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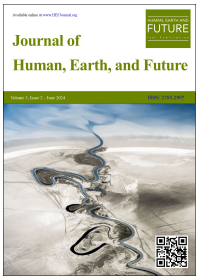
Review Article



A Brief Overview of Spray Drying Technology and Its Potential in Food Applications

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Abstract

Spray drying is one of the most preferred preservation methods that converts an aqueous feed containing solvent, carrier agent, and food compounds into dry powder with superb physicochemical and functional properties. This paper reviews the fundamental and important operating parameters, product characteristics, current and potential applications, and techno-economic aspects of spray drying. The key operating parameters should be chosen to achieve the highest spray drying performance in terms of operational efficiency and product quality. A successful spray drying operation is greatly dependent on the feed material properties, the mechanical design of the equipment, and selected operating parameters. This paper also found that water content, water activity, and glass transition temperature are the main parameters that really determine product quality in terms of shelf life and storage conditions of food powder obtained from the spray drying process. Recent advances in the development of new heatless spray drying technology in the manufacture of food flavoring and nutraceuticals are interesting to develop, in addition to the potential to produce nano-sized powders with distinctive properties and the use of superheated steam and carbon dioxide to sterilize products. The appropriate information on spray drying technology featured in this paper is targeted to reinforce researcher and practitioner understanding for widening its applications in pertinent food industries.

Keywords: Equipment; Food Application; Operation Method; Performance; Powder Product; Spray Drying.

1. Introduction

In addition to the produce of farms, greenhouses, gardens, forests, orchards, poultry, beekeeping, dairy, and fishing, agricultural produce also comprises animal and fish products [1–2]. In their raw form, these products are perishable, so they require preservation to avoid undesirable damage, decay, or spoilage at ambient conditions due to microbial attacks such as bacteria, yeast, and molds [3]. Moreover, agricultural produce preservation also prevents other spoilage due to enzyme activity and the auto-oxidation of their containing fats [4]. Indeed, preservation does not solely prolong the shelf life; however, it also sustains the physicochemical quality of agricultural produce as well. In addition to refrigeration and fermentation, drying is one of the primaeval and simplest techniques of maintaining agricultural produce for later use. On the other hand, canning, pasteurization, freezing, irradiation, the addition of specific

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chemicals, and the use of advanced packaging materials are regarded as modern preservation techniques. Basically, drying reduces the moisture content of food and, hence, hinders the growth of bacteria, mold, and yeast. Furthermore, drying also retards enzyme action without significantly deactivating them. Some preservation techniques that also alter the phase of liquid agricultural produce into powder form and make it easier to store, carry, and use are spray drying, foam mat drying, etc. [5].

The spray drying operation requires the transformation of a liquid feed material, slurry, or emulsion carrying one or more compounds of the desirable product into fine droplets by spouting and accompanied by a quick evaporation of the spouted droplets to form solid powder by hot air at a particular humidity, temperature, and pressure [4]. This drying process aims to continuously dry the solute containing slurry, solution, emulsion, or suspension to produce granulated powder or agglomerated particles of a specific quality, controlled by the characteristics of the materials utilized in the feed, the mechanical characteristics of the dryer, and the working conditions [6]. The steps of the spray drying process involve: (1) atomization of fluid feed; (2) feed spray and drying medium contacts; (3) evaporation of moisture and particle formation; and (4) segregation of the resulting powder from the drying medium [7]. Generally, spray drying operations utilize air or scarcely a less reactive gas, specifically nitrogen, carbon dioxide, or superheated steam [8]. Even though the temperature of the spray dryer is generally high to facilitate water evaporation from the droplets [9], the wet bulb only needs a brief exposure duration (a couple of seconds), and moisture vaporization will occur within 30 to 50 ^{o}C [10]. Indeed, spray drying is an exceptionally fast and consistent drying technique caused by the extremely large surface area provided by the division of the liquid feed into a fine spray to allow sufficient access to the drying air [11]. Some basic quality requirements for granulated powder are flowability, bulk density, granule shape and size distribution, granule true density, solubility, etc., within specified values [12]. These properties specify the process control achievable in the succeeding powder-associated processes.

This paper reviews the fundamental, influential operating parameters, current and potential applications, and techno-economic aspects of spray drying technology. To trigger further discussion, the challenges that are currently faced by spray drying technology are also elaborated on at the end of this paper.

2. Technical Aspects of the Spray-Drying Process

Spray drying can be described as the transformation of a liquid feed solution by spouting it into a hot drying medium to obtain dried particles [13]. This process commences with the spraying of a liquid solution or dispersion to form tiny sprays inside the spray drying compartment. In a situation of high blocking tendency attributable to the presence of coarse particles, a rotary atomizer is commonly applied in a spray dryer. As the liquid feed is spouted by an atomizer or nozzle, many sprays with a large surface area-to-mass ratio are formed. Then, the hot drying medium that flows inside the compartment quickly binds with these sprays along the drying compartment. Although hot air is commonly employed as the heating medium; but nitrogen or carbon dioxide is also frequently used (if the liquid encompasses a combustible solvent). For an easy and efficient drying process, the flow of the drying air is kept in a co-current direction that allows rapid solvent evaporation from the liquid feed solution or dispersion. Then, the solid particle or dry powder is usually picked up from the underside of the drying compartment. Ordinarily, the process can be completed within 3 to 30 seconds. Therefore, the product's physical quality and alimentary values are preserved. In most cases, spray drying results in flowing powders of specific particle size (ranging from 2 to 500 mm) and an exceptional conglomeration or reconstitution property [14]. This property allows these powders to dissolve very quickly in the solvent for the specific objectives. One of the best examples of spray drying operations is the manufacture of milk powder to improve its preservation quality [5]. Fresh milk is regarded as an easily spoiled food product because it is vulnerable to rapid decomposition in just 24 hours if it is not deposited under appropriate storage conditions due to its extremely high-water content, which is 80–90 wt.%. Thus, spray drying is currently applied on a commercial scale to reduce its bulk mass, prolong its shelf life, and appreciably reduce its conveying costs. Indeed, powdered milk can be stored for about a half-year without any signs of deterioration [16]. As expected, the nutritional composition of the powdered milk also remains well preserved. Therefore, in the event of a food shortage or any unforeseen occurrences, powdered milk products can be demonstrated as the best survival supplies.

2.1. Stages of the Spray Drying Process

Generally, a spray dryer is operated in convective mode, which provides its unique rapid drying rate feature due to the quick moisture evaporation induced by intensive contact between the feed solution with the low-humidity hot drying air. A feed mixture in the form of liquid coming into the spray drying system experiences a sequence of changes prior to it turning into powder. The shifts are attributed to the impact of every relevant stage, namely the breaking of the liquid feed mixture into fine sprays, contacting the fine sprays with heated air, the removal of moisture to produce particulates, and fine powder separation (Figure 1). Each stage significantly affects the final product quality.

Stage 1: Atomization

In a spray dryer, a peristaltic pump delivers the liquid solution feed from its container into a nozzle and subsequently atomizes the liquid solution to form tiny sprays inside the drying compartment [17]. Therefore,

atomization propels the following spray drying steps by lessening the intrinsic recalcitrance of solvent movement from the spray to the drying air. In consequence of the significant enlargement of the interfacial area of the liquid solution feed as the spray division starts, its susceptibility enhances following the ferocity of atomization. Indeed, atomization determines the performance of a spray drying process, which largely determines the geometry, structure, size distribution, velocity of the sprays, particle size, and characteristics of the output [18]. In most cases, one meter cubic of liquid could produce about 2×10^{12} uniform 100 micron-sized sprays, which bring an overall surface area of more than 60,000 m^2 [19].

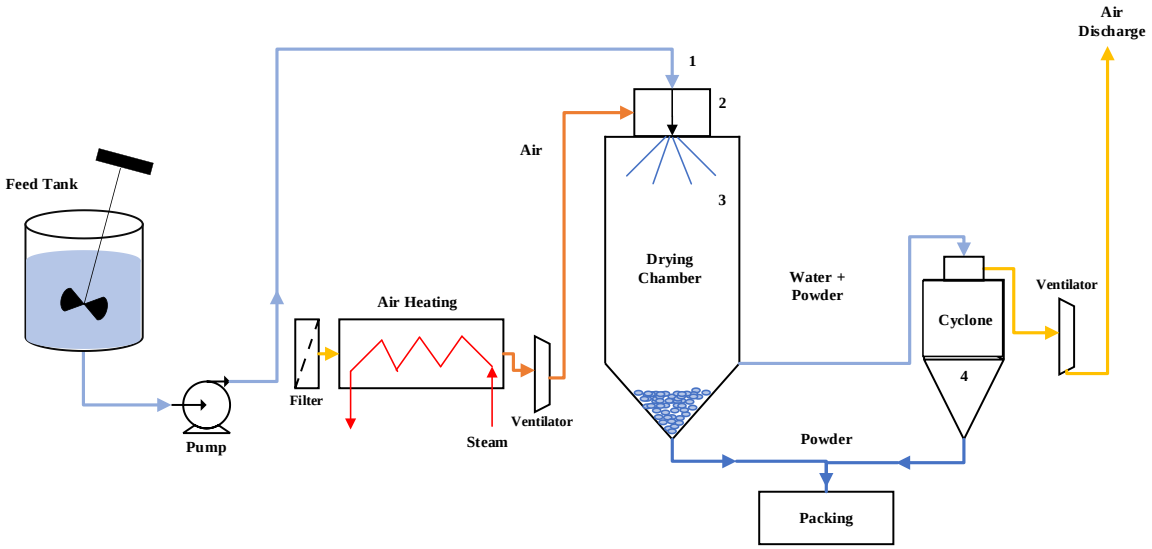

Figure 1. An illustration of the sequence of spray drying steps. (1) Atomization. (2) Feed fine sprays – heated drying air contact. (3) Removal of moisture and particles formation. (4) Product separation

A larger specific surface value allows the spray dryer to obtain a quicker drying rate because the drying time is commensurable to the square of the spray diameter. Accordingly, dry particles of a preferred morphology with specified physical attributes and a minimum loss of heat sensitive constituents can be obtained. Upon breakup, a pipe of length $4.51d$ will produce a globular drop (Figure 2) and, therefore, can be estimated as a ball of the same volume:

$$\frac{(\pi {d_D}^3)}{6} = \frac{4.51d(\pi d^2)}{4} \quad (1)$$

where d_D and d are the spray diameter and initial jet diameter, respectively, which can be obtained as:

$$d_D = 1.89d \quad (2)$$

Spray diameter generated from an electro-spraying of liquid feed can also be estimated based on its volumetric flow rate and some relevant physical properties [18, 20]:

$$d_D = \alpha.\left(\frac{\varepsilon_0.\rho.Q^3}{\gamma.\sigma.\pi^4}\right) \quad (3)$$

where d_D is the spray diameter, Q is the volumetric flow rate, and ε_0 is the permittivity of vacuum. On the other hand, ρ, γ, and σ are respectively the density, surface tension, and conductivity of the liquid feed. In practical application, α is a constant which is usually set to 2.9.

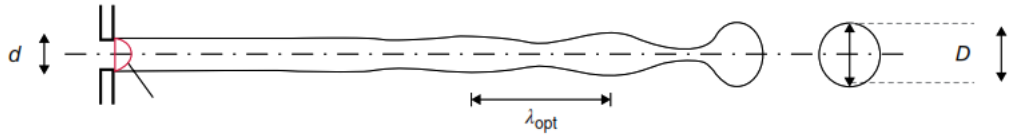

Figure 2. An illustration of droplet generation from a nozzle tip

Stage 2: Feed spray and drying medium contacts

This step and the succeeding spray drying steps set up the particle development phase. As the bulk feed is disintegrated into microscopic sprays, the subsequent step is to facilitate intensive contact between the sprays and the hot drying medium. This allows quick and uniform moisture evaporation from the spray surface. Therefore, an evenly distributed drying medium flow to all sections of the drying compartment should be provided. The sprays normally enter the hot drying air in the spray drying compartment, either following the co-current or counter-current flow modes.

In co-current flow mode (Figure 3a), the product and drying medium travel along the drying compartment parallelly. Therefore, the atomized sprays are intensively exposed with the heated inlet drying medium inside the drying compartment for about a few seconds, and the drying medium temperature drops instantly. However, their temperatures are usually maintained low as a result of the rapid evaporation rate and is roughly at the wet-bulb temperature. The cold drying medium, by turns, pneumatically carries the dried granules along the system. This creates the benefits of both low temperature and granules residence time, which result in a lower thermal degradation of the heat-sensitive constituents. Therefore, this configuration is frequently employed to dry heat-sensitive materials, especially food products, because the product temperature is lower than 100 ºC [21].

Inversely, in the counter-current more (Figure 3b), the product and drying medium come into the drying compartment oppositely. The relatively high slip velocities of particles provide greater heat and mass transfer than that of co-current flow mode. Hence, the outlet product temperature will be greater than the temperature of the exhaust drying medium and close to the fresh drying medium temperature, with which it is exposed. As a result, these dryers are considered to have higher throughput and thermal efficiency than co-current spray dryers [22]. Additionally, this type of configuration is only employed for the drying of thermal-resistant products [23].

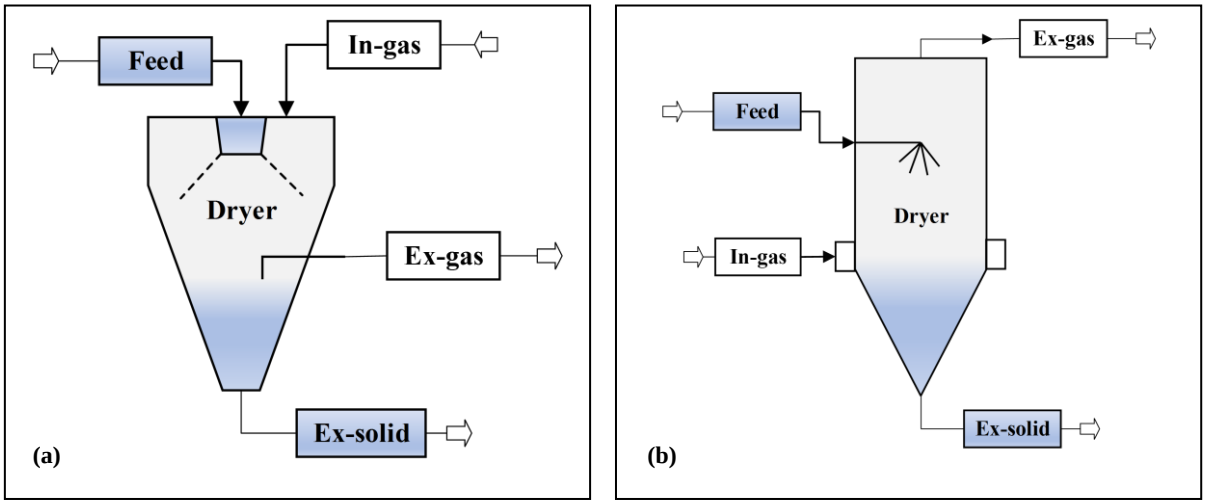

Figure 3. Spray dryer flow arrangements: (a) co-current; (b) counter-current

In addition to those basic operational modes, another spray dryer configuration consolidates both co-current and counter-current flow operation modes and is called mixed flow. Generally, this spray dryer configuration is applied for the drying of rough, free-flowing granules. However, this spray drying operation suffers from a higher departure temperature of the resulting granules as the most considered limitation.

Stage 3: Evaporation of moisture and particle formation

The evaporation of moisture throughout the spray drying process can be described as two consecutive stages, namely the constant rate period and the falling rate period. Initially, the sprays are exposed to hot drying air and are heated from their original temperature (T_o) to the equilibrium evaporation temperature (T_{eq}). During this drying stage, the moisture evaporates quickly following the constant rate period because the moisture is taken out continuously from the spray surface, which maintaining them cool enough. Therefore, the spray surface continues to be saturated with moisture, and their temperature is persistent at the wet-bulb temperature [24]. The spray shrinks due to moisture evaporation [25]. As the solvent elimination from the sprays progresses, the concentration of the dissolved solute in the solution is ahead its equilibrium concentration and is likely to develop a thin coat at the surface of the spray, reflected as “crust development” which changes the drying mechanism from low to high temperature drying (Figure 4). Upon crust development, the solvent removal shifts into a diffusion-governed mechanism with its evaporation rate depends on the rate of solvent vapor diffusion through the dried surface shell. This condition is regarded as the falling drying rate period. Interestingly, although the granules will start to heat during the falling drying rate period, they are nearly located at the segment of the drying compartment with the lowest temperature, where the drying medium is at or close to the dryer’s outlet temperature. Accordingly, the granules formed will absolutely not be heated surpassing the dryer’s outlet temperature, although the inlet temperature may be remarkably greater. As a result, the temperature of the dried granules obtained would be roughly 20°C lower than the temperature of the drying medium exiting the drying compartment [26].

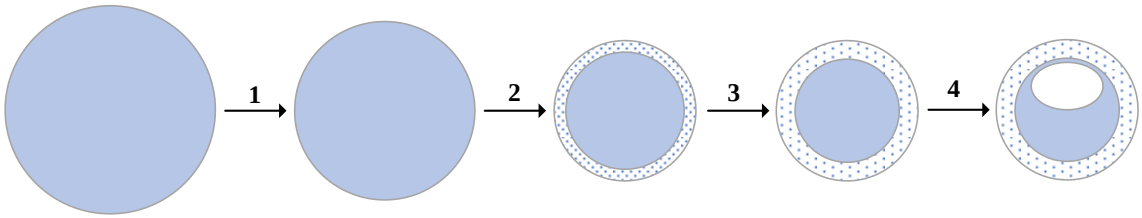

Figure 4. A schematic illustration of the progress of the spray drying process

Other interesting phenomena are the "bubble development" and succeeding temperature enhancement, which occurs when the partial pressure of solvent vapor at the spray center surpasses the pressure of the surrounding air (Figure 5). A large quantity of energy is needed for this vaporization, which subsequently ceases the appreciable heating. The spray puffed out to the outer radius and eventually brings about randomly asymmetrical-shaped granules [27]. As the most pivotal stage in particle development, this stage is linked to the morphology of the resulting products. The produced powder may be of somewhat homogeneous hollow spheres or porous and irregularly shaped particles [28].

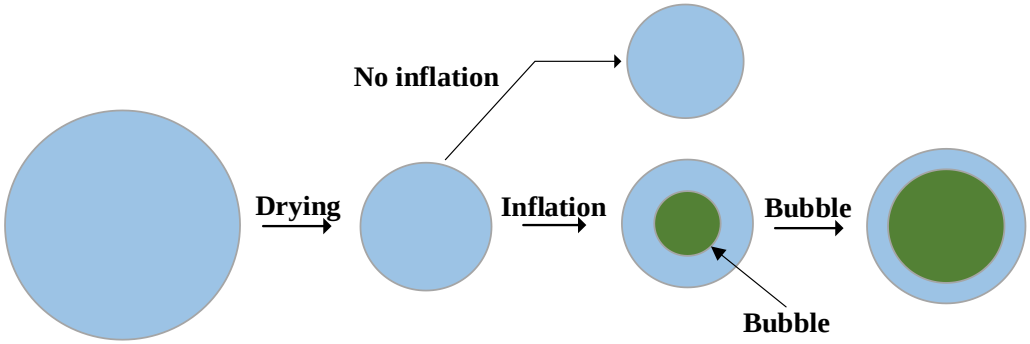

Figure 5. A schematic illustration of the bubble growth phenomenon during spray drying

Concerning the particle's morphology, an accelerated solvent evaporation rate (lower boiling point) generally promotes the formation of more porous particles that is due to a briefer time for the sprays to undergo shrinkage [13]. Consequently, higher liquid feed flow rate, bigger nozzle diameter and greater formulation concentration promote the development of bigger particles. On the other hand, low surface tension, high atomization pressure, and small nozzle diameter contribute to the formation of smaller particles. Ultimately, the outlet temperature of the drying medium will strongly depend on the other process variables.

Stage 4: Particle Separation from the Drying Medium

Generally, a spray drying system utilizes primary and secondary separation units to separate the desired product from the drying air. To enable facile collection of the dried granules as the first separation, the spray drying compartment possesses a conical base [21]. Then, the dry powder is discarded using a screw conveyor and is further delivered using a pneumatic system to a cyclone separator for secondary separation. The wet drying medium stream containing the evaporated solvent is taken from the center of the cone above the funnel-shaped bottom and is released through a side outlet. However, a relatively low collection efficiency requires the employment of an extra granules collection system consisting of a dry collector and a wet scrubber. The size of the granules transported by the exhaust drying medium and the finished product specifications determine the most suitable dry collecting equipment, which can be a cyclone separator, a bag filter, or an electrostatic precipitator (Figure 6) [29].

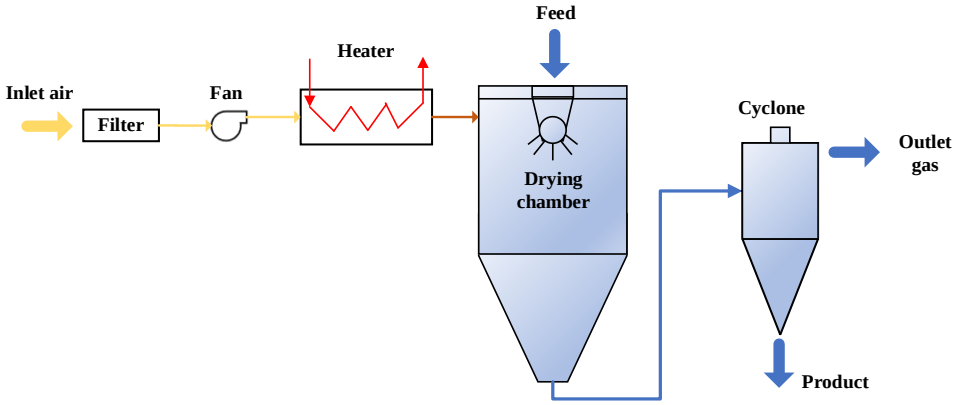

Figure 6. Schematic diagram of an open-cycle spray dryer [29]

2.2. Main Parts of a Spray Drying System

During operation, spray drying equipment facilitates a sequential stage, namely preheating of drying medium, atomization of feed, contacting feed spray with hot drying medium, evaporation of moisture and particles formation, and final product separation. Therefore, a basic spray drying unit consists of the following essential mechanical parts:

Preheating System:

For the purpose of increasing the drying medium temperature, a preheating system involving either direct or indirect heating method can be designed. In the direct heating methods, the drying medium is directly made into contact with a heat source. In contrast, the indirect heating method employs a heat exchanger to heat up the drying medium. Indeed, the thermophysical properties, flow rate, and temperature of the drying medium play important roles as the most influential design parameters of the indirect heating method [30].

Atomizer:

An atomizer functions to transform the liquid feed into tiny sprays and substantially helps the process in the formation of dried powder with desirable properties. Basically, the type of energy utilized for creating the sprays determines the design of the nozzles, which includes pressure, centrifugal, and pneumatic nozzles [31]. Pressure nozzles are created contingent on the conversion of pressure energy of the bulk liquid into kinetic energy of the moving thin liquid layers along the channel [32-33]. Therefore, pressure change is the governing parameter of the nozzle characteristics and feeding rate. Because the liquid layers are split from one another by reason of their physical characteristics and the friction with flowing drying medium, the average nozzle dimension is also instantly commensurate to the volumetric flow rate and viscosity of the feed. The use of pressure nozzles causes a diminution of deposition in the dryer compartment and generation of asymmetrical high bulk density coarse dry powders [31, 34-35]. The design of centrifugal nozzles allows the liquid to migrate approaching the axis of a rotary disk due to the centrifugal force, and the sprays are further distorted by the disk knives [36-37]. As a result, the produced particle size is oppositely correlated with the disk diameter and rotation velocity and is straightly affected by the physical features of the liquid feed, especially the viscosity, density, and surface tension. Therefore, this system is free from fouling and plugging problems and causes it feasible to produce dry powder from a highly viscous feed containing a lot of crystals [31]. Pneumatic nozzles atomize the liquid feed by employing high air velocity to generate friction forces for the formation of numerous tiny sprays by breaking up the feed liquid [38-39]. The spray's development by these nozzles occurs following two consecutive steps, where the first step implies the conversion of the liquid feed into big sprays, followed by the second step that alters the big sprays into microscopic sprays. Practically, the rheological properties of the drying medium and liquid feed, such as viscosity, density, and surface tension, affect the final product quality. However, these systems may suffer from fouling and clogging issues [31]. The selection of the atomizer type and arrangement depends strongly on the nature and physical properties of the feed and the intended attributes of the end granule products [40-41].

Drying Compartment:

Normally, the spray drying operation is performed in the designated drying compartment. The solvent contained in the liquid feed is removed by spraying it as many tiny sprays into heated drying medium in the drying compartment. During intensive contact with the hot drying medium, either following co-current, counter-current, or mix flow current, the moisture of the sprays is quickly evaporated, and afterward it is pneumatically released from the drying compartment together with the drying medium.

Usually, the major portion of the spray drying operation occurs at a constant drying rate period, and therefore heat and mass transfer on the spray surface play as the controlling parameters. In the constant drying rate period, solvent evaporates very quickly from the saturated surface according to the diffusion mechanism across the static drying medium film at a speed adequate to sustain spray surface saturation. Upon the achievement of critical moisture concentration, the internal framework of the dried granules governs the falling drying rate period [42].

In the falling drying rate period and as solvent removal proceeds, the sprays achieve a solid concentration beyond its equilibrium concentration to develop a thin shell at their surfaces. Therefore, moisture transfer inside the granules is the governing parameter of the drying rate. However, it should be acclaimed that the size and dimensions of the drying compartment can be influenced by the volumetric flow rate of the feed, physical nature of the coating agent, the type of atomizer, the distributor type of feed and inlet temperature of the drying medium [42-43].

Recovery System:

The dried tiny particles resulting from a spray drying process must be separated from the hot drying medium, leaving the drying compartment [44-46]. To fulfill this objective, cyclonic separating units employing centrifugal force are generally utilized. The dried tiny granules come out from the bottom side of the cyclone, while the drying

medium leaves from the top side of the cyclone [47]. Technically, the separation efficiency of dried granules from the drying medium is affected by the inlet geometry of the entering mixture (granule and drying medium) as well as the dimension and number of the cyclone [48]. The inlets of drying medium and granules mixture into the cyclone body are in the shape of envelope and tangential. The envelope inlets are designated to increase the quantity of the delivered drying medium and, thus, enhance the drying medium velocity and overall efficiency of the solid-fluid separation system. Additionally, the number of cyclones is determined by the drying medium and granule mixture mass ratio, and generally varies from 1 to 4. Numerous works have reported that the highest separation efficiency of about 95% can be achieved by cyclones with a diameter of less than one meter [19].

2.3. Classification of Spray Dryers

In practical applications, the technical and operational design of spray dryers is classified according to the flow configuration, the number of stages and the type of cycle. In addition, both commercial and economic considerations are also taken into account for the more comprehensive design of the dryers [49].

From a flow configuration point of view, spray dryers are categorized into co-current, counter-current, and mixed-flow type dryers [19]. The co-current dryers allow the drying medium and the product to travel parallelly, which makes them suitable for thermal-sensitive products with low particle density and hollow frameworks [9]. This is because the hottest drying medium (normally 150 to 220°C) is made into intensive contact with the sprays at their highest moisture content [21, 50-51], evaporation happens immediately, and then dry granules will be subjected to medium temperatures (ordinarily 50 to 80°C) that minimize the possible thermal deterioration [52]. In contrast, counter-current flow dryers apply opposite direction for the introduction of the product and the drying medium. In this type of dryer, the atomizer is situated at the top of the drying compartment, while the drying medium goes into the drying compartment from its bottom end. Accordingly, nearly all dried granules are exposed to the hottest drying medium. The counter-current dryers provide quicker evaporation and more efficient energy utilization compared with the co-current configurations [53-54]. For commercial applications, soaps and detergents are usually manufactured using counter-current dryers. Meanwhile, there are intermediate configurations mixed-flow dryers that integrate the co-current and counter-current flow configurations [55].

Giving consideration to the number of stages, spray dryers are divided into single-stage and multi-stage dryers. Indeed, the single-stage dryer is the simplest and most frequently employed type of spray dryer utilized for manufacturing powdered products. However, a single-stage dryer is still capable of reducing the moisture content of the product to around 2-5% by mass. As a comparison, the residual solvent concentration of the granules exiting the drying compartment is roughly 5-10% by mass in a multi-stage dryer. For the sake of reducing residual solvent concentration to a greater extent, other types of dryers, mainly fluidized bed dryers are utilized. As expected, multi-stage dryers permit the application of lower temperatures in the dryers, allowing them a better option for thermal-sensitive products. Therefore, multi-stage dryers offer higher energy efficiency and better preservation of the taste, flavor, and nutritional components of the products. Multi-stage dryers are utilized for handling viscous and high-lipid agricultural produce [56].

With regard to the cycle operations, spray dryers are categorized into open-cycle and closed-cycle operations. In an open-cycle spray drying operation (Figure 6), the drying medium is cleaned by a secondary separator after being used for drying in the drying compartment, and subsequently delivered into the surrounding area. In contrast, a closed cycle spray dryer (Figure 7) requires immediate cleaning, drying, and recycling of the drying medium (e.g., nitrogen or carbon dioxide) back into the drying compartment after it is completely used for drying in the drying compartment. It has been reported that, in most cases, the open cycle has been proven to be more stable and cost-effective [57]. However, closed-cycle dryers provide higher energy efficiency, better prevention of oxygen-sensitive substances, and better protection against explosive gases mixing than open-cycle dryers [56].

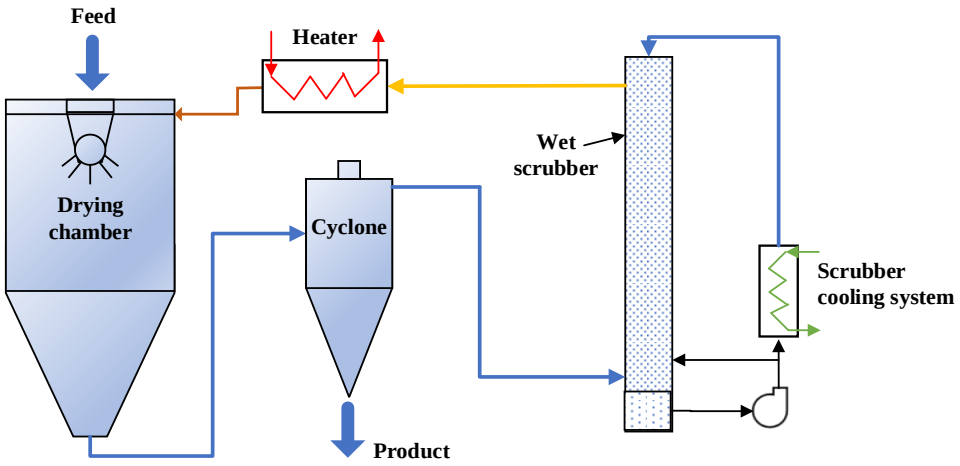

Figure 7. Schematic representation of a closed-cycle spray dryer.

3. Spray-Drying Operating Variables and Their Effects on Product Characteristics

Typically, spray drying technology is chosen for its ability to produce specified particles. However, the operation of spray dryers is restricted by two sequential key issues, namely the dripping issue at the atomizer and the product encrusting issue [58]. Usually, the dripping issue is caused by the direct collision of semi-wet particles on the wall of the drying compartment. To reduce this problem, feed atomization must be enhanced, mainly by increasing the atomization revolution, reducing feed flow rate, lowering feed concentration, and improving moisture removal speed to rapidly produce drier products hitting the wall [58]. Hence, if a sufficiently high inlet temperature is applied, this influence will be minimum if the sprays move with a high-speed flight path at the atomizer level. In regard to the product caking issue, reducing product stickiness can be an efficacious solving strategy. This strategy can also be done by modifying the sticky point [59], lowering the residual solvent concentration, or decreasing the temperature of the resulting granules [60].

The product caking issue might be eliminated by varying the sugar to carrier agent proportion because this parameter determines the glass transition temperature (T_g) of the granule surface, which eventually influences the development of a liquid connection between granules [58]. Therefore, optimization of relevant operating parameters for process monitoring is crucial for the successful application of spray drying. A successful spray drying operation is greatly dependent on the feed material properties, mechanical design of the equipment and selected operating parameters. The physical properties (density, viscosity, surface tension, hygroscopicity, etc.) of the feed largely influence the formation of sprays and the overall drying process [58]. These factors determine the quality of the final product, especially its remaining moisture, particle size, microstructure, and morphology. Optimizations of these operating parameters are frequently attained through an in-depth understanding of the spray drying method to manufacture the desirable granules with the required properties. Despite the fact that the optimization of these factors is generally obtained by "trial and error", a comprehension of the fundamental directives of spray drying would bear an ingenious performance of the system. The spray drying operating parameters, which correspond to each of the four spray drying stages, are reviewed in the next section. The common directives for determining the influential factors for a spray drying process and the details associated with their effect on product quality are also elaborated. This rough approach is advantageous because thorough experimental investigations within an operating spray dryer are nearly unfeasible as result of the antagonistic atmosphere of high temperature two-phase flow, which may be unstable, and the expensive cost that would have to bear.

3.1. Feed Parameters

Carrier Agent:

A feed containing material with a high latent heat of crystallization is likely to produce smaller, denser, and regularly-shaped particles. Moreover, if the material is highly soluble in the solvent, the resulting powder will comprise small, dense, irregularly-shaped particles. However, if the feed contains materials that have a higher tendency to form an elastic shell structure. It will be likely to produce particles with hollow structure [61]. The existence of low molecular weight organic acids and sugars, such as sucrose, glucose, and fructose, in the products triggers crucial issues related to powder stickiness. The powder stickiness can be associated with their low T_g, which indicates a temperature at which the amorphous state of a polymeric substance changes to a condition between rubbery and glassy states. A good example is when spray drying is employed to manufacture powder from fruit juice [62]. Accordingly, they can adhere on the wall of the drying chamber during drying, which causes low output yield and more operating issues. The low T_g, high water vapor absorption capacity, low melting point, and considerable water solubility of the dry granules induce the formation of extremely sticky granules.

Roos [63] explained that these granular materials are exceptionally hygroscopic in an amorphous state and lose their free-flowing property at higher moisture content. However, those issues could be overcome by the incorporation of appropriate carrier agents, such as natural or synthetic polymers and gums, to the feed solution prior to its transformation into tiny sprays. Furthermore, the carrier agents can be utilized for microencapsulation that protects unstable food constituents against harsh environmental conditions, masks or maintains flavors and fragrances, lowers volatility and reactivity, and gives extra allurement for the marketing of food products [64]. Maltodextrins are cheap and highly beneficial for the spray drying of food substances. Indeed, distinct carrier agents and spray drying conditions result in dried powders of different physicochemical properties. Hence, a comprehensive understanding of food properties is critical for optimizing processes, expanding functionalities, and reducing costs. Basically, moisture content and water activity are important properties that affect granule stability and storage. In addition, bulk density is also a principal factor for packaging and transportation considerations.

Type of carrier material: The introduction of high molecular weight carrier material with a high glass transition temperature (T_g) to the liquid feed solution before atomization is broadly applied as a strategy to enhance the T_g of powder [9, 51]. Gum Arabic, degraded alginate, maltodextrins, carrageenan, waxy starch, modified starch, and microcrystalline cellulose as carrier agents have been proven to effectively alter the physical properties and stability of

the powder. Maltodextrin is the most preferred carrier agent in spray drying operations due to its low water vapor absorption capacity, low particle's agglomeration tendency, high solubility in cold water, and inexpensive [65]. Gum Arabic is generally utilized in microencapsulation for its high solubility, low viscosity, and excellent emulsifying capacity, which is associated with its protein fractions and a good flow conferred to the particles [66]. However, its capacity to preserve the bioactive compounds against oxidation is limited because it usually functions as a semi-permeable membrane, which potentially influences the durability and stability of the microcapsules [67]. Nevertheless, its utilization is limited because of its high price and availability issues, since it is only produced in certain regions subjected to unforeseeable climatic disparities. The modified starches are broadly utilized as coating agents for their superior volatile's retention (higher than 93%), stable emulsion forming ability, and low viscosity [9]. Unfortunately, they have a low safeguarding capacity from oxidation during storage of the products. A higher value of maltodextrin dextrose equivalent (DE) results in a higher moisture content of the granules. The chemical structure of high-DE maltodextrins is reported to promote a high number of ramifications with hydrophilic groups and thus can comfortably attach to water molecules from the surrounding air during powder handling after spray drying. Moreover, the higher stickiness of the higher DE maltodextrins boosts the increase in bulk density in the powder. Hence, a blend of 6% maltodextrin with 6 DE and 2% gum Arabic is the most efficient carrier agent utilized for spray drying in terms of product yield, morphology, bulk density, and solubility [66].

Concentration of carrier material: The concentration of the carrier material in the feed affects the granule characteristics. Generally, a low carrier material concentration leads to increased powder stickiness. Hence, an incorporation of maltodextrins could be expected to improve total solid content in the feed, and hence, decrease the moisture content of the resulting granules [68]. In fact, maltodextrins could change the stickiness of the surface of low molecular weight sugars, especially glucose, sucrose, and fructose, as well as organic acids [69]. Hence, this phenomenon promotes drying and decreases the stickiness of the spray-dried granule. Nevertheless, if the incorporated maltodextrin is beyond 10% wt., the manufactured powders lose their appealing original color. In addition, a higher maltodextrin concentration also brings about a reduced bulk density of various fruit juice powders [70].

Concentration of solute: Feed solution containing solid concentrations higher than 20% (w/v) results in spray patterns with a considerable portion of big sprays and an appreciable reduction in the recovery percentage that passed from 27% [71]. Therefore, a higher initial solid concentration in the feed is favorable for the formation of a large and dense particle [61]. This is because the rate of solvent evaporation only increases slightly with a decreasing initial solute concentration. The use of more volatile solvents, i.e., water/ethanol mixtures are favored to pure water mainly because of two aspects: firstly, the existence of the organic solvent promotes evaporation rate and hence decreases the time and energy needed for particle formation; secondly, the utilization of ethanol in a mixture with water could improve the percentage of product yield as well [71].

Feed Volumetric Flow Rate:

The feed volumetric flow rate must be selected to ensure that the liquid exists in the sprays will completely evaporate prior to collision with the drying compartment walls [9]. A higher feed volumetric flow rate causes a briefer contact time between the sprays and drying medium and thus reduces heat transfer efficiency. As a consequence, the solvent evaporation is slower, which increases the risk of incomplete spray drying [71]. Furthermore, when a feed is passed straight to the drying compartment at a higher volumetric flow rate, it will not be completely atomized, and subsequently induce dripping inside the drying compartment. Therefore, the higher feed volumetric flow rate will result in a lower yield, predominately as a result of the adhesion of a large portion of sprays to the drying chamber wall [9,71]. On the contrary, if the feed flow rate is too low, the yield will also be low and is uneconomical in terms of energy cost used to preheat and deliver the drying medium gas. As a remark, an appropriate value of feed flow rate should exist for a particular type of feed.

3.2. Drying Medium Parameters

Drying Medium Inlet Temperature:

The temperature of the drying medium, which is delivered inside the chamber by an aspirator, is one of the key parameters, specifically associated to particle recovery and material stability [71]. It should not trigger any possible thermal deterioration of the material to be dried and a nearly sudden solvent evaporation. The inlet temperature of the drying medium determines the physical characteristics of the powder, namely moisture content, bulk density, particle size, water vapor absorption capacity, and morphology. The spray's temperature inside the chamber falls significantly as a consequence of the high heat transfer involved. However, at about halfway through the drying compartment, their temperature is nearly constant and will almost be equivalent to that of the outflow granules temperature. Generally, the inlet temperature applied for the spray drying of food products ranges from 150 to 220 ^{o}C. Based on their study on the influence of inlet drying air temperature (110 to 190 ^{o}C) on the spray drying of orange juice. Chegini et al. [72] observed that at a certain feed volumetric flow rate, the increase in inlet drying air temperature significantly reduces the residual moisture content in the products due to a larger temperature difference between the feed sprays and drying

air as the trigger for water evaporation. However, the application of higher inlet air temperatures causes the development of larger granules and a higher swelling tendency. A higher drying medium temperature promotes fast solvent evaporation, which results in the first appearance of crystals and early crust formation. On the contrary, a lower drying air inlet temperature is favorable to producing smaller, denser, and regularly-shaped particles [61]. Nijdam et al. [73] reported a similar result in the spray drying of milk powder at 120°C and 200°C. The higher drying medium temperature produces granules with lower moisture content and higher hygroscopicity. This high hygroscopicity value can be associated with the difference in water concentration between the granules and the ambient air, which is larger for the dried granules. However, a higher inlet drying air temperature leads to a higher yield as a result of higher heat and mass transfer efficiency.

When the drying medium temperature is high enough, the moisture in the powder evaporates more rapidly, resulting in a drier and harder crust. As a consequence, the hollow particles cannot draw in when vapor condenses within the vacuole as the granules travel into the cooler sections of the dryer compartment. Nevertheless, when the drying temperature is lower, the crust keeps moist and flexible for a longer time, so that the hollow particle can flatten and shrink as its temperature decreases. An advanced increase of temperature (from 100°C to 160°C) provides an increase in particle recovery from 12% to 26% [71].

Drying Medium Volumetric Flow Rates:

In most cases, the drying medium volumetric flow rates are set at a maximum value. The movement of the drying medium governs the flow pattern of the drying medium, which subsequently determines the rate and degree of moisture evaporation from the spray to facilitate the formation of dry powder. An augmentation of the drying medium volumetric flow rate causes a shorter transit time of sprays through the spray drier and consequently reduces their contact time with the sprayed sprays, giving an advantage for the thermolabile compounds [71]. In contrast, a lower drying medium volumetric flow rate induces an increase in the resulting granules travel time in the drying compartment and imposes circulatory influences.

Usually, both the moisture content and density of the powder strongly affect powder solubility, which is controlled by drying medium flow rate. Theoretically, the variation of powder density can be affected by temperature changes and migrating pollution. The increase in drying medium flow rate leads to the enhanced residual moisture content of the granule. In contrast, an increase in drying medium volumetric flow rate reduces granules solubility [74].

3.3. Atomization Parameters

The atomization process determines the intensity of spray-drying medium contact, the flight path of the sprays, and the free flight time of the spray along the drying compartment. In practice, the accomplishment of atomizers to produce a preferable spray size is strongly affected by three parameters, namely the atomization pressure, feed volumetric flow rate, and feed physical properties (viscosity, surface tension, and density). When the same type of nozzle and feed material are used, a higher atomization pressure decreases the spray size, following the below empirical correlation:

$$D_2/D_1 = (P_2/P_1)^{-0.3} \quad (4)$$

where D_1 and D_2 are the initial and final spray sizes due to the change of the atomization pressure from P_1 to P_2, respectively. A higher atomization pressure will provide a more effective energy delivery for the bulk liquid to promote spray fission.

At a constant atomization pressure, an increase in feed flow rate enhances the spray size. This is because the hydraulic energy of the nozzle has to be able to atomize a larger amount of liquid. As a result, the interaction between the liquid and the atomization energy is minimum, which leads to insufficient spray fission to lower its size. In practice, the feed volumetric flow rate depends on the peristaltic pump speed, which delivers the feed solution to the atomizer.

A higher feed viscosity requires more atomization energy provided to the nozzle to overpower large shear forces for the formation of smaller spray sizes. The shear forces will decrease the energy ready for spray fission, thus creating larger sprays.

$$D_2/D_1 = (\mu_2/\mu_1)^{-0.2} \quad (5)$$

where D_1 and D_2 are the initial and final spray sizes due to the change of the feed viscosity from μ_1 to μ_2, respectively.

The surface tension of the liquid feed also provides a significant influence in the achievement of the degree of atomization. To attain a successful atomization, the atomizer should vanquish the surface tension of the liquid feed. Consequently, a liquid with a higher surface tension is harder to atomize. Accordingly, in particular instances, a specific preparation step by incorporation of emulsifier to the high surface tension feed is required. Indeed, a

homogenization step prior to spray drying can also be needed to decrease the surface tension of a certain liquid feed, specifically that contains multi-components. Furthermore, a common principle for atomization choice is presented in Table 1 [75].

Table 1. General principles for selection of spray dryer design

Product criteria	Selection
Fine-particle product (30 – 120 μm) and low product temperature.	Co-current flow with a rotary atomizer
Coarse-particle product (120 –250 μm), high product temperature to be reached for porosity and bulk density	Counter-current nozzle tower design with pressure nozzle atomizer.
Coarse product (120 – 250 μm), medium product temperature and moderately resistant-heat products	Mixed flow nozzle chamber

3.4. Feed Spray-Drying Air Contact Parameters

Spray angle, which can be appraised exactly at the nozzle orifice and is associated with liquid tangential velocity, plays an important role in the formation of sprays. This velocity refers to the velocity at which the liquid feed rotates inside the nozzle before it is uniformly distributed into fine sprays and further spouted into the drying compartment. Hence, broadening the spray angle should enhance this velocity to allow spray size reduction. The selection of this spray angle depends on the drying medium flow mode (co-current or counter-current), with co-current flow mode requiring a wider angle and vice versa. In the co-current flow mode operation, the downward-flowing hot drying medium reduces the spray angle. In contrast, the downward-flowing spray angle is broadened by the upward-flowing hot drying medium for counter-current mode operation. The other key variables in this step are the suction rate, drying medium relative humidity, inlet and outlet of drying medium temperature, the glass transition temperature of the coating material, and granules residence time in the spray drying compartment.

The aspirator is responsible to the drying air supplied to the spray drying compartment at the selected operating pressure. Hence, the aspirator flow rate determines the amount of heated drying medium coming into the spray drying compartment. The inlet temperature of the heated drying medium plays a pivotal role in the cooling of the atomized feed sprays to their wet-bulb temperature and directly influences the wet-bulb temperature of the surrounding hot drying medium [76]. Therefore, the drying air inlet temperature also determines the moisture evaporation capacity and thermal efficiency of the dryer. Indeed, a higher drying air inlet temperature is preferred for the achievement of a higher spray dryer capacity. Nevertheless, a lower value of the inlet temperature decreases the wet-bulb temperature of the surrounding hot drying air and leads to avoid heat-sensitive compound degradation in the initial steps of spray drying. The quid pro quo between the aforesaid conditions is critical in determining the optimum inlet drying air temperature of the spray drying process. The outlet drying air temperature that indicates the temperature of the solid particles loaded air with before coming into the cyclone is an outcome of the heat and mass balances in the drying chamber, and thus cannot be adjusted. Outlet drying air temperature influences the final moisture content and surface topography of the dried products [77].

For example, the use of high outlet drying medium temperature is performed with high moisture content to produce agglomerated "instant granule" products. This is due to the fact that higher outlet drying medium temperature stimulates quick crust development, while the drying of the inner core has not been accomplished. Besides, an increase in the outlet drying medium temperature also enhances the granule temperature by switching the wet-bulb temperature lines on the psychrometric chart. A noticeable optimum temperature difference between the inlet and outlet temperatures of the drying air is most pivotal for a successful spray drying process. When air is used as the drying medium, as the inlet and outlet drying air temperatures are provided for a given drying air relative humidity and water activity of the solid powder, it is practicable to estimate the particle temperature by employing the above correlation. The wet-bulb temperature (T_{wb}) is constant throughout the drying process and can be approximated using the following equation [13]:

$$T_{wb} = \left\{137.\left({T_b}/{373.15}\right)^{0.68}.\log(T_{in})\right\} - 45 \quad (6)$$

where T_b and T_{in} are boiling point of the solvent and inlet drying air temperature, respectively. Then, the outlet particle temperatures can be roughly estimated from wet-bulb lines using the following relationships:

Moisture mass transfer rate ($\dot{m}$) from particle to the drying air:

$$-\dot{m} = k_c.A_p.(Y_s^* - Y_{air}) \quad (7)$$

Heat transfer rate from particle to the drying air:

$$-m.\dot{h}_{fg} = h.A_p.\left(T_{air} - T_p\right) \quad (8)$$

where k_c, A_p, h, T_p, T_{air}, h, Y_s^*, Y_{air}, and h_{fg} are the mass transfer coefficient (m/s), surface area of the particle (m^2), heat transfer coefficient ($W/m^2.K$), particle and air temperatures (K), moisture content of particle surface and surrounding air, and latent heat of vaporization of moisture (J/g), respectively. The outlet granule temperature is then predicted by following the wet-bulb lines from the outlet drying air temperature to the relative humidity line, which corresponds to the equilibrium relative humidity (ERH) on the dried granule surface. The ERH of the dried granule can be approximated from its water activity (a_w = ERH/100), determined from the moisture sorption isotherm of the dried granule using the measured moisture content of the granule [78]. Nevertheless, the above method for granule outlet temperature prediction supposes that there is no considerable influence of temperature, and the evaluated moisture content represents the surface moisture content as the granules come out from the spray drying compartment. But practically, the particles surface moisture content will consistently be lower than the granules average moisture content and hence, the predicted granule outlet temperature would be lower than the real one.

Glass transition temperature (T_g) of a material usually exhibits a second-order time temperature dependent transition, which is normally indicated by a discontinuity in the physical, thermal, mechanical, electrical, and other properties of a solid material [79]. Therefore, T_g is the temperature above which the solid matrix structure changes from a rigid glassy state to a rubbery state, which is linked with the stickiness of the product on the spray drying compartment wall. This product stickiness brings on a product agglomeration tendency and causes product caking and lumping problems during packaging. For that reason, stickiness is regarded as a serious problem in spray drying operations. The T_g of a spray-dried feed is dependent on the solutes existing in the feed. A rough T_g estimation for a multi-component system is given by the Gordon-Taylor equation (Equation 9) [79]:

$$T_g = \left(W_1.T_{g1} + c.W_2\right)/(W_1 + c.W_2) \tag{9}$$

where w_1 and w_2 are mass fraction of solute and solvent, Tg_1 and Tg_2 are glass transition temperatures (K) of solute and solvent (138 K), respectively. Accordingly, c is the ratio of specific heat change of solute to solvent at the glass transition temperature.

Granule residence time (*RT*) is a crucial spray drying parameter from two points of view, namely, with regard to a perfect drying of feed sprays and in the adjustment of particle temperature to decrease thermal degradation of heat-sensitive constituents. Furthermore, this parameter also influences product quality attributes, especially solubility and bulk density. Theoretically, the primary *RT* is evaluated from the time required by the sprays to travel from the nozzle and hit the base of spray drying compartment wall or leave at the outlet. On the other hand, the secondary *RT* can be explained as the time required by a granule to slide along the wall from the hitting point to the exit [80]. Even though the direct measurement of *RT* in a spray drying compartment through experimental is troublesome, the latest progress in mathematical modeling and computer simulation methods provides *RT* estimation more effectively.

3.5. Evaporation of Moisture and Particle Formation Parameters

Many points of the granule development phenomenon in spray drying are restricted by the interrelation between surface decline and migration of the solutes via diffusion mechanisms. The ability of the solutes to migrate alters during the evaporation step due to the rise of solution viscosity or precipitation process [81]. A generally accepted estimation of the evaporation rate in a spray drying process refers to the "d^2 law" [82]. This approach is drawn contingent on the reality that, during the constant drying rate period, the steady-state evaporation of a liquid spray of diameter d is equivalent to its surface area.

$$\mathrm{d}_{(t)}^2 = \mathrm{d}_0^2 - \kappa.t \tag{10}$$

The initial diameter, d_0, of the sprays was evaluated using the mass balance:

$$\mathrm{d}_o = \left(6\dot{V}/\pi f\right)^{1/3} \tag{11}$$

which is applicable on the grounds that the frequency, f, and the volumetric flowrate of the feed solution, $\dot{V}$, are selected such that monodisperse operation is reached.

Hence, the Peclet number (P_e) relationship can be computed using Equations 12 and 14. Accordingly, Peclet number can regarded as the key governing parameter of the spray development in the drying process. Therefore, the granule formation can be estimated [83]:

$$dC/dr = P_e.C \tag{12}$$

where C is the concentration of the solute on weight-by-weight basis, r is the spray radius, κ is the evaporation rate, and $\mathcal{D}$ is diffusion coefficient of the solute in the solvent. The steady-state evaporation of a spray in an infinite, uniform, stagnant gas was described by Fuchs et al. [84]:

$$\mathrm{r}^2 = \mathrm{r}_0^2 - 2\,\mathcal{D}.\frac{\rho_g}{\rho_l} ln\left(\frac{1-Y_\infty}{1-Y_s}\right).t \tag{13}$$

$$P_e = \kappa/\mathcal{D} \tag{14}$$

The evaporation rate (κ) is easily calculated using Equation 15 in which the steady-state spray temperature, T_e, can be obtained from iteration using Equation 15 [85]:

$$\kappa = 8\,\mathcal{D}.\frac{\rho_g}{\rho_l} ln\big((1 - Y_\infty)/(1 - Y_s(T_e))\big) \tag{15}$$

$$\frac{\Delta H_v}{C_p} = -\frac{(1-Y_s(T_e))^{1/Le}(T_\infty - T_e)}{(1-Y_\infty)^{1/Le} - (1-Y_s(T_e))^{1/Le}} \tag{16}$$

$$L_e = \lambda_{g/\,(C_p.\rho_g.\mathcal{D}\,)} \tag{17}$$

As the moisture is continuously removed from the spray, the solute dissolved in the liquid achieves a concentration beyond its equilibrium concentration and leads to develop a thin coating layer at the spray surface defined as "*crust development*". The above detailed explanation suggests that operating temperature and composition of the gas phase are the most influential parameters in this stage, as they directly affect material properties such as density, diffusion coefficient, specific heat capacity, and heat conductivity [85].

3.6. Product Separation Parameters

Cyclones are broadly utilized in the chemical, cement, fertilizer, food, and pharmaceutical industries for their easy operation and low operating expenses. Commonly, cyclone separators are able to separate about 50-99% particulate matter up to 5 to 25 μm from the gas stream [86-87]. Basically, the overall capabilities of a cyclone separator are characterized by flow pattern, pressure drop, and collection efficiency. High tangential velocity is needed in the cyclone to ascertain good dried granule separation from the drying air stream, specifically for the fine powders [58]. When the gas comes into the cyclone, its tangential velocity (V_{ct}) enhances with the decrease in the cyclone's radius, as represented by:

$$V_{ct} \approx r^n \tag{18}$$

Although, with the exception of wall friction, the value of *n* should be equivalent to 1.0 in many real observations. However, the observable *n* value has been reported to vary from 0.5 to 0.7 over a wide range cyclone radius. Generally, for cyclone equipment operated at ambient pressure, the fan limitation requires a maximum allowable pressure drop equivalent to a cyclone inlet velocity range from 20 to 70 feet per second. Therefore, cyclones are commonly designed for an inlet stream velocity of 50 feet per second.

Because a spray drying system usually employs cyclone separators to separate the dried particles from the drying medium stream using centrifugal force, the collection efficiency of cyclone separators enhances with the increase in particle density, particle size, speed of drying medium revolution, and drