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Review

Powered Foods: Structure, Processing, and Challenges: A Review

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Abstract: Powdered foods are easy to store and transport, with a longer shelf life that minimizes potential waste, contributing to sustainable development. Each food category has a unique composition, responsible for its chemical and physical attributes, which directly influences the stability of powdered products. The drying method used is essential to obtain the desired characteristics of the powdered food, and the choice of each technology can provide unique morphological properties regarding size, shape, and density, among other factors. Furthermore, rehydration properties must also be investigated, as they play a fundamental role in the reconstitution of powdered foods, influencing the dispersion and dissolution of the powder in liquids. Therefore, this review provides a comprehensive overview of the powdered food manufacturing process and its advantages. Special attention is given to the desirable properties of food powders, challenges related to stability, powdered food reconstitution properties, and case studies regarding many powdered foods.

Keywords: powdered product; drying process; rehydration properties; food microstructure

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1. Introduction

With exponential population growth, the consequent demand for food and, above all, a notable increase in diet-related diseases, there is a demand for healthier and more nutritious foods. Likewise, food waste is also increasing, making it essential to seek methods to extend shelf life. Examples of existing alternatives include the use of natural or synthetic additives, heat and cold treatments, coatings, and the production of powdered foods [1,2].

Powdered products are commonly found in markets, either by using the product itself for reconstitution with water, such as powdered milk, or as ingredients and dietary supplements. Powdered foods are practical, whether for easy handling, transport, or storage, and have an extended shelf life compared to fresh products. However, they have a disadvantage in terms of stability in relation to hygroscopicity, having a high degree of moisture absorption [3,4].

Although low-moisture foods are generally considered safer due to their low water activity (less than 0.85), and pathogens cannot grow under these conditions, this does not mean that they cannot survive and pose potential health risks, remaining viable during storage [5,6]. Pathogens commonly associated with low-moisture foods include *Salmonella* spp., *Clostridium* spp., *Listeria monocytogenes*, *Bacillus cereus*, *Staphylococcus aureus*, and *Cronobacter*, which can contaminate a range of products such as flour, powdered infant formula, grains, seeds, herbs, and spices [6].

The safety of powdered foods can be compromised via cross-contamination, storage under inadequate temperature and humidity conditions [6], and contamination during processing (e.g., drying towers) [7]. Therefore, the production of powdered foods is not intended to replace processes that guarantee food safety, such as thermal processing and other emerging technologies [6].

Changes in water activity can also impact enzymes; their reduction can reduce the enzymatic activity of lipoxygenase, for example, which is responsible for imparting undesirable characteristics to food, such as negative impact on color, flavor, and antioxidant activity [8,9].

Powdered products are defined as solid particulate substances with a size ranging between 50 and 1000 µm, which can be classified based on their primary (individual or inherent properties) or secondary characteristics (bulk properties) [10]. Particle density, porosity, shape, diameter, hardness, and stickiness are considered primary properties, while secondary characteristics are related to bulk density and porosity, particle size distribution, and moisture content. Additionally, powdered products can also be classified regarding their physical (size, shape, density, and porosity) or chemical characteristics (composition, interactions with other substances, and instant properties) [10].

This review paper aims to establish new topics related to powdered foods via a brief bibliometric analysis, in addition to presenting in a comprehensive way the process of production and rehydration of powdered foods, such as the influence of intrinsic parameters on fresh food when transformed to powder. Furthermore, recent case studies related to powdered foods are also discussed in detail within this review paper.

2. Bibliometric Data

A current and comprehensive bibliometric analysis was conducted using the Scopus database on 7 November 2023 (https://www.scopus.com/home.uri, accessed on 23 October 2023), employing the search string 'food' and 'powder'. The search considered article title, abstract, and keywords in the Scopus database, resulting in 22,768 documents. However, due to the broad scope of these documents, most authors did not specifically cover powdered foods, often emphasizing areas other than food science. Therefore, the words 'food' and 'powder' were considered exclusively for article title and keywords, with a total of 346 documents found, spanning the years between 1981 and 2023. For the bibliometric analysis, the data were exported to VOSviewer software (version 1.6.20, 2023).

Out of the 346 evaluated documents, division by document type revealed four major groups, with 255 articles, 33 conference papers, 30 reviews, and 24 book chapters, representing 95% of all analyzed documents. Across subject areas, the majority belonged to Agricultural and Biological Sciences (29.3%), followed by Chemical Engineering (13.2%), General Engineering (12.3%), and Chemistry (10.0%). The most frequently used keywords were also evaluated, in which keywords that occurred in more than 15 articles were considered, resulting in a total of 45 keywords (Figure 1).

The 45 keywords were categorized into three clusters. The first cluster was related to powdered food production processes (agglomeration, spray-drying, storage, and glass transition). The second cluster focuses on intrinsic food properties, including antioxidant capacity, particle size, and nutritional profile. Finally, the third group gathers keywords related to the effects of ingesting powdered foods, such as controlled studies in humans and animals.

The clusters were also divided by the year of publication, suggesting that older topics addressed the drying process and quality control. In contrast, more recent topics addressed the evaluation of the antioxidant properties of functional food powders, and studies conducted in animal and humans regarding the potential effects of the food and ingredients tested. For more recent documents (2021–2023), studies explored powdered foods and their potential as functional foods. Examples include research on animal proteins with enhanced digestibility [11], fruit powders with improved antidiabetic properties [12], and even the utilization of protein powder obtained from insects as nutritional enrichment for human and animal consumption [13].

