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Sustainable Drying Technologies for the Development of Functional Foods and Preservation of Bioactive Compounds

Ester Betoret, Laura Calabuig-Jiménez,
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Abstract

Nowadays, the sustainability of a product, a process or a system is assessed according to three dimensions: environmental, social and economic. Sustainability challenges occur at all stages in the food system from production through processing, distribution and retailing to consumption and waste disposal. The promotion of organic and local food is not the only way to reach the sustainability. There is other possibility that implies to continue the production hegemony. Increasing research is being focused on the development of healthy, quality and safety food products adapted to consumer's needs and more environment-friendly processes, that is, processes consuming energy more efficiently, generating less waste and emitting less greenhouse effect gases. Drying technology is applied in the food industry not only for preservation but also to manufacture foods with certain characteristics. Drying technology operations need to be precisely controlled and optimized in order to produce a good-quality product with the highest level of nutrient retention and flavor together with microbial safety. This chapter contains detailed information about some measurements taken by the food industry to ensure the supply of bioactive nutrients to as many individuals as possible, assuring the global sustainability. More specifically, the contribution of some drying techniques employed in the development of functional foods to increase the sustainability of the feeding process is discussed.

Keywords: sustainability, functional foods, drying, bioactive compounds, structure

1. Introduction

Sustainability means meeting the needs and aspirations of the present without compromising the ability of future generations to meet theirs. As a result of environmental imbalances caused by intensive production and massive use of resources, to achieve food and agricultural sustainability, traditionally, the system has been directed toward promotion of organic and local food, but this is not the only way, as explained in [1]; there is other possibility that implies to continue the production hegemony, emphasizing biotechnology and technological panaceas.

Nowadays, the sustainability of a product, a process or a system is assessed according to three dimensions: environmental, social and economic. Sustainability challenges occur at all stages in the food system from production through processing, distribution and retailing to consumption and waste disposal. The development of a sustainable agri-food system places responsibilities on both the natural and the social sciences [2]. While advances in basic and strategic biological research have greatly expanded, the potential to produce nutritious food in an efficient and environmentally sustainable manner, social and economic factors will determine the uptake and value of this research as well as its future direction [3].

Food processing can be defined as the set of operations which allow manufacturing, preservation and distribution of food products from suitable raw materials. The improvement of the food products is now directed toward ensuring nutritional and specific functional benefits. Regarding the process improvement it is directed to ensure the quality and safety of environment-friendly food products, prepared by optimizing the resources used, minimally affecting or even enhancing their nutritional and beneficial characteristics [4].

Sustainable food production stands at the intersection of several growing needs. First, the needs of consumers for improved food security and safety as well as more sophisticated needs. Second, the quest for economic sustainability of food production based on cost reduction and increased product differentiation. Third, the growing concern for reversing the over-exploitation of natural resources, waste generation and the contribution to climate change [5].

Functional foods are foods that beneficially affect one or more target functions in the body, beyond an adequate nutritional effects, in a way that is relevant to either an improved state of health and wellbeing and/or reduction of risk of disease, and it is consumed as a part of a normal food pattern (not a pill, a capsule or any form of dietary supplement) [6]. Many diseases strictly related with diet and lifestyle concern the society because of their prevalence. Functional foods can help prevent or improve these diseases, thus contributing directly to public health. But the functional effect of a food or food component depends on the active component gaining access to the functional target site. Foods are mostly complex mixtures of macro- and micro-components organized in a structure that can trap active compounds, modulating their release or inhibiting their activity. The selection and development of both appropriate food matrix and technological process, able to maintain the active molecular form until the time of consumption is the key step for the success of a specific functional food [4].

This chapter contains detailed information about some measurements taken by the food industry to ensure the supply of essential nutrients and bioactive compounds to as many

individuals as possible assuring the global sustainability. More specifically, the contribution of some drying techniques employed in the development of functional foods to increase the sustainability of the feeding process, is discussed.

