging technologies

As mentioned above, there are several methods for berries dehydration. However, berries are characterized by their high-viscosity and by being sensitive to heat and dehydration, which could lead to a degradation of bioactive compounds such as phenolic compounds and vitamins (Araujo-Díaz, Leyva-Porras, Aguirre-Bañuelos, Álvarez-Salas, & Saavedra-Leos, 2017). Bearing this in mind, the food industry has looked for new methods, modified existing ones, or applied known techniques not previously used in food dehydration to avoid the undesirable effects that conventional methods could have on berries (Sun et al., 2019). In this regard, novel dehydration technologies have emerged mainly with the purpose of saving energy or optimizing the cost and quality of berries.

The concept of emerging dehydration technology includes new techniques or derived methods from conventional dehydration, as well as their combination with other technologies (*e.g.*, microwave, pulsed electric fields, ultrasound). These methods contribute to improve the dehydration process, reducing drying time, increasing energy efficiency, and/or improving the quality of the final product (Radojčin et al., 2021). On the other hand, these methods are not necessarily cost-effective, so the food industry often combines different dehydration methods to maximize the benefits of each dehydration technology (Richter Reis, Marques, Moraes, & Masson, 2022). For instance, vacuum dehydration technology is often used in combination with freeze-drying and microwave drying to reduce drying time and enhance drying efficiency.

Heat pump drying

As already mentioned above, the energy losses that occur in conventional hot air dehydration are significant. This has made that many methods have been reformulated to avoid this loss of energy. In this regard, heat pump dryer was designed to recover sensible and latent heat, normally lost in other methods. In this case, dehydration is carried out by condensing the air in a compression evaporator, which is supplied as hot dry air to the product, and the latent vaporization heat is recovered by condensation to be reused for reheating the drying air (Fig. 2a). In fact, this drying method is considered an improvement on convection dryer with refrigeration system (Figiel & Michalska, 2017; Moses, Norton, Alagusundaram, & Tiwari, 2014).

This dehydration method allows to reduce the time and temperatures used in comparison with conventional hot air dryer. In this regard, samples dried by heat pump have a higher overall quality, drying times are reduced by 20 % and costs by 19 % (Zhao, Peng, Li, & Ni, 2016). In addition, the energy efficiency can be improved if a chemical heat pump is installed in the processing or a hybrid system with other technologies (*e.g.*, microwave, radio frequency, or infrared) is used. In the first case, the chemical heat pump absorbs the misused heat (*e.g.*, dryer exhaust or solar energy) endothermally and releases it exothermically in chemical form, using the reversible chemical reaction to change the temperature level of thermal energy stored by chemicals (Figiel & Michalska, 2017; Moses et al., 2014).

Electromagnetic radiation drying

In addition to hot air-based methods, there are others that use electromagnetic wavelength spectrum to produce heat. Some electromagnetic radiation dehydration techniques available to be used in fruits are microwave, infrared, radio frequency, and refractance window drying.

Regarding microwave drying, this method is based on the transmission of electromagnetic waves (1 mm to 1 m spectrum, 915 and 2450 MHz frequency), where the heat generated by molecular vibration passes through berries generating an oscillation of the molecules, which produces the thermal energy used to dehydrate the berries. Compared with conventional methods, this technology allows to obtain high quality products while reducing costs and heating time with higher energy efficiency (Kumar & Karim, 2019). These characteristics make it one of the most used methods by the industry for drying berries. Moreover, it allows to reduce the microbial load due to thermal and non-thermal effects (Sun et al., 2019). Microwaves also promote porous products as a result of the drying mechanism, which evaporates bounded water through volumetric heating (Zheng et al., 2013). However, there was a greater and faster shrinkage of the microwave-dried samples. This would be related to the strong penetration of microwaves, which cause the internal temperature of the berry to rise rapidly, accelerating the removal of water from the sample tissue. Besides this drawback, a significant degradation of thermolabile bioactive compounds can occur due to the high temperatures generated inside the berries during drying. Therefore, proper control of heat and mass transfer during the process is necessary to avoid product damage (Kumar & Karim, 2019). In addition, although microwave allows better control of the dehydration process, penetration, reflection, and refraction phenomena or browning reactions caused by microwave radiation could result in uneven heating of the product, which makes it the main disadvantage of this technology (Sun et al., 2019). Jiang, Shen, Zhen, Li, and Zhang (2019) evaluated the effect of microwave drying on the physicochemical parameters of *Fragaria ananassa* "Hong Yan" strawberries. The application of 800 W during 40 min resulted in color deterioration compared to those found in other electromagnetic radiation dehydration techniques (*e.g.*, radio frequency). This would be related to the browning reactions that occur during drying due to non-uniform heating and long drying times. In addition, there was a decrease in the contents of carotenoids, anthocyanins and total phenols, which were sensitive to overheating with hot spots that are easily formed during microwave heating.

Finally, it is also important to highlight that the use of microwave-combined or microwave-assisted hybrid drying processes (*e.g.*, microwave-hot-air and microwave-vacuum drying) allows to improve the quality of dehydration, achieving organoleptic properties similar to those obtained by freeze-drying, but reducing the drying time by half (Feng, Zhang, & Adhikari, 2014).

The infrared-drying method transfers thermal energy regularly and uniformly from the heat source to the fruit in the form of electromagnetic waves (0.75–1000 μm), which allows to remove the moisture content quickly and efficiently. Compared to conventional methods, this technology requires simple equipment, shorter drying times, and consumes less energy, leading to a better-quality product at a lower cost in an environmentally friendly way. In this regard, the shrinkage of the infrared-dried berries was significantly lower than that observed in those dried with hot air (Wang, Zhang, Fang, & Xu, 2014). Therefore, this method is one of the most appropriate to be used in combination with conventional dehydration methods (Moses et al., 2014).

The effects of infrared parameters on fruit quality are variable. In general, as the infrared power increased, color change, effective diffusivity coefficient, hardness and shrinkage increased (Huang, Yang, Tang, Luo, & Sunden, 2021). Adak, Heybeli, and Ertekin (2017) evaluated the effects of infrared drying parameters (power, air temperature and velocity) on strawberry quality characteristics. Strawberries cut in halves were subjected to different conditions of power (100, 200 and 300 W), air temperature (60, 80 and 100 °C) and velocity (1.0, 1.5 and 2.0 m/s). The authors found that the application of 200 W, 100 °C and 1.5 m/s allowed to preserve the nutrients of strawberry. However, the highest contents of polyphenols and anthocyanins were obtained when the lowest temperature and air velocity conditions were used.

In regards to radio frequency, has been widely assessed as an alternative to hot air-drying. In this case, the heating is produced by the interaction between the electromagnetic field, produced by a radio-frequency generator, and the fruit. The product is located between two electrodes exposed to an alternating electric field, which causes an oscillatory migration of polar molecules and charged ions. As a result, electrical energy is converted into thermal energy that penetrates deep and wide into the berry, heating the whole product (Fig. 2b). Radio frequency drying reduces the effects on the structure of the dried material, causing a barely perceptible shrinkage that prevents fruit cracking (Zhang et al., 2017). Although it allows to maintain the quality of the obtained dried product, this technique has some limitations such as thermal migration problems and corner effects (Jiang et al., 2019).

Jiang et al. (2019) compared the effects of radio frequency drying on the physicochemical parameters of strawberries. The results were compared with those obtained in microwave-dried, freeze-dried, and hot-air dried strawberries. Compared to microwave drying, radio frequency allowed a better uniformity in temperature distribution, together with a higher retention of colour, carotenoids, anthocyanins and total phenolic compounds. In fact, there are studies that indicate that the quality of radio frequency-dried samples is similar to that obtained from freeze-dried fruits.

Conduction, convection and radiation are the heat transfer mechanisms included in refractance window drying technology. The dehydration process involves placing the fruit on the surface of a conveyor belt (usually made of infrared transparent plastic) that floats on a heated hot water circulation area, which allows to improve the drying

