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Review Article

Functional Dehydrated Foods for Health Preservation

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The market of functional foods has experienced a huge growth in the last decades due to the increased consumers' awareness in a healthy lifestyle. Dried fruits constitute good snacks, in alternative to salty or sweet ones, and food ingredients due to their taste and nutritional/health benefits. Bioactive molecules are interesting sources to develop functional foods, as they play a major role in improving the health status and minimizing disease risks. The bioactive compounds most widely discussed in literature are presented in this review, for example, polyphenols, phytosterols, and prebiotics. Different technologies to dry bioproducts for producing functional foods or ingredients are presented. New drying techniques for the preservation of bioactive compounds are proposed, focusing more specifically on dielectric drying. A discussion on the techniques that can be used to optimize drying processes is performed. An overview on dehydrated plant based foods with probiotics is provided. The microorganisms used, impregnation procedures, drying methods, and evaluated parameters are presented and discussed. The principal bioactive compounds responsible for nutritional and health benefits of plant derived dried food products—fruits and vegetables, fruits and vegetables by-products, grains, nuts, and algae—are presented. Phytochemical losses occurring during pretreatments and/or drying processes are also discussed.

1. Introduction

In the last decades, views on the role of foods in human health have changed markedly. Even though a balanced diet remains a key objective to prevent deficiencies and respective associated diseases, an excellent nutrition will aim at establishing the optimum intake of as many food components as possible in order to promote health or reduce the risk of diseases. At the beginning of the twenty-first century, the major challenge of the science of nutrition is, thus, to progress from improving life expectancy to improving life quality. On the road to an excellent nutrition, functional food is an interesting and stimulating concept, as much as it is supported by sound and consensual scientific data generated by the recently developed functional food science. This aims at improving dietary guidelines by integrating new knowledge on the interactions between food components and body functions and/or pathological processes.

The emergence of bioactive compounds with health benefits offers an excellent opportunity for food scientists to depict their role in health. Despite the mechanisms of bioactive substances in physiological functions not being yet fully depicted, their addition in food products is recognized as holding high potential to decrease disease risk [1, 2]. The

incorporation of bioactive compounds, such as vitamins, prebiotics, carotenoids, phenolic compounds, and phytosterols, in food systems provides a way to develop novel functional foods that may present health benefits or reduce the risk of disease [3].

Functional foods could be (i) usual foods with naturally occurring bioactive substances (i.e., dietary fibre), (ii) foods supplemented with bioactive substances or microorganisms (i.e., antioxidants, probiotics), and (iii) derived food ingredients introduced to conventional foods (i.e., prebiotics). It may also be referred that functional foods are not medicines, such as pills or capsules, but are consumed as part of a normal daily diet.

The effectiveness of functional foods in preventing diseases depends on preserving the stability, bioactivity, and bioavailability of the active compounds [4]. This represents a great challenge because only a small proportion of molecules remains available after oral administration, usually due to insufficient gastric residence time, low permeability, and/or solubility in the gut, as well as instability under conditions encountered in food processing or in the gastrointestinal tract [5]. Dehydration of functional foods is an alternative to make food products with longer shelf life, and easier transportation and manipulation. However, the process of drying food materials is extremely complex, involving coupled transient mechanisms of heat and mass transports accompanied by physical, chemical, structural, and phase change transformation [6]. Therefore, the production of dehydrated functional food will require food formulations and production techniques to provide protective mechanisms that maintain the active molecular form until the time of consumption and its release in the physiological target within the organism [7, 8].

The objectives of this manuscript are to present different technologies to dry bioproducts for producing functional foods or food ingredients rich in bioactive compounds, to describe new drying technologies for the preservation of bioactive compounds, focusing more specifically on dielectric drying, and to discuss the techniques that can be used to optimize drying processes. Moreover, this review presents an overview on dehydrated plant based foods with probiotics.

2. Functional Foods

According to the International Life Sciences Institute (ILSI), a food might be considered functional when consumed as part of a normal food pattern and that exerts one or more target functions in the human body, thereby improving health status or minimizing disease risk [9]. Several organizations admit that functional foods are "foods or ingredients of foods that provide an additional physiological benefit beyond their basic nutrition" [10]. It is important to distinguish functional food from nutraceutical.

Due to their importance, scientific research has extensively been developed during the last decade, producing many advances for functional foods (Figure 1).

The market of functional foods has experienced an amazing growth of around 100% from 2010 to 2017 due to the increased consumers' awareness and the interest

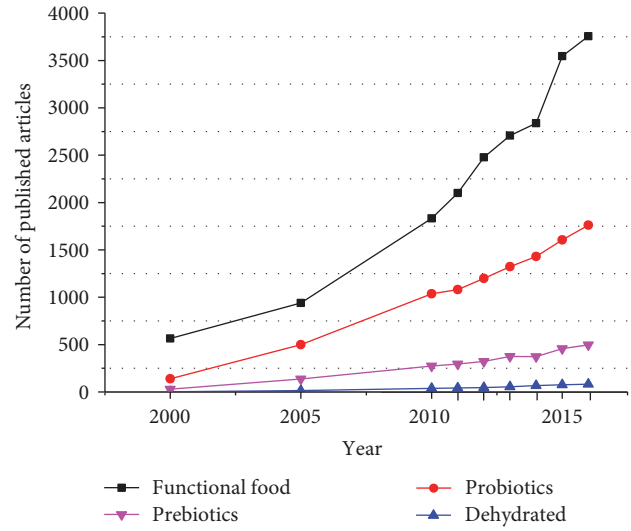

Figure 1: Number of published articles, from 2000 to 2016, related to the concepts of "Functional food," "Probiotics," "Prebiotics," and "Dehydrated functional food" (Web of Science, 2017) [11].

in promoting healthy diets and lifestyle. As examples of already marketed functional foods, we cite the whole grains and fibre breads (natural products), calcium-fortified milk, vitamin D-fortified milk and vitamin C-fortified fruit juices, margarine with phytosterols, prebiotics (chicory roots and garlic), probiotics (yogurt and kefir), and eggs with increased omega-3 produced by altering chicken feed (enhanced commodities) [12]. According to Fito et al. [13], the most frequent ways of producing functional foods are (a) improvement of conventional natural products, that is, plants and animal production (i.e., eggs with a lower cholesterol content); (b) genetically modified products (i.e., rice with enhanced β-carotene content); (c) addition of functional ingredients to the foods (i.e., breakfast cereals and bread); and (d) matrix engineering (i.e., vacuum impregnation).

The development of functional foods turns out to be increasingly challenging, as it has to fulfil the consumer's expectancy for products that are simultaneously relish and healthy. Functional ingredients, such as purified bioactive compounds or concentrated extracts from natural sources, can be incorporated into conventional foods, providing novel functional product categories and new commercial opportunities. However, the challenge of ensuring that functional ingredients remain stable and active and bioavailable after food processing and storage endures. Therefore, food industry developers have to takes into consideration many variables to develop functional products, such as sensory acceptance, stability, price, functional properties, and convenience.

2.1. Bioactive Compounds in Functional Foods. Recent trends have demonstrated that bioactive molecules are interesting sources to develop many functional foods, as they play a major role in the improving health status and minimizing disease risks. Nutritionists and biomedical and food scientists are working together to discover new bioactive molecules that

have increased potency and therapeutic benefits [14]. These bioactive compounds include vitamins, prebiotics, bioactive peptides, carotenoids, phenolic compounds, phytoestrogens, glucosinolates, phytosterols, fatty acids, and structured lipids, which are already naturally present in foods, or can be added to conventional foods to produce new functional foods. These bioactive molecules can be obtained either by extraction from natural sources or by chemical and biotechnological synthesis. In the following the most widely discussed bioactive compounds in literature are summarized, for example, phenolic compounds, phytosterols, and prebiotics. Probiotics are discussed as well while bioactive ingredients for functional foods.

2.1.1. Phenolic Compounds. Phenolic compounds are plant secondary metabolites commonly found in plants and derived products [15]. These compounds have diverse biological activity, being mainly acknowledged for their preventing action against the damage caused by oxidative stress. Due to their several physiological roles, phenolic compounds are essential for the human diet and health [16]. For example, phenolic acids may be about one-third of the phenolic compounds in human diet, where these substances have a high antioxidant activity [17].

Flavonoids are the most common and widely distributed group of plant phenolic compounds. They comprise a large class of plant secondary metabolites with relevant action on the plant defense system, having been reported as important constituents of the human diet [18]. These compounds have attracted interest due to the discovery of their pharmacological activities and health regulation function. Regarding their biological activity, they were previously reported to have antioxidant, hepatoprotective, antibacterial, anti-inflammatory, anticancer, and antiviral effects, besides inhibiting lipid peroxidation [19]. When added to food products, flavonoids are responsible for preventing fat oxidation and protecting vitamins and enzymes, while also contributing to food sensorial properties. Tannins are polymeric flavonoids that form the anthocyanidins pigments [20]. Although the antioxidant activity of tannins has been less reported than the activity of flavonoids, recent research studies have shown that the degree of polymerization is related to the antioxidant activity: in condensed and hydrolysed tannins of high molecular weight, this activity can be up to 15–30 times superior to that attributed to simple phenols [21]. As it would be easily anticipated, considering the diverse biological activity of phenolic compounds, their incorporation into food products has been largely studied. Some of the most relevant examples include meat and fish products, pasta [22, 23], ice cream, cheese, yogurt, and other dairy products [24, 25].