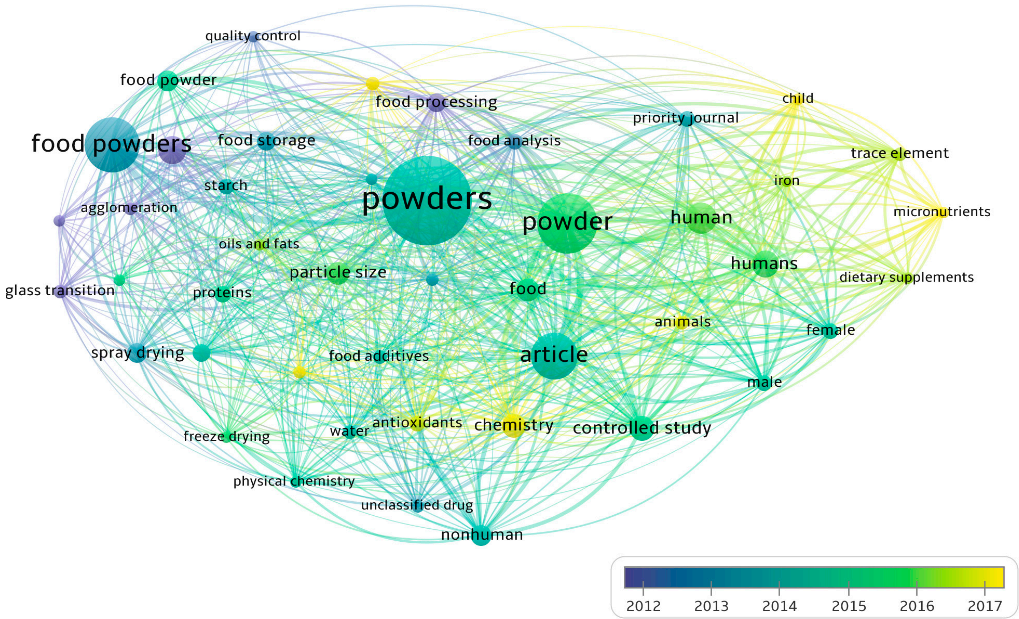

Figure 1. Keyword map representing publications on powdered foods. The circle size indicates the number of publications and the circle color represents the average year of publication. Two circles are close to each other if the keywords co-appeared more frequently. The data were obtained from the Scopus database and analyzed using VOSviewer software version 1.6.20.

3. Powdered Food Production Processes

Production of powdered foods is usually divided into two main processes: transformation from liquid to powder and solid to powder. For solid materials, the powder production process involves reducing the size of the material (crushing, grinding, or pulverization), followed by granulation and mixing. This size reduction occurs via the application of energy to the solid material, and this mechanical activity can generate stress on the food structure, leading to rupture and size reduction. Furthermore, moisture content is inversely proportional to grinding process efficiency, which requires a higher energy consumption due to the water content, making the material breaking process more difficult [4,14,15].

To achieve smaller-sized particles, the superfine grinding method is an interesting emerging technique, capable of obtaining sizes on the nanometer scale. This technique can improve several food characteristics, including flow properties, morphological structure, bioactivity, and bioavailability [16]. Archana et al. [17], for instance, evaluated the morphological and antioxidant properties of ginger, obtaining particles ranging in size from 1 to 100 nm from high-energy ball milling equipment. Their findings suggested that the superfine grinding process could extract more phenolic content, resulting in higher antioxidant activity due to enhanced interaction between the solvent and the food matrix [17]. Similarly, Gao et al. [18] observed a significant increase in polyphenol and anthocyanin content in rose myrtle powder, with particle sizes ranging between 0.79 and 41.57 µm.

On the other hand, when the material is liquid, the process can occur via spray-, freeze-, drum-, or belt-drying; crystallization; or other methods [4]. In this review, the spray- and freeze-drying processes will be covered, as they are the most widely used technologies, as well as their respective processes to obtain powdered foods (Figure 2).

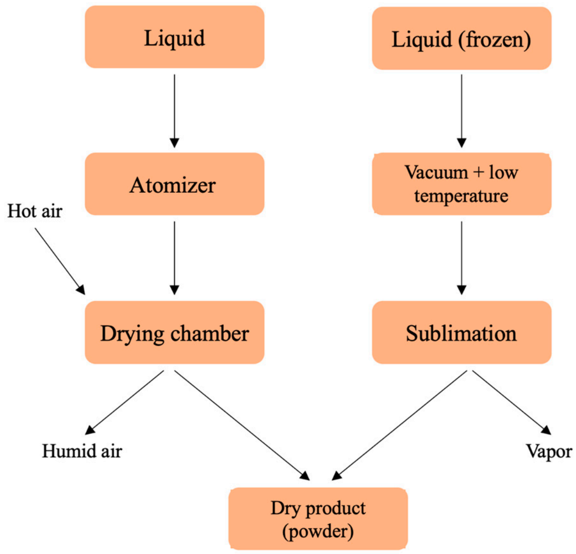

Figure 2. Spray-drying (**left**) and freeze-drying (**right**) processes.

To produce powdered foods on an industrial scale, Marinelli [19] highlights some aspects associated with production difficulty. Among them, the author included the flow properties of powdered foods, agglomeration in tanks, contamination, and structural problems in silos [19]. Regarding flow, at the beginning of the process, material blockage can occur due to the accumulation of material at the exit of the silo, which requires methods to force product flow, such as air blowers or sledgehammers. The ratholing process can also occur, characterized by material friction on the silo walls, leading to flow only in the central internal part [19].

In addition to powder properties, factors such as temperature, relative humidity, and storage time also impact food flow. For instance, the presence of lactose at low relative humidity can result in the caking effect (agglomeration of particles and sticky material), leading to a decrease in the flow rate [20].

Flow limitations can also occur, caused by the exit of air between the powdered material, resulting in the formation of a vacuum, requiring the application of a countercurrent flow of air or gas. Therefore, these flow challenges, among other factors, contribute to the complexity of establishing an industry for powdered products, which are needed to evaluate the physical and chemical characteristics, silo properties, and solids flow [19].

3.1. Spray-Drying

The spray-drying process comprises transforming a liquid substance into a powder by releasing droplets into a hot convective medium. These droplets are released via an atomizer, facilitating the evaporation process in the drying chamber and generating powdered products. This process has several technological applications, such as the production of instant food powders, pharmaceuticals, food additives, and the encapsulation of bioactive compounds [21–23].

This method has the advantages of being a low-cost process, adaptable to industrial scale, forming almost spherical particles, suitable for both thermosensitive and thermoresistant products, and providing good stability of the final products. Regarding its limitations, the product must have a low viscosity, and the drying process is less effective for large droplet fractions due to the short process time, in addition to necessitating high energy consumption and having problems regarding food oxidation [22,24,25].

Different authors have evaluated spray- and freeze-drying in different food matrices. For example, Pellicer et al. [26] assessed the stability of strawberry flavor, comparing different drying methods, including spray- and freeze-drying. Despite lower moisture content in the spray-drying method, the freeze-drying process exhibited higher yield values.