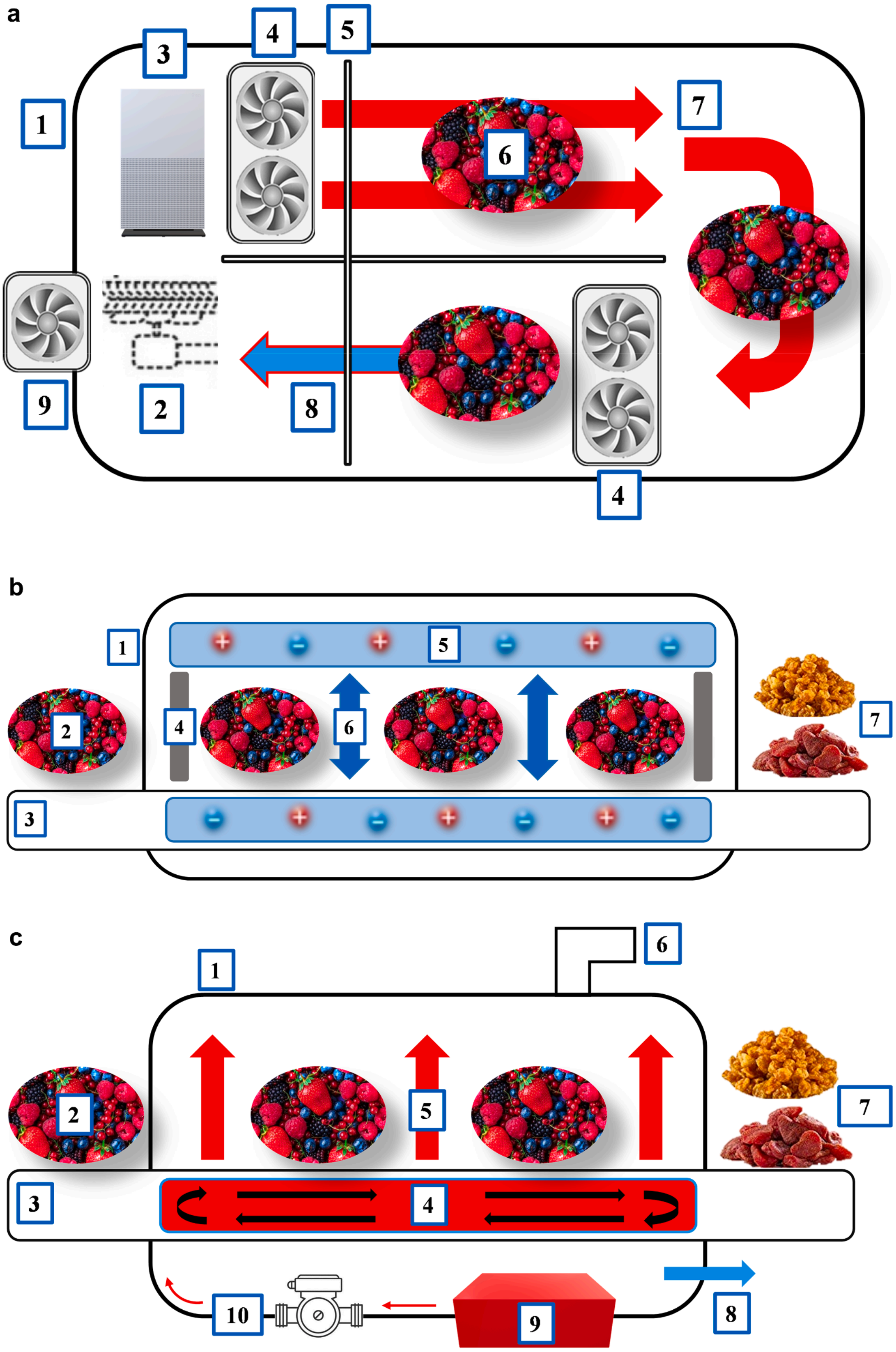

Fig. 2. a) Heat pump drying: 1. Drying chamber, 2. Compression evaporator, 3. Condenser, 4. Fan rack, 5. Partition board, 6. Fresh berries, 7. Hot air flow, 8. Cooled air flow, 9. External fan; b) Radio frequency drying: 1. Drying chamber, 2. Fresh berries, 3. Conveyor belt, 4. Radio frequency shield, 5. Electrode, 6. Electromagnetic field, 7. Dehydrated berries; and c) Refractance window drying: 1. Drying chamber, 2. Fresh berries, 3. Conveyor belt, 4. Hot water flume, 5. Surrounding air (water vapor + air), 6. Exhaustor, 7. Dried berries, 8. Cooling water, 9. Water tank and heat unit, 10. Hot water pump.

efficiency (Fig. 2c). Furthermore, the contact between the material and the plastic allows direct transfer of infrared energy to the berry creating an infrared window. Therefore, heat transfer is achieved primarily by conduction and radiation from the water to the sample, but also by convection from the heated berry to the surrounding air (Sun et al., 2019). This dehydration method can be applied to heat-sensitive fruits, since its processing conditions at atmospheric pressure and low temperatures (around 43 °C in most cases) allow to reduce the oxidation and maintain the colour and nutrients of the berries. Moreover, it is considered an energy efficient method, which uses shorter drying times and has low installation and operation costs. On the other hand, the principal limitation is the low system capacity (Raghavi, Moses, & Anandharamakrishnan, 2018).

Explosion puffing drying

Explosion puffing drying is high-efficiency technology consisting of a puffing chamber, a vacuum chamber and pump, a steam generator with a decompression valve, and an air compressor. During the process, the berries are puffed at 80–130 °C with a pressure of 0.1–0.3 MPa for 5 min, and then vacuum-dried at 50–70 °C for 180 min until reaching the final moisture content (Xiaoping, Yajun, Zijue, Fangying, & Danyang, 2018) (Fig. 3a). The vaporization of the bounded water of the fruit results in an expansion of the product due to a sudden decrease in pressure and/or an increase in temperature, which modifies the internal structure of the product making it more porous. The effects on heat and mass transfer, mechanical deformation, fracture resistance and shrinkage depend on pore size and the thickness of the solids between pores. Moreover, this drying method allows to preserve most of the berry's nutrients during the drying process. However, there are some that could be degraded due to the high temperatures reached during the vacuum-drying stage.

This method is usually an intermediate stage of drying, where it is often combined with other techniques (*e.g.*, convective drying and freeze-drying) to reduce processing time and energy. Chen et al. (2017) evaluated the effect of these hybrid drying methods on antioxidant properties, nutritional quality, and physicochemical parameters of dried black mulberries (*Morus nigra* L.). The conditions applicated at hot air and freeze-drying were 70 °C for 3 h and −55 °C for 12 h and 0.01 kPa, respectively. The conditions applied below were common in both cases: (1) Explosion puffing drying 80 °C for 5 min; (2) vacuum drying 70 °C for 3 h and 0.1 MPa. The combination with freeze-drying resulted in

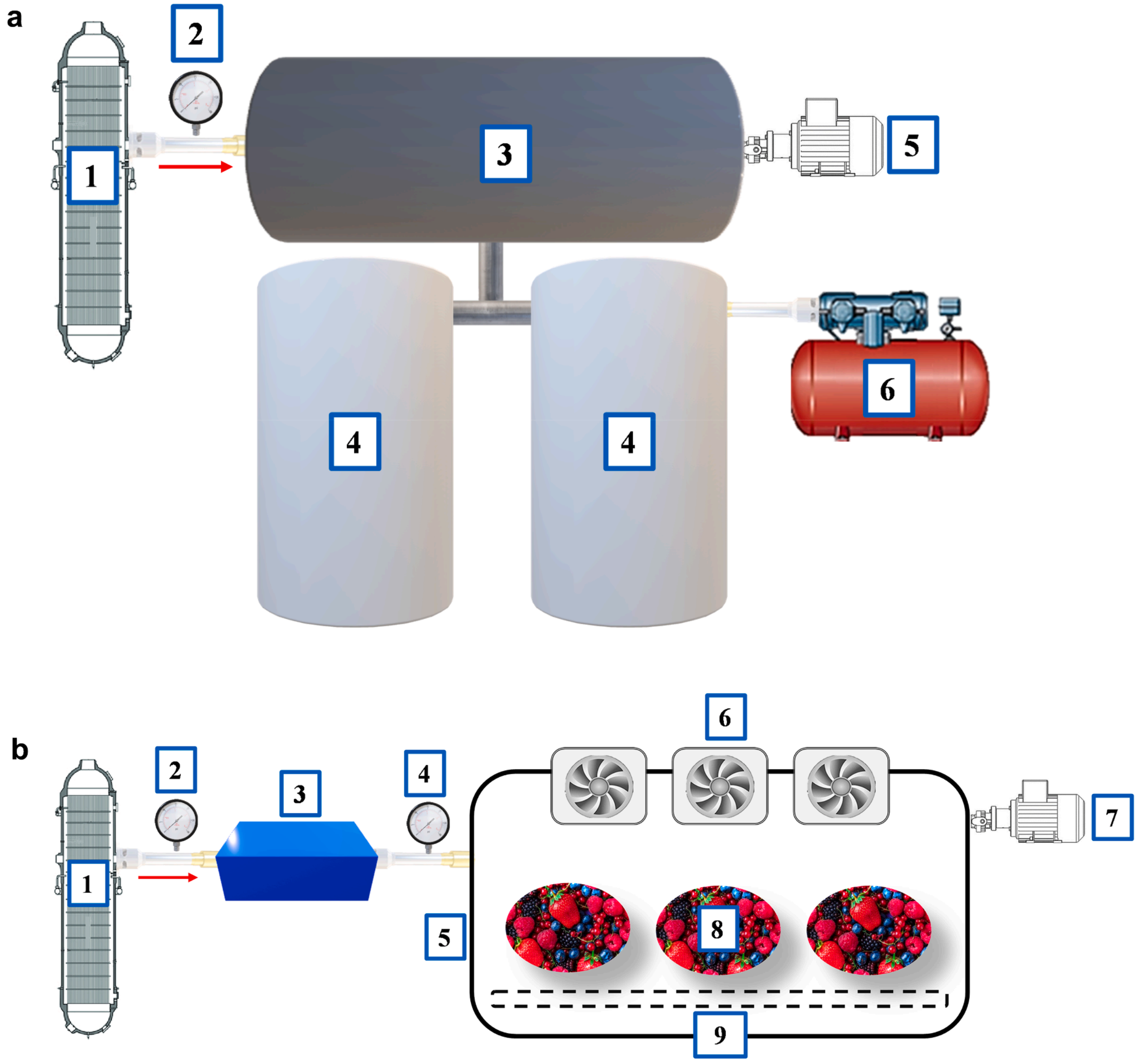

Fig. 3. a) Explosion puffing drying: 1. Steam generator, 2. Decompression valve, 3. Vacuum chamber, 4. Puffing chamber, 5. Vacuum pump, 6. Air compressor; b) Low-pressure superheated steam drying: 1. Steam generator, 2. Valve, 3. Steam reservoir, 4. Steam regulator, 5. Drying chamber, 6. Electric fan, 7. Vacuum pump, 8. Fresh berries, 9. Sample holder.

berries with the best properties of texture, colour and sensory attributes. This combination of dehydration methods also allowed to retain a higher content of bioactive compounds such as anthocyanins (12.38 mg/g *vs* ≈8 mg/g for freeze- and convective-explosion puffing drying, respectively), cyanidin-3-glucoside (8.60 mg/g *vs* ≈5 mg/g for freeze- and convective-explosion puffing drying, respectively), cyanidin-3-rutinoside (2.62 mg/g *vs* ≈2 mg/g for freeze- and convective-explosion puffing drying, respectively). This higher content of bioactive compounds was also reflected in the high antioxidant activity of dried berries by freeze-explosion puffing drying. The values obtained for TPC (25.65 *vs* 27.56 mg GAE/g for freeze-explosion puffing and freeze-drying, respectively) and DPPH (91.53 *vs* 101.57 mg Trolox equivalent/g for freeze-explosion puffing and freeze-drying, respectively) were close to those observed in freeze-drying. In fact, it is considered a cheaper alternative to freeze-dried products (Chen et al., 2017). Similar results were found by Si et al. (2016) in raspberry (*Rubus idaeus*). The outcomes obtained by hot air and explosion puffing drying [(1) Hot air 70 °C/90; (2) Explosion puffing drying 97 °C; (3) Vacuum drying 69 °C for 150 min and 5 KPa] were compared with those obtained by hot air drying (70 °C, 2.1 m/s) and freeze-drying (−56 °C, 0.01 kPa, 36 h). Raspberry freeze-dried powders displayed significantly better physical properties (*e.g.*, color parameters, hygroscopicity, soluble solid, water solubility) than those found in the combined drying method. The same effect was observed in anthocyanin content where the highest retention among three drying techniques was observed in raspberry powders obtained by freeze-drying (0.33 g/kg *vs* ≈0.25 and ≈0.18 g/kg for freeze-drying, hot air and explosion puffing drying and hot air drying, respectively). On the contrary, raspberries dried by the combined method showed the highest contents of total polyphenols (≈120 g GAE/kg) and total flavonoids (≈0.27 g catechin equivalent/kg). This was also reflected in the antioxidant activity values, which were higher than those obtained with freeze-drying (4510 *vs* 4252 μmol TE/g, 2734 *vs* 2588 μmol TE/g, 5679 *vs* 5282 μmol TE/g for ABTS, DPPH and FRAP, respectively). Therefore, explosion puffing drying could be recommended for use in the berry drying industry.