2.1.2. Phytosterols. Phytosterols, which include plant sterols and stanols [26], are currently among the most successful phytochemicals for the development of functional foods with unique health claims [27]. When incorporated as a functional food ingredient, plant sterols and stanols are frequently esterified with a fatty acid ester to increase the solubility in the food matrix [28]. Furthermore, dietary phytosterols were reported as inhibiting the uptake of both dietary and endogenously produced cholesterol on the intestinal cells and several studies suggest a protective role of phytosterols against colon, prostate, and breast cancer [29]. Phytosterols have been included in several food matrices with different degrees of effectiveness [30]. While their incorporation in chocolate, orange juice, cheese, nonfat beverages, meats, croissants and muffins, oil in bread, and cereal bars was not much efficient in cholesterol lowering, the results were more satisfactory when added to fat spreads, mayonnaise, salad dressings, milk, and yogurt [31].

2.1.3. Prebiotics. The International Scientific Association for Probiotics and Prebiotics (ISAPP) defined a prebiotic as a "selectively fermented ingredient that allows specific changes both in the composition and/or activity in the gastrointestinal microflora that confers benefits upon host wellbeing and health" [32]. This definition expands the concept of prebiotics to possibly include noncarbohydrate substances, applications to body sites other than the gastrointestinal tract, and diverse categories other than food. Actually, health effects of prebiotics are evolving but, currently, they include benefits to the gastrointestinal tract (i.e., inhibition of pathogens, immune stimulation), cardiometabolism (i.e., reduction in blood lipid levels, effects upon insulin resistance), mental health (i.e., metabolites that influence brain function, energy, and cognition), and bone (i.e., mineral bioavailability). Currently established prebiotics are carbohydrate-based, but other substances, such as polyphenols and polyunsaturated fatty acids converted to the respective conjugated fatty acids, might fit the updated definition, assuming convincing weight of evidence in the target host. To be an efficient prebiotic, a molecule should possess some qualities such as it should not be hydrolysed or absorbed in the upper part of the gut, gut microflora should consume it, and beneficial bacteria of colon should be stimulated by it [33].

Most prebiotic candidates identified today in the world belong to saccharides group and can be classified according to its number of monosaccharide's units forming the molecules (Table 1). The major prebiotics established in the market are inulin, fructooligosaccharides (FOS), and galactooligosaccharides (GOS) (Table 2). Inulin and FOS, GOS, and lactulose are three major marketed prebiotics.

Industrially, inulin is most often extracted from chicory. The structural relatives of inulin and FOS have been the best-documented oligosaccharides for their effect on intestinal bifidobacteria and are considered important prebiotic substrates. They are produced in large quantities in several countries and are added to various products such as biscuits, drinks, yogurts, breakfast cereals, and sweeteners. Inulin occurs naturally in Western foods such as onion, asparagus, leek, garlic, wheat, and artichoke, although to a lesser extent than in the commercial source chicory *(Cichorium endivia)*.

Inulin and oligo-fructose proved to be the most widely examined prebiotic compounds with the most important prebiotic efficacy [36]. Now, inulin is gradually being used in functional foods, particularly in a complete variety of dairy products to enhance the intensification of the beneficial intestinal bacteria [37]. Drabińska et al. [37] studied

Table 1: Classification of potential prebiotics [34].

	Origin
Disaccharides	
Lactulose	Synthetic: enzymatically from lactose
Oligosaccharides	
Fructooligosaccharides (FOS)	Enzymatic hydrolysis of inulin
Galactooligosaccharides (GOS)	Naturally in human breast milk Enzymatic conversion of lactose (GOS-LA) or lactulose (GOS-LU)
Xylooligosaccharides (XOS)	Naturally in bamboo shoots, fruits, vegetables, milk, and honey Enzymatic hydrolysis of xylan containing lignocellulosic materials
Isomaltooligosaccharides (IMOS)	Naturally in sake, soy sauce, honey, sugarcane juice and derived products
Arabinoxylan oligosaccharides (AXOS)	Enzymatic hydrolysis of arabinoxylan (part of fibre fraction of cereal grain)
Polysaccharides	
Inulin	Chicory root, wheat, barley, onion and garlic

Table 2: Example of marketed prebiotics [35].

Food product	Company	Prebiotics	Dosage form
Nutren Fibre®	Nestle	Inulin	Powder
Miracle Fibre	The Vitmin Shoppe, North Bergen, NJ	Inulin	Powder
Kal NutraFlora FOS	Nutraceutical Corp, Park City, UT	Short-chain fructooligosaccharides	Powder
Solaray NutraFlora FOS	Nutraceutical Corp	Short-chain fructooligosaccharides	Capsules
Fiber Choice	GlaxoSmithKline, Philadelphia, PA	Inulin	Chewable tablet/drops
Smart Fiber Stixx	Intelligent Nutrition LLC, New Orleans, LA	Oligofructose and inulin	Powder
Balance, Prebiotic Fibre	pHion	Inulin fibre; psyllium seed husk *(Plantago ovata)*	Powder
Organic, Inulin	Now Foods	Organic inulin (FOS)	Powder
Frutafit® HD	Sensus	Inulin FOS	Powder
Frutalose® L85	Sensus	Oligofructose	Syrup
Vivinal GOS	Friesland	Galactooligosaccharides	Syrup

the addition of inulin to gluten-free products. The authors showed that the new enriched flour has the potential to improve the technological properties and sensory perception of the obtained products. Palatnik et al. [38] developed a novel reduced-fat cheese from partially skimmed bovine milk with the addition of Agave fructans. The new product with fructans showed an appropriate moisture and protein retention. The sensorial aspects, including colour, did not show significant difference in comparison with the control samples, indicating that the fructans did not affect these parameters. Even though it would be difficult to mimic completely a full-fat cheese after fat has been removed, the presence of fructans in reduced-fat formulations suggests an acceptable likeness in comparison with the structure and general characteristics of the full-fat control cheese.

Various prebiotic dairy desserts having low fat content have been prepared using inulin as a prebiotic, in which inulin supplementation not only presented a prebiotic effect but also reduced the fat content and sugar content (12% reduction) without affecting its acceptability to consumers [39]. As inulin is metabolized in different parts of the large intestine (short-chain inulin in the proximal colon portion

and long-chain inulin in the more distal colonic portion), the use of a blend of short and long-chain inulin to increase fermentative and prebiotic effects is suggested in several nutritional studies [40, 41]. Although lactulose was used originally as a laxative [42], it has also received attention as a potential prebiotic. Lactulose increased lactobacilli and bifidobacteria and significantly decreased *Bacteroides* in mixed continuous fecal culture [43], although total bacterial numbers decreased. Lactulose has been consistently found to have prebiotic potential in human trials. Although lactulose looks to be a very promising prebiotic, it is not yet widely distributed as such. It has an established market as a medical product and would seem to have much value in the food sector.

2.2. Probiotics as Bioactive Ingredient for Functional Foods. Probiotics are viable microorganisms, such as lactobacilli and bifidobacteria, that benefit the host by improving the intestinal bacterial balance [44]. Multiple reports have described their health benefits in gastrointestinal infections, antimicrobial activity, improvement in lactose metabolism, reduction in serum cholesterol, immune system stimulation, antimutagenic properties, anticarcinogenic properties, antidiarrheal properties, improvement in inflammatory bowel disease, and suppression of *Helicobacter pylori* infection, by addition of selected strains to food products [45]. Because of their perceived health benefits, probiotic bacteria have been increasingly incorporated into a range of functional foods including yogurts, cheeses, ice cream, milk powders, and frozen dairy desserts [46].

For industrial applications, probiotic strains have to respond to several criteria. Barbosa and Teixeira [47] provided valuable criteria.

Probiotic status assessment requires demonstration through human studies, and a scientific and technical guidance in presenting applications for health claims on food has been provided by the EFSA (Reg. EC 1924/2006). The EFSA has rejected all health claim applications on probiotics since 2008, which reflects the need for more scientific evidence and well-designed human intervention studies. Contrary to the European standard, Canada has a positive list of species that can be marketed as probiotics. This list represents a core group of well-studied species likely to contribute to a healthy gut microbiota [48].

Each microorganism present in probiotic products must be identified at species and strain level, according to the International Code of Nomenclature, and its microbial genome must be completely sequenced. This allows the identification of every single gene involved in bacterial metabolism and its function. Consequently, the safety of food products and, above all, of commercial probiotic strains should be evaluated before their launch on the market. Generally, the guidelines require (i) a minimum concentration of 10^9 cfu of live microorganisms/daily dose on labels (even less if the usefulness of this lower dose has been clearly shown and supported at scientific experimental level); (ii) the identification of each probiotic strain by integrating phenotypic and genotypic characterization; (iii) the absence of pathogenic factors [49].

Currently, most of industrial functional foods containing probiotics are mainly found in dairy products with limited shelf life and are not suitable for consumers dealing with lactose intolerance [50]. The microorganisms most used in commercialized probiotic foods belong to genera *Lactobacillus (Lactobacillus plantarum, Lactobacillus acidophilus*, and *Lactobacillus rhamnosus)* [51, 52] and *Bifidobacterium (Bifidobacterium bifidum, Bifidobacterium longum)* [53, 54], which belong to the group of lactic acid bacteria. Infrequently, other bacteria *(Enterococcus faecium, Lactococcus lactis)* [55, 56] and yeasts *(Saccharomyces boulardii)* [57] may also be used as probiotic strains (Table 3).

Leone et al. [59] studied four different conditions for the incorporation of *Lactobacillus casei* in dried yacon *(Smallanthus sonchifolius)*, which was crushed in the form of flakes. The temperature of 25°C was the most appropriate for the incorporation of probiotics in dried yacon at the end of the 56 days. Granado-Lorencio and Hernández-Alvarez [60] stated that adding probiotics to fruit-based and cereal-based matrices was more complex than formulating dairy products, because the bacteria need protection from the acidic conditions in these media. To solve this problem, microencapsulation technologies have been developed and successfully applied using various matrices to protect the bacterial cells from the damage caused by the external environment [61]. Puupponen-Pimiä et al. [62] proposed the encapsulation of probiotics to enhance their viability and stability in food matrices and controlled release during human digestion. A recent industrial application, the American company Kraft® launched in 2008, produced the first mass-distributed shelf stable probiotic nutrition bar, by using the bacteria *L. plantarum* 299v [63].

Borges et al. [64] studied the effect of processing stages to develop fruit powders (apple, banana, and strawberry) enriched with a probiotic strain (*L. plantarum* 299v). The authors found that hot air drying of the fruit followed by addition of spray-dried probiotic culture was better than hot air drying of the fruit incorporated with the probiotic culture. The viability of *L. plantarum* 299v was considerably higher during spray drying, and fruit powders with a microbial content suitable for a probiotic food (10^8–10^9 cfu g^{-1}) were obtained.

In all the above cases, the rate of recovery of the probiotics to the viable state is significantly influenced by the rehydration conditions (temperature, volume of rehydrating media, and rehydration time), physical properties of the material to be rehydrated, and properties like osmolarity, pH, and nutritional energy of the rehydration solution. The rehydration temperature is a critical factor influencing cell recovery of freeze-dried and spray-dried probiotics. Various studies have indicated that there is not an "ideal" single point rehydration temperature for the optimum growth of cultures. For thermophilic cultures, temperature between 30 and 37°C was found best for posthydration viabilities, while the optimum range for mesophilic bacteria is 22–30°C. The rehydration temperature should not be higher than 40°C in any case [58].

Table 3: List of probiotic strains used in commercial applications [58].

Company name	Source/product	Strain
Chr. Hansen	Produces natural ingredients (food cultures, probiotics, enzymes and colors) for the food, beverage, dietary supplements and agricultural industry	*L. acidophilus* LA1/LA5; *L. delbrueckii* ssp. bulgaricus; Lb12; *Lactobacillus paracasei* CRL431; *Bifidobacterium animalis* ssp. lactis Bb12
Danisco	Activities in food production, enzymes, other bioproducts and pharmaceutical industries	*L. acidophilus* NCFMs; *L. acidophilus* La *L. paracasei* Lpc; *Bifidobacterium lactis* HOWARUTM/Bl
DSM Food Specialties	Manufacturer of food enzymes, cultures, savory ingredients and other specialties for the food and beverage industries	*L. acidophilus* LAFTIs L10; *B. lactis* LAFTIs B94; *L. paracasei* LAFTIs L26
Nestle	Manufacturer of baby food, medical food, bottled water, breakfast cereals, coffee and tea, confectionery, dairy products, ice cream, frozen food, pet foods, and snacks	*Lactobacillus johnsonii* La1
Snow Brand Milk	Dairy products	*L. acidophilus* SBT-20621; Products Co. Ltd. *B. longum* SBT-29281
Yakult	Probiotic drinks	*L. casei* Shirota; *Bifidobacterium breve* strain Yaku
Fonterra	Dairy products	*B. lactis* HN019 (DR10); *L. rhamnosus* HN001 (DR20)
Danone	Business lines: fresh dairy products, waters, early life nutrition and medical nutrition	*L. casei* Immunitas; *B. animalis* DN173010
Essum AB	Manufacturer of probiotic bacteria that are distributed to companies that produce pharmaceuticals, dietary supplements and food	*L. rhamnosus* LB21; *Lactococcus lactis* L1A
Institute Rosell	Probiotics, dairy cultures, lactic bacteria, acidophilus & lactic starters	*L. rhamnosus* R0011; *L. acidophilus* R0052
Probi AB	Probiotics research and development	*L. plantarum* 299V; *L. rhamnosus* 271

3. Advances in Dehydration Technologies towards Healthy Products

3.1. Drying and Its Consequences on the Product Quality and Energy Consumption. Drying is probably the most important unit operation for most industrial processes, especially because of its impact on the quality of the end product and on energy consumption [65]. Thus, according to Chua et al. [66], this process would be the most energy-intensive, among all industries, with consumption of dried foods about 10–25% of total consumption. In most cases, drying involves the application of different temperature conditions, which may cause irreversible damage. In the case of freeze drying, the temperature applied can be −30°C or −80°C, and in the case of other methods such as air drying or spray drying, the temperatures can be 45–80°C or 125–140°C, respectively. Changes may occur in cellular structures (cell membranes) constituting probiotics cells, and in key properties responsible for the product functionality (cell membrane permeability, mechanical strength of the cell membrane assembly, etc.) [58, 67, 68]. Moreover, drying might cause changes in the chemical structures responsible for the biological value of various bioactive components (protein, fat) [67]. Besides, drying with hot air can induce reactions, mainly of oxidation, which decrease the functional value of nutritive compounds (vitamin, antioxidant). This must be put into perspective facing the high reactivity of phytochemicals leading to various degrees of degradation during processing [69].

Since the drying process always comprises a second phase, which is generally long to very long, depending on the hygroscopicity of the product, it is mainly responsible for the numerous adverse effects that are linked to drying. Most organic products are, in fact, deeply modified by drying (colour, taste, texture, nutritional characteristics, functional

properties, etc.) [70]. The bioactive compounds are, thus, particularly altered during this drying phase. Therefore, obviously this phase and/or its consequences on the quality of the dried products are sought to be reduced by new drying techniques and optimization of drying processes.

3.2. Conventional Techniques Used for Drying Foods or Functional Ingredients. The most commonly used techniques to produce fruit or vegetable powder are freeze drying, foam drying, drum drying, and spray drying [71]. Freeze drying is the technique that allows the best preservation of phytochemicals and their bioactivity in fruit and vegetable powders [71]. It is the most widely used technique for drying probiotics, but in view of its high operating costs and low productivity [71], spray drying seems to be a good alternative for production of probiotics powder at industrial scale [72].

In spray drying, it is often necessary to use a carrier agent for the product to be atomized [73]. Shishir and Chen [71] reported about thirty studies in the literature on the spray drying of various fruit or vegetable juices, showing that different phytochemicals (anthocyanins, total flavonoids, total polyphenol, gingerol, etc.) were more or less preserved depending on the type and concentration of the carrier agent used (maltodextrin, Arabic gum, inulin, mixture of carrier agents, etc.).

Spray drying is also used for the drying of probiotics. The carrier agents allow the preservation of molecules of interest or probiotics by their encapsulation effect [74]. Concerning probiotics, the main question is the viability of the cells after drying. Spray drying to produce probiotic fruit powders will be discussed in Section 4.

3.3. Drying Kinetics versus Kinetic Degradation of Indicators of Interest. Alteration of product quality during drying is linked to the time-temperature couple. Low temperatures tend to have a positive effect on the quality of the final product, which is generally found in low temperature processes such as freeze drying or vacuum drying. Similarly, short drying times allow better preservation of bioactive compounds [69]. This situation is found for fast drying processes such as spray or drum drying. In general, degradation of most phytochemicals and probiotics follows first-order or a pseudo first-order kinetics [69]. Hence, good fits with first-order kinetic models applied to thermal degradation of different phytochemicals were obtained by several authors. This is the case for the degradation of anthocyanins [75–78] as well as polyphenols [75, 78, 79]. However, simple first-order models are not suitable when the residual concentration of the bioactive compound is different from 0 for a very long heating time. The kinetics of degradation of the bioactive compound is then described by an equation called first-order fractional conversion kinetic model [80].

Whatever the order of the thermal degradation reaction, the rate constant of the kinetic depends on the temperature according to the Arrhenius equation [75–77, 79] and normally the rate of degradation of biocompounds or probiotics is higher at high temperatures. However, during convective drying, it is possible to obtain a lower degradation of some bioactive compounds, such as polyphenol (total polyphenol content, TPC) and flavonoids, at higher temperatures [81]. The same trend was observed for TPC loss in convective drying of carrot peels [82] and blueberries [83]. Hence, the residual content of bioactive compounds after drying depends at least on three parameters: its initial content, the temperature, and the duration of the drying [78–80]. Therefore, to minimize the degradation of bioactive compounds or probiotics, drying processes at low temperature (freeze drying, vacuum drying) may be used. However, under these conditions the drying time will necessarily be long. Therefore, the alternative is to use short drying methods, such as spray drying, drum drying, dielectric drying, microwave drying, and infrared (IR) drying. In these cases, the drying temperature will necessarily be high, but the duration will be short, which makes it possible to limit the degradation of biocompounds and probiotics. Clearly, the kinetics of drying must be sufficiently rapid with respect to the kinetics of degradation of the compounds of interest. It is approximately one of the targeted goals with advanced drying techniques.

3.4. Advanced Drying Techniques. Even though freeze drying, vacuum drying, or spray drying techniques limit the degradation of bioactive compounds, they are either unsuitable for the drying of certain products or have too low productivity and excessively high operating cost to be implemented at industrial scale. Conversely, the other techniques of conventional drying by hot air (cabinet, tunnel, etc.) have a strong negative effect on the retention of bioactive compounds. For this reason, advanced drying techniques have been proposed for many years. The majority of these techniques have one thing in common, the type of energy used which is always of electromagnetic (EM) nature: radio frequency (RF), microwave (MW), IR, and ultraviolet (UV). These new techniques can be used alone or in combination with one another or with conventional techniques.

3.4.1. Dielectric and Microwave Drying. Actually, from a physical point of view, the notion of dielectric heating can be applied to all frequencies from high frequencies to IR. However, from a practical point of view, the term dielectric heating is reserved for frequencies between 1 and 100 MHz, while the MW heating is between 300 MHz and 300 GHz [84].

Throughout MW drying of high moisture content product, the high energy density absorbed results in a rapid increase in temperature and an instantaneous vaporization inside the product [65]. The internal pressure increases and expulsion of liquid water towards the surface occurs [84]. This phenomenon has been observed by many authors in the case of different products (cotton, wood, slices of oranges, apple, carrot, etc.). This outflow of water limits the phenomenon of crusting and browning of the surface contrary to what is observed in conventional drying. This also results in high drying rates leading to considerable reduction in the drying time. Even if the drying speed is always faster than that of hot air drying, the drying efficiency is limited due to the rapid saturation of the air, whose temperature is relatively low, at the surface of the product. For this reason, microwaves are

generally associated with hot air to improve water transfer at the product surface.

At this stage, two fundamental points radically differentiating dielectric drying from hot air drying should be mentioned: (1) during convective drying by hot air, the surface temperature of the product evolves until reaching the air temperature at the end of drying and it is worth noting that it can in no case exceed this temperature. This explains why it is sufficient to dry thermosensitive products at low air temperature to prevent their alteration. Regarding MW drying, there is no real limit to the temperature rise of the product except temperatures leading to its carbonization and its destruction. (2) Given that drying involves removing water from a product, this action will have a decisive effect on how the product will behave vis-a-vis the EM wave during drying. Since water is the main molecule of the product concerned by the absorption of EM energy, the dielectric properties (ε' and ε'') of the product will tend to evolve during drying. For most products, the values of these properties will drop during the two phases of the drying process [84]. ε'' falls very quickly throughout the drying of the free water (1st phase), and, then, ε'' decreases with a lower slope after the critical moisture content, corresponding to the beginning of drying of the bound water. The critical moisture content is between 10 and 40% (dry basis) for highly hygroscopic products and about 1% for nonhygroscopic products [84]. From what has just been said and from point (1), it could be concluded that this is rather positive for controlling the temperature of the product and therefore its quality at the end of drying. Things are not so simple because several other elements must be taken into consideration. Firstly, if the applied power is kept constant during drying (as is the case in most studies in the literature), the energy density delivered to the product, which can be evaluated by the specific power applied (i.e., the ratio between the applied MW power and the mass product) increases during drying. Koné et al. [85] showed that this evolution was exponential with drying time in the case of drying of tomatoes by microwaves/hot air. In other words, more and more energy is being supplied to the product when less and less is needed. The consequence of this is the phenomena of thermal runaway reported in many studies on microwave drying. In addition, another aspect must be considered, namely, the change of the thermal properties of the product during drying. Indeed, the thermal properties of foods also depend on their moisture content. Thus, the specific heat and the thermal diffusivity of the product decrease during drying. Hence, it takes less and less energy to heat the product and similarly, an area of the product that has undergone overheating will find it increasingly difficult to evacuate its overflow of heat by diffusion. All these elements make it possible to understand that even if the dielectric properties of the product decrease during drying, phenomena of thermal runaway during microwave drying may arise [86]. The only solution to control the quality of the product during a microwave drying is therefore to control the energy supply by adapting the specific power as a function of the moisture content by acting on the power applied. By applying such a strategy, Koné et al. [85] succeed in drying of tomato by microwave/hot air with an improvement in the colour of the dried product and in the residual content of lycopene. We may conclude by saying that the management of the energy supplied to the product during drying and the optimization techniques may be useful for the control of microwave drying in terms of organoleptic and nutritional qualities and energy consumption.

3.4.2. Hybrid Drying Techniques. More and more studies have suggested the synergistic effects of the combination of different drying techniques on the quality of the dried product and on the performance of the drying process (drying time and energy consumption). Some hybrid drying (HD) techniques are presented below.

(i) Microwave-Assisted Hot Air Drying (MWHAD). The simplest combination imaginable for microwave drying is its combination with hot air drying. It is also the one that is by far the most used according to the literature. Schiffmann [84] retains three possible modes from a perspective of application at industrial scale. (1) *Preheating*. The microwaves are used to preheat the product and, subsequently, the drying continues with hot air only. The instantaneous generation of steam inside the product due to the absorption of the MW energy forces the flow of water towards the surface, thus allowing conventional hot air drying to operate under conditions of maximum efficiency. (2) *Booster Drying*. Drying starts with hot air only and the MW energy is fed when the drying rate begins to fall. The surface of the product being dry at this point, by the effect of pumping on the internal water of the product, the MW energy leads to the rewetting of the surface, which makes it possible to maintain a high drying rate. (3) *Finish Drying*. The falling phase of the drying rate is responsible for the greatest degradation of the product quality due to its length (more than two-thirds of the total drying time). By introducing microwaves at the beginning of this phase, internal energy generation allows the bound water to be pushed towards the product surface, which increases the drying rate and thus reduces the drying time.

This combination of microwaves and hot air results in an improvement of the quality of the dried product, as well as a reduction of the drying time and energy consumption [65, 84].

(ii) Microwave-Assisted Freeze Drying (MWFD). Freeze drying provides a good quality of the dried product by preventing the degradation of the thermosensitive compounds due to the low temperature used for the sublimation of water. The major drawback of this technique is the very long drying time required. Hence, it entails a low productivity and a large consumption of energy [87]. The combination of microwaves with freeze drying makes it possible to shorten the drying time (e.g., 40% in the case of the drying of protein of duck egg white) without modification of the nutritional quality [87].

(iii) Microwave-Assisted Vacuum Drying (MWVD). Like freeze drying, vacuum drying preserves the characteristics of the dried product, but it also has the same drawbacks, namely, a long drying time and a strong energy consumption. Thus, the combination of microwaves with vacuum drying allows a

better anthocyanin retention and a better antioxidant activity in the case of MWVD of blueberries [87]. In general, MWVD makes it possible to obtain dried products of a quality as good as those obtained by freeze drying with a colour closer to the fresh product in the case of tomato, carrot, and banana [88].

(iv) Microwave-Assisted IR Drying (MWIRD). IR radiation is characterized by a shallow depth of penetration inside the product. Therefore, once the EM energy is absorbed at the surface it is transmitted to the interior of the product by conduction, which brings IR drying closer to conventional hot air drying. The combination of IR with microwaves allows a faster and more homogeneous heating of the product and a quicker drying of the product with an improved quality. Thus, in the case of MWIRD of raspberries, a 2.4 times higher crustiness, a 25.63% higher rehydration, a 17.55% additional retention of anthocyanins, and a 21.21% higher antioxidant activity were obtained in relation to IR drying [88].

(v) Ultrasound-Assisted Drying (UAD). Ultrasonication is one of several techniques used in the concept of hybrid processes. It has already been applied to drying, among other processes [89]. The mechanical energy provided by ultrasound contributes to the reduction of internal and external resistances to mass transfer and, particularly, to water transfer, thanks to expansion and compression cycles (sponge effect) [81]. In addition, microstreaming is produced at the interfaces because of high-intensity airborne ultrasound, which reduces the diffusion boundary layer. This leads to diffusion enhancement and, hence, to mass transfer increase [81, 90]. Musielak et al. [91] indicate that the first studies on the use of ultrasound in drying were carried out in the 1950s. However, even if there is a renewed interest on this technology in recent years, it remains, for the moment, limited to laboratory scale [90].

Numerous studies show the interest of combining ultrasound with a convective drying process to reduce energy consumption and drying time as well as to improve the quality of the dried product. Szadzinska et al. [92] compared a convective drying (CVD) to different hybrid drying processes—convective-ultrasonic drying (CVUD), convective-microwave-ultrasonic drying (CVMWUD), and convective-microwave drying (CVMWD)—in drying of strawberry. In all cases, the hybrid processes made it possible to obtain lower energy consumption and shorter drying time than the convective drying. The energy consumption gain was only 6.4% in CVUD, while it reached about 82% in CVMWUD, and even 89% in CVMWD. Likewise, the drying time was reduced by 52% and 93% in CVUD and CVMWD, respectively.

3.5. Drying Optimization. The combination of several drying techniques makes it possible to obtain synergistic effects both on the preservation of the bioactive compounds and on the energy consumption. However, it is necessary to optimize these processes since many factors of the process can have a decisive impact on the quality of the dried product. In the past years, the food processes optimization was performed by observing the effect of variation of a single variable at a time on an experimental response, keeping constant all others. This technique has the disadvantage of requiring numerous tests and it does not take into account the effect of interactions between variables on the assessed responses [93]. These difficulties can be circumvented using the Response Surface Methodology (RSM). This method consists in linking each studied response of the process to the different inputs (the factors) by means of a quadratic model [93]. This method is regularly used for the optimization of drying processes as reported by different authors. The goal pursued in these different studies was to optimize drying conditions for preserving certain bioactive compounds such as beta-carotene and lycopene, phenolic compounds and antioxidant activity [94], vitamin C, flavonoids, and anthocyanins [95].

In fact, RSM is a relatively efficient method for the optimization of drying processes or others. Nonetheless, it has some limitations: (1) it uses a priori models. Indeed, whatever the response studied, a quadratic model is postulated, which is not always adequate. (2) The number of tests to be carried out increases very quickly with the number of factors. Thus, a three-factor Box Behnken Design (BBD) requires 13 experiments whereas it is necessary to carry out 29 experiments for a four-factor BBD; (3) the factors must be fully independent; (4) the uncontrolled factors of the plan cannot be taken into account.

These difficulties can be overcome using a method proposed by Lesty [96] based on a new approach: the CORICO method (ICOnographic CORrelation). CORICO is a multidimensional data analysis method that also allows experimental design analysis. Its peculiarity with conventional optimization software based on the RSM methodology is that it does not use a priori models for the responses. Indeed, it proposes a model only after the data analysis of the experimental design (ED). Hence, the shape of the models will be different from one response to another. CORICO proposes regression models, whose regressors are logical interactions (AND, exclusive OR, IF, etc.) between the factors. Unlike conventional EDs, CORICO accepts that factors are linked and, moreover, it may take into account noncontrolled factors. Furthermore, it requires very few tests to establish the models of the ED. Thus, a CORICO design with five factors requires only 13 assays against a minimum of 31 assays for a five-factor Doehlert design.

The CORICO method has recently been used successfully in the agrofood sector for the optimization of microalgae drying process [97].

4. Dehydrated Foods with Probiotics

Due to the low stability of probiotic strains, the food industry is facing a challenge to develop new functional food with probiotics, especially dehydrated food products. Drying probiotic foods is a challenge as it causes severe loss in viability of probiotics.

Generally, food products are dried in order to increase their shelf life at ambient temperature and to reduce the cost of frozen storage [58]. Hot air drying, freeze drying, spray, and vacuum drying are the common technologies used for drying food products. Spray drying is the most common

and economical method for drying liquid foods. However, this process leads to a loss of viability of probiotic cells due to the high temperature, mechanical shearing, dehydration, and osmotic pressure [98]. On the other hand, freeze drying maintains the viability of the probiotic cells, but the cost of the process is one of the limitation for industrial application [99]. Saarela et al. [100] studied the stability and functionality of freeze-dried probiotic *Bifidobacterium animalis* ssp. *lactis* E-2010 (Bb-12) cells during storage in juice and milk, using sucrose as cryoprotectant and low-pH to improve stability. Recently, fluidized bed drying and radiant energy under vacuum drying techniques have successfully been applied for improving the stability of dehydrated probiotics [50, 101]. Noorbakhsh et al. [50] studied the radiant energy under vacuum technology for producing probiotic enriched apple snacks. They concluded that this technology, a form of vacuum microwave dehydration, is a rapid drying method resulting in products with unique characteristics while retaining biological functions and properties. The retention of biological activity is enhanced by the low drying temperature and short drying time. In the case of fruits and vegetables, the gas and liquid in the intercellular spaces (20–25% of the total volume) can be removed by means of vacuum and replaced by diffusion with compounds of interest such as microorganisms (bacteria *L. rhamnosus*, for example), minerals, or other bioactive and nonbioactive compounds [10]. This would lead to the development probiotic enriched dried fruits by vacuum impregnation. The apple pieces were air-dried at 40°C to a water content of 0.37 kg water kg DM^{-1} and stored at room temperature for two months [50]. The content of *L. casei* viable cells in the dried apple was greater than 10^6 cfu g^{-1}, which is similar to that in commercial dairy products. In an attempt to introduce probiotic properties to breakfast cereals and similar food products, Patel et al. [102] confirmed that oat bran contained balanced nutrients to support a 25-fold *L. plantarum* propagation within a range of moisture content from 50% to 58%, after 36 h of cultivation. They applied the technique of solid-state fermentation. This technique presents not only the potential of simple downstream processing but also a more natural growth environment for the target bacterium. Consequences of increased microbial growth with low water content include slowdown of the growth of spoilage microorganisms and the generation of microbial metabolites, which in turn provide a range of health benefits (Figure 2). On the other hand, the adequacy of raw materials with regard to probiotics technology (including finding solutions for the stability and viability problems of probiotics in food matrices, such as fruits, cereals, and other vegetables) is certainly the key in the research and development area for functional food markets [50].

Some nondairy products with probiotics have been developed, in order to surpass the two main drawbacks of the consumption of dairy products, namely, lactose intolerance and the cholesterol content [104]. In Table 4 are described some of the dehydrated functional plant foods that have been developed. Apple is still the preferred base, although other plant products may be used. Nevertheless, the fruit matrix is an important parameter to take into account because those

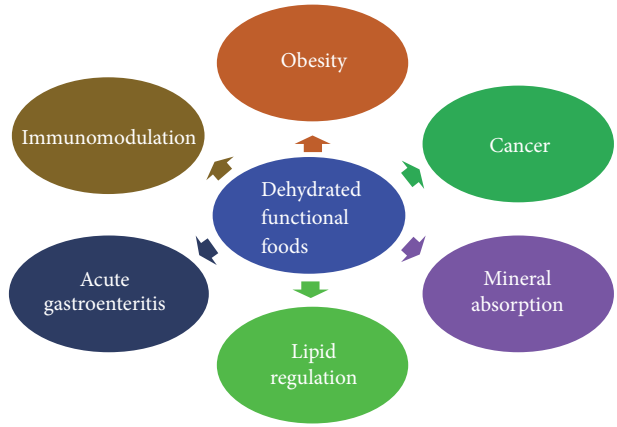

Figure 2: Health benefits of dehydrated functional foods [103].

more porous fruits seem to facilitate the incorporation of probiotics in their tissues during immersion [105] and/or during vacuum impregnation [13]. The probiotics tested include several bacteria, *Lactobacillus* spp. and *Bifidobacterium* spp. being among the strains most commonly used. Besides being generally considered to be safe for consumers, some *Lactobacillus* spp. show interesting health effects. For example, Betoret et al. [106] verified that *Lactobacillus salivarius* incorporated in a low moisture apple snack showed a potential effect against *H. pylori* infection.

All studies performed until now tried to create a dry fruit matrix with a high number of viable probiotic cells (>1 × 10^7 cfu g^{-1}) as suggested by Betoret et al. [106] and Rêgo et al. [107]. To achieve this value, it is important to (i) have a high cell concentration (approx. 10^{10} cfu ml^{-1}) in the initial suspension in which the product will be immersed; (ii) guarantee a high adherence of the probiotics to the fruit matrix; and (iii) assure that, after drying, the adhered cells still have high viability [107]. Furthermore, it is also important that the impregnation liquid must present certain physicochemical characteristics, namely: (i) the pH of the impregnation liquid and the fruit must be suitable for microorganisms' growth; (ii) the viscosity of the impregnation liquid should also allow flux inside the pores or intercellular spaces; and (iii) the natural characteristics of the impregnated fruit should not be affected [106]. Another important point to consider is the method used to promote cells adherence because it might influence their viability. By observing Table 4, vacuum impregnation is the most used method for probiotics impregnation into fruit matrices. Nevertheless, Rêgo et al. [107] verified that apple cubes that had been subjected to immersion under vacuum presented lower viable numbers of probiotic bacteria than those cubes subjected to immersion at normal pressure and, so, no advantage, such as the increase of the number of adhered cells or the stability during drying, was observed by using vacuum. Furthermore, the vacuum immersed samples had worse visual aspect (with more damage) after drying than immersed samples at atmospheric pressure [107]. When preparing cylindrically shaped apple samples with probiotics, Betoret et al. [104] also observed that vacuum impregnation seemed to decrease the microbial content by one logarithmic

Table 4: Dehydrated plant products with probiotics.

Dehydrated food	Organisms	Impregnation procedure	Drying method	Evaluated parameters	Reference
Apple (cv. Granny Smith)	*L. salivarius* spp salivarius CECT 4063 *L. acidophilus* CECT 903 Two commercial fruit juices (mandarin Don Simon and pineapple/grape Don Simon) were selected as impregnation liquid Mandarin juice inoculated with *L. salivarius* spp. salivarius, pH 6 and 24 h → selected as impregnation liquid	Vacuum impregnation (50 mbar, 10 min) + atmospheric pressure (10 min)	Pilot scale air dryer (30°C, 4 m s^{-1}, 24 h)	Total soluble solids, pH, density of the juices, water activity, water content and microbial content An *in vivo* study was undertaken involving 5 children chronically infected with *H. pylori*	[106]
Apple (cv. Granny Smith)	*S. cerevisiae* CECT 1347 + transferred to a commercial apple juice *L. casei* (spp *rhamnosus*) CECT 245 + transferred to whole milk or apple juice	Vacuum impregnation (50 mbar, 10 min) + atmospheric pressure (10 min)	Pilot scale air dryer (40°C, 4 m s^{-1}, 48 h) Rehydration using milk or apple juice (25°C, 24 h)	Volumetric impregnation parameter, volumetric deformation of the sample and effective porosity Microscopic observations Moisture content, water activity and pH of the dried products	[104]
Apple (cv. Golden Delicious)	*L. plantarum* *Lactobacillus kefir*	Two methods: (i) Immersion (1 h, gentle agitation); (ii) Vacuum impregnation (50 mbar, 1.2 s)	Tray dryer: (i) At room temperature (ca. 20°C, 0.5 m s^{-1}, one week); (ii) At 40°C, 1.5 m s^{-1}, approx. 27 to 30 h + Storage (Vacuum conditions and in sterile Schott flasks under normal atmosphere conditions) at room temperature (ca. 20°C) and 4°C.	Bacterial enumeration	[107]

Table 4: Continued.

Dehydrated food	Organisms	Impregnation procedure	Drying method	Evaluated parameters	Reference
Apple (cv. Fuji)	*L. rhamnosus* (ATCC 7469) in apple juice-water	Vacuum impregnation (200 mbar, 15 min) + atmospheric pressure (15 min)	(i) Pilot scale air dryer at 40°C, air circulation of 1.8 m/min (28 h); (ii) Freeze drier (−86°C, 72 h); (iii) Cabinet air drier (40°C, 3 h) + radiant energy under vacuum (REV) dehydrator[1] (9 min at 1200 W and 3 min at 600 W, absolute pressure at 98.4 kPa) Storage (in LDPE[2]) at room temperature (ca. 20°C) and 4°C	Enumeration of bacteria, cryoscanning electron microscopy, total titratable acidity, pH, moisture content, water activity, acid tolerance of free and incorporated bacteria Sensory evaluation	[50]
Cherry Tomatoes (*Solanum lycopersicum* var. cerasiforme)	*L. acidophilus* TISTR 1338 (added to a mixture of a formulated tomato extract (FTE) and sucrose syrup (20, 40 and 60°Brix))	Osmotic dehydration (OD) (soaking halved tomatoes in FTE) (atmospheric pressure, 6 and 12 h) Pulsed vacuum osmotic dehydration (PVOD) (soaking halved tomatoes in FTE) (50 mbar, 10 min); afterwards, the tomatoes were restored in atmospheric pressure for 6 and 12 h		Water loss, solid gain, lycopene, ascorbic acid, texture, color, enumeration of *L. acidophilus*	[108]
Guava and papaya	*L. casei* 01	Vacuum impregnation natural fruit extract (4°Brix) and 15 and 30°Brix fruit juices (50 mbar, 5, 10 and 15 min) + atmospheric pressure (10 min)	Impregnated guavas and papayas (15°Brix extracted fruit juices) + cabinet dryer (40°C, 36 h) Storage in plastic bags (4°C, 4 weeks)	Structural and physicochemical analysis of raw materials (total soluble solids, pH, acidity, ripeness index, moisture content, apparent density, real density and fruit porosity) Scanning electron microscopy Bacteria counting Moisture content	[109]

Table 4: Continued.

Dehydrated food	Organisms	Impregnation procedure	Drying method	Evaluated parameters	Reference
Kiwi (variety "Hayward") Mango (variety "Tommy") Strawberry (variety "Camarosa") Pineapple (variety "Gold") Banana (variety "Cavendish")	*L. plantarum* MGLp	Immersion technique (1 h, gentle agitation)	Pilot-scale tray dryer (40°C, 1.5 m s^{-1}, 24 h) Storage (sterile Schott flasks under normal atmosphere conditions) at room temperature (ca. 20°C) and 4°C	LAB enumeration Water activity	[105]
Pumpkin waste (*Cucurbita moschata* Duchesne ex poiret)	*L. casei* ATCC-393	Pumpkin powder (vacuum dried, 24 h) + water + cheese whey + *L. casei* (orbital shaking 24–72 h, 37°C)	Pellets subjected to vacuum drying (25°C, 0.045 mbar, 24 h); this powder was added to chocolate milk and to a soy milk and apple juice based beverage	Bacteria counting and environmental scanning electron microscopy pH, water activity, moisture content Simulated gastrointestinal conditions Sensory evaluation	[110]
Yacon root *(Smallanthus sonchifolius)*	*L. casei* LC-01	Dried yacon[3] and LC-01 (25 or 37°C, 1 h) Dried yacon[3], Trehalose and LC-01 (25 or 37°C, 1 h)	Air-drying at 40°C, 2 m s^{-1}	Cellular viability on days 1, 14, 28, 42 and 56 of storage Simulated gastrointestinal conditions Scanning electronic microscopy pH values	[111]

[1]Radiant energy under vacuum (REV): it is a form of vacuum microwave dehydration; [2]LDPE: low density polyethylene. [3]Forced air circulation oven (70°C, 2 m s^{-1}).

cycle. Additionally, some works have used osmotic dehydration and pulsed vacuum osmotic dehydration as impregnation methods [108] and it was observed that vacuum's application promotes the mass transfer in short-time period processes [108]. However, the effect of vacuum on probiotic cell entrapment was variable and depended on the solute concentration and time.

In order to protect the probiotic cells, fruit juice, milk, or trehalose may be used [107, 111], making the cells more resistant to drying and in the human gastrointestinal tract. Nevertheless, Betoret et al. [104] verified that yeast growth (namely, *Saccharomyces cerevisiae*) was not influenced by the culture media, while the growth of *Lactobacillus* strain decreased when milk or commercial apple juice were used. Furthermore, Leone et al. [111] verified that trehalose did not have a protective effect on *L. casei* (LC-01) when incorporated in dried yacon flakes.

In order to dehydrate foods with probiotics, the most commonly used equipment are pilot scale air dryers or tray dryers. In several situations, air drying of the impregnated samples resulted in a reduction of the microbial content, although the level of cells was enough to be considered as probiotic, as stated by Betoret et al. [106] and Ribeiro [105]. When Noorbakhsh et al. [50] applied air drying, freeze drying, and air drying + radiant energy under vacuum (REV) to apple slices impregnated with *L. rhamnosus*, they verified that freeze drying protected bacteria better than the other two methods.

Concerning storage, temperature and time are important factors to be considered. For example, the best way to preserve probiotic cell viability in dried apple cubes or slices was at 4°C [46, 107]. Nevertheless, Betoret et al. [104] also observed that cylindrically shaped dried apple samples with probiotics stored at 20°C for 15 days kept an adequate microbial load to achieve the desired probiotic effect. Storage time may also play an important role because it may be prejudicial for the survival of probiotics in proportion to its length, as reported by Leone et al. [111]. The drying method may also affect probiotics survival during storage. Noorbakhsh et al. [50] observed a higher survival of *L. rhamnosus* in apple slices subjected to air drying + radiant energy vacuum drying when stored at 25°C than air drying and freeze drying. They explained this result based on the different structures that may be obtained, as well as possible changes in the glassy state of the dried apple slices. In fact, an amorphous glassy state is important for the stability of bacteria during storage of dried cells [112].

Probiotic fruit powders have also been developed, as presented in Table 5. These powders have longer shelf life and lower transportation cost and may produce an easy-handling form that reconstitutes rapidly to a product resembling the original juice [113]. These powders have been obtained by spray drying, freeze drying, and spouted bed drying of fruit juices. Fruit juices atomization is not an easy process because the powders obtained have tendency to form agglomerates and become sticky [114], leading to lower product yield and severe operating maintenance problems. Thus, it is important to adjust the drying temperature, outlet air temperature, feed flow rate, air drying speed, atomization pressure, and the use of drying agents to ensure the physicochemical quality of the powder product [115]. Barbosa and Teixeira [47] discuss the current knowledge on the different spray drying parameters to obtain high-quality powders. Spray drying is commonly used as microencapsulation method; however, the high temperatures applied might cause injuries to microbial cells. Good results have been obtained with freeze drying, as stated by Vikram Simha et al. [113] and Barbosa et al. [116], when producing probiotic pomegranate and orange powders, respectively. Spouted bed drying has also been used in some works because lower temperatures are applied [117] when compared to spray drying. Alves et al. [117] observed that spouted bed orange juice dried samples presented higher viable microbial cell counts than the spray-dried ones; however, the last ones showed lower values of moisture content and water activity. Both samples, spray-dried and spouted bed dried, presented acceptable glass transition temperatures (Tg), which can assure powder quality when stored at temperatures below 30°C [117]. The encapsulating material is also very important. The common strategy to spray-dry sticky products is to use wall materials with high molecular weight [118] such as maltodextrin, Arabic gum, starch, and gum acacia. Anekella and Orsat [119] verified that increasing the microencapsulating material concentration increased the survival rate of probiotics. Furthermore, using suitable wall materials such as maltodextrin can reduce the stickiness to the walls of the spray dryer and increase the free-flowing nature of the powder [119]. Nevertheless, Chaikham et al. [120] when preparing dehydrated maoluang juices with probiotics verified that the treatments with maltodextrin alone showed higher cell loss than the mixtures of maltodextrin with *Tiliacora triandra* gum and/or with inulin, showing these protective effects. Kingwatee et al. [121] and Pereira et al. [122] also stated that the addition of inulin with other carriers and gum Arabic combined with maltodextrin would enhance cells survival, respectively. Furthermore, powders produced with gum Arabic presented a higher rehydration time (approx. 9 times) than those obtained with maltodextrin, probably due to its higher solubility in water [122]. This is an important property because the powders with higher rehydration capacity will be easily reconstituted by the consumers [117]. Another important point to raise is that Anekella and Orsat [119] also refer that exposing the probiotics to a sublethal thermal shock before spray drying might increase the subsequent tolerance to near lethal thermal stresses. These authors stated that spray-dried raspberry juices with probiotic cells subjected to a heat shock treatment had higher viability than nonheat shock treated cells.

Concerning storage, temperature and powder's characteristics are important factors. Barbosa et al. [118] and Pereira et al. [122] when producing orange and cashew apple juice powders, respectively, with lactic acid bacteria (LAB) verified that the powders stored at 4°C presented higher survival rates than at room temperature. Furthermore, the highest level of probiotic bacteria was observed for the orange juice powders produced at the lowest feed flow rate ($0.2\,\mathrm{L\,h^{-1}}$), probably due to their low water contents [117]. However, these results were different to Mestry et al. [126], who when preparing

Table 5: Fruit powders with probiotics.

Vegetable	Organisms	Drying conditions	Evaluated parameters	Reference
Cashew apple juice	*L. casei* NRRL B-442	Cashew apple juice Bacterial cells (30°C, ~15 h) + maltodextrin or mixture of maltodextrin plus gum Arabic Spray dryer: Feeding rate = 0.3 L h^{-1} Hot air flow = 3.0 m^3 min^{-1} Pressurized air flow = 30 L min^{-1} Inlet air temperature = 120°C Outlet air temperature = 75°C The powders were sealed in polyethylene bags and stored in the dark at 25 and 4°C at 68% relative humidity	Viable cell counts A_W pH Color Powder rehydration time Powder yield Viable cell count determination	[122]
Cereal extracts, soya bean extract and Job's-tears extract, fortified with sesame and glucose	*L. plantarum* TISTR 2075	Fermented cereal extracts (37°C, 24 h) + Maltodextrin Spray dryer: Inlet temperature = 130°C Outlet temperature = 70°C	Simulated gastrointestinal tract tolerance Inhibitory activity against *Escherichia coli* O157:H7 DMST 12743 and *Salmonella typhimurium* ATCC 13311 Enumeration of viable cells Determination of soluble calcium Scanning Electron Microscopy	[123]
Chestnut mousse (anhydrous basis)	*L. rhamnosus* RBM 526 *L. rhamnosus* GG	*L. rhamnosus* were resuspended in a chestnut extract Spray dryer: Inlet/outlet temperatures: 140/60°C, 140/65°C, 140/70°C, 130/65°C	Moisture content of dried samples Enumeration of lactobacilli after spray drying Sensitivity test Production of chestnut mousse (pilot-scale anhydrous formulation) and sensory analysis	[124]

Table 5: Continued.

Vegetable	Organisms	Drying conditions	Evaluated parameters	Reference
Fruit powders (apple, banana, strawberry)	*L. plantarum* 299v	Two different procedures were followed: (i) Immersion of the fresh fruit pieces in the probiotic culture (1 h), drying (pilot-scale tray dryer, at 40°C, air flow of 1.5 m s^{-1}, 24–48 h) and grinding (ii) Drying the fresh fruits in a pilot-scale tray dryer at 40°C and air flow of 1.5 m s^{-1}, followed by grinding. Simultaneously, drying of probiotic culture by spray drying in skim milk with outlet temperature = 75°C and inlet temperature = 200°C and atomizing air pressure 4 bar Addition of dried probiotic to fruit powders (15 and 30%, w w^{-1} of dry weight)	Water activity of the fruit powders Enumeration of viable cells Storage (at room temperature or at 4°C)	[64]
Lychee juice	*L. casei* 01	Lychee juice + bacterial cells + maltodextrin, mixtures of maltodextrin plus inulin, gum Arabic plus inulin, or gum Arabic Spray dryer: Feeding temperature = 25°C Feeding rate = 0.6–1 L h^{-1} Atomizing pressure = 15 psi Inlet air temperatures = 150–170°C Outlet air temperature = 60–90°C	Quantification of the encapsulated cells Microstructure-scanning electron microscopy Glass-transition temperature Bulk density Solubility Hygroscopicity Water activity Moisture content Total phenolic compounds Ascorbic acid Total anthocyanins Survival of encapsulated probiotic cells in gastric or bile fluids	[121]

Table 5: Continued.

Vegetable	Organisms	Drying conditions	Evaluated parameters	Reference
Maoluang juice	*L. casei* 01 *L. acidophilus* LA5	Inoculated Maoluang juices + Maltodextrin + *Tiliacora triandra* gum and/or inulin Spray dryer: Feeding temperature = 25°C Inlet temperature = 160°C Outlet temperature = 80°C Feeding rate = 0.6–1 L h^{-1} Atomizing pressure = 15 psi The powders were vacuum sealed in laminated bags (polyethylene terephthalate/ polypropylene/aluminum) and kept in a refrigerator	Viable cells after spray drying Microstructure analysis of spray dried probiotic-maoluang juice powders (SEM) *In vitro* stomach and small intestine experiments *In vitro* colon experiment	[120]
Orange juice	*L. plantarum* 299v *Pediococcus acidilactici* HA-6111-2	Orange juice + 10 DE maltodextrin + lactic acid bacteria Spray dryer: Feed flow rate = 25 mL min^{-1} Inlet air temperature = 150°C Outlet air temperature = 70°C Orange juice + 10 DE maltodextrin (with and without) + lactic acid bacteria Freeze-dryer: vacuum (6.7×10^{-2} mbar), 7 days, condenser at −55°C Orange pieces + Lactic acid bacteria (1 h) Pilot-scale tray drier: 40°C, 48 h, 1.5 m s^{-1} Grinding	Drying yield for spray dried powders A_W Dissolution test Color Vitamin C Enumeration of LAB cultures Storage conditions (180 days, 4°C and room temperature, in the presence or absence of daylight, a_w = 0.03–0.11)	[116]

Table 5: Continued.

Vegetable	Organisms	Drying conditions	Evaluated parameters	Reference
Orange juice	*L. casei* NRRL B-442	Fermented orange juice + maltodextrin or gum Arabic (both at 15% (w w^{-1})), 25°C, 30 min Spray dryer: Inlet air temperature = 140°C Nozzle air flow rate = 30 L min^{-1} Hot drying air flow rate = 3.5 m^3 min^{-1} Feed flow rates = 0.2, 0.5 and 0.7 L h^{-1} Spouted bed dryer: Inlet air temperature = 60°C Fluidizing air flow rate = 1.7 m^3/min Nozzle air flow rate = 30 L min^{-1} Feed flow rates = 0.2, 0.3 and 0.4 L h^{-1}	Microbial viability Moisture content Water activity Glass transition temperature (DSC) Particle size Scanning electron microscopy Rehydration time Rheological characterization Storage conditions (sample with the best viability, moisture and *Tg* results): 3 weeks in hermetically sealed polypropylene packages at 25°C	[117]
Orange juice	*L. plantarum* 299v *P. acidilactici* HA-6111-2	Orange juice + 10 DE maltodextrin or gum Arabic + lactic acid bacteria Spray dryer: Feed temperature = 40°C Feed flow rate = 5 mL min^{-1} 86% of drying air flow rate Compressed air flow rate = 550 L/h Inlet air temperature = 120°C Outlet air temperature = 65°C	Drying yield A_W of the dried products Data adjustment: Logistic model	[118]

Table 5: Continued.

Vegetable	Organisms	Drying conditions	Evaluated parameters	Reference
Pomegranate juice	*L. acidophilus* MTCC-447	Pomegranate juice + bacterial cells (37°C, 48 h) + gum Arabic and maltodextrin Spray dryer: Inlet air temperatures = 130, 140 and 150°C Feed flow rate = 3 mL min^{-1} Outlet air temperature = 70°C Freeze-dryer: −40°C, 48 h	Moisture content Bulk density Solubility Water activity Color pH Acidity Bacterial enumeration Total anthocyanin content Reconstitution of probiotic pomegranate juice powder Shelf-life studies (aluminum laminated foil, room temperature, 4 weeks)	[113]
Pomegranate juice	*L. rhamnosus* MTCC-1408	Pomegranate juice + bacterial cells (37°C, 24 h) + maltodextrin and gum Arabic Spray dryer: Inlet air temperatures = 110–150°C Outlet air temperature = 80°C Freeze-dryer: −40°C	Survivability testing Acid tolerance testing Antibiotic sensitivity testing Moisture content A_W Colour Bulk density and tap density Total anthocyanin content	[125]
Raspberry juice	*L. rhamnosus* *L. acidophilus*	Raspberry juice + maltodextrin + mixture of lactobacilli (subjected to sublethal treatment) Spray-dryer: Cyclone air flow rate = 30 m^3 h^{-1} Temperatures used = 100, 115 and 130°C Feed rates = 10, 15 and 20 cm^3/min Total solids: maltodextrin ratios = 1 : 1, 1 : 1.5 and 1 : 2	Growth curve and dry biomass estimation Sub-lethal temperature (T_{sl}) treatment (45, 50, 52 and 55°C) Color	[119]

Table 5: Continued.

Vegetable	Organisms	Drying conditions	Evaluated parameters	Reference
Watermelon and carrot juices	*L. acidophilus*	Watermelon and carrot juices + *Lactobacillus* cell suspension (37 °C, over a period of 44 h) + maltodextrin Spray dryer: Inlet air temperature = 120–160°C Feed flow rate = 2.0–5.0 mL min^{-1} Atomization pressure = 1.0–3.0 kg cm^{-2}	Determination of viability Determination of lycopene content β-carotene assay Vitamin C assay Measurement of moisture content Calculation of bulk and tap density Measurement of particle density, porosity, Carr index (flowability), Hausner ratio (cohesiveness) and water solubility index Colour Wettability time Sensory Evaluation Scanning Electron Micrographs Differential Scanning Calorimetry	[126]

Table 6: Main bioactive compounds responsible for nutritional and health benefits of plant derived dried food products (fruits and vegetables, fruits and vegetable by-products, grains, nuts, and algae).

Bioactive compounds	Nutritional benefits	Health benefits	Dried product	References
Polyphenols, carotenoids, melanoidins	Antioxidant activity	Chronic disease Protection (CVD, cancer, macular degeneration)	Stone fruits, apple, figs, pear, pineapple, kiwi, berries, carrots	[131–137]
Phenols, indols, glucosinolates	Detoxification	Chronic disease protection	Stone fruits, apple, pear, pineapple, kiwi, berries, carrots, cruciferous vegetables	[137–139]
FOS, GOS, inulin, glucan, etc.	Resistant starch, Prebiotic content	Immunity boost, colonic and systemic health benefits	Chicory, Jerusalem artichoke, garlic, onion, asparagus, banana, broccoli, dandelion	[140]
Beneficial microorganisms (Probiotics)	Regulation of gut microbiota	Immunity boost, colonic and systemic health benefits	Anhydrobiotics	[141]

carrot and watermelon juices powders, observed that higher feed rates resulted in higher retention of viability due to the formation of larger droplets, resulting in less exposure to higher air temperatures.

5. Health Benefits of Functional Dehydrated Foods

From the point of view of consumers' health, dried foods are a good source of nutrients, minerals (i.e., magnesium, potassium, calcium, and/or phosphorus) and vitamins (i.e., vitamin E, niacin, choline, and/or folic acid), and, especially, bioactive compounds. In addition, plant derived foods contain fibre, phytochemicals (phenolic compounds, carotenoids, and/or phytosterols) [127] (Table 6). In general, phytochemicals from this type of food are well absorbed and their bioavailability is high. For example, polyphenols and tocopherols from nuts and dried fruits have proved to be rapidly accessible in the stomach, thus maximizing the possibility of absorption in the upper small intestine [128, 129]. Antioxidants from dried fig can increase the plasma antioxidant capacity and protect lipoproteins from subsequent oxidation, therefore, demonstrating the bioavailability of antioxidants in dried fruits [130].

Dried fruits constitute a healthy snack, as an alternative to salty or sweet ones, and food ingredients to other foods due to their taste and nutritional/health benefits [142]. In fact, they provide concentrated compounds, such as the ones mentioned above, since a considerably large quantity of water is removed from the fresh commodity, through several different drying technologies. They also combine this healthy issue with a unique taste and aroma, very attractive to consumers. In fact, the natural sugars in fruits (glucose, fructose) are concentrated as well, the dried fruit becoming sweeter that the fresh equivalent. This type of food product is in the current dietary recommendations of various countries. Scientific evidence (epidemiological and *in vitro* and *in vivo* studies) suggests that individuals who regularly consume great amounts of dried fruits suffer lower incidence of cardiovascular diseases, obesity, various types of cancer, type 2 diabetes, inflammation, brain dysfunction, and other chronic diseases [143–150].

Most chronic diseases involve inflammatory processes. Additionally, free radicals induce oxidative stress, which leads to DNA damage and other genetic alterations that may cause cancer if left unrepaired [151, 152]. As disease prevention is the key to mitigating the damage caused by these disorders, the consumption of phytochemicals from fruits, vegetables, whole grains, and algae, in foods, may decrease the risk of CVD and stroke [153–158].

Selected dried fruits, rich in specific compounds, such as amla fruits or Indian gooseberries, avocados, berries, mangoes, mangosteens, persimmons, prunes, raisins, and kiwi fruits, may also present cancer chemopreventive effects [159].

Processing to produce dried fruits significantly decreases the content (on a dry weight basis) of bioactive compounds, such as vitamins and phenolic compounds. Pretreatments before drying may also influence the loss of these compounds during drying. For example, depending on the product, some vegetables that are adequately blanched before drying may present less than 5% decrease in the carotenoids content, while if they are processed without enzyme inactivation, this reduction is increased to 80% [160]. Dipping in sulphite and other solutions has also shown to reduce the loss of vitamins during drying. Lin et al. [161] reported that losses of vitamin C and carotene were higher during air drying than with vacuum freeze drying. This may be explained by the fact that the main losses in vitamins and other substances occur due to water solubility, heat sensitivity, and enzymatic oxidation during processing [162], which are absent during vacuum freeze drying. Most vitamins such as A, C, and thiamine are heat sensitive; some (A and C) are also sensitive to oxidative degradation. Sulphuring can destroy thiamine, and riboflavin is light sensitive. Consequently, the losses of bioactive compounds also depend on the drying operations

Table 7: Phytochemical losses during the pretreatment and/or drying process [166].

Phytochemicals/vitamins	Product	Pretreatment	Drying method	Phytochemicals/vitamins Losses	References
Carotenoids	Carrot	With blanching treatment	Fluidized bed dryer	15.7% carotenoids	[167]
	Carrots, broccoli and spinach		Microwave drying	63% carotenoids	[168]
	Paprika	Without treatment (without enzyme inactivation)	Flow dryer	80% carotene	[160]
	Paprika	With blanching treatment	Flow dryer	5% (depends on the product)	[160]
Lycopene	Tomato		Osmotic-vacuum drying	Better than vacuum drying and air drying 8.1 to 20.9%	[169]
	Tomato pulp			Depends upon the conditions	[170]
	Carrots		Inert gas drying	No effect	[171]
Vitamin C	Carrot	Blanching treatment	Vacuum, microwave, air and freeze-drying	37% before drying	[161]
	Apple and strawberry	60% Sucrose solution	Microwave vacuum	40%	[172]
Vitamin C and carotenoids	Carrot	Blanching with sulphite and L-Cysteine-HCl	Fluidized bed dryer	L-Cysteine-HCl retained highest content of vit. C Na metabisulphite able to reduce oxidation of carotenoids	[173]
Carotene and vitamin C	Carrots, paprika, potatoes		Inert gas drying	15% carotene; 13% vit.C	[162]
	Strawberry and carrot			Refractance window similar to freeze-drying	[174]
Vitamin C and PUFA's	Seaweed		Sun-drying, oven-drying, and freeze-drying	Much lower in freeze-drying than oven and sun-drying	[175]
Tocopherol, carotenoids and vitamin C	Paprika	Blanching by steaming or hot air	Flow dryer	Better retention	[160]
Total phenolic content and antioxidant activity	Apple		Microwave drying	39% (TPC) and 30% (AA)	[176]
D3 (milk powder)	Milk		Spray-drying	Negligible losses	[177]
Folic acid	CMC model system		Spray-drying	Increase folate retention	[178]
Thiamine, riboflavin and niacin	Spaghetti		Convection air	Loss of vit. Drying 16–28%	[179]
Vitamin E	Whole meal wheat flour		Drum dryer	More loss of vit. E during scalding (75%) than during drum drying (15%)	[180]

(time, temperature, atmosphere composition, and others). Experimental studies have been conducted to reduce such losses by using pretreatments, selection of adequate drying methods, use of novel methods of drying, and optimization of drying conditions. In the literature, the methods reported for drying of food materials vary from solar techniques to recently developed microwave and heat pump drying [163–165]. An overview of phytochemical losses prior to or during drying is provided in Table 7. From this table, it becomes apparent that inert gas drying, spray drying, and freeze drying produce negligible/low losses of phytochemicals and vitamins, namely, carotene and vitamin C, while microwave drying results in high losses of carotenoids.

However, the drying process may lead to an elevated antioxidant activity (AA). Vitamin C, Vitamin E, carotenoids, polyphenols, melanoids, and indoles are some bioactive compounds that present AA [181]. In fact, during drying, phenolic compounds may be generated as Maillard reactions products [131]. The net antioxidant activity reflects the cumulative effects of the total phenolics losses and Maillard reaction

production. Antioxidants in dried cranberries, grapes, and plums showed to be twice as potent as those in the fresh fruits [130].

Storage of dried food products may bring more severe losses of nutrients and bioactive compounds than during the drying process itself [163, 182–184]. For example, Kaminski et al. [185] observed a rapid degradation of carotenoids in freeze-dried carrots during storage.

6. Conclusions

Due to the importance of functional foods for a healthy lifestyle, scientific research has extensively been developed in this domain during the last decade, namely, focusing on prebiotics, probiotics, and bioactive compounds, in general. The number of published research on this type of foods has duplicated in the last 5 years, reaching almost 4,000.

Drying is a unit operation of stabilization and conservation of the bioproducts much used. However, it entails many modifications and alterations of the dried product. The drying processes having the least adverse effects on the quality of the product and the bioactive compounds are those operating at low temperature (freeze drying, vacuum drying) or with very short durations (spray drying, drum drying). Freeze drying is the technique of drying allowing the greatest preservation of the antioxidant properties of the phytochemicals and the viability of the probiotics. However, it presents high operating cost and low productivity. Spray drying is a good alternative for industrial development. New drying techniques based mostly on electromagnetic energy (dielectric drying, MW, IR, UV, etc.) show encouraging results in terms of preservation of bioactive compounds. Nevertheless, all these processes need to be optimized. The RSM is an increasingly used optimization method but new approaches such as the CORICO method bring new possibilities.

This review also reports the most recent findings on dehydrated plant products with probiotics and the studies that have been made, highlighting the microorganisms used, the impregnation procedures, drying methods, and evaluated parameters. Apple is still the preferred matrix; however, the use of other plant products may be noticed. Furthermore, the production processes of fruit powders with probiotics were discussed, focusing the drying processes and carriers used.

Dried fruits and vegetables, fruits and vegetable by-products, grains, nuts, and algae are rich in bioactive compounds, whose properties are responsible for a lower incidence of cardiovascular diseases, obesity, various types of cancer, type 2 diabetes, inflammation, brain dysfunction, and other chronic diseases. This review presents these health benefits.

The losses of bioactive compounds, such as phytochemicals and vitamins, during drying depend on the drying method and drying conditions, but also on the pretreatment eventually used. These losses may be considerable, but the drying process may lead to an increase in the antioxidant activity. Storage may bring higher losses in important bioactive compounds than the drying process itself.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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