In general, the spray-drying technique showed greater stability concerning temperature and exhibited better morphological characteristics such as spherical and smooth particles [26].

To facilitate the spray-drying process, substances known as drying carriers or encapsulating agents are employed. These drying carriers act as protective barriers for substances that will be encapsulated, ensuring greater stability for compounds sensitive to light, humidity, oxygen, and heat [27].

The choice of the drying carrier material depends on the purpose for which the powdered food will be used. Drying carriers can impart new properties to the powder, such as changes in solubility and viscosity. Using the right material can also decrease undesirable effects for powdered foods, such as the stickiness effect [28].

For honey and other foods with a high sugar concentration in their composition, the use of maltodextrin and gum arabic can be viable alternatives, reducing the high hygroscopicity of powdered foods, consequently minimizing stickiness effects due to their high molecular weight and glass transition temperature (Tg) [29].

The concept of glass transition is defined by the change in state from an amorphous solid to a rubbery state. This concept is important, as many foods that are turned into powders enter an amorphous state after the drying process [4]. Unlike crystalline structures, in the amorphous state, the solvent will penetrate the solid and, due to the glass transition, the amorphous material will migrate to the water on the surface of the powder, significantly increasing its viscosity. This viscoelasticity depends on the deformation rate of the material, temperature, and moisture content of the powdered food [30].

3.2. Freeze-Drying

Freeze-drying is defined as the process of removing water from a frozen product via sublimation, followed by desorption. The product, initially frozen, goes through the phase transition between ice and vapor at low temperatures and pressure. The second stage of drying occurs when the remaining water in the product is removed via desorption. Due to its operation at low temperatures and under vacuum conditions, this process is recommended for foods sensitive to higher temperatures and oxidation [31,32].

This method has the advantages of generating a final product with high yields (little or no deterioration reaction); flavors and nutritional characteristics similar to the original product (retarding or inhibiting chemical, physical, and microbiological processes); and preserved bioactive properties (little or no influence of temperature and oxygen) [33]. In this sense, the authors have reported that the freeze-drying process prevents the action of enzymatic browning, thereby preserving the color of the powdered product.

As a bottleneck, the freeze-drying process is associated with a high cost (about 4 times higher than spray-drying) due to the entire process occurring with the frozen product, demanding high energy consumption. Another disadvantage is the time required to produce powdered foods, as the food must undergo the sublimation and desorption process for a correct duration to achieve low moisture content [24,31].

Gomes et al. [34] studied the effects of different drying techniques on the physicochemical and bioactive characteristics of papaya pulp, with no significant changes in color and pH between the treatments applied. The study revealed that due to the oxidation process, the spray-drying process reduced vitamin C content by approximately 15% compared to fresh and freeze-dried pulp. Additionally, the freeze-drying technology significantly increased the antioxidant activity of the pulp, while both drying methods were able to preserve the antioxidant characteristics of papaya pulp [34]. Vardanega et al. [35] also compared the freeze- and spray-drying methods to obtain a functional powdered tea using ginseng roots. The authors found that the freeze-dried powder had a shorter dispersion time in water than the spray-dried powder, justified by the greater porosity of the structure. Lastly, the solubility, moisture content, and hygroscopicity parameters did not show statistically significant differences between the two processes [35]. Lastly, in a study by Guo et al. [36], microencapsulation of a natural pigment (curcumin) revealed that despite the spray-drying process yielding particles with smaller size and more regular shapes, the freeze-drying method demonstrated greater efficiency in the microencapsulation process.

4. Instant Properties

For the evaluation of powdered products, a fundamental attribute to be considered is their 'instant' properties, referring to the ability of these products to disperse and dissolve in liquids. These properties are related to the formation of agglomerates and their behavior, indicating how easily the powdered product can be reconstituted in a liquid [10].

As for instant properties, the desirable characteristics of powdered products can be categorized into four dissolution parameters: wettability, sinkability, dispersibility, and solubility. These properties represent the steps involved in the reconstitution of powdered products [10,37,38]. Figure 3 presents dissolution properties and how to improve their characteristics.

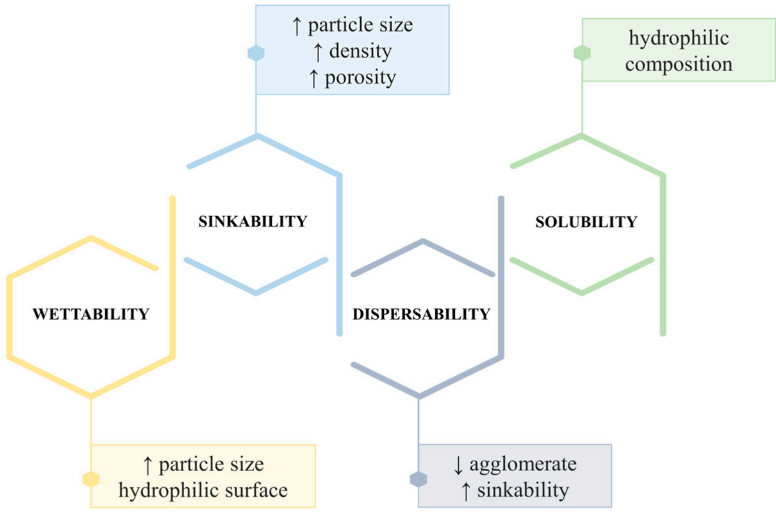

Figure 3. Desirable characteristics for reconstitution processes.

Wettability is defined as the ability of a liquid to penetrate a porous agglomerate, replacing the gaseous phase with water on the surface of the powder. The efficiency of this process is affected by particle size (directly proportional) and the degree of polarity on the surface (hydrophilic compounds have greater wettability) [10,37]. To enhance wettability properties, one approach is the use of additives with surfactant or emulsifying properties, providing greater control over the surface and interfacial tension between solids and liquids [39].

Sinkability is the process described by the ability of agglomerates to sink below the surface of water, evaluated in terms of how fast the process occurs. This property strictly depends on the physical characteristics of the particle, namely size, density, porosity, and particle size distribution. In general, larger particles with higher density exhibit better sinkability, but particles with high porosity (low density) also demonstrate a high degree of sinkability due to the diffusion process within the particle [10].

Dispersibility is defined by the ability of a powder to disperse in water, which occurs with reduced efficiency when there is formation of agglomerates and increased efficiency with enhanced sinkability. Efficiency is reduced when agglomerates form because the dispersibility process involves breaking down particles to increase the surface area between the powder and liquid. Lastly, solubility is the ability of particles to dissolve in liquid, resulting in the complete disappearance of the solute in the solvent, which mainly depends on the chemical composition of the powder and its physical state [10,37].

5. Rehydration Behavior

Regarding the models that describe the rehydration behavior of powdered foods, Fick's law represents moisture's movement in food; the first law is defined for stationary movement. As the concentration (moisture) varies with time, Fick's second law is used, defined by the following equation [40]:

$$V.\frac{\partial W}{\partial t} = D.\frac{\partial^2 W}{\partial x^2} \tag{1}$$

where V: volume (m^3); W: moisture content (g H_2O/m^3); t: time (s); D: diffusion coefficient (m^2/s); x: spatial coordinate (m).

However, Fick's second law describes only the diffusion process, and therefore there are models that describe the rehydration process more precisely, such as Peleg's kinetic and Weibull's probabilistic models (Equations (2) and (3), respectively) [41].

$$X_t = X_0 + \frac{t}{(k_1 + k_2)} \tag{2}$$

where X_t: moisture content (kg/kg dry solid); X_0: initial moisture content (kg/kg dry solid); t: time (h); k_1: Peleg rate constant (kinetic parameter); k_2: Peleg capacity constant (parameter related to equilibrium moisture content).

$$\frac{X_t - X_e}{X_0 - X_e} = \exp\left[-\left(\frac{t}{\beta}\right)^{\alpha}\right] \tag{3}$$

where X_t: moisture content (kg/kg dry solid); X_e: equilibrium moisture content (kg/kg dry solid); X_0: initial moisture content (kg/kg dry solid); t: time (s); α: dimensionless shape parameter; β: rate parameter (min).

Compared with Fick's second law, both the Peleg and Weibull models demonstrate better representation of the rehydration process of powdered foods, as specific food parameters are considered, such as equilibrium moisture content and shape [40,41].

Rehydration kinetics are also conditioned by other properties, as moisture absorption depends on temperature, immersion medium, and food composition [42]. As for immersion medium, incorporating skim or whole milk affects the hydration properties of food, changing the liquid movement rate and driving force for mass transfer. Additionally, the presence of lipids in foods can make mass transfer difficult by forming barriers between the immersion medium and the powdered food [42]. Finally, the temperature of the immersion medium can also influence the rehydration rate and capacity [43].

6. Improvements and Challenges on Powdered Foods

To optimize processes and ensure high-quality products, an in-depth study of the characteristics of powdered products is required. This section will approach the important properties to be evaluated, desirable characteristics, and challenges regarding the stability of these products.

In terms of shelf life, powdered foods are considered sensitive to different conditions, whether due to the presence of oxygen, light, heat, or humidity, in which each of these conditions will be more influential for each type of food. In general, powdered foods present very low water activity (aw) and are mainly affected by the availability of water (responsible for microbial growth), change in the molecules' state, and consequently its product stability [44].

6.1. Undesirable Properties

Among undesirable effects in powdered foods, Bhandari [4] identifies three main properties: dustiness, stickiness, and caking. These properties not only lead to a loss of functionality and quality of the final product but also impact the powder formation process [45]. Powdered foods, due to their small size, contribute to dust formation, which is undesirable due to the loss of final product, greater difficulty in cleaning, and respiratory problems for workers. It is inversely proportionally affected by particle size, density, and cohesiveness [46].

Stickiness is defined as an adhesive force in which powder particles adhere to different surfaces, which occurs in the drying process, processing, and handling of the powdered product. This phenomenon is often attributed to the chemical composition of foods (sugars, whey, high-fat milk, fruit juices, and others) and is also affected by the temperature and humidity of the environment [4]. Finally, the caking effect is defined as the agglomeration of powdered particles leading to the formation of a solid block and then a sticky material. This effect is generated from the melting of fats, moisture absorption, or sugar crystallization, which depends on some factors such as environmental temperature and humidity [4,45].

To prevent the caking process, one effective approach involves the use of food additives, specifically anticaking agents, which are defined as substances with a very low particle size (between approximately 40 and 100 µm) and a high surface area, enabling them to absorb significant amounts of water. These agents can be either synthetic or natural, and they need to have a smaller particle size compared to the applied food matrix [47]. In a study by Chang et al. [48], the application of tricalcium phosphate (E 341) and calcium silicate (E 552) as anticaking agents was explored to enhance the stability of soursop powder produced via spray-drying. The findings revealed an increase in the powdered product yield, in addition to increasing stability in terms of moisture content, water activity (aw), and density. These salts demonstrated the ability to absorb moisture from the environment and prevent loss of product quality [48].

6.2. Microstructure

The microstructure of powdered materials plays an important role regarding product stability. Among the existing forms, powdered foods can be crystalline, amorphous, or mixed, depending on the type of processing used to obtain the powder and the intrinsic characteristics of the food, with the crystalline structures exhibiting greater molecular organization and the amorphous structures displaying less organization. Examples of food with a crystalline structure include salts and sugars, while the majority of foods have an amorphous structure due to their complex matrix, as seen in powdered dairy foods, fruit juices, and hydrolyzed protein powder [4].

Powdered foods in crystalline form tend to have little or no hygroscopicity, are stable, and flow easily, whereas foods with an amorphous structure have greater porosity and high hygroscopicity, besides being thermodynamically unstable. On the other hand, foods with an amorphous structure are easier to dissolve compared to powders with a crystalline structure due to differences in molecular organization [4]. Furthermore, Taskin et al. [49] reported that particle size is directly proportional to the degree of rehydration. Zotarelli et al. [50] emphasize the importance of particle shape in achieving desirable rehydration characteristics. Spherical particles, commonly formed via the spray-drying process, have less interaction with water due to their smaller contact surface angle compared to irregular particles, generally created from the freeze-drying process.

6.3. Pretreatment

Dziki [51] reported the advantages and importance of pretreatment in the freeze-drying process. Many methodologies can be applied to food, including size reduction, bleaching, osmotic dehydration, ultrasound, and others. For instance, the application of bleaching not only induces enzymatic inactivation in fruits and vegetables but also contributes to a reduction in drying time [51]. Figure 4 illustrates the pretreatment methodologies commonly employed in the drying of foods.

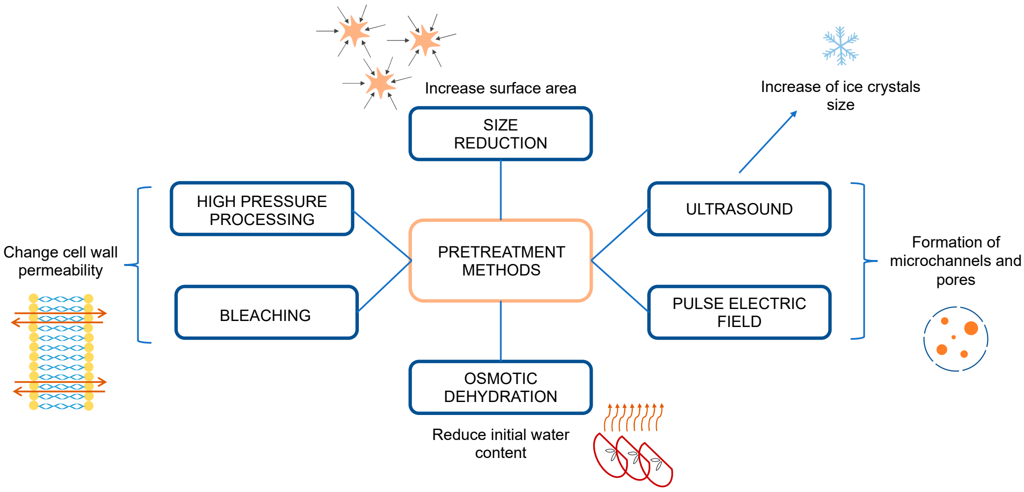

Figure 4. Pretreatment methods applied to foods to reduce drying time.

Ultrasound induces the formation of microchannels, facilitating water removal in the drying process, besides increasing the size of ice crystals in the freezing process. The freeze-drying sublimation process generates high porosity in the powdered food structure, facilitating food rehydration [31,51].

Osmotic dehydration is considered a viable alternative as a pretreatment for drying foods since it is low cost and easy to apply industrially [52]. The pretreatment is based on immersion of the food matrix into an osmotic or hypertonic solution, with diffusion of moisture from the food into the osmotic solution and entry of the solute into the product [52,53]. Water removal occurs as the food interacts directly with the osmotic solution, with the cell wall acting as a semipermeable membrane, allowing for the passage of water while preventing the movement of larger molecules [53].

To preserve organoleptic properties, sugar solutions (sucrose) are commonly used in fruits and salt solutions (sodium chloride) for vegetables and meat, in which the osmotic solution is characterized by having a high osmotic pressure and low water activity [53]. While osmotic dehydration can remove a significant amount of water (up to 50%), it is considered only a pretreatment since this method does not impart the properties of a dry or powdered food, such as long shelf life and high stability [52,53].

Pulse electric field (PEF) and high-pressure processing (HPP) are also two methodologies that are applied as pretreatment for food drying. PEF can create pores via high-voltage electric pulses, while HPP technology modifies the cellular structure via high hydrostatic pressure. Finally, both processes can impart properties to the food that facilitate mass transfer, consequently reducing drying time [54].

6.4. Agglomeration Process and Fluidized Bed Technology

To enhance rehydration properties, the agglomeration process, which is known for the various functionalities it imparts to the final product, is defined by the joining of particles to form large agglomerates. This process can improve powder characteristics, from its rehydration properties (wettability, dispersibility, and solubility) to flow, storage, and other properties. This improvement is achieved by changing the powder properties, including increasing particle size and porosity, reducing the bulk density, and avoiding the caking and dustiness process during storage [55].

Agglomeration can occur in two ways, either by applying pressure or via wet controlled growth agglomeration. Pressure agglomeration occurs via simple compression of the particulate material, causing adhesion between the particles via van der Walls forces, requiring that the particles deform with the application of pressure to reduce the distance between the surfaces [56].

However, wet controlled growth agglomeration is a more complex process, as it occurs in several stages. The first step (wetting and nucleation) consists of the application of water to the dry particle and its homogeneous distribution within the powder, besides the initial formation of a stable structure between the water and the solid [56,57]. The second stage (consolidation and coalescence) results in the production of larger particles via collision and interaction between smaller particles, strengthening the formed particles via the migration of liquid to the surface of the agglomerate. Finally, the last stage, attrition and breakage, consists of the rupture and separation of certain particles until a balance between the formation and rupture of these agglomerates is achieved, and consequently the final drying occurs to remove the liquid from the agglomerates, as well as reducing the temperature below the glass transition temperature (Tg) to avoid the caking effect on storage [56,57].

Handling powdered food presents a major challenge in production, and the agglomeration process can modify the physical properties of the powder, being able to change the particle size, flowability, and water content [58]. The fluidized bed process can impart these properties when applied below a spray-dryer, in which the liquid is applied under intense heat and constant agitation, resulting in high mass transfer [59].

The agglomeration process can be undesirable (e.g., the caking effect), or, when applied in a controlled way in which materials with desired porosity and density are obtained, it can lead to improved instant properties [60]. Fluidized bed agglomeration technology is not recommended for foods with a high concentration of carbohydrates and organic acids, since the low glass transition temperature can create high stickiness and reduced yield [61].

7. Powdered Products: Case Studies

As previously discussed, powdered foods can be produced in different ways, creating unique characteristics for each type of process used. Moreover, the food's properties are also relevant to evaluate, since its chemical composition and microstructure affect the final product. Although the initial purpose of producing this type of food is to prolong shelf life, other characteristics must be studied, such as physical, chemical, nutritional, and organoleptic changes, in order to guarantee the stability of the final product [62].

The composition of the food matrix plays an important role in the stability and properties of the powder. For instance, food matrices containing fats on the powder surface may face challenges due to reduced wettability and dispersibility, along with potential issues related to lipid oxidation [63]. Similarly, foods with a high sugar content present problems such as stickiness due to the amorphous and hygroscopic nature of sugars [39]. Figure 5 presents different types of food and their specific properties to be evaluated.