Low-pressure superheated steam drying

Compared with traditional low-temperature dehydration methods, this technology is more energy efficient since it can save 50 % of the basic energy without combustion or oxidation reactions during processing, leading to a better quality dehydrated products (Sun et al., 2019). These benefits are the result of low temperature and pressure operation (maintained by a vacuum pump), and the complete lack of oxygen. Dehydration processing occurs in an insulated drying chamber, where the drying agent is steam (not hot air) that is dispersed with an electric fan throughout the drying chamber (Fig. 3b). Drying is achieved by the use of superheated steam at a temperature above steam saturation and at a defined pressure. However, the system has limited applications due to this method is quite complex and slow (Calín-Sánchez et al., 2020). Drying times, which depend on pressure and temperature, range between 280 and 400 min when 7 kPa are applied at 75 and 65 °C, respectively (Kongsoontornkijkul, Ekwongsupasarn, Chiewchan, & Devahastin, 2006; Methakhup, Chiewchan, & Devahastin, 2005). This makes it usually combined with other technologies (*e.g.*, far-infrared) to speed up the process.

Intermittent drying

Intermittent drying is one of the most energy-efficient fruit dehydration methods in which drying is carried out by controlling some of the parameters involved in the drying process, interspersing periods of effective drying with periods of tempering (Kumar et al., 2014). Airflow rate, drying air temperature, humidity, energy intake (*e.g.*, conduction, convection, microwave, radiation) and/or pressure are among the factors that can be varied over time. Therefore, hot air, microwave power, vacuum, ultrasound, or infrared can be used as drying agents (Duc Pham et al., 2019; Chandan Kumar et al., 2014; Onwude et al., 2017). The most common form of intermittent drying is achieved by changing drying air conditions (Chin & Law, 2010).

During the tempering stage, the temperature is standardized and water is transferred from the interior to the surface of the product, which prevent overheating. Therefore, physical and chemical degradation, and heat damage are reduced by the constant presence of water on the surface (Kumar et al., 2014). Moreover, although intermittent drying prolongs the total drying time, it also shortens the effective drying time required to reach the desired final moisture content (Chin & Law, 2010). Therefore, according to the reported information, the advantages of this method are related to the repetition of the process (surface moisture evaporation and displacement of inner moisture to the surface), which allows to reduce the overheating. This together with the short heating times leads to the reduction of oxidative and enzymatic processes, which prevents the damage of heat-sensitive bioactive compounds (Duc Pham et al., 2019). As a result, undesirable effects are reduced, maintaining the properties (*e.g.*, colour and texture) and enhancing shelf-life of dried berries.

This technique emerges as an alternative to those methods that lead to significant drawbacks during the drying process. In this regard, intermittent microwave-convective drying significantly improves the limitations associated with microwave drying, especially those that occur at the early drying stage or higher powers, minimizing overheating, non-uniformity of temperature distribution, severe cell membrane breakage, surface or inner cracks, overall shrinkage as well as cellular collapse. On the other hand, compared to convection drying, intermittent drying reduces time processing and total shrinkage, and improves the quality of the final products (Duc Pham et al., 2019; Chandan Kumar et al., 2014). In addition, this method allows to protect bioactive compounds, and reduce browning effects and hydrothermal stress in the fruit (Duc Pham et al., 2019; Chandan Kumar et al., 2014). Therefore, it can be used in all kinds of fruits to produce plant-based food material.

Combined drying methods for dehydration

The combination of dehydration methods can be considered as one more emerging technology. Their use is promising since the combination of the advantages of the methods can reduce the negative aspects of each one. Although there are several possible combinations of dehydration methods, only those that deserve special attention for berry dehydration will be discussed in this review: (i) microwave-convective drying, (ii) vacuum-microwave drying, (iii) convective and vacuum-microwave drying, (iv) microwave-assisted fluidized bed dryer, (v) microwave and far-infrared combination, (vi) ultrasound-assisted convective drying, and (vii) swell drying. Even so, it is important to highlight that these combinations still need future research to achieve the process optimization.

As already discussed, convective drying is the most common dehydration method used on berries. However, this technique has some disadvantages, which can be reduced if it is combined with other technologies. In this regard, microwave-convective drying allows to solve the problem related to heat transfer, since hot air reduces unbound moisture from the surface of the product and microwave energy removes bound moisture from the interior of the product (Kumar & Karim, 2019).

Vacuum-microwave drying is an innovative technology, which is still common in the food industry. This technique would solve the disadvantages associated with conventional drying, since it fulfils four of the most important requirements for dehydration improvement: costs, energy efficiency, operational speed and product quality. Vacuum conditions favour mass transfer, and avoids product oxidation and high temperatures, while microwave heating ensures accelerated energy transfer. On the other hand, the lack of uniformity of microwave radiation stands out among its disadvantages, which could result in overheating of the sample (Zielinska & Michalska, 2016; Zielinska et al., 2018).

Nawirska-Olszańska, Stępień, Biesiada, Kolniak-Ostek, and

Oziembłowski (2017) evaluated the effect of microwave drying on the rheological, chemical and physical characteristics of golden berry (*Physalis peruviana* L.). The fruits were dried under reduced pressure (4–10 kPa) in order to achieve drying with a minimum swelling effect, and with a power of 120 and 480 W. Compared to convective drying, samples dried by microwave-vacuum at 480 W displayed the highest resistance to compression (10 mJ *vs* 2 mJ for microwave at 480 W and convective method, respectively) and the lowest a_w (0.232 *vs* 0.524 for microwave at 480 W and convective method, respectively). Moreover, these fruits presented a more attractive color for the consumer, being brighter (62.89 *vs* 40.66 for microwave at 480 W and convective drying, respectively) and with a soft yellow color (52.82 *vs* 19.41 for microwave at 480 W and convective drying, respectively). Regarding bioactive compounds, berries dried by microwave-vacuum showed the highest polyphenol (436.3 *vs* 177.6 mg GAE/100 g for microwave and conventional drying, respectively) and carotenoid content (296.94 *vs* 169.85 mg/kg dm g for microwave and conventional drying, respectively). The same effect was observed in all-*trans*-lutein, β-cryptoxanthin, α-carotene, all-*trans*-β-carotene and 15-*cis*-β-carotene contents. These results were also reflected in the antioxidant activity, which was higher in microwave-dried fruits (191 and 19.06 mmol Trolox/100 g for FRAP and ABTS assays, respectively). These results are due to the fact that microwave-vacuum drying prevents the partial oxidation of bioactive compounds that occurs during conventional drying, associated with the use of high temperatures and the presence of oxygen.

In addition to the vacuum-microwave technology, microwave-vacuum puffing method was suggested by Zheng et al. (2013) as a new way of berry processing (*e.g.*, blackcurrants, cranberries, raspberry). In fact, this method could be used to produce a fat-free alternative (*e.g.*, snacks) with the original flavor and nutrients of fresh berries, and a crunchy texture. The equipment used consists of a drying chamber that houses the magnetrons that transform the electrical into electromagnetic energy in the form of microwaves, a vacuum pump and a ventilation system. Three microwave output power intensities, at 1.34, 2.68 and 4.02 kW, and a vacuum pressure in the range of 0–100 kPa are commonly applied. Puffing causes an expansion of the berry's volume due to pressure differences between internal vapor and external vacuum pressure, resulting in a product with a porous structure (Zheng et al., 2013).

The combination of convective with vacuum-microwave drying leads to better quality products at lower cost and energy consumption. In this case, fruit dehydration occurs in two phases: (1) convective drying, which reduces fruit free moisture without effects on its bioactive compounds, and (2) vacuum-microwave drying, which decreases moisture content to the desired level (Figiel & Michalska, 2017). Similar to convective drying, fluidized-bed drying can be combined with microwave. In this drying method, the movement of liquid water from the interior to the surface of the berry is initiated by internal heating. As the temperature within the material approaches the boiling point of water, the pressure developed pushes the moisture to the surface and the water begins to evaporate inside the fruit. In the latter period, the moisture content near the surface decreases below the critical moisture content (Chen, Wang, & Mujumdar, 2001). The main parameters involved in the process are microwave power, temperature, and air flow rate. The application of this combined method prevents overheating, while increasing diffusivity and reducing drying times by up to 50 %, resulting in products with lower moisture content and better quality (Sivakumar, Saravanan, Elaya Perumal, & Iniyan, 2016). However, in this case the costs are high, and more studies are needed to know what are the necessary steps to carry out the drying, and the types of products in which this method could be used. On the other hand, far-infrared assisted fluidized-bed drying aims to raise the temperature of fruits with wavelengths that induce vibration of the molecules. Unlike the previous method, far-infrared rays can be applied at any stage of drying, allowing product quality to be controlled more efficiently.

Ultrasound-assisted hot air drying it is considered an alternative for the drying of those fruits that are sensitive to heat. This method, considered low-cost and energy efficient, dehydrates the products by speeding up mass transfer, resulting in a high-quality dried product (Onwude et al., 2017). The ultrasound-assisted convective dryer consists in a cylindrical vibrating radiator activated by a piezoelectric transducer, which generates a high-intensity ultrasonic field in the aerial environment where the berries are placed (Gamboa-Santos, Montilla, Cárcel, Villamiel, & Garcia-Perez, 2014a). The lower temperature (30–70 °C) and time (0.5–5 min) required for the drying process reduce undesirable effects on the fruit such as cracking, colour darkening, shrinkage, and nutritional losses (Rodríguez et al., 2018). Gamboa-Santos et al. (2014) evaluated the application of air-borne ultrasound in the convective drying of strawberry (*Fragaria* × *ananassa Duch*). Drying times were reduced with increasing acoustic power and temperature due to the improvement of the diffusivity and the mass transfer coefficient. Moreover, this combined technology did not have a significant effect on shrinkage.

Finally, swell drying is a unique method for fruit dehydration that combines convective drying with instant controlled pressure drop (DIC) drying. This technology consists in subjecting the fruit to a sudden pressure drop ($\Delta P/\Delta t > 0.5$ MPa/s) towards a vacuum (around 4.5 kPa). These pressure drops cause thermomechanical effects (*e.g.*, expansion and instantaneous cooling), which allow drying to be reached more quickly. Moreover, the combination of high pressures (0.1–1 MPa) and temperatures (80–200 °C) during short times (less than a minute) improves drying process performance (Mounir et al., 2012), functional foods quality and sensory properties (*e.g.*, aroma, colour, crunchy texture, flavour) (Sabah Mounir, Téllez-Pérez, Alonzo-Macías, & Allaf, 2014; Téllez-Pérez et al., 2020). In this regard, the expanded structure allows microbiological decontamination and bioactive compounds preservation, while preventing shrinkage and structure collapse of dried fruits, reduces energy consumption and manufacturing costs compared to conventional drying technologies (Téllez-Pérez et al., 2020). In addition, this easily scalable method was first used to produce dried vegetables for instant soups in the 90 s.

