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Chapter

Drying and Quality of Microalgal Powders for Human Alimentation

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Abstract

The demand for natural foods with high protein content and functional properties is constantly growing in the last years. In this context, microalgae as *Spirulina* (*Arthrospira* spp.), *Chlorella* spp., *Haematococcus pluvialis*, *Dunaliella salina*, and others, assume a key role to diversify the offer of nutritious and functional ingredients and supplements. Microalgae are commercialized, mostly, as dried powders to facilitate their use as food ingredients and to allow easy transportation and long-term stability. Microalgal powder quality and storage stability depend mainly on drying method, packaging, and storage conditions. Most of the studies that approach the subject of microalgal drying evaluate the efficiency of the process and suitability for this raw material. However, studies that assess the effect of traditional and innovative drying methods on quality of microalgal powder for human consumption are rare in literature. In this chapter, the state of the art of drying processing technology for microalgae was reviewed, discussing the effect of dehydration on quality and stability of microalgal powders with potential use in human alimentation.

Keywords: microalgae, dry biomass, biomass quality, microalgal powder, functional supplements

1. Introduction

Microalgae are photosynthetic microscopic organisms that convert CO2 and water in biomass and O2. This group of organisms is very diverse and abundant around the globe. They occur most in freshwater and saltwater aquatic ecosystems but also at other environments [1]. The main groups are Cyanophyta, Chlorophyta, Ochrophyta, Dinophyta, Rhodophyta, Euglenophyta, Haptophyta, and Prymnesiophyta [2]. It is estimated that there are around 300,000 of microalgal species around the world [1].

Microalgae have a great ecological importance as they are primary producers contributing to a lot of food chains; they produce around 40–60% of the oxygen available on Earth atmosphere, convert inorganic nutrients in organic matter, and for millions of years have produced the oil that today economy is still dependent [1].

Also, microalgae have been used in different industries for decades. These microscopic organisms are produced in ponds or photobioreactors to be used directly as live feeds for aquaculture hatcheries or to be used in food industry as food supplements or source of nutrients and vitamins, in agriculture as biofertilizer,

in pharmaceutical and cosmetic industry as raw material to extract specific molecules, and in other different biotechnology applications [3]. Also, microalgae have been used for environmental purposes as in tertiary wastewater treatment, as system for carbon fixation, and as raw materials to produce biofuels [4].

Despite all economic potential applications of microalgae and the great diversity of species, the microalgal industry is based mainly in few applications and species. The majority of microalgal biomass production is destined for food industry as food supplement. The main species belongs to the genus *Spirulina* also known as *Arthrospira*, *Chlorella*, *Haematococcus*, *Dunaliella*, and few others [5].

Spirulina (*Arthrospira*) is a cyanobacteria and the same as the green algae *Chlorella* (chlorophyte); both usually are sold as dry biomass. Meanwhile, the microalgae *Haematococcus pluvialis* and *Dunaliella salina* are usually used as source of the carotenoids astaxanthin and beta-carotene, respectively. However, some companies also sell the entire biomass and, even when extracting the pigments, need to dry the biomass previously [5].

To dry the microalgal biomass is the way microalgae are most commercialized because this method increases the product stability and durability, also allowing easy storage and transportation.

There are different dryers being used in microalgal industry. The main dryer used is the spray dryer [6], and in small spirulina farms, the utilization of ovens with forced ventilation is very common. However, freeze-dryer, drum dryer, natural sun dryer, and other processes to dry the biomass can be also used [6–8].

It is well known that, depending on the drying process method and conditions, there is a potential to lose quality of the microalgal biomass. For example, the microalgal properties change with the dry process, and for the food industry, the nutritional quality can decrease as proteins, lipids, pigments, and other nutrients are lost. In particular, functional components (i.e., phycocyanin from spirulina or astaxanthin from *H. pluvialis*) are very sensible to drying conditions, that is, time, temperature, and oxygen, among others.

Therefore, the purpose of this chapter is to provide a review of the common and innovative dry process technologies available for microalgal biomass, discuss the effect of dehydration on quality and stability of microalgal powders used in human alimentation, and then support the microalgal industry and researchers to choose the most suitable drying method for each different use of dried microalgae.