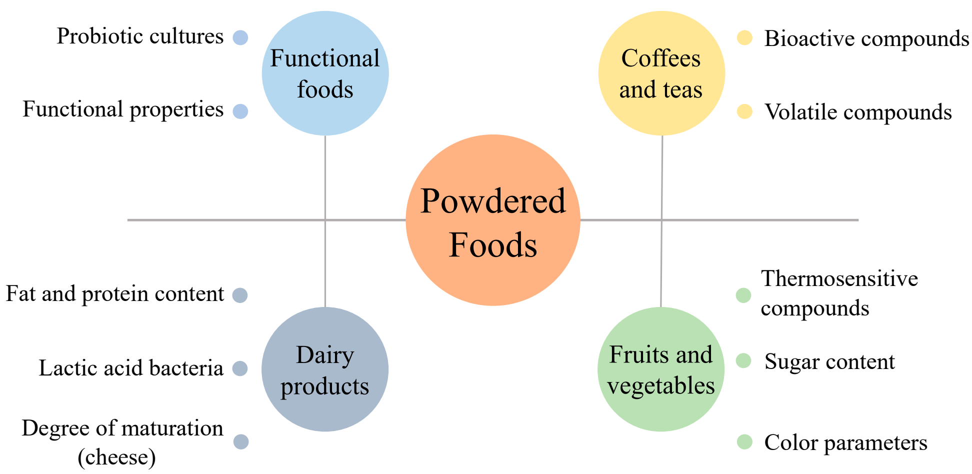

Figure 5. Distinct properties according to each food classification.

Each food group undergoes a unique evaluation process to determine the most suitable drying method. The freeze-drying process is preferable when treating foods with heat-sensitive compounds, for example. Other components should also be highlighted when choosing the drying process, such as the presence of enzymes, probiotic microorganisms, coloring substances, flavorings, and more [36,44]. Table 1 shows examples of different food products (namely dairy, fruit, and vegetable products), the drying method used for them, and the resulting powder characteristics and rehydration properties.

Table 1. Food powders and rehydration parameters.

Food Product	Particle Size	Powder Process	Powder Characteristics	Rehydration Characteristics	References
	Dairy products				
Skim milk	14–20 µm	Spray-drying	Very bright, low color saturation, irregular and rough surface	Non-wettable, hardly dispersible, fairly soluble	[64]
Milk protein concentrate	18.9–57.3 µm	Spray-drying	Smooth and dimpled surface, high viscosity, for powders with high protein content	Greater wettability, dispersibility and solubility for powders with lower protein content	[65]
Yogurt	3.053 µm	Spray-drying	Fair porosity, spherical particles, and not very hygroscopic	Low wettability and solubility	[66]
Cheese	42.0–86.1 µm	Spray-drying	Particle size and amount of surface fat are dependent on the formulation	Greater rehydration power for young cheeses and faster dispersibility for old cheeses	[66,67]
	Fruit and vegetable products				
Blueberry juice	-	Spray-drying	Shrunken and smooth spheres, low moisture content, and bright color	High solubility, lower rehydration time when compared to foam-mat freeze-drying	[68]
Sugarcane juice	1.84 µm	Spray-drying	Spherical shapes, high hygroscopicity, and dented surface	High dispersibility, wettability, and solubility	[69]
Mango pulp	267.95 µm	Freeze-drying	Color similar to the raw pulp, presence of starch granules and viscous characteristics	High wettability and solubility	[50]
Orange puree and juice	245–261 µm	Freeze-drying	Crunchier texture, rounded and porous powder with the increase of natural fibers	Viscous and worse wettability with the increase of natural fibers	[70]
Cranberrybush puree	63–100 µm	Freeze-drying	Large porosities and skeletal-like structures	Low solubility, wettability, and rehydration power when compared to larger particles	[49]
Kiwi slices	-	Freeze-drying	Smooth, porous, and spongy structure	High rehydration rate	[33]

7.1. Dairy Products

The dairy industry stands as one of the most consolidated food industries in the world, with dairy products representing one of the largest fractions of powdered foods on the market. This category includes whole and skimmed milk powder, concentrated and isolated milk protein, isolated and concentrated whey protein, caseins, and more. Powdered dairy products are also used in confectionery, bakery, infant formulas, meat products, and even the pharmaceutical industry [44].

Milk, as an emulsion in a dispersed system (oil-in-water), is a complex food due to its mixture of components (macronutrients, minerals, vitamins, and water) [71]. Therefore, the application of heat in the drying process can induce physicochemical changes in milk, resulting in loss of nutrients (e.g., water-soluble vitamins), such as a decrease in the quality of powdered products [44]. For instance, Koç et al. [66] highlighted that the conditions of the spray-drying process are essential to improve the survival of lactic acid bacteria in yoghurt and its sensory acceptance.

Felfoul et al. [64] explored different air outlet temperatures in the spray-drying process for skim milk, achieving a product with high yields and low water activity. As for rehydration properties, regardless of the temperature degree, skimmed milk powder was soluble, but was nonwettable and hardly dispersible [64]. On the other hand, McSweeney et al. [65] investigated the physical and rehydration properties of concentrated milk protein, obtaining particles with high viscosity content with increasing protein content, such as a smooth surface. The concentrated protein showed good instant properties in samples that had a lower protein concentration [65]. Lastly, Silva et al. [67] evaluated the behavior of other dairy products, such as powdered cheese, and showed that cheeses have unique characteristics influenced by cheese ripening and the addition of different powdered dairy ingredients (buttermilk and sodium caseinate). Their findings demonstrated that the dispersibility of cheese increased with the maturation degree, while lower degree of maturation had the best rehydration results due to an enhanced interaction of food with water [67].

The characterization of fermented powdered dairy products is not only defined by their chemical composition and physical properties, but also by microbiological factors. Lactic acid bacteria (with probiotic properties) are naturally present in fermented dairy products as part of their production (as starter culture) and can be intentionally added to improve probiotic function, and ensuring the survival of these bacteria during the drying process and storage is a challenge [44,72]. To minimize the loss of lactic acid bacteria, Hedegaard and Skibsted [44] described some solutions. One option is pretreatment in the drying process, drying the bacteria in an aqueous solution to encapsulate the bacteria and increase their viability. This process is also noted to prevent enzymatic browning processes and the contact of bacteria with oxygen [44]. Koç et al. [66] investigated the physical properties of powdered yoghurt made by spray-drying, highlighting particles that had little water absorption power (not very hygroscopic) and were spherical and porous. As for instant properties, they presented low wettability and solubility [66].