Pretreatments to improve dehydration performance

Fruits are often covered by a protective layer that makes drying difficult. In fact, fruits such as wolfberries (goji berry) (Dermesonlouoglou, Chalkia, & Taoukis, 2018; Zhou et al., 2020) and cranberries (Zielinska et al., 2018) are covered by thin wax layer, which makes drying difficult. The use of pre-treatments (*e.g.*, cavitation, electroporation, moisture reduction, protective barriers, surface etching, surface temperature elevations) before drying has shown to be beneficial in the quality of dehydrated berries, since they modify the fruit surface. As a result, permeability is increased, mass transfer is favoured, enzymes are inactivated, drying time and energy consumption are reduced, and oxidation is prevented, improving fruit quality (Bassey et al., 2021; Huang, Wu, Wu, & Ting, 2019).

The conventional pre-treatments generally include hot water or steam blanching, mechanical methods, and chemical treatments with acid or sulphating liquor, alkaline and hyperosmotic solutions. However, these methods can present drawbacks (*e.g.*, chemical absorption, nutrient loss, poor rehydration, and structural collapse) that could deteriorate the quality of the fruits. Therefore, emerging nonthermal (*e.g.*, cold plasma, edible film coating, pulsed electric fields, and ultrasonication) and thermal (*e.g.*, infrared blanching, high-humidity hot air, and microwave blanching) pre-treatments have been developed to avoid these inconveniences (Bassey et al., 2021).

Conventional pretreatments

Blanching is commonly used as a pre-treatment for microbiological and enzymatic (*e.g.*, polyphenol oxidase and peroxidase) inactivation. The use of hot water or steam for a short period of time can benefit dried berries quality, since it could promote rapid water precipitation, retention of anthocyanins and volatile compounds content, and improvement in their antioxidant capacity. However, the traditional hot water blanching, where the berries are immersed in hot water (70–100 °C) for several minutes, has some shortcomings since water is used as heat source and water-soluble nutrients could be affected. In the case of steam blanching, most of the minerals and water-soluble components are retained compared to hot water blanching due to negligible leaching effects. However, there is less heat transfer, which leads to longer drying times and possible softening of the tissues (Xiao et al., 2017). Therefore, new blanching technologies (*e.g.*, microwave, ohmic, radio frequency, ultrasonic assisted heat treatment) have emerged to improve blanching effects and compensate for the aforementioned problems, mainly caused by a diffusion-controlled phenomenon. For instance, the use of ultrasonic-assisted heat treatment would allow the same inactivation level but using shorter times and lower temperatures, since ultrahigh temperature would improve the steam temperature and ultrasound would increase the thermal sensitivity of the enzymes (Sun et al., 2019).

Compared to steam blanching, mechanical pre-treatment is the best method to preserve the sensory attributes of berries, since it hardly causes the degradation of bioactive compounds sensitive to high temperatures. Some examples of this type of pre-treatment are berry surface scratching and rubbing out the epidermis. The first method is proposed as a mechanical pre-treatment to form many small holes in the epidermis of berries, while the second is associated with low costs (Sun et al., 2019). However, these methods are not appropriate for too soft berries.

Chemical treatments with hyperosmotic solution (*e.g.* NaCl), alkaline solutions (*e.g.* K_2CO_3, Na_2CO_3 or Na_2SO_3), sulphating, and acid liquor are examples of osmotic dehydration methods (Huang et al., 2019; Zhou et al., 2020). In this technique, the fruit is immersed in a highly concentrated solution and dehydrated by the semi-permeability of the cell membrane. The most common osmotic solutions are NaCl, lyophilized protectants (*e.g.*, glucose, maltodextrin, sucrose, xylitol), and water activity reducing agents (Ahmed, Qazi, & Jamal, 2016; Bae, Choi, Lee, Kim, & Moon, 2020). During this process, some soluble substances present in the berries (*e.g.*, aromatic substances, minerals, reducing sugars) could be exuded. However, colour, flavour and nutritional properties of the product are maintained because unlike conventional drying, moisture is removed through a physical diffusion process rather than vaporization. This prevents the need for a phase change and the need to supply latent heat.

In the case of osmotic dehydration, mainly used as pre-treatment in microwave drying, it is necessary to evaluate its effect on the dielectric properties of the berry, since microwave drying depends on these properties (Sun et al., 2019). This combination results in high levels of porosity, which is considered an important property of dried fruits (Calín-Sánchez et al., 2015). In this regard, Calín-Sánchez et al. (2015) compared the porosity of chokeberries dehydrated by convective drying, vacuum-microwave drying, and their combination. The authors observed an increase in porosity when chokeberries were pre-treated with osmotic dehydration.

Emerging non-thermal pre-treatments

Non-thermal techniques (*e.g.*, cold plasma, edible film coating, pulsed electric fields, ultrasound) facilitate moisture removal, permeability, and release of cellular constituents. Cold plasma allows to improve the drying process due to the formation of micro-holes on the surface of the fruits, minimizing nutritional and sensory losses (*e.g.*, colour), increasing phenolic content and antioxidant capacity. Moreover, it is characterized by its high antimicrobial activity, its low thermal effect, and its short processing times (Hou et al., 2019; Zhou et al., 2020). Its application in wolfberries (goji berries) (Zhou et al., 2020) and grapes (Huang et al., 2019) resulted in a reduction in drying time during hot air drying, and thus improving rehydration capacity.

Pulsed electric fields (PEF) is one of the most promising non-thermal food processing technologies. The implementation of PEF in the food industry arises from the loss of quality that occurs in heat-treated products. This food processing technology allows to permeabilize cell membranes by emitting short high-voltage pulses (0.1–80 kV/cm for nanoseconds to milliseconds) through a food product placed between two conductive electrodes (Pateiro, Domínguez, et al., 2021). As a result, drying speed is improved and energy consumption is reduced (Li, Chen, Zhang, & Fu, 2017).

Ultrasonication is a nonthermal food processing technology with many applications in the food industry. It consists of the application of pressure waves at frequencies between 20 kHz and 10 MHz in an ultrasonic bath, using water or an osmotic solution as solvents (Mothibe, Zhang, Nsor-Atindana, & Wang, 2011). When they are applied in the band from 20 to 100 kHz, a phenomenon known as cavitation occurs that causes the inactivation of microorganisms. With the passage of ultrasound waves, oscillations (cycles of compression and decompression) are produced in the molecules of the liquid. Initially, compression generates a localized pressure increase. Then, a decompression and the generation of negative pressure regions take place until cavities or bubbles are formed. These cavities grow until they spontaneously explode, generating regions of high pressure and temperature (Zhang et al., 2020). These air pressure disturbances favour the formation of microchannels in the tissues that intensify the mass transfer during dehydration on the surface of the fruit without a significant increase in temperature, but reducing processing time (Bassey et al., 2021). Moreover, this technology is generally considered safe, non-toxic, and with a reduced impact on the environment (Fan, Wu, & Chen, 2021).

Zhang et al. (2020) evaluated the influence of ultrasound as pre-treatment on the properties of vacuum-freeze dried strawberry slices. Strawberry slices, placed in an ultrasonic bath with distilled water, were subjected to ultrasonic waves at 200 W and 40 kHz for 25 min. Its application prior to dehydration improved the color, the content of total phenols, anthocyanins and flavonoids as well as its antioxidant capacity (Zhang et al., 2020). On the other contrary, the application of ultrasound vibration amplitude (0–90 μm), sonication time (10–30 min) and air temperature (40–60 °C) in Andean blackberries (*Rubus glaucus*) favoured the formation of radicals and facilitate the leakage of bioactive compounds, which would lead to the loss of their functional quality (Romero & Yépez, 2015).

Another possibility is the use of edible films, which are natural biopolymers developed to maintain food quality by protecting the fruit against enzymatic and oxidation reactions, mechanical damage, loss of volatile compounds and senescence. This is related to its ability to reduce solute input and, at the same time, increase water removal during drying. They can also be used to incorporate functional components such as antimicrobials, antioxidants, and/or nutrients (Bassey et al., 2021). However, there are still few studies about its application as a pre-treatment technique for berry dehydration. Gamboa-Santos and Campañone (2019) evaluated the application of edible films as a pre-treatment to the drying process of strawberries (*Fragaria* × *ananassa* Monterrey). The process consisted of dipping the strawberries first in a sodium alginate solution for 5 min. Once drained, they were dipped for another 5 min in a 5 % calcium lactate solution. Finally, the coated samples were left on filter paper to remove excess solution on the surface. As a result, the coated strawberries with edible alginate-lactate films before osmotic dehydration significantly reduced solids gain without affecting water and weight losses. Moreover, no significant effect on drying speed and moisture diffusivity was observed after microwave drying compared to uncoated samples.

Emerging thermal pre-treatments

High-humidity hot air, infrared and microwave blanching have also been evaluated as emerging pre-treatment methods to facilitate drying and prevent quality loss of the dehydrated product. High-humidity hot air blanching is based on launching hot air with high humidity on the surface of the material to be dried at high speed, which favours heat transfer and greater energy efficiency. In contrast, microcracks can be produced by the difference in pressure between the interior and the surface of the material, which would alter its tissue and structure. These variations reduces the moisture diffusion, losses of water-soluble nutrients, and exposure of material to heat (Bassey et al., 2021).

When infrared radiation is used as pre-treatment, changes in molecular rotation and vibrations occur due to the transmission of infrared waves as radiant energy, which is converted into heat. As a result, a greater heat transfer is achieved and the periods of exposure to heat are reduced, which reduces drying times and improves nutritional properties by avoiding a degradation of thermolabile compounds (Pawar & Pratape, 2017).

Another technology that is often used for berry dehydration is microwave heating, since reduces processing time, promotes heating efficiency, is easy and safe to handle, improves quality, and prevents water-soluble nutrients losses (Chizoba Ekezie, Sun, Han, & Cheng, 2017). This translates into a higher antioxidant capacity, a higher content of flavonoids, phenolics and anthocyanins, and a better color of the dehydrated product (Zielinska et al., 2018). Its efficiency is due to volumetric heating by which the energy of the alternating electromagnetic field is absorbed by the food and transformed into thermal energy (Bassey et al., 2021).