2. Drying operation

Drying is an energy-intensive well-studied unit operation in process engineering to reduce moisture content in the food matrix to a level that is safe for storage and transportation, to avoid microbial multiplication, slow down/inactivate microbial activity and the associated product quality deterioration. It involves the removal of water from a wet feedstock by inducing phase changes of water from solid or liquid into a vapor phase via the application of heat (except in the case of osmotic dehydration during which the water is removed without a change in phase by the diffusion of liquid water from solid foods to an osmotic solution through an osmotic pressure difference). The process of drying food materials is extremely complex, involving coupled transient mechanisms of heat, mass and momentum transfer processes accompanied by physical, chemical, structural and phase change transformations [7, 8].

Drying is applied in the food industry not only for preservation but also to manufacture foods with certain characteristics. The nature of the process along with the food structural characteristics results in a very marked effect on the quality characteristics of the final product. There are many different methods of drying food materials, each with their own advantages and disadvantages for particular applications. A vast number of dryer designs reported in the literature are due to the differences in the physical attributes of the product, modes of heat input, operating temperatures and pressures, quality specifications on the dried product and so on [9]. The methods most commonly employed for biotechnological and food products include freeze-drying, spray drying, convective drying, vacuum drying, microwave drying, osmotic drying and combinations thereof (reviewed in [9, 10]). Overall, the quality characteristics of the final product are significantly affected by the process conditions and the way it is conducted. Thus, drying operations need to be precisely controlled and optimized in order to produce a good-quality product with the highest level of nutrient retention. The changes caused to the food properties include discoloring, aroma loss, textural changes, nutritive value and changes in physical appearance and shape [11]. Conditions of drying have a great effect on quality attributes of dried product. For example, higher drying temperature reduces the drying time but may result in poor product quality, heat damage to the surface and higher energy consumption [12]. On the other hand, mild drying conditions with lower temperature may improve the product quality but decrease the drying rate thus drying period is lengthened.

The problems of drying are diverse as various food materials with very diverse physical/chemical properties need to be dried at different scales of production and with very different product quality specifications [13]. The materials preserved by dehydration vary a lot, not only fruits and vegetables to probiotic microorganisms and animal products in the food area, but

also other biological materials with important physiological activities, such as human blood cells and insulin.

As described in [4], in most cases, drying involves the application of different temperature conditions (e.g., 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) that cause irreversible damage due primarily to:

- changes in cellular structures (e.g., cell wall, cell membrane) constituting biological tissues and the induction of changes in key properties responsible for product functionality (e.g., cell membrane permeability, mechanical strength of the wall membrane assembly, etc.).

- changes in the chemical structures responsible for the biological value of nutritious components (e.g., protein, fat). The structural changes also cause changes in the technological functionality that these compounds give to the food to which they belong.

- reactions, mainly oxidation, that decrease the functional value of nutritive compounds (e.g., vitamin, antioxidant).

The major challenge is to remove water from the material in the most efficient way with better product quality, minimal impact on the environment and at the lowest capital and operating costs of the process. Today's increased competition due to globalization, together with the growing consumer demand for better quality products, coupled with the need for eco-friendly and sustainable processes to maintain competitiveness with minimal impact on the environment, will continue to seek innovations in the drying process [9].

3. Strategies to increase the functionality of food products in drying processes

One important part of the sustainability to point out is the minimization of residues on the bioactive compounds recovery from the food waste. During bioactive compounds recovery from food waste, it is common to carry out a drying operation in order to concentrate these ones and use the minimum quantity of solvent. A lot of papers have been written studying the optimal exploitation and revalorization of food waste extracting the maximum quantity of bioactive compounds and minimizing the environmental impact. Some examples of articles/reviews published are those from [14, 15]. However, in this chapter, we focus on the contribution of functional foods to global sustainability concept. In this way, the principal strategies to increase the functionality of food products during drying as indicated in [9] can be divided into three groups. These strategies can be applied regardless of bioactive compound source either being naturally present in the food matrix or derived from food waste recovery:

1. Addition of ingredients that protect the degradation of bioactive compounds.

2. Creation of structural elements that protect/maintain the functionality of bioactive compounds.

3.   Prevention of reactions causing a degradation of bioactive compounds and promotion of those that result in a functional effect.