7.2. Fruits and Vegetables

Fruits and vegetable are known mainly for their potential to bring health benefits via the bioactive compounds present in them, reducing the risk of some chronic diseases. However, they have the disadvantage of being foods with a limited post-harvest shelf life, and an effective solution to overcome this challenge involves the production of powdered foods, this being an alternative to delay spoilage by significantly reducing the moisture content in food. The drying process for fruits and vegetables can include the production of instant juices and instant soups, including the dehydration of spices and herbs for cooking [73,74]. Maintaining the stability and functionality of these powdered foods is one of the biggest challenges [73,75].

Gong et al. [76] investigated changes in the physicochemical properties of cabbage powder with different drying methods (air vacuum and freeze-drying). The authors found that the freeze-drying process obtained the best results among the different drying methods, with higher color retention and vitamin C (60.42%), justified by the reduced contact with oxygen and drying at low temperatures, besides better retained shape [76]. For spinach powder developed from different drying processes (sun-, freeze-, and tray-drying) [77], the authors obtained similar microstructures between the different drying methods, with an amorphous nature. Regarding bioactivity, the freeze-drying process showed the best results with a higher total phenolic content and antioxidant activity, compared to the sun and tray drying methods [77].

Singh and Hathan [78] optimized the process to produce powdered beetroot juice from spray-drying, evaluating different feed rates, processing temperature, and maltodextrin concentration, in which the lowest maltodextrin concentration tested (20%) presented the best results of packed bulk density, moisture content, and betalain content. The morphology of the optimized powder was also evaluated, obtaining spherical particles with several dents on the surface, these dents being justified by shrinkage during the drying process [78]. With new trends in clean-label foods and the use of natural ingredients, the partial replacement of maltodextrin with vegetable fibers is an interesting alternative [79]. The utilization of fruit and vegetable powders (agus fiber, citrus fiber, and microcrystalline cellulose) obtained from spray-drying showed similar results in terms of physical properties, in addition to not having a harmful effect on the aroma profile of the powdered product. The authors also mention the limitation of the use of these fibers due to their low solubility, with a solution being a pretreatment of these fibers for their solubilization [79].

Due to the different chemical and physical characteristics of fruits, maintaining stability is one of the biggest difficulties of these powdered products. Fruits in general have a high concentration of low molecular weight sugars and some organic acids, giving the product the 'sticky' characteristic after drying. Furthermore, they also have high hygroscopicity and water solubility, providing some undesirable effects during storage, and it is recommended to keep the powdered fruit below the glass transition temperature (Tg) [79].

To preserve the bioactive compound content of the fruits, the freeze-drying process is considered the best option, although it is not the most viable. Since fruits have several thermosensitive compounds, it is possible that there is a degradation of these compounds in drying processes that involves the application of heat. Furthermore, via freeze-drying, it is possible to maintain the color characteristics of the original food, such as maintaining a porous microstructure of the powdered food, facilitating its rehydration [73]. The application of a microwave drying pre-treatment can also leads to a faster dehydration of fruits and maintain their bioactive properties [80].

Zotarelli et al. [50] evaluated mango pulp powder from the freeze-drying process for its morphological, rheological, and rehydration properties. The authors reported that the freeze-drying process was able to maintain color parameters similar to the natural product, besides its rheological characteristics. Furthermore, the powdered mango pulp showed high wettability and solubility due to the drying process used and its characteristics with respect to the microstructure of the particle, such as its chemical composition [50]. For blueberry juice obtained from the spray-drying process [68], the particles presented a small, smooth, and spherical shape, besides having a high brightness of purple color. The authors also verified that the product formed from spray-drying had better rehydration characteristics, such as high solubility and shorter rehydration time, when compared to the foam-mat freeze-drying method [68]. For cranberrybush puree [49], the powders (divided between different particle sizes) presented large pores and skeletal-like structures. Regarding rehydration properties, the authors reported that the larger the particles, the greater their solubility, wettability, and rehydration power [49].

As discussed earlier, chemical composition is a crucial factor in obtaining a powdered product with good rehydration characteristics. Uscanga et al. [70] reported that natural fibers (mainly pectin) in orange puree compared to juice collected into a porous cake and exhibited numerous negative qualities, such as a decrease in flowability and worse wettability, making the rehydrated sample more viscous. Furthermore, the authors recommended not performing heat treatment of the juice for the consumption of the powdered product before the freeze-drying process, as it causes solubilization of part of the pectin and gel formation [70].

7.3. Non-Alcoholic Beverages

Non-alcoholic beverages such as coffees and teas are widely consumed around the world, either for the beneficial properties of bioactive compounds or for the effects produced by caffeine (increased alertness and reduced fatigue). According to the National Center for Health Statistics (NCHS), the contribution of coffees and teas constituted more than 20% of all nonalcoholic beverages consumed by the US population between 2015 and 2018, in which coffee was the most consumed beverage (14.9%) after water, and tea the fourth most consumed beverage (8.4%) [81,82].

Ishwarya and Anandharamakrishnan [83] evaluated different drying methodologies, namely spray–freeze-drying (SFD), freeze-drying, and spray-drying, to produce soluble coffee. SFD showed a higher retention of volatile compounds (93%), an important characteristic to produce soluble coffee, since coffee is often appreciated for its aroma, followed by freeze-drying (77%) and spray-drying (57%). The authors also evaluated the morphology of the powders, in which the SFD and spray-drying processes resulted in spherical shapes, while the freeze-drying process yielded a flaky structure [83].

Susantikarn and Donlao [84] optimized powdered green tea extracts (*Camellia sinensis*) extracts by testing different concentrations of maltodextrin and the inlet temperature in the spray-dryer, in which the authors found that with increasing inlet temperature there was a decrease in solubility and moisture content. On the other hand, the increase in maltodextrin concentration decreased the content of phenolic compounds and increased the hygroscopicity of the powder [84]. Regarding the antioxidant activity of *Vitex* spp. leaves [85], the microwave and freeze-drying methods maintained the antioxidant properties of the leaves, while oven- and sun-drying methods resulted in deterioration of the compounds.

The drying conditions used are essential to produce a high-quality soybean milk powder, in which the protein dispersibility index (PDI) is a factor to determine the solubility of the soybean powder in water, affected by the pH and the manufacturing process of the soybean milk product [86]. To produce soy beverages, Silva et al. [87] prepared water-soluble extracts of powdered soybean, in which the beverage prepared with the extract diluted to 10% presented the best general acceptance and with a greater purchase intention among the evaluated consumers.

The agglomeration process has already been discussed due to the benefits of agglomerated powder, such as improved rehydration properties. Gong et al. [88] investigated the effect of the agglomeration process on powdered bayberry produced via spray-drying. Among the results obtained, the wettability power was the most significant, with a reduction time of 2 min to 15 s, besides decreasing bulk density and increasing the particle by more than 2 times. For powdered sugarcane juice, Nishad et al. [69] evaluated the physical properties obtained from the spray-drying process, obtaining spherical particles with high hygroscopicity and good rehydration properties, such as high dispersibility, wettability, and solubility. Furthermore, the authors evaluated the incorporation of citric acid into sugarcane juice before the drying process, which had a negative effect on the reconstitution properties but produced particles with a smooth surface and more agglomeration [69].

Alternatives that help with rehydration characteristics are also investigated, helping to improve the texture or flavor of the final product. Abdelaziz et al. [89] evaluated the effect of adding sugar to powdered coconut beverages, finding that the concentration of sugar affects the solubility of the drink; the larger the sugar particle size, better the rehydration process. Furthermore, the authors concluded that the mixture of two sugars (sucrose and lactose) had better rehydration results compared to the individual sugars studied [89].

7.4. Functional Ingredients

According to the European Commission [90], a functional food ingredient is defined as 'a food ingredients that beneficially affects one or more target functions in the body beyond adequate nutritional effects in a way that is relevant to either an improved state of health and well-being and/or reduction of risk of disease'. The concern and care of the population regarding the consumption of functional foods has increased due to their beneficial effects on health, such as better early development and growth, health maintenance, reduced risk of obesity, and chronic diseases related to diet [90].

Some of the major interest in probiotics (lactic acid bacteria) in powdered foods is due to their viability regarding the survival of microorganisms in the final product. Lipan et al. [91] investigated the survival of Lactobacillus plantarum in almond milk powder produced via spray-drying at different storage temperatures. In storage at 4 °C, the bacteria survived for 8 months in an amount sufficient to show the probiotic effect (minimum 107 living cells), while they survived only 6 months when stored at 22 °C [91].

Wu et al. [92] evaluated the combination of sodium caseinate and concentrate powder of blackcurrant (*Ribes nigrum* L.) regarding its functionality, with the freeze and spray-drying processes, in which the powder mixture was later incorporated into cookies. Both drying methods were able to increase the total phenolic content of the cookies, with the best results obtained via spray-drying. Furthermore, both powders were able to show a low glycemic response (in vitro), justified by the presence of fibers and phenolics creating hypoglycemic properties in cookies [92]. For encapsulation, the freeze-drying process has a greater potential to preserve anthocyanins when compared to spray-drying, as they are thermosensitive compounds and due to the interaction between anthocyanin molecules and proteins used for encapsulation (sodium caseinate) [93]. Mollica et al. [94] investigated the beneficial effects of powdered *Juglans regia* L. produced by freeze-drying for antidiabetic properties when administered to diabetic rats for 28 days. The authors evaluated the potential of the plant in relation to its antidiabetic properties, in which it was able to reverse hyperglycemia, hypercholesterolemia, and liver and kidney damage related to diabetes mellitus [94].

To produce functional powdered beverages, an alternative is the incorporation of soybean powder, which can produce a beverage with a high fiber content, shortening the transit time of the digestive system [95,96].

Powdered fungi are also used to develop functional foods; mushrooms are known for their anticancer, hypolipidemic, and hypoglycemic properties [97]. Among its possible food applications, *Pleurotus* spp. can generate an increase in dietary fiber content, improving intestinal functions, besides decreasing in vivo glycemic index [98].

Lastly, the use of jackfruit rind powder is considered an interesting solution for the partial replacement of flours for bread production, as it can generate a significant increase in both soluble and insoluble fibers, which favors intestinal regulation function, such as controlling diabetes and lowering cholesterol levels [99].

8. Conclusions and Future Perspectives

In summary, from this review, it was possible to approach the different processes to produce powdered foods, with an emphasis on the spray- and freeze-drying processes, widely used methodologies, and their advantages and disadvantages. Moreover, instant properties, essential attributes in the study of rehydrated foods, were also presented, as well as desirable characteristics, problems and potential solutions for the processing, transport, and storage of powdered products. Case studies were also explored in which each type of food was individually evaluated due to its unique and complex matrix of compounds.

Regarding the stability of powdered foods, alternatives are investigated since the hygroscopicity of the material, while being an advantage due to its reconstitution properties, is a challenge due to the high absorption of humidity from the environment. Several studies in this review have proven the efficiency of maltodextrin in this process, an additive widely used in powdered products, but with the arrival of 'clean labels', natural alternatives are more desirable in solving this problem.

The search for innovation is also growing, whether for processes (new drying methods, grinding, and pretreatments) or for the product itself, in which there is still a large space in the market for the study and production of powdered foods. This review highlights the importance of studying the morphology of the powder, drying conditions, and intrinsic characteristics of the food to obtain a powdered food with desirable properties.

The concept of circular economy emerges as a strategic approach, which aims at a closed loop in the reduction and reuse of materials, giving the product as much value as possible. Powdered foods can collaborate in this strategy, as they are products with easy use, longer shelf life, and, consequently, less waste. Furthermore, there is also the use of by-products to use material that would otherwise be wasted, such as leaves and stems of plants, and to transform them into powders with high added value due to their beneficial health properties.

Therefore, this review highlights the difficulty in handling and controlling different classes of food, in which alternatives are found to obtain a good final powdered product, whether for its functionality, stability or economic viability, requiring complete knowledge and in-depth study of the food to be researched.

With ongoing advancements, more efficient drying methods are expected, with lower energy costs and better preservation of food properties, with an emphasis on the development of sustainable technologies. Regarding powdered products, prospects for the future include improving reconstitution and dissolution properties; the development of new powdered foods the expectation of a deeper understanding of functional foods and ingredients and their powder transformation and stability; and the effects of ingestion and potential health benefits of these products.

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