Effect of dehydration on berries quality, bioactive compounds, and shelf-life

As already mentioned, the botanical definition of berries structurally describes these fruits in three parts (developed from the pistil): (i) thin exocarp (outer skin), (ii) fleshy mesocarp (inner skin), and (iii) endocarp (innermost part, which holds the seeds) (D'Urso et al., 2017). The common berries include genera *Vaccinium* (*e.g.*, blueberries), *Rubus* (*e.g.*, blackberries), *Ribes* (*e.g.*, blackcurrants) (Michalska, Wojdyło, Lech, Łysiak, & Figiel, 2017), *Morus* (*e.g.*, black mulberry), *Fragaria* (*e.g.*, strawberries) (Méndez-Lagunas et al., 2017), and *Physalis* (*e.g.*, golden berry or cape gooseberry) (Puente et al., 2021). Conversely, concerning the botanical classification, fruits such as blackberries, mulberries and strawberries, which are notably popular and commonly known as berries, are not real berries (D'Urso et al., 2017). However, in view of the socioeconomical importance of the berries in terms of botanical definition and those commonly known as ones, in present review these fruits will be discussed bearing in mind both approaches.

In relation to their characteristics, fresh berries are highly susceptible to deterioration during harvest, storage, and transportation. Their high-water content and their delicate texture characteristics make them susceptible to microbial growth and physiological deterioration. Consequently, their sensory and nutritional quality can be modified due to the appearance of discolorations and the mold formation. Therefore, it seems that maintaining or improving berries quality involves reducing their moisture content. In this regard, dehydration is one of the most efficient technologies used in the preservation of perishable fruits (Sun et al., 2019). However, dehydration process, especially conventional methods, could modify the nutritional value of the final product, its sensory and physicochemical characteristics and/or its biological activity (Li et al., 2017). In the following sections, the effects of dehydration on their quality, bioactive compounds and shelf life will be further reviewed (Table 2).

Dehydration effects on berries quality

The concept of quality is a complex term that mainly includes the organoleptic characteristics and the nutritional value of the berries (Di Vittori, Mazzoni, Battino, & Mezzetti, 2018). In relation to the sensorial properties of dehydrated fruits, the most affected attributes are colour, size, brightness, shape, sweetness, bitterness, adhesiveness, and caramel flavour, which are correlated to the drying temperature (Calín-Sánchez et al., 2015, 2020). Regarding colour, changes have been observed in berries such as blueberries (Nemzer, Vargas, Xia, Sintara, & Feng, 2018; Zielinska & Michalska, 2016), tart cherries, strawberries, cranberries (Nemzer et al., 2018), black mulberry (Chen et al., 2017), blackcurrant (Michalska et al., 2017), and chokeberry (Samoticha et al., 2016). According to these studies, this parameter can be affected by many factors such as raw material properties, pre-treatment and drying methods (*e.g.*, temperature and duration time). Maintaining of natural colour in dehydrated berries is very important since visual appearance is considered an indicator of quality that could condition consumer acceptability. In this regard, one of the biggest challenges of dehydrating berries is obtaining a product with an attractive color (Calín-Sánchez et al., 2020).

During drying step, browning (enzymatic and non-enzymatic) is the most common colour variation. Enzymatic browning is produced by the oxidation of phenolic compounds (*e.g.*, anthocyanins and carotenes) and the activity of polyphenols oxidase, which stimulate de production of melanins o-quinones; while non-enzymatic browning is the result of ascorbic acid oxidation, caramelization or Maillard reactions. Browning is accelerated when the water content is intermediate, while it decreases at the end of the drying (Zielinska, Sadowski, & Błaszczak, 2016). In the first case, pre-treatments before berries drying (*e.g.*, microwave, ohmic, radio frequency, steam blanching, ultrasonic assisted heat treatment) can inactivate oxidative enzymes, which would avoid the appearance of undesirable effects.

In addition, the color changes observed after drying could also be related to the high content of carbohydrates, especially glucose and fructose, that the fruit contains. These reducing sugars could undergo the Maillard reaction by reacting with amino compounds during drying due to exposure to high temperatures, long drying, and moisture (Calín-Sánchez et al., 2020). Therefore, dehydration methods should be designed to accelerate drying time while achieving the desired moisture content and reducing browning time. With this in mind, conventional dehydration techniques (*e.g.* convective drying) produce significant color losses, while the combination of emerging technologies (*e.g.* convective - microwave drying) limit these alterations by reducing heat exposure and/or shortening processing time (Zielinska & Michalska, 2016).

In relation to the structural characteristics of the dried fruits, bulk density, porosity and shrinkage are the most studied properties (Calín-Sánchez et al., 2020). For instance, constant porosity and minimal shrinkage are often taken into account when establishing the design of dehydration models, since the water is removed from the matrix during drying and significant changes in structural properties occur (Téllez-Pérez et al., 2020). These physical properties are also very important in the subsequent rehydration of the product, since the resulting product should have characteristics as similar as possible to the fresh product. Factors such as moisture content, processing method, type of pre-treatment and drying conditions determine this process (Zhou et al., 2020).

Dehydration techniques alter the above-mentioned physical properties of the fruits and the ability of the dried product to recover its shape, since this depends mainly on the degree of tissue deterioration suffered during the dehydration process. Taking this into account, the new techniques (*e.g.*, vacuum-microwave drying, freeze-drying) make possible to guarantee less shrinkage, and low alterations in both chemical composition and color than traditional methods. The puffing phenomenon would be responsible for the structural changes and shrinkages that occur in the fruit during drying, since it influences the pore structure of the product. This process would be enhanced by the high internal pressure associated with the temperature reached in the dry material (Zheng et al., 2013). In addition, the combination of techniques that avoid overheating of the sample are a good way to reduce the bulk density (Michalska et al., 2017).

In the last years the physical properties of the products (*e.g.*, texture)

Table 2
Dehydration effect on berries quality, bioactive compounds, and shelf life.

Berry	Dehydration method	Effects			Reference
		Quality	Bioactive compounds	Shelf life	
Conventional methods					
Berries: raspberry (*Rubus idaeus* var. Autumn Bliss), boysenberry (*Rubus ursinus* × *R. idaeus* var. Black Satin), redcurrants (*Ribes rubrum*), and blackcurrants (*Ribes nigrum*)	Convective drying (50 °C for 48 h, 65 °C for 20 h, and 130 °C for 2 h)	Intermediate conditions allowed to preserve the color. Temperature above 100 °C promote the deterioration of berry characteristics.	Increase in TPC content under intermediate drying conditions, and anthocyanin (delphinidin and cyanidin derivatives) preservation		Bustos et al. (2018)
Grape berries (white cultivar Xiangfei)	Convective drying (30 °C, 40 °C, 50 °C)	Higher temperature, higher water loss rate and therefore, higher weight loss (75 % after 5 and 30 days of treatment at 50 °C and 30 °C, respectively). High temperature dehydration favours sugar accumulation.	High temperatures favoured the accumulation of some phenols (mainly gallic acid and its derivatives), while the highest accumulation of flavonoids and proanthocyanidins was achieved when lower temperatures were used.		Chen et al. (2021)
Strawberry	Convective drying (50 °C and 60 °C, 1.5 m/s)	ΔE was greater in strawberries dried longer (9.3 *vs* 5.3 for 50 °C and 60 °C, respectively).	Higher loss of TPC (60.9 % *vs* 78.1 % for 60 °C and 50 °C, respectively) andanthocyanins (45 % *vs* 26 % for 60 °C and 50 °C, respectively) with temperature.	Higher temperatures retained antioxidant activity better (74.7 % *vs* 66.2 % for 60 °C and 50 °C, respectively)	Méndez-Lagunas et al. (2017)
Conventional and emerging methods comparison		**Effects**			**References**
		Quality	**Bioactive compounds**	**Shelf life**	
Berries: blueberries, tart cherries, strawberries, and cranberries	• Convective drying (70 °C, 0.76 m/s up to 32 h) • Freeze-drying • Refractance window drying (samples at 88 °C for 3–4 min.)	Freeze-drying: better quality retention. Higher vitamin B retention in blueberry and cherry, and C in cherry and cranberryHot air: lesser quality retention (higher ΔE, lower glass transition temperature, and rough surface morphology) Refractance window: higher vitamin B retention in cranberry and strawberry, and C in strawberry and blueberry	Freeze-dried berries: higher TPC, anthocyanin and chlorogenic acid contents. Flavonoids were also superior in strawberries. Hot-air dried samples: Lower abundance of organic acids and condensed tannins.	Hot-air dried samples: Less antioxidant activity, while no significant differences were found between freeze- and refractance window drying.	Nemzer et al. (2018)
Blackcurrant (*Ribes nigrum* L.) pomace powders	• Convective drying (50 °C –90 °C, 0.8 m/s • Freeze-drying (24 h at 65 Pa) • Microwave-vacuum drying (120 W, 240 W, 360 W, 480 W at 4–6 kPa) • Convective-microwave drying	Microwave vacuum: higher bulk density and lower porosity, darkest powder Freeze-drying: highest true density, a*, b*, C*, and ΔE*		Convective drying: lower water activity and solubility. Significant loss of antioxidant capacity	Michalska et al. (2017)
Black mulberries (*Morus nigra* L.)	• Convective drying (70 °C, 2.5 m/s, 9 h) Freeze-drying • Convective-explosion puffing drying (70 °C for 3 h, 80 °C for 5 min, −0.1 MPa and 70 °C for 3 h) • Freeze-explosion puffing drying (-55 °C, 0.01 kPa for 12 h, 80 °C for 5 min, −0.1 MPa and 70 °C for 3 h)	Freeze drying: best colour (L*, a*, C*)Freeze-explosion puffing drying: best texture (hardness, crispness, rehydration ratio), colour (h*) , and overall score of sensory evaluation	Freeze drying: higher anthocyanin (cyanidin-3-glucoside, cyanidin-3-rutinoside) content	Freeze drying: higher antioxidant activity	Chen et al. (2017)

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Table 2 (*continued*)

Berry	Dehydration method	Effects			Reference
		Quality	Bioactive compounds	Shelf life	
Blueberries rabbiteye (*Vaccinium* spp.; Brightwell and Powderblue cultivars)	• Convective: fluidized bed dryer, air-impingement dryer and forced air dryer at 85 °C and 107 °C	Fluidized bed dryer: shorter drying time Air-impingement dryer: quality similar to control			Yemmireddy et al. (2013)
Blueberry (*Vaccinium corymbosum* L., *cv.* Bluecrop)	• Convective drying (60 °C – 90 °C, 1 m/s • Microwave-vacuum drying (1.3 W/g, 4–6 kPa) • Convective-microwave-vacuum	Convective drying produced the hardest, chewiest, and gummiest blueberries, and the most relevant changes in colour density, polymeric colour, and polymeric colour percentage.	Convective drying: higher TPC content at higher air temperatureConvective (90 °C) - microwave - vacuum: higher total monomeric anthocyanins retention	Convective (90 °C) - microwave - vacuum: higher antioxidant capacity	Zielinska & Michalska (2016)
Blueberry juice	• Convective drying (85 °C • Cold plasma (1 kV, 1000 Hz, 2.0 cm, O_2 0–1 %, 2–6 min	Cold plasma: better colour retention	Cold plasma: long treatments decrease anthocyanin, vitamin C and antioxidant activity, and increased TPC content. High oxygen concentration decreased vitamin C concentration, and increased TPC content	Cold plasma: *Bacillus* inactivation and increased TPC and antioxidant activity (DDPH and ABTS)	Hou et al. (2019)
Chokeberry (*Aronia melanocarpa* Elliott)	• Convective drying (50–70 °C, 1.2 m/s) • Freeze-drying • Vacuum drying (50 °C, 100 Pa, 24 h) • Microwave drying (240–480 W, 4 and 6 kPa) • Convective-vacuum-microwave	Separate use of convective drying and microwave reduces the quality of the dried product, while their combination improves the quality. Regarding color, convection-vacuum-microwave, and vacuum drying resulted in darker fruits. Redness and yellowness were higher in convection-vacuum-microwave.	Freeze-drying: higher TPC and anthocyanin content	Freeze-drying: lowest a_w values, which favours dried fruit stability. Antioxidant activity preservation	Samoticha et al. (2016)
Chokeberry (*Prunus virginiana* L.)	• Convective drying (50 °C for 24 h) • Freeze (−20 °C for 24 h), • Freeze-drying (24 h) • Swell drying (pre-drying, DIC treatment, and post-drying)	Convective drying: higher shrinkage and dense structure. Freeze and swell drying minimally affected the structure and no noticeable shrinkage.	Freezing and swell drying: preserved TPC, flavonoid, and kuromanin contents	Convective drying: lower of antioxidant activity Freezing and swell drying: preserved antioxidant activity	Téllez-Pérez et al. (2020)
Chokeberry (*Aronia melanocarpa*)	• Convective drying (60 °C, 0.8 m/s) • Freeze drying • Vacuum-microwave drying (240 and 360 W, 4–6 kPa, 22 °C, 1 m/s) • Convective (60 °C, 4 h) – vacuum-microwave (360 W 4 h) • Osmotic dehydration (45 °C, 2 h 40 °Bx) - vacuum microwave • Osmotic dehydration (45 °C, 2 h 40 °Bx) - convective (60 °C for 1.5 h min) - vacuum microwave (360 W)	Freeze drying: highest porosityVacuum-microwave (360 W): shortest drying time, best sensory properties (reduction of sourness, bitterness, astringency)			Calín-Sánchez et al. (2015)
Goji berries (*Lycium* spp.)	• Convective drying (60 °C, 5 h) • Osmotic dehydration (glycerol,	Combination: drying time (2 h) decrease, bright red colour and texture improved	Combination: higher TPC content	Combination: higher antioxidant capacity and shelf life	Dermesonlouoglou et al. (2018)

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Table 2 (*continued*)

Berry	Dehydration method	Effects			Reference
		Quality	Bioactive compounds	Shelf life	
	maltodextrin, ascorbic acid, sodium chloride for 1 h at 55 °C) with convective (60 °C, 5 h)			prolongation (3.3 times)	
Golden berry (*Physalis peruviana* L.)	• Convective drying (60 °C and 80 °C) • Freeze-drying • Infrared drying	Convective and infrared drying degraded fiber precursors (celluloses, hemicellulose and pectin), decreasing crude fiber content.Drying increased L* (freeze-drying), and decreased a* and b* values (convective drying at 80 °C). Berries dried by infrared showed lower ΔE, displaying similar color than fresh fruit		a_w values obtained guarantee stability during shelf life. Convective (80 °C) and infrared: better antioxidant activity	Puente et al. (2021)
Golden berry (*Physalis peruviana* L.)	• Convective (70 °C,1.5 m/s) • Microwave (4–10 kPa at 120 W and 480 W)	Microwave (480 W): higher resistance to compression, brightest and smooth yellow colour	Microwave drying (480 W): higher bioactive compounds	Microwave drying (480 W): better antioxidant properties and lowest a_w	Nawirska-Olszańska et al. (2017)
Maqui (*Aristotelia chilensis* (Mol.) Stuntz)	• Convective (60 °C for 4.5 h) • Solar (45 °C, 40 % RH, 3 days, 18 h day light) • Infrared (900 W, 60 °C, 4.5 h) • Vacuum (60 °C, 0.15 bar, 4 h)		Freeze-drying: highest TPC Vacuum-drying: higher flavonols. Sun: most affected bioactive compounds	Freeze-drying: highest antioxidant compounds Sun: most affected antioxidant activity	Quispe-Fuentes et al. (2018)
Strawberries	• Convective (70 °C) • Radio frequency (20 W/g) • Freeze-drying (100 Pa, −55 °C.) • Microwave drying (800 W, 20 W/g)	Radio frequency: better temperature uniformity and energy efficiency Similar quality between methods	Radio frequency: greater retention of TPC, carotenoid, and anthocyanins		Jiang et al. (2019)
Strawberry (*Fragaria* × *ananassa* Duch)	• Convective (60–100 °C, 1–2.0 m/s) - Infrared drying (100, 200, 300 W)	Drying time and fruit color quality decreased with increased power, temperature, and velocity	The application of 300 W, 60 °C, 1.0 m/s resulted in higher TPC and anthocyanin contents	200 W, 100 °C and 1.5 m/s: optimal to preserve nutrients	Adak, Heybeli, & Ertekin (2017)
Wolfberry (*Crataegus* spp.) juice	• Ultrasound (120 W, 0.7 W/cm^2, 10 s:10 s and 10 s:90 s) - assisted vacuum drying (40–60 °C, 100 Pa).	Conditions of 50 °C, 10 s:10 s generates minor color changes and minimal quality loss			Qi et al. (2021)
Dehydration methods with pre-treatments (PT)		**Effects**			**References**
		Quality	**Bioactive compounds**	**Shelf life**	
Amelanchier berries (*Amelanchier canadensis* L. Medik.)	• Convective drying (60 °C, 3.5 m/s, 12 h) • Vacuum-microwave drying (355 W, 35 min., 2.8 kPa) • Convective (PT: 60 °C, 9 h, 3.5 m/s) - vacuum-microwave (370 W, 15 min, 2.8 kPa)	Convective: higher density and lower ΔE Vacuum-microwave: higher anthocyanins and moderate shrinkage PT: higher Aw, dry matter, L*, and ΔE	Vacuum-microwave: retention of bioactive compounds	Vacuum-microwave: higher antioxidant activity	Piecko, Konopacka, Mieszczakowska-Frąc, & Kruczyńska (2017)

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Table 2 (*continued*)

Berry	Dehydration method	Effects			Reference
		Quality	Bioactive compounds	Shelf life	
Andean blackberry (*Rubus glaucus* Benth)	• Ultrasound: 0–90 µm, sonication time 10–30 min • Convective drying (40–60 °C, 3 m/s, 65 % RH)	Ultrasound increased drying rate up to 5 times	Ultrasound increased the antioxidants compounds migration to the liquid medium (useful for extraction processes). Lower vibration amplitude and time of sonication resulted in higher antioxidant activity		Romero & Yépez (2015)
Cranberries (*Vaccinium macrocarpon*)	• Osmotic PT (sucrose solution 65° Brx, 21 °C, 1: 4 for 6 h)-microwave vacuum • Microwave-vacuum PT (100–800 W, up to 20 min, 5 kPa)-osmotic-microwave-vacuum (100 W, 5 kPa)	Microwave-vacuum pre-treatment (100 W) produced high-quality berries	PTs: similar TPC retention	PTs: similar antioxidant activity	Zielinska et al. (2018)
Gapes (white) seedless (*Sugraone* variety)	• Convective drying • Atmospheric-pressure air plasma jet PT (500 W, 25 kHz) • Chemical-soaked PT (0.5 % NaOH and 2 % ethyl oleate for 30 s at 80 ∘C)	PTs individually: Decrease in drying time by more than 20 %. Effects were not significant on color and texture.	PTs: Total phenolic content and antioxidant capacity doubled		Huang et al. (2019)
Strawberry (TianXianZui)	• Vacuum-freeze drying (−50 °C, 10 Pa, heating plate temperature of 4 °C, 20 h) • Ultrahigh pressure PT (100 MPa and 5 min) • Ultrasound PT (25 min, 200 W and 40 kHz) • Combination ultrahigh pressure-ultrasound	Ultrahigh pressure or ultrasound: Increase a*, hardness, and cross-sectional areas of the matrix PTs combination: higher effect on quality and enlargement of porous structure	PT individually: TPC, anthocyanin, and flavonoids increased, as well as antioxidant activity		Zhang et al. (2020)
Wolfberry (*Lycium barbarum* L.)	• Cold plasma (3 L/min, 20 kHz, 750 W for 15, 30, 45, 60 s) • Convective drying (65 °C, 3.0 m/s)	Cold plasma PT: drying time reduction (50 %), ΔE decrease, higher rehydration ratio and L*, a*, and b*. Cell wall and membranes are disintegrated by increasing treatment time, which favoured moisture diffusion and cell release of phytochemicals	Cold plasma PT: Decrease in bioactive compounds with treatment time		Zhou et al. (2020)

a*: Redness; b*: Yellowness; DIC: Instant controlled pressure drop; L*: lightness; PT: pre-treatment; TPC: Total phenolic content; ΔE: Color difference.

has been evaluated by sensory panels or by instrumental methods with texture analysers. However, recently 3D image analysis such as X-ray microtomography (XMT) is useful in evaluating the internal structure of dried fruits as it provides relevant data on volume, wall thickness and size, allowing a non-destructive 3D viewing of the product. For instance, XMT has been successfully used on dried chokeberries (highly porous product) to assess cracking, internal moisture and shrinkage (Calín-Sánchez et al., 2015).

Concerning nutritional value, the vitamin C is the most labile of all the water-soluble vitamins, since it is sensitive to heat, light and ultraviolet radiation, and it is even susceptible to oxidation in the presence of oxygen from the environment (Hou et al., 2019). Therefore, it could be degraded during the berry drying. In addition, a reduction in the sugar content of the plant material occurs after dehydration as a result of the Maillard reaction, also known as non-enzymatic browning. This phenomenon is favoured by the increase in temperature and time during convective dehydration, which causes a reduction in sugars such as glucose and fructose. The dehydration method can also affect the functional properties of proteins, especially through the basic amino acid lysine, which can be used as an indicator of protein deterioration (Calín-Sánchez et al., 2020).

With that being stated, the effects of dehydration on berry quality are closely related to the optimization of the drying processes. Outstandingly, sensory evaluation makes possible to determine the effects of a dehydration technique on the products obtained, but also to know if the improvement of the process results in a better acceptance by the consumer.

Dehydration effects on berry bioactive compounds

In addition to the large number of nutrients (*e.g.*, sugar, protein, organic acids, and minerals), berries also contain bioactive compounds (*e.g.*, phenolic compounds, polyphenols, and vitamins) (Li et al., 2017). Although they are found in lower quantities, these metabolites have an important role (*e.g.*, defence from pathogens, growth, intermediates in reactions of photosynthesis, plant pigment, and reproduction) in the secondary metabolism of berry crops (D'Urso et al., 2017).

Berries are one of the best-known sources of phenolic compounds, with contents higher than 200 mg per 100 g of fresh fruit (Arfaoui, 2021). Among them, flavonoids, phenolic acids and tannins stand out. In addition, significant concentrations of anthocyanins are found in these fruits (Vargas-Ramella, Pateiro, Gavahian, et al., 2021). This richness in bioactive compounds gives them health-promoting properties linked to the antioxidant activity, metal chelation capacity and affinity for proteins of these metabolites.

Their potential therapeutic effects have attracted the attention of the scientific community and consumers since these characteristics makes them natural functional foods (Bustos et al., 2018; D'Urso et al., 2017), being able to be used as an ingredient in functional food products (Echegaray et al., 2020). Antioxidant activity, anti-inflammatory properties, reduction of metabolic syndrome-related disorders, oxidative stress and risk of obesity are the most important biological properties associated with phenolic compounds (Sun et al., 2019; Vargas-Ramella, Pateiro, Gavahian, et al., 2021). However, the concentration and the bioavailability of these compounds can be compromised by the dehydration process, since they could be degraded during the process (Arfaoui, 2021). Exposure time, light, oxygen and temperature are the parameters that have the most influence (Vargas-Ramella, Pateiro, Gavahian, et al., 2021). Therefore, optimization is crucial to obtain a dehydrated product of high quality.

Regarding temperature, it has been observed that the contents of bioactive compounds are higher in low-temperature dehydrated berries than in those exposed to high temperatures (Bustos et al., 2018; Huang et al., 2019; Rodríguez et al., 2018). However, it is important to highlight low temperatures do not guarantee a better preservation of bioactive compounds, since time is another important parameter to take into account. In this regard, long time can decrease phenolic content and increase oxidation reactions. For instance, Bustos et al. (2018) dehydrated by convection raspberries, boysenberries, redcurrants, and blackcurrants using drying temperatures of 50 °C (48 h), 65 °C (20 h), and 130 °C (2 h). The outcomes showed that a drying temperature of 65 °C was the most efficient method in terms of retention of total polyphenol content, while the higher temperatures (above 100 °C) or prolonged time (48 h at 50 °C) were detrimental for these compounds. Alternatively, some conventional methods (*e.g.*, vacuum-drying) and emerging methods (*e.g.*, microwave-drying, refractance window drying technology and low pressure superheated steam drying) allow to increase the retention of these compounds by reducing oxygen levels in the absence of light. In addition, an intense decrease in the water level at the beginning of the process (first few minutes) and the pressure reduction near the product, caused by the evaporation of moisture, can also prevent the oxidation of phenolic compounds (Calín-Sánchez et al., 2020).

According to the available literature, although dehydration technologies allow to obtain products with more bioavailable polyphenols, the ultimate effect depends on the type of polyphenol, the compounds evaluated, and the time–temperature regime (Arfaoui, 2021). For this reason, it is important to select the most appropriate dehydration method for each berry in order to avoid bioactive compounds losses in the final product.

Dehydration effects on berries shelf life

It is necessary to know in depth the dehydration effects on the nutritional, functional and sensory quality attributes, since they could condition the shelf life of dehydrated berries (Calín-Sánchez et al., 2015). The water activity (a_w), which is defined as the chemical potential of water at constant pressure and temperature, is the water that is really available for microbial grown and chemical and enzymatic reactions. Hence, it is an important parameter that conditions the shelf life of dehydrated products (Ahmed et al., 2016). During drying, the supply of thermal energy reduces a_w, which prevents from microbial growth and chemical reactions (Duc Pham et al., 2019). In addition to a_w, there are other factors such as additives, activity of electrons, pH and temperature that can also influence the stability of dehydrated berries. Moreover, the combined use of intermittent drying with suitable pretreatments would also improve the product shelf-life, since can affect a_w and, hence, the growth, sporulation and survival of microorganisms (Duc Pham et al., 2019).

In addition, berry shelf life can also be conditioned by the stability of the bioactive compounds that are part of their composition. Their antioxidant activity depends mainly on factors such as raw material, processing time and temperature. Therefore, most of the antioxidants are retained during dehydration. This makes it necessary to know the retention level achieved with each technique to choose the most appropriate to produce higher quality dried berries. In this regard, oxygen-free environment and low temperatures are often recommended to prevent the loss of these valuable compounds (*e.g.*, phenolic compounds). In contrast, the antioxidant capacity of dried berries can occasionally improve due to the formation of new antioxidants derived from browning, such as the melanoidins produced in the Maillard reaction (Calín-Sánchez et al., 2020).

Dehydrated berries as food products

Dehydrated berries are of great interest to be used as food products due to their quality, phenolic content, and antioxidant properties. In addition, these products have a very positive image by consumers. In this regard, dehydrated berries have many species that are used *per se* as food products (Chen et al., 2021), and as an ingredient to obtain functional products (Oliveira et al., 2021) or as natural antioxidants (Echegaray et al., 2020; Lorenzo et al., 2018) (Fig. 4). This has meant that in recent years dehydrated berries have become part of the research focus of the food industry within the development of healthier products to improve the well-being of consumers (Zura-Bravo et al., 2019). This demand creates an opportunity to dehydrated berries, which can be used to elaborate foods such as biscuits, cereals, cheese, cookies, fermented milk, ice creams, marmalades, snacks, syrups, and yogurts, among others (Bórquez, Canales, & Redon, 2010; Stojanovic & Silva, 2006).

In recent years, the most abundant studies with dried berries as a food product have focused mainly on berries as natural additives and functional food. Indeed, this is associated to the fact that berries are a rich source of bioactive compounds, which can act as antioxidant, colourant and flavouring ingredient. Moreover, their functional properties and health-promoting potential mean that could be considered as probiotic carriers (Karam, Petit, Zimmer, Baudelaire Djantou, & Scher, 2016; Oliveira et al., 2021). In relation to functional activity, dairy products such as beverages, butter, cheese, ice cream, and yogurt are one of the most common source of probiotics (Borges et al., 2016; Vargas-Ramella, Pateiro, Maggiolino, et al., 2021). However, dairy products cannot be consumed by some people (*i.e.*, dietary restrictions, intolerances or allergies), so berries could offer an alternative in the probiotic food market (Oliveira et al., 2021).

Taking this into account and considering that scientific research on this topic continues to grow, some of the most recent studies in this field are discussed below.

Food products

Dried berries have been studied for many years by food processors as

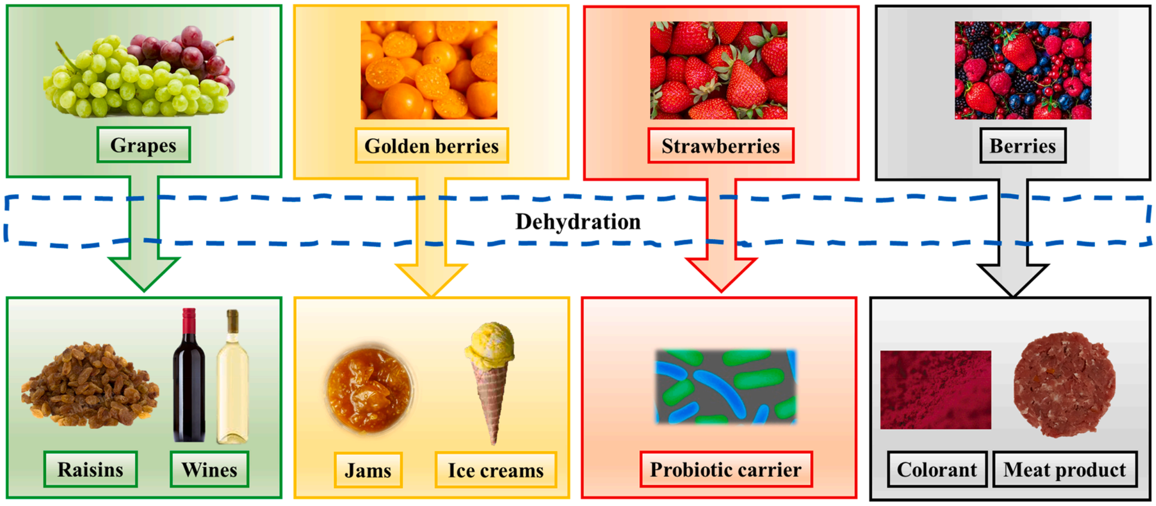

Fig. 4. Application of dehydrated berries on food processing.

an economically viable alternative to offer food in different markets. In this regard, dehydrated berries have been proposed as a resource to formulate cereals, confections, ice creams, snacks, or simply to reduce the transporting and storing costs of these fruits. However, success in achieving these goals depends largely on the drying technique and pre-treatment used (Stojanovic & Silva, 2006). In addition, considering that drying is a preservation technique, its development can contribute to reducing the high percentages of fruits losses that occur every year worldwide. According to Xu et al. (2022), up to 50 % of fruits and vegetables produced annually in the world are lost.

In line with this and according to the study published by Bórquez et al. (2010), for over a decade, there is a significant economic motivation for berries dehydration. The authors reported that berries, mainly used in the production of biscuits, cookies, dairy products, marmalades, syrups, or for direct consumption, are products that can be exported by producing countries to several markets. This economic purpose continues to arouse the interest of producing countries to convert them into new added-value products. In addition, today there is still a growing demand for dehydrated berries and this product is part of the commercial relations that exist between producers and importing countries (Borges et al., 2016; Cao, Cai, Wang, & Zheng, 2018; Echegaray et al., 2020; Oliveira et al., 2021; Qi et al., 2021; Quispe-Fuentes et al., 2018; Sette, Franceschinis, Schebor, & Salvatori, 2017).

Fruits such as raspberries are one of the most popular berries exploited and consumed worldwide. However, their lability and short season justify that they are mainly destined for the frozen market (Sette et al., 2017). For this reason, alternatives to improve dehydration methods are leading many studies with this fruit. Sette et al. (2017) evaluated the feasibility of raspberries as fruit snacks, suggesting dry infusion with pre-treatments as the most suitable drying method. Despite the fact that the authors observed the lower bioactive compounds content in pre-treated samples, this treatment was recommended due to its greater acceptability by consumers. In addition, authors highlighted that the inclusion of these fruits in the diet of children and adults favours healthier foods consumption, decreasing the intake of high-calorie snacks such as candies, chips and cookies.

Another example of a demanded product obtained from berries are raisins produced from grape berries dehydration. In recent years, several reports have been published that evaluate grape drying for raisin elaboration (Barbanti, Mora, Ferrarini, Tornielli, & Cipriani, 2008; Doymaz & Pala, 2002; Huang et al., 2019; Pangavhane, Sawhney, & Sarsavadia, 1999; Ruiz-Bejarano, Durán-Guerrero, Castro, Barroso, & Rodríguez-Dodero, 2020; Wang et al., 2020). This popular and healthy snack is a common constituent of many foods due to its high amounts of phenolic compounds, strong antioxidant activity, desirable glycemic index, and long shelf-life (Chen et al., 2021).

Food ingredients

Berries are traditionally consumed as food and some of them are even known as a “super fruit” (*e.g.*, Maqui, *Aristotelia chilensis*) due to their high content of alkaloids, anthocyanins, and flavonoids. These attributes have become berries a promising natural source of compounds with beneficial properties for human health (Quispe-Fuentes et al., 2018).

Considering berries as food ingredients, previous studies reported that dehydrated berries (*e.g.*, *Physalis* sp. golden berries) can be used to prepare different berry-based foods such as confectionary products, ice cream garnishes, meat or seafood glazes, sauces, syrups, jams and jellies preservative, and as a medicinal plant (Nawirska-Olszańska et al., 2017; Puente et al., 2021). In fact, berries syrups have also been reported to be used as a pre-treatment for dehydration techniques with the aim to improve this method. These syrups, characterized by being highly nutritious due to their significant sugar content (mainly glucose and fructose), minerals and organic acids, would contribute to improve the nutritional value and the total quality of the dried fruits. In this regard, recent researches published that the combination of techniques (mulberry or grapes syrups as osmotic solution with ultrasound dehydration) would protect the health-promoting properties of dried fruits from the undesirable dehydration effects (*e.g.*, loss of vitamin C and total chlorophyll) (Xu et al., 2022).

Furthermore, the literature also provides the potential use of berries in meat products to replace synthetic additives associated with toxicological effects (*e.g.*, butylated hydroxytoluene – BHT) (Lorenzo et al., 2018). Although dried berries are largely used in the meat industry as a well-known flavour enhancer (Alirezalu et al., 2020), dehydrated berries are also commonly incorporated as additives because of their antioxidant properties, the pungency of their extracts, their aroma and colour (as colorants) (Pateiro, Gómez-Salazar, Jaime-Patlán, Sosa-Morales, & Lorenzo, 2021). In this regard, their incorporation reduce the oxidation reactions (lipid and protein oxidation) that often occur during processing and storage of meat products, offering the consumer products with better sensory attributes and functional properties (Lorenzo et al., 2018).

Several authors have reported successful results when berries were used as powerful natural antioxidants in meat products. For instance, it highlights the antioxidant activity of blueberries (*Vaccinium* sp.) in sausages (Hur, Kim, Chun, & Lee, 2013) and pork meat (Muzolf-Panek, Waśkiewicz, Kowalski, & Konieczny, 2016), blackberries (*Rubus* sp.) in pork burgers (Ganhão, Morcuende, & Estévez, 2010), cranberries (*Vaccinium* sp.) in pork meat (Lee, Reed, & Richards, 2006) and fermented sausages (Karwowska & Dolatowski, 2017), and grape berries (*Vitis* sp.) in lamb meat (Guerra-Rivas et al., 2016) and sausages (Riazi, Zeynali, Hoseini, Behmadi, & Savadkoohi, 2016). These positive effects would be related to their high polyphenol content.

Beverages

As already mentioned, berries are commonly transformed in beverages (*e.g.*, juices and wines) due to their short shelf-life and season availability (Li et al., 2017). In fact, fruit powders are often used as intermediate products in the beverage industry (Quispe-Fuentes et al., 2018). In this regard, Camire, Dougherty, and Briggs (2007) observed that consumers found beverages more attractive when they were elaborated with intensely colored berries such as blueberry and cranberry. Moreover, berries are also considered as flavouring agents, being including in other products such as fruit bars, ice creams, and yogurts (Quispe-Fuentes et al., 2018).

High-pressure processing is a common technology in the beverage industry, which allows to obtain better quality products compared to conventional methods. Previous studies assessing high-pressure processing of berry juices obtained from aronia (chokeberry) (Błaszczak, Amarowicz, & Górecki, 2017) and mulberry (Yu et al., 2014) showed an improvement in the stability of phenolic content and therefore, a higher antioxidant capacity in non-thermally treated samples. In addition, fruit beverages have been also combined with dairy products to provide to consumers new flavoured products to which berries also confer health-promoting properties associated with their bioactive compounds (Borges et al., 2016).

Concerning wines, there are many formulations obtained from dehydrated berries, and an important amount of dehydrated grape berries has been used to produce special wines (Chen et al., 2021). An example of these beverages are sweet sherry wines, a traditional product elaborated from dehydrated grapes in the south of Spain. Ruiz-Bejarano et al. (2020) compared a traditional drying method (under sunlight on esparto mats for 10–15 days) with climate chambers (with forced ventilation under controlled conditions, 5 days at 40 °C and 10 % relative humidity) to obtain raisins for elaboration of sweet wines. Although traditional methods have been used since ancient times, the authors obtained a better quality of the products when the grapes were dehydrated in climatic chambers, avoiding undesired alterations that are normally observed in traditional methods.

Functional products

Functional foods are products that contain bioactive compounds with the aim of preventing, control, or treat disorders such as gastrointestinal diseases, obesity, diabetes, cardiovascular diseases, and cerebral stroke. Carotenoids, probiotics, and vitamins are one of the most commercialized products in this market. Concerning probiotics, the most common microorganisms and yeast utilized are *Bifidobacterium, Lactobacillus, Escherichia, Saccharomyces, Kluyveromyces, Streptococcus, Enterococcus, Propionibacterium, Pediococcus, Leuconostoc, Bacillus,* and *Clostridium* (Vargas-Ramella, Pateiro, Maggiolino, et al., 2021).

The health benefits of the above-mentioned probiotics and their activity as growth inhibitors of spoilage and pathogenic bacteria in foods has been studied with the aim of elaborating functional foods with dehydrated berries. In line with this, foods such as cereal based products, fruits and vegetables (non-dairy probiotic foods) are promising food matrices to be used as probiotic carriers. Among the techniques developed for this purpose, drying has been successfully applied to several fruits as food matrices that can be enriched with probiotics (*e.g.*, *Lactobacillus casei* var. *rhamnosus*) to produce healthy flavoured products (Zura-Bravo et al., 2019).

In a recent paper, Oliveira et al. (2021) proposed the use of dehydrated strawberries (by freeze- and oven-drying) as probiotic carriers by impregnation with a probiotic suspension (*Bacillus coagulans*). According to the authors, freeze-dried berries showed a higher preservation of bioactive compounds, physical properties (aspect and texture), sensory acceptance and probiotic viability. On the other hand, Zura-Bravo et al. (2019) suggested murta (*Ugni molinae* Turcz.) dehydrated (convective-, freeze- and vacuum drying) impregnated with *Lactobacillus casei* as functional food. The authors concluded that with freeze-drying technique, consumers could obtain the maximum health benefits provided by murta bioactive compounds and *L. casei*.

Finally, it is necessary to highlight that further research is required in the field of dehydrated berries for the elaboration of functional foods, since food matrices have different properties that can affect the probiotics viability. In this regard, a liquid matrix (*e.g.*, yogurt) is different from a solid matrix (*e.g.*, fruit). Therefore, the probiotic interaction with the food matrix is an important parameter to investigate when developing functional foods (Borges et al., 2016).

Conclusions and future perspectives

In order to maintain functional properties and quality characteristics of dried berries as similar as possible to those of fresh fruit, it is necessary to select the most appropriate dehydration method. Although the most common dehydration methods are convective, and microwave-vacuum, these techniques are associated with the appearance of browning, degradation of bioactive compounds, and deterioration of dried berries texture and flavour. Convective drying is one of the simplest and low-cost technologies, but it is also the method with the highest impact on berries properties. On the contrary, although freeze-drying is one of the most expensive treatments, it is the best technique to obtain high-quality dried berries. On the other hand, recent studies on emerging dehydration methods showed that there are promising technologies that ensure obtaining high-quality products with more energy efficiency, reduced processing time and temperature. Moreover, all these techniques have strengths and weaknesses, so the combination of methods can be used to enhance their benefits. In addition, the use of pre-treatments before berries drying improves permeability, accelerates drying rates, and inactivates oxidative enzymes, resulting in higher quality products.

Concerning the production costs and the final quality of products related to berry dehydration, conventional and emerging methods showed different cost benefits and applications. On the one hand, convective conventional methods are cheaper and easier to operate, however these methods are long and promote quality loss. Conversely, freeze-drying is one of the techniques that allows to obtain high-quality berries, since it makes possible to maintain the shape and composition of these delicate and high-valued fruits, and it allows their immediate rehydration. This justifies that freeze-drying is one of the most expensive methods (up to 8 times if compared to conventional hot air). On the other hand, in relation to the emerging techniques, heat pump, microwave, and infrared drying methods demonstrated to be low-cost alternatives, mainly due to energy efficiency and/or drying time. However, their application can cause thermal effects and depending on the equipment settings can affect the quality of the products. In this sense and to avoid these issues, it is important to emphasize that these methods are highly recommended to be used in combination with conventional methods to improve drying and products quality. Among electromagnetic radiation methods, refractance window allows to obtain high quality products at a low cost, but has low capacity to operate.

Finally, further research is necessary to evaluate the benefits of low-pressure superheated drying since, although it is a promising energy efficient method (it can save 50 % of energy consumption compared to some conventional methods) to obtain high quality products, there are few information available about the most suitable conditions to be used for berries.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

Acknowledgements

Thanks to GAIN (Axencia Galega de Innovación) for supporting this research (grant number IN607A2019/01).

Funding for open access charge Universidade de Vigo/CISUG.

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