3.1. Addition of ingredients that protect the degradation of bioactive compounds

As mentioned earlier, drying operation involves removing large amounts of intracellular and extracellular water from food matrices that results in structural and biochemical changes that at the end can affect the functionality of bioactive compounds. The bioactive compounds to be protected vary a lot, from probiotic microorganisms to other important biological compounds such as red blood cells and insulin. As a result, a variety of protectants have been added to the drying media in order to protect the viability of these bioactive compounds. Following this strategy, the researchers aim to not only reduce the degradation of bioactive compounds during drying but also increase their functionality.

Regarding probiotic microorganisms protection during drying, a lot of literature can be found. The probiotic microorganisms are dried in order to extend their viability in dried form or during their incorporation into functional foods. Several works show that properly dried microorganisms remain viable during long-term storage at room temperature [16]. However, the stresses suffered during processing may lead to significant losses in viability and func-tionality. As explained by Iaconellia et al. [17], the stresses applied on microorganisms by drying processes can be divided into two main categories: the mechanical stresses, mainly localized to the cell membrane, and the intracellular accumulation of reactive oxygen species that causes damage to cell proteins, lipids and nucleic acids. Structural changes can lead to membrane deformation that with fast dehydration-rehydration processes result in membrane permability leading to cell death [18–20]. Moreover, reduced water activity induce phase transitions from crystalline to a gel in cell membrane [21], which may lead to leakage and cell death [22].

A variety of protectants have been added to the drying media before freeze-drying or spray drying to protect the viability of probiotics during dehydration, including skimmed milk powder, whey protein, trehalose, glycerol, betaine, adonitol, sucrose, glucose, lactose and polymers, such as dextran and polyethylene glycol [23]. The beneficial effects of the protectants seem to be related to their protective effect on proteins and cell membranes [24].

As reviewed by Meng et al. [25], drying injuries to the cell depend on probiotic strain, drying method and conditions of processing.

Some examples of new protectants and applications in the area of functional foods develop-ments are described later. In most of the studies, not only the survivability of the probiotic cells is considered but also their functionality is measured in terms of enzyme activity, acid tolerance and hydrophobicity.

The benefit of disaccharide protectants such as cellobiose, lactose and sucrose, for maintaining viability and b-glucosidase activity of *Bifidobacterium infantis* UV16PR during freeze-drying and storage in different food matrices was evaluated [26], concluding that at 10% concentration both trehalose and cellobiose significantly enhanced enzyme activity, viability and acid tolerance.

Resistant starch was found to protect *Lactobacillus plantarum* CIF17AN2 during drying process and could potentially protect it from gastric acid and bile exposures [27]. In the same way, whey protein isolate (WPI) was able to protect *Lactobacillus plantarum* A17 in the encapsulation process. A unique layer-by-layer electrostatic mechanism involved in encapsulation of A17 at pH 7 was found responsible for higher survival of cells [28].

The capability of different fiber preparations to protect the viability and stability of *Lactobacillus rhamnosus* during freeze-drying, storage in freeze-dried form and after formulation into apple juice and chocolate-coated breakfast cereals was studied [29]. The stability of freeze-dried *L. rhamnosus* cells at 20°C was higher in chocolate-coated breakfast cereals in comparison to low-pH apple juice. As in freeze-drying stability, wheat dextrin and polydextrose proved to be better carriers than oat flour in chocolate-coated breakfast cereals. In the development of probiotic chocolate, as reviewed by [30], the lipid fraction of cocoa butter was shown to be protective for bifidobacteria.

Regarding other bioactive compounds, trehalose seems to be the most studied protectant. For example, trehalose has shown to have a protective effect on insulin structure, probably via substitution of hydrogen bonds, while the mild surfactant, sodium deoxycholate, was more protective on the native structure of insulin and, therefore, results in high bioactivity mainly due to resistance to the frozen concentration and interface denaturation in a concentration-dependent manner [31]. Intracellular trehalose has been shown to be necessary for successful stabilization of the membrane during freeze-drying of liposomes and cells [32]. In the same way, trehalose-loaded red blood cells lyophilized in the presence of liposomes demonstrated high survival and low levels of methemoglobin during 10 weeks storage at 4°C in the dry state. A detailed investigation on the liposome size revealed that extruded egg yolk phosphatidyl-choline vesicles with an average diameter of 270 nm are the most effective in inhibiting hemoglobin release. Smaller vesicles could access membrane disruptions and be responsible for membrane repair, which was reflected in reduced hemoglobin leakage [33].

Sometimes, the addition of key ingredients can not only help to reduce the degradation of bioactive compounds but also increase their functionality. It was demonstrated that the addition of a cationic amphiphilically modified dextran could act as excipient in drug delivery nanocarriers of dry power inhalation and significantly increase the drug functionality and its effect [34]. In the same way, a dry powder phage K preparation for oral delivery to control *Staphylococcus aureus* using alginate whey protein microspheres was developed [35]. The results showed that maltose provided the best protection to encapsulated phage K during drying. Both the microsphere size and polymer concentrations in the encapsulation matrix were important factors to determine the degree of protection against stomach acids.

3.2. Creation of structural elements with protective effect

Creation of structural elements with protective effect like encapsulation by using spray drying to create a protective structure, the application of drying operation to form edible films and coatings and the use of vacuum impregnation and its subsequent drying are strategies which

can reduce the negative effect of dehydration on biomolecules, protect and even improve the functional value of the food.

3.2.1. Encapsulation

Encapsulation is defined as a technology of packaging solids, liquids or gaseous materials in miniature, sealed capsules that can release their contents at controlled rates under specific conditions [36, 37]. The main objective of encapsulation is to protect the core material from adverse environmental conditions such as moisture, heat, oxygen or other extreme conditions. Thereby encapsulation can contribute to increase the shelf life of the product; increase functionality, promoting the controlled liberation of the encapsulated bioactive compound in the target site [38] and keep its properties protecting its bioactive compounds. To extend its shelf life and hence reduce food losses is related with a waste of land, water, energy and several inputs used in production, so any technique effectively reducing these losses will also contribute to the more efficient use of natural resources and therefore sustainability.

Regarding encapsulation technologies, spray drying is an economical, flexible, continuous operation, which produces particles of good quality. For this reason, it is the most widely used microencapsulation technique in the food industry. Encapsulation with spray drying is typically used for the preparation of dry, stable food additives and flavors and to protect functional ingredients such as polyphenols and probiotics [4].

In most of the cases, the capsule is mainly made up of polysaccharides, proteins and their combinations for the microencapsulation of antioxidant components and probiotics. Some polysaccharides such as inulin and polydextrose may act as prebiotic, as they are not hydro-lyzed by human digestive enzymes, and have been used to protect probiotic bacteria during spray drying and storage [39].

Recently, food industry by-products have raised considerable interest for their use as encap-sulant because of being a sustainable source of material. Chiou and Langrish [40] demonstrated in their study that milled citrus fiber can be used as a replacement for maltodextrin-type carriers to encapsulate hibiscus extract. Also, whey protein is an excellent encapsulating material due to its emulsification, gelation and film-forming properties. Denaturing the whey protein ensures higher tensile property and lower oxygen permeability which protects the probiotic cells from adverse gastrointestinal conditions [41, 42]. Concretely, microencapsula-tion of *Lactobacillus plantarum* with fructooligosaccharide and denatured whey protein as wall material was found to be most effective in maintaining the viability of bacteria after drying, during storage and in simulated gastric and intestinal conditions [43]. Reconstituted skimmed milk has demonstrated to behave as a protective carrier for improving the survival ratio of lactic acid bacteria (LAB) after spray drying. Such protective effects has been attributed to calcium, which might enhance the heat resistance of LAB cells, and proteins, which lead to a mild temperature variation rate that is beneficial to cell survival [44]. Other example of food-derived protein that is able to protect probiotics from hot temperatures is derived from flaxseed (*Linum usitatissimum L.*) and its mucilages; reference [45] has demonstrated its efficiency as wall materials for microencapsulation by spray drying of *Lactobacillus acidophilus* La-05.

3.2.2. Edible films and coatings

Recently, the interest in high-quality food products, increased shelf life and reduced environmental impact has promoted the development of edible and biodegradable polymer films and coatings. Extending shelf life is nowadays one of the main objectives of scientific research and industrial application of edible films and coatings on the surface of several foods.

Use of edible film in multiple food-packaging applications has emerged as an environment-friendly technology with regard to its film-forming properties. An edible film or coating of any material used for enrobing (i.e., coating or wrapping) various foods to extend shelf life of the product that may be eaten together with food or without further removal is also considered [46]. Edible film or coating can control moisture transfer, gases exchange, lipid migration and/or oxidation processes. An edible coating is a thin layer of edible material formed as a coating on a food product, while an edible film is a preformed, thin layer, made of edible material, which once formed can be placed on or between food components [47].

Edible films are obtained from food-grade suspensions and are usually molded as solid sheets onto inert surfaces. They are dried and put into contact with food as wrappings, pouches, capsules, bags or casings through further processing [48]. Biopolymer edible films can be formed via two basic technologies: dry and wet processes. In a dry process, the biopolymer relies on the thermoplastic behavior exhibited by some proteins and polysaccharides at low moisture levels in thermo-compression molding and extrusion. And in wet process, biopolymers are dispersed or solubilized in a film-forming solution (solution casting), and drying steps to make the film matrix [49], solvent removal is required to achieve solid film formation and control its properties [50]. In this case, most of the times, drying operation is applied to form the structure not to obtain dried foods as in aforementioned cases. Those drying operations are generally with air flow at moderate temperatures ranging from 30°C to 60°C, depending on the characteristics of the product. When the edible film is applied in a dehydrate product, drying temperature can be higher; in reference [51], an edible film is applied in an apple snack enriched with fructooligosaccharides and *Lactobacillus plantarum* with methylcellulose, acid citric and sorbitol at different temperatures ranging from 50°C to 140°C during a range of 3–90 minutes.

Edible films and coatings contribute to the revalorization of some industrial by-products which are included in their formulation. This is the case of starch, cellulose and hemicellulose from plant origin, chitosan from crustacean, gums, carrageenan and protein extracted from seaweed, whey protein from the dairy industry, gelatin from slaughterhouses and tanneries, plant-based proteins as soybean and sunflower proteins from oilcakes and keratin from feathers [52–55]. The use of by-products contribute to reduce the waste and hence to increase the sustainability of the process.

In addition, edible films and coatings can act as carriers of functional bioactive compounds as antioxidant and/or with antimicrobial properties, bacteria with probiotics effect or antimicrobial and other components which raise the value of the product by increasing the food's shelf life and protecting its physicochemical properties while maintaining its mechanical integrity and handling characteristics [55–57].

3.2.3. Vacuum impregnation

Vacuum impregnation is a mass transfer operation where a liquid medium is introduced into a solid porous food structure due to pressure gradients created [58, 59]. The liquid amount impregnated into the food matrix depends on the food structure (pore size, distribution, morphology and porosity) and on the vacuum force applied (time and intensity).

Vacuum impregnation can be considered as a useful technology to introduce solutes into the structural food matrix to modify its composition. Generally, it is applied to add bioactive compounds to achieve a technological and/or nutritional functionality [4]. In most cases, this technological operation is used as a pre-treatment for other operations such as frying, drying and freezing due to its effectiveness in reduction of enzymatic and browning reactions, without using antioxidants, by removing oxygen from the food matrix [60]. Vacuum impregnation with a subsequent drying operation is a good combination to obtain stable and enriched functional foods. This operation can also be used to mitigate drying effect by introducing protector compounds as sugars, sugar alcohols and non-reducing sugars in the food matrix. Functional compounds added into the food matrix are more protected from oxygen and other degradation factors than the free functional compound itself; hence functional properties and shelf life are improved, even synergies between some bioactive components can occur and enhance its functionality. It has been demonstrated that bioactive compounds provided by foods can have synergic effect, for example hesperidin is more efficient in combination with ascorbic acid [61]. In reference [62], a probiotic apple snack impregnated with mandarin juice and enriched with *Lactobacillus salivarius* spp. *Salivarius* was developed. The inclusion of the probiotic into a food matrix by vacuum impregnation demonstrated a protection against degradation reactions and at the same time, the new structure could permit the liberation of the bioactive compound in the target site hence improving its functionality.

3.3. Prevention of reactions causing a degradation of bioactive compounds and promotion of those that result in a functional effect

Because of the decrease in the moisture content during drying, most of the nutrients present in the food undergo substantial concentration, thus increasing its nutritional value. However, other more sensitive nutrients are irreversibly transformed and/or destroyed during the dehydration step mainly due to the effect of light, oxygen, heat and the presence of sensitizers. The extent of such changes would depend not only on the processing conditions but also on the sensitivity of each particular compound, their interaction with other food components and the protection conferred by structural matrices, such as cells or microcapsules. From deterio-rative reactions occurring during drying of foodstuff, those having a chemical basis are basically oxidation and Maillard reactions. Lipids, vitamins, carotenoids and phenolic compounds are particularly sensitive to oxidation which, in turn, can take place enzymatically or non-enzymatically.

Lipid oxidation leads not only to the development of the typical aroma of many meat products but also to the formation of unpleasant odors and flavors. From a nutritional point

of view, oxidation may affect the fatty acid composition and fat quality of meat and fish products. Significant decrease in long-chain polyunsaturated fatty acids (LC-PUFA) was reported during dry-cured ham processing [63]. Also the exposure to light and oxygen during sun drying and controlled oven drying induced a noticeable reduction of the most important ω-3 fatty acids, eicosapentaenoic acid (EPA) and docosahexaenoic acid (DHA), in both lean and fat fishes [64]. In addition, free radicals and peroxides originated during lipid oxidation are closely related to the pathology of some cancers, arteriosclerosis, arthritis, neurodegenerative diseases and the aging process [65]. Moreover, oxidized lipids can react with proteins and other food components and reduce their nutritional quality and safety [66]. Regarding the application of a salting process, brine contact with fish has also been reported to enhance lipid oxidation of the highly unsaturated lipids, which is directly related to the production of off flavor, protein denaturation and texture changes [67]. Specific techniques reported to prevent lipid oxidation in fish oil processing include microencapsulation and the application of natural food additives with antioxidant capacity like rosemary extracts, α-tocopherol or polyphenols from grape pomace [68]. Among simpler technical proposals for reducing lipid oxidation during fish and meat drying, those focused on reducing the exposure to oxygen in the drying chamber and, to a lesser extent, the drying temperature are particularly of interest. To this end, satisfactory results have been reported from vacuum drying and ultrasonic vacuum drying [69], microwave drying [70], ultrasound assisted drying [71], freeze-drying [72] and low-pressure superheated steam drying. Although there is little evidence about the impact of such techniques on the lipid profile of treated products, one intuits that these treatments result in more porous structure entailing greater risk of damage by oxidation during further storage. Also in fruits and vegetables, such techniques have resulted in reduction of pigments, vitamin C, phenolic compounds and other minor ingredients losses due to oxidation.

Carotenoids are natural pigments synthesized by plants and microorganisms. Their importance in human nutrition and health is mainly due to their capability to inhibit oxidative reactions. This property is particularly high in the case of lycopene, closely followed by α-carotene and β-carotene and, to a lesser extent, zeaxanthin [73]. Carotenoids may be free in the lipid phase of the food, forming complexes with proteins, bound to carbohydrates or as fatty acid esters. Carotenoids oxidation can be indirectly catalyzed by lipoxygenase, the enzyme responsible for the peroxides formation from lipid oxidation of unsaturated fatty acids, and results in important color changes and losses in antioxidant activity. Isomerization is also involved in carotenoids loss during food dehydration. Indeed, naturally occurring carotenoids are in all-trans form, which is the most stable chemical form to heat treatments. Thermal treatments applied during food processing promote isomerization of trans-carotenoids to their cis-form, mainly on the 9-cis and 13-cis types; it is not entirely clear whether it adversely affects their ability to scavenge free radicals [73]. As reported in reference [74], 13-cis-β-carotene is formed in carrots as the temperature of the product reaches 60°C, when submitted to hot air drying, or even lower temperature, when applying vacuum drying and low-pressure superheated steam drying. Although the antioxidant activity is unaffected in this case, the conversion of trans-β-carotene in any of its cis-isomers might imply a notable decrease in its activity as vitamin A precursor [75]. Negative effects of isomerization are usually offset by an increase

in bioavailability. All-trans forms naturally existing in foods are linear, long and rigid molecules, whereas their cis isomers are shorter molecules that can be more easily solubilized, absorbed and transported at a cellular level [76]. Even the irreversible degradation of carotenes by oxidation could be compensated by this increase in bioavailability [77]. For this purpose, losses during processing should be minimized by using one of the alternatives to aforementioned conventional drying techniques. Preventing the loss of cellular integrity also contributes to diminish the incidence of oxidation, as well as some pretreatments, such as blanching and osmotic dehydration. Blanching benefits are attributed to enzyme inactivation, while osmotic treatments for a short period in the presence of sucrose at 30–40°C have been reported to encourage these phytochemicals generation [78].

Other food components having beneficial health effects due to their high antioxidant and antimicrobial activity, and therefore being susceptible to oxidation, include polyphenols and ascorbic acid. Phenolic compounds and vitamin C are known to prevent free radicals formation and reduce molecular damage on DNA, lipids and proteins, which is directly related to a decrease in the incidence of cancer and coronary diseases. They also play a decisive role in the color and flavor of certain fruits and vegetables. Most of the polyphenols are present in foods as esters, glycosides or polymers, that is, as forms that cannot be absorbed [79]. However, as previously mentioned for other functional compounds, structural and chemical changes taking place during fruits and vegetables drying can contribute in increasing their bioavailability during further consumption. In general, reducing the contact with oxygen in the drying chamber by reducing the drying time reduces losses in phenolic compounds, but due to its greater sensitivity to high temperatures, reducing the vitamin C losses might imply a noticeable decrease in the drying temperature [80]. In spite of these considerations, certain fruits and vegetables show an increase in their ability to scavenge free radicals after drying in adverse conditions [81], which has been explained in terms of the generation of new compounds with higher antioxidant activity as the ones resulting from the Maillard reaction.

The Maillard reaction or non-enzymatic browning reaction is the chemical reaction that occurs between compounds with a primary amine function and compounds with carbonyl groups, which generate different flavors and brown color [82]. This reaction is accelerated under alkaline conditions, intermediate moisture content ($0.55 < aw < 0.75$) and high temperatures, but it is also observed under refrigeration [83]. The type of compounds involved also influences the reaction rate, as well as the presence of certain metals. Logically, meat and fish products, with a particularly high protein content, are most susceptible to experience such reaction. However, by-products of the Maillard reaction have also been found to be less in lysine products, such as fruits and vegetables. Adverse effects associated with this reaction include alteration of the organoleptic properties and decrease of the nutritional value since essential amino acids, mainly lysine, and certain vitamins, such as vitamin K and C, are generally involved. In addition, some of the compounds formed in the Maillard reaction are toxic or mutagenic. This is the case of high carboxymethyl lysine that promotes diabetes and cardiovascular diseases, and some recognized it as a probable human carcinogen compounds, such as acrylamide and hydroxymethylfurfural [82]. On the contrary, melanoidins formed at the

last stage of the Maillard reaction are non-digestible compounds having antioxidant and antimicrobial activity against pathogenic microorganisms of the colon [83]. Non-enzymatic browning in foods also includes caramelization reaction, but it involves only sugars or polyhydroxycarboxylic acids and usually requires more drastic conditions. Since the pyrolysis of sugars starts at temperature above 110°C, caramelization reaction in foodstuff drying is not as worrisome as compared to other chemical reactions.

4. Energetic considerations

Drying is probably the most energy-intensive process of the major industrial processes because it consumes large amounts of energy and releases significant amount of carbon oxides to the environment [84]. In an energy-intensive industry like heating or drying, improving energy efficiency by 1% could result in as much as 10% increase in profit [85]. Any small improvement in energy efficiency in food drying process will lead to a sustainable development to global energy perspective.

Condition of drying air has a great effect on the quality attributes of dried product. Thus, one of the key issues of drying technology is to reduce the cost of energy sources to increase the efficiency of drying facilities for good quality of dried products. On the other hand, the design of an energy-intensive system for lower cost and higher efficiency is one of the essential approaches for sustainable development [86].

There are a lot of studies modeling drying operation. Most of the times, the models are directed to analyze heat and mass transfer in order to improve the quality of the final products obtained. With the aim to evaluate the drying operation, there are a lot of studies directed to analyze the energy used during process in order to optimize the drying method and contribute to the sustainability of the process. It is necessary to combine all process variables (drying process, installation design, time, temperature and product characteristics) to minimize energetic and product losses.

Usually, an energy analysis is carried out in most of the studies. The energy analysis is a basic and traditional approach to estimate various energy conversion processes [87]. The energy analysis is based on the first law of thermodynamics, which is expressed as the principle of the conservation of energy. According to Singh [88], energy analysis is useful in quantitative evaluation of energy requirements of energy generating and delivery systems and in the detection of mode and evaluation of energy loss. However, it provides no information about the irreversibility aspects of thermodynamic processes. The energy analysis is unable to distinguish the different qualities of energy such as heat quality which is dependent on the heat source temperature.

The exergy-based analysis and subsequent optimization of drying processes is having a growing interest among the researchers. Exergy is the maximum amount of work obtained from a stream of matter, heat or work when some matter is brought to a state of thermodynamic equilibrium with the common components of natural surroundings by means of reversible

processes, and is a measure of the potential of a stream to cause change, as a consequence of not being completely stable relative to the reference environment [89, 90]. The exergetic performance assessments not only distinguish the magnitudes, location and causes of irreversibilities in the plants, but also enables the locations, types and magnitudes of waste emissions and internal losses to be determined [91, 92]. The main objective of exergy analysis of drying systems is to provide a clear picture of the process, to quantify the sources of inefficiency, to distinguish the quality of energy consumption, to select optimal drying conditions and to reduce the environmental impact of drying systems. The exergy analysis is being applied to more and more products. In recent years, some articles have been published combining both energy and exergy calculations in order to have a more completed analysis and sustainability evaluation of the process [93].

5. Conclusions

The development of functional foods can clearly contribute to the global concept of sustainability. The negative effects related to the application of extreme temperatures in drying operations can be minimized by incorporating ingredients that protect structural elements, creating protective structures and avoiding degradation reactions. Management of drying processes in an adequate way can contribute to prevent bioactive compounds losses, maintain and even increase the functionality of dried products.

Acknowledgements

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