2. Preprocess in algae drying

Microalgae have been studied largely because they have an industrial importance with their bioproducts, such as lipids, carotenoids, etc. Also, their lipid content is considered a potential feedstock for biodiesel production [9, 10]. Some adversities found in preprocessing are the presence of rigid cell walls surrounding the algae cells and the biomass moisture that interferes in some extraction solvent performance [11]. It can be solved with chemical, mechanical, and biological means of cell wall disruption and can be used alone or in combined forms [9]. Also, in these cases, the step of dewatering is important, that is, with flocculation and centrifuge [12]. The proportions of microalgal biomass in cultivation are generally relatively low, being around 0.02–0.05% of dry biomass in raceway tanks and between 0.1 and 0.5% of dry biomass in tubular photobioreactors. This aspect, together with the size of microalgae, turns microalgal biomass separation very complex [13]. Ref. [14] presents that separation costs can be around 20 and 30% of the total production cost.

There are different ways to perform biomass separation. The most common processes are flocculation followed by sedimentation, centrifugation, and filtration. Sedimentation, considered the simplest option, can retain 85% of biomass, with the percentage of dry biomass around 3%, depending on the species used. However, this process requires significant additional space. The most efficient method for separating biomass is centrifugation, but it represents a significant increase in production costs, so it is widely used when the extracted product has high value. Filtration can be performed mainly to separate biomass from filamentous microalgae, but it is a slow process and in large-scale systems requires a large infrastructure [13].

Cell disruption is an alternative to cellular disintegration of many microorganisms, like bacteria, yeasts, and microalgae, and can be classified as mechanical and nonmechanical manner [15, 16]. Among the mechanical methods, there are high-pressure homogenization, ultrasonication, bead milling, autoclaving, lyophilization, and microwaving, being the first and second ones the widely used methods for laboratory-scale microalgal cell disruption. The nonmechanical methods involve lysing the cell wall with acids, alkalis, enzymes, or osmotic shocks [15, 17].

Some mechanisms involved to the cellular disruption are achieved: impingement of the cells on the hard surface of the valve seat and their impact on each other during collision, turbulence, viscous and high-pressure shear, pressure-drop-induced shear passing from the valve to the chamber, and sudden pressure drop caused by rapid release of gas bubbles within the cells [10, 15, 18].

Concerning low-energy input, chemical treatments have advantages, in addition to showing good scalability. However, they should be carefully selected and applied considering their bio-toxicity and reactivity to some compounds [9].

Physicochemical extraction process can cause thermal and/or chemical stresses inducing structural changes and denaturation/degradations of compounds, like astaxanthin isomers, and affecting significantly the product qualities, such as antioxidative activity, bioavailability, and purity [9]. To guarantee the extraction efficiency of astaxanthin, some operating conditions should be properly considered, like temperature and the use and minimization of less toxic chemicals [19].

3. Drying and microalgal quality

Drying of foods can be defined as a unit operation of water removal aiming to reduce moisture content and water activity and consequently stabilize foods by inhibiting the microbial grow and enzymatic activity and slowing chemical reactions [20]. Dried foods present advantages which are easy to store and transport and have long shelf life.

After separation and concentration, microalgal biomass has a high water content, presenting high perishability once it represents a good substrate to microbial grow and enzymatic activity if commercialized without any stabilization treatment. Stabilization of moist biomass by pasteurization is possible, but the prolongation of the shelf life is limited, refrigerate storage is needed [21], and degradation of functional components may occur if high temperatures are used. Thus, to extend shelf life and allow storage at room temperature, drying of microalgae biomass is generally considered an effective alternative. Many drying technologies can be potentially used to dry microalgae biomass as well as other foods with high viscosity. Different factors should be taken in consideration to choose the best drying method. In most cases the main factors that influence this choice are energy efficiency and installation and operation costs. However, if the dried microalgal biomass is produced to human alimentation, the preservation of nutritional and functional components of the biomass must be also considered [22, 23].

In the literature many drying methods applied to microalgae biomass are discussed. Most of them are related to the stabilization of biomass for nonhuman use such as oil extraction for biofuel industry or feed production. These methods are in general very effective on the point of view of energy efficiency and processing time; among them the following methods can be cited: rotary drying, solar drying, cross-flow and vacuum shelf drying and flash drying. The main challenge in these cases is the processing cost and energy requirement, but not much attention is given to degradation on functional and nutritional components [6, 24].

On the other hand, studies on the assessment of drying methods applied to microalgae to human use are not so common in literature. In **Table 1**, a summary of the different drying methods used to produce dried biomass with potential application in human alimentation is presented in which, together with the engineering of the drying process, the impact on nutritional and/or functional components was assessed.

One of the conditions that affect the choice of method and the drying performance is the initial moisture that the microalgal biomass presents. The algal biomass starts the drying process with initial moisture values between 55 and 88% (wet basis) in different dehydration processes [25–30].

Apart from the color change, the compound degradation, and the drying kinetics, the final moisture content can be one parameter to compare different drying methods and demonstrates how these methods can affect the sample. Based on the initial moisture and the chosen method, the drying can show high or low drying rates, can influence the velocity heat and water mass transfer through the samples, and in some conditions not allow the diffusion between the interior and the surface [26, 28]. In short, apart from the initial moisture that can influence the chosen method, some physical parameters can influence in velocity and water outlet, impacting in final moisture and in quality of the product. Further, some storage conditions, like light, temperature, water activity, oxygen concentration, relative humidity, existence of coating matrix, etc., are important parameters to study compound degradation and product shelf life [31, 32]. Assessing sorption isotherms, stability studies and DSC, the sample behavior during storage, and how the environmental factors influence these parameters is important to evaluate the effect of storage on quality retention of the final products [28, 32–34].

Many different methods were presented in **Table 1**; however, similar drying technologies have the same principle with few modifications of processing parameters or equipment design but are named with different denominations, according to the authors, in papers. **Figure 1** exemplifies this segregation, based on the same principle. The principle depends on the conditions during the drying, physical apparat, and intrinsic processes and interactions that occur with the sample and the drying environment, that is, mass transference process and water outlet [38]. As it can be seen from **Figure 1** in most of the drying methods used for microalgal drying, water is removed by an airflow. Different heat transfer principles can be found, that is, convection, conduction (e.g., cast-tape drying), and radiation. The moisture and the viscosity of the sample are also variable of these processes.

To enrich the discussion about drying methods and applicability to microalgal powder production, the main, traditional, and innovative drying methods are briefly presented in their principle and applications to microalgae.

3.1 Spray drying

Spray drying is the most common drying method applied to microalgae biomass for human uses [6] and, more general, is one of the most widely diffused drying technologies when dehydration of liquid foodstuff is required.

Algae species*	Dry method	Dry specifications/ variables	Quality assessment	Findings/conclusions
Chlorella vulgaris [26]	Freeze-drying (FD)	Temperature: −30°C Pressure: 3 mbar Time: 4.5 h Final moisture content: 0.88 ± 0.05% (w.b.)	• Color characterization • Total carotenoid • Chlorophyll content • Characterization of carotenoid-rich extracts • Protein content • Determination of antiradical activity	• FD powder shows intense green color, while HAD powder shows dark brown color • Carotenoid degradation was of 57.12 ± 3.74% for FD and 91.06 ± 2.37% for HAD • Protein content was not significantly influenced by drying method Freeze-drying is the most suitable drying method to maintain the nutrient and bioactive compounds
	Hot-air drying (HAD)	Temperature: 60°C Time: 4.5 h Final moisture content: 3.58 ± 0.19% (w.b.)		
Spirulina sp. [29]	Heat pump drying	Temperature: 30, 40, and 50°C Sample thickness: 1, 3, and 5 mm Drying time: 85–560min Final moisture content: 10.4 ± 1.2% (w.b.)	• Color measure • Phycocyanin content • Total activity antioxidant (DPPH) determination	• Color difference (ΔE): 4.22–13.51 • Phycocyanin content loss: 15–83% • TAA loss: 11–87% The optimal condition for lower color and phycocyanin degradation was air temperature of 50°C and sample thickness of 5 mm
Spirulina sp. [33]	Convective drying in thin layer	Temperature: from 40 to 60°C Air velocity: 1.9–3.8 m/s	• Drying kinetic • Effect of drying conditions and temperature on sorption isotherm	• Spirulina is very hygroscopic in the 25–40°C temperature range • Equilibrium moisture content is not dependent on the storage temperature

Algae species*	Dry method	Dry specifications/ variables	Quality assessment	Findings/conclusions
Spirulina sp. [35]	Convective drying (CD)	Temperature: 40, 50, and 60°C Air velocity: 0.15 m/s Drying time: 2–3 h	• Microscope characterization • Protein analysis • Total sugar analysis	• Protein loss: 10% in FD; 10–15% in SD; 10–25% in ID • Total sugar loss: 30% at 40°C and higher temperatures (mean) FD showed the highest retention of proteins and sugars Structure damage is caused by the air-drying temperatures
	Infrared drying (ID)	Temperature: 40, 50, and 60°C Radiative flux: 2.71 kW/m^2		
	Spray drying (SD)	Temperature: 130–150°C Feed rate: 0.09 l/h		
	Freeze-drying (FD)	Temperature: - 20°C Pressure: 8 Pa Drying time: 18 h		
Spirulina sp. [36]	Convective drying	Average temperature: 50°C Relative humidity: 12%	• Shrinkage coefficient and isotropicity • Porosity and apparent density	• Weak and anisotropic shrinkage • Final porosity approaching 80%

Algae species*	Dry method	Dry specifications/ variables	Quality assessment	Findings/conclusions
Arthrospira spirulina LEB-18 [28]	Vacuum drying (laboratory scale)	Temperature: 40, 50, and 60°C Pressure: 13.3 kPa Final moisture content: 0.10 g/g (w.b.)	• Phycocyanin content • Total phenolic compounds (TPC) • Lipid oxidation • Color parameters • Rehydration analysis • FTIR spectroscopy • DSC analysis • Morphologic analysis	• Phycocyanin content: higher losses (80.5%) in OD at 55 °C than the VD at 60°C drying (71.7%) • TPC: VD samples showed increase of values (from 18 to 48% (w/w)) in relation to in natura sample • The lipid oxidation increases with the increase in drying temperature • Sample drying at 60°C presented the highest peak of temperature (143.8°C) and the lowest enthalpy value (189 J/g) • Morphologic analysis: rigid shape of irregular and compact particles for both samples Vacuum drying at 40°C causes the lowest losses of phycocyanin, phenolic compounds, the minor lipid oxidation, the good rehydration capacity, and the highest thermal stability
Spirulina LEB-18 [37]	Spouted bed dryer (SBD)	Temperature: 80, 90, 100, and 110°C Air velocity: 0.33 ± 0.01 $m.s^{-1}$ Drying time: 210 min	• Centesimal composition • Total antioxidant activity (TAA)—DPPH • Total phenolic compounds • Protein solubility • Phycocyanin content • Lipid oxidation (TBA) • Color analysis • Thermal analysis • FTIR spectroscopy • Scanning electron microscopy	• TAA values: 34.6 ± 1.1% for CTD sample; TAA increases with the inlet drying air temperature increase for SBD samples • Phycocyanin content, the color difference for samples, and TBA values were affected by the temperature in SBD • SB drying at 80°C and CT drying obtain minor lipid oxidation and phycocyanin degradation SBD drying at 100°C reached greater thermal stability
	Conventional tray drying (CTD)	Temperature: 55°C Air velocity: 2.5 $m.s^{-1}$ Tray thickness: 4 mm Final moisture: 0.10 $kg.kg^{-1}$ (w.b.)		

Algae species*	Dry method	Dry specifications/ variables	Quality assessment	Findings/conclusions
Spirulina platensis LEB-52 [30]	Perpendicular airflow drying	Temperature: 50 and 60°C Air velocity: 1.5 m/s Relative humidity: 7–10%	• Experimental design for protein solubility response • Centesimal composition • Phycocyanin content	• Protein content: 74% (d.b.) • Protein solubility in acid medium: 42.6–79.1% • Higher solubility results occurred at 60°C • Phycocyanin determination: 12.6% (w.b.)
Spirulina LEB-18 [38]	Discontinuous tray drying	Temperature: 50, 60, and 70°C Sample thickness: 3, 5, and 7 mm Hot-air velocity: 2.5 $m.s^{-1}$	• Phycocyanin content • Lipid oxidation (TBA) • Fatty acid profiles	Oil obtained from spirulina: important source of monounsaturated and polyunsaturated fatty acids The best drying condition, 55°C and 3.7 mm, showed 37% phycocyanin loss and 1.5 $mg_{MDA}kg^{-1}$ TBA value, and the fatty acid composition did not show significance difference in relation to fresh biomass
Spirulina sp. [22]	Tray drying	Temperature: 50, 60, and 70°C Air velocity: 2.2 $m.s^{-1}$ Foaming agent: glair/albumin	• Color • Texture • Beta-carotene	Beta-carotene: 140.0 mg/100 g in dried sample at 60°C Improve the drying rate: 2.5% with the foaming agent The quality of spirulina dried (color, texture, and beta-carotene content) by foam mat drying is higher than that of produced by industry
Spirulina maxima [31]	Convective drying at atmospheric pressure	Benchtop chamber Temperature: 30, 50, 70, and 80°C Relative humidity: 13, 20, 50, and 60% Air velocity: 2.0 m/s	• Phycocyanin content • Total phenolic content (TPC) • Antioxidant capacity—ABTS • Phycocyanin denaturation kinetics	Significant loss of phycocyanin at drying temperatures above 70°C Significant influence in TPC values at drying temperature of 80°C Phycocyanin and total phenolic contents were largely dependent on the drying temperature rather than on humidity

Algae species*	Dry method	Dry specifications/ variables	Quality assessment	Findings/conclusions
Arthrospira platensis [39]	Convective drying at atmospheric pressure	Layer thickness: 1 and 4 mm Temperature: 45°C Cylinder diameters: 2, 3, 4, and 6 mm Temperature: 45°V	• Photography and SEM view • True density • Volume shrinkage characterization	Cylinders: initial porosity, 20%; final porosity, 65–78% Layers do not show macroporosity; the product is homogeneous without any pores Microporosity: present in cylinder and layer forms Porosity can be linked to the shrinkage phase durations, an improvement of organoleptic taste of dried spirulina Cylinders for drying indicate optimum drying conditions
Haematococcus pluvialis [40]	Spray drying	Not informed	Economic feasibility and the return for astaxanthin production	The results have proven the economic feasibility of the production for different astaxanthin market prices Evaporative rate: 26.125 kg/h
Aphanothece microscopica Nugeli [41]	Tray drying with air circulation	Temperature: 40, 50, and 60°C Constant speed: 1.5 m/s Sample thickness: 5 and 7 mm	• Total protein determination • Total carbohydrate determination • Total lipid determination • Fatty acid determination	• Protein content: 0.413–0.493 g/g (dry weight) • Carbohydrate fraction: 0.134–0.176 g/g (dry weight) • Lipid fraction: 0.071–0.079 g/g (dry weight) • Fatty acids: chain lengths with 14 and 24 C The drying conditions were shown to affect the macronutrient composition (protein, carbohydrate, and lipid contents), but did not influence the polyunsaturated/saturated ratio of the biomass.
Dunaliella salina [32]	Spray drying	Inlet temperature: 130°C Outlet temperature: 85°C Sprayed rate: 200 $mL.h^{-1}$ Prevent degradation agent: antioxidants	• Stability studies • Solid determination • Carotenoid analysis	Spray drying with TBHQ and α-tocopherol was efficient to preserve algal carotenoid and minimize degradation of beta-carotene Between the two antioxidants, α-tocopherol had a small protective effect on beta-carotene degradation

Algae species*	Dry method	Dry specifications/ variables	Quality assessment	Findings/conclusions
Dunaliella salina [34]	Fluid-bed drying with alginate cells	Temperature: 70°C Airflow: 3.5 $m.s^{-1}$ Time: 10 min	• Beta-carotene analysis • Stability of total carotenoid during storage of the beads	• Total carotenoid losses: 13–20% during fluid-bed drying • Spray dry microencapsulation can reduce degradation of carotenes *D. salina* cells in alginate followed by fluid-bed drying have the potential in producing a carotene-rich nutraceutical product with good carotenoid stability characteristics
Tetraselmis chuii [42]	Spray drying	Temperature: 110/130/150°C Pressure: 40 bar and 2.5 mL/min Microencapsulation with maltodextrin	• Carotenoid analysis • Beta-carotene estimation • Antioxidant activity analysis	• Preservation of 80–92% of beta-carotene and 46–81% of phenolic compounds in microencapsulated microalgae and dried in spray dryer

Species name used in the paper.

Table 1.
Different drying methods applied in some microalgal species with an interest in evaluating quality characteristics.

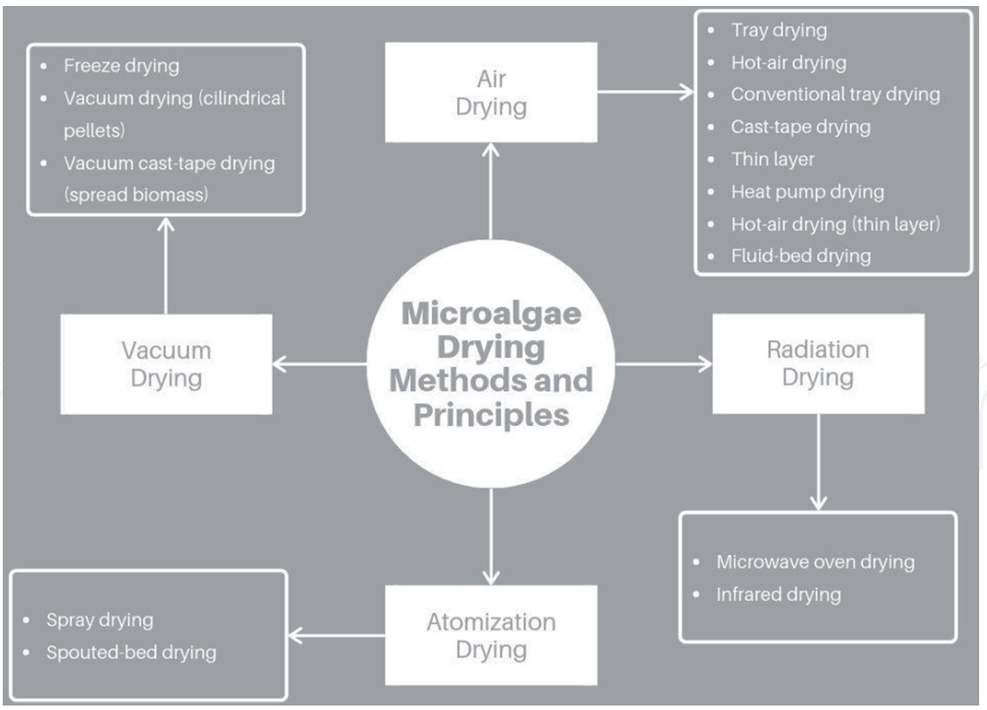

Figure 1.
Drying methods of microalgal biomass. Filled shapes, general method denomination; empty shapes, method denominations used in articles.

Spray drying uses the atomization of a liquid food to create droplets which are dried as individual particles while moving through a heated gas (hot air) [20]. Drying of single droplet provides a large surface area per unit volume of liquid, which favors rapid drying [43] and also causes a very short exposition of food to a very high temperature causing moderate degradation of product quality (high-temperature exposition for short time). The main steps of the spray drying process are atomization of the liquid, mixing of the droplets with the heated air, and separation of the dried powder in a cyclone [44]. Size of the droplet, air temperature, and liquid flow are the main factors that influence the quality of the dried product. Other factors that should be taken into account for the optimization of quality of spray-dried products are related to the biomass characteristics such as glass transition temperature, surface tension, liquid density, viscosity, and composition. The presence of high content of sugars, for example, impacts negatively the yield of this process. This problem is especially present when fruit pulps are dried; on the other hand for microalgae that present mostly long-chain carbohydrates, it does not represent an important issue [43, 44].

Among the advantage of this technology, it can be cited the high versatility, the possibility of pack directly, the powder produced without any milling process, and the easiness of the processing control allowing quality of the product remain constant (uniform) during processing [44]. On the other hand, this technology has a high installation and energy/operation costs, volatile compounds can be lost, and products that present high sensibility to high temperature could lose quality. It can cause rupture of cells, due to the high pressure generated during the atomization process, causing, in some cases, degradation in product quality [6], that is, promoting oxidation. However, spray drying is the only drying technology used in large-scale microalgal biomass drying for human consumption [6] mainly due to the equilibrium between high productivity and quality of the dried product. Although this drying method is the most used by the industry, few papers approach the effect of processing parameters, such as air temperature, viscosity of the moist biomass, and size of the biomass droplet on microalgal powder quality loss [32, 35, 40, 42].

Spray drying of *D. salina* biomass allowed production of powder with very low degradation of β-carotene and its isomers. On the other hand, during 5 days of storage, it degraded to less than 10% of retention. Damages to the membrane cell caused by the very fast water vaporization facilitate the oxidation and degradation of this functional compound, due to oxygen and light exposition [32]. To avoid this problem, a possible strategy is mixing the microalgal biomass with some encapsulating agent (e.g., maltodextrin, gum arabic, etc.) producing microcapsules by spray drying; in this case the high retention of functional compounds can be maintained during storage [42].

3.2 Drum drying

Another technology widely diffused in the food industry to produce dried product, from viscous foodstuff, is the drum drying. Drum drying consists in cylindrical metallic heated rollers or drums rotating at a variable speed. The material to be dried comes into contact with the surface of the drum in a thin layer of film, and heat is transferred through the metal. A slide is arranged in the apparatus to remove the dry thin film layer from the drum surface [8]; after that, the dried material is commonly milled to produce a uniform powder. This technology presents low operation costs and can be easily managed by small producers. On the other hand, it presents some limitation such as the processing time/temperature binomial which the sample must be submitted to be dried [8]. Although this method is widely used in microalgae biomass drying, the high temperature of the drum causes degradation of quality of the dried product; for this reason, this method is used to produce raw materials for biofuel industry but presents no particular interest for dried biomass for human alimentation. Alternatives have been developed to overcome the problem of high degradation of nutritional and functional components and allow the use of this technology to produce algal powders for human use. One example that can be cited is the use of an inert bed to increase the surface contact between a hot-air flow inside of the drum and the moist spirulina biomass, increasing the drying rate and the processing yield; this system also allows to overcome problems such as the bed agglomeration [25]; on the other hand, no assessment on biomass quality was done with this method, and further studies should be done to improve quality of products dried by this method.

3.3 Freeze-drying

Freeze-drying is a well-known drying process that allows production of dried food with high added value and high quality. Freeze-drying consists in two main steps; firstly the product is frozen and is transferred in a vacuum chamber, and water is sublimated [45] providing heat (latent heat of sublimation) by radiation or conduction (hot plates). Freeze-drying is particularly indicated to dry products with high sensibility to high temperature and oxygen exposition and with high added value. On the other hand, it presents high installation and operational cost, especially for industrial-scale equipment and requires long drying time (commonly up to 12 h). This method is highly recommended when the conservation of the nutritional and functional components of the raw material is desired. On the other hand, stability of freeze-dried foods could be compromised by their very high porosity that facilitates the contact with oxygen and air humidity promoting oxidation during storage [46]. In general, freeze-drying of microalgal biomass is considered an ideal method because it causes no degradation of biomass quality [21]. On the other hand, the very low water activity reached in freeze-dried powder could promote, combined with the high porosity, the oxidation of lipids and pigments;

thus, vacuum packaging should be considered in freeze-dried powder storage. The effect of drying method on stability of functional components of microalgae was assessed by [7]. Different drying conditions and storage methods were studied assessing their effect on the astaxanthin concentration in *Haematococcus pluvialis*-dehydrated powder. As expected, freeze-drying resulted in products with higher (approximately 30%) astaxanthin retention than spray-dried biomass. On the other hand, both powders present similar pattern of degradation during storage under different temperatures (from −20 to 37°C) and packaging (vacuum and air). A higher degradation of functional component was found in samples stored at 20 and 37°C in normal packaging (without vacuum); the highest astaxanthin degradation for freeze-dried powder was >80% at 37°C and > 60% at 20°C, both after 20 weeks of storage. Vacuum packaging efficiency was confirmed avoiding degradation of functional components of microalgae also when storage was performed at room temperature [7, 47]. However, due to the higher initial retention of function components, freeze-drying was considered a good option for high-quality dried biomass production. Stability of dehydrated product during storage plays a key role for the drying method chosen. For freeze-dried products, to maintain the high quality of the product obtained by this expensive method, specifically storage strategies must be used, that is, vacuum, light barrier, and low temperature.

3.4 Solar drying

Solar drying is a traditional drying method used for hundreds of years to stabilize the moist algal biomass. In this method the heat for water evaporation is provided by the solar radiation and the moisture removal by the natural airflow. Although it presents the obvious advantage of the low processing cost both in direct solar radiation method or in solar dryers, the efficiency of the method is directly dependent on weather condition and only applicable in few producing locations. Moreover, the long processing time and the exposition to the open environment increase the risk of spoilage or production of off-odors [6]. Strategies and dryers have been developed to overcome these problems optimizing the efficiency of the drying equipment and allowing drying of microalgal biomass with acceptable quality retention [48].

3.5 Convective drying and thin layer drying

Convective drying of a thin layer of spread biomass or extruded biomass cylinder is a method widely used especially by small-scale producers. Ref. [41] produced an *Aphanothece microscopica* Nägeli powder by spreading, in a convective oven, layers of biomass with thickness of 5 and 7 mm and testing the effect of drying temperature (40–60°C) on protein, carbohydrates, lipid content, and fatty acid profile, finding only small differences among treatments. On the other hand, the same research group found that in the same drying condition, chlorophyll a content and hue angle (related with sample color) were strongly influenced by the process temperature and chlorophyll concentration decreases intensely at temperature up to 40°C of drying [49], demonstrating the importance of the optimization of the drying temperature for producing high-quality dried microalgal powder. The effect of temperature on stability of functional components was also proven with spirulina. Many papers approach this issue [33, 30, among others] showing the importance of temperature and thickness optimization during convective drying (air-drying) to maximize the conservation of phycocyanin. This fact was confirmed by [50] that assessed the effect of drying temperature on spirulina functional components showing that temperatures above 45°C cause degradation, reducing its health benefits.

Other technology that can be used to dehydrate viscous foodstuff is the refractance window drying [51] or the cast-tape drying [52–55]. In both methods the liquid food is spread on surface, and the heat transfer occurs by radiation or by conduction. These methods allow producing high-quality fruit pulp powder with very low processing time. On the other hand, the temperature used in these processes could be above the limit for functional component preservation in microalgal biomass; thus, a vacuum chamber can be coupled to the cast-tape drier, and lower processing temperature can be used [56]. The vacuum drying removes the sample moisture thru low atmospheric pressure, showing many advantages comparing the conventional drying methods, that is, oxidation reducing. The low pressure in the drying chamber substitutes the hot-air flow, avoiding significantly compound degradations that lead to low product quality [57, 58]. This technology has been studied recently to spirulina biomass with interesting results in terms of quality and processing time [59, 60]. The cast-tape drying method used in preliminary studies for spirulina biomass drying has proved to be a very effective method in terms of drying time and efficiency. Using the same principle (thin layer of sample on a heated surface), vacuum cast-tape drying allows drying at lower temperatures, thus avoiding the degradation of important compounds such as phycocyanin. Preliminary studies conducted by our group showed phycocyanin preservation values greater than 60% in the method using vacuum and milder temperatures. The authors showed and reported that this technology is a promising method, which can achieve excellent moisture and water activity values, better performance, and low energy costs compared to conventional and/or expensive drying processes.

4. Conclusions

Microalgae are dried to allow easy storage and transportation as well as to facilitate their use in biorefinery and food and feed industry. In this chapter a concise overview of the state of the art about drying of microalgal biomass with potential use for human alimentation was presented. In literature, drying of algal biomass is approached, in most cases, focusing on energy efficiency and engineering of processes. Not much attention is given to the effect of dehydration on functional and nutritional components of the final product. Among the methods that are studied and applied to produce algal biomass for human use, spray drying is the most widely used; it is a very efficient method especially adequate for large-scale producers. Although, this method allows producing powders with relatively high retention of functional components, it was demonstrated that the due to cell structure degradation that occurs during drying, these components can be lost during storage under inadequate conditions. The same problem was found in freeze-dried powders; however, freeze-drying allows higher retention of functional components immediately after drying; thus, with adequate storage condition, this can be considered the best method to maintain quality of biomass. On the other hand, this method is very expensive and energy costing and thus is adequate only to produce high added value products. Air-drying is one of the most studied methods, and it was proposed, when performed adequately, as a good method to allow quality retention in dehydrated products. For example, spreading of the moist biomass in a thin layer increases the evaporation rate allowing lower drying time and the use of lower temperature, thus allowing higher retention of functional components in the final products. Alternatives to this technology have been developed combining thin layer drying with a vacuum chamber allowing reducing drying temperature and time and obtaining higher-quality products. Air-drying or thin layer drier (air or vacuum) is, in general, less expensive than spray driers or freeze-driers, in terms of

installation and operational costs, and thus is a better option for small-scale producers. Finally, it can be concluded that more studies are necessary to improve not only the drying methods but also to understand the degradative phenomena that occur during storage in particular with regard to the high sensitivity to light, heat, and oxygen of dried microalgal biomass, to allow providing the consumers high-quality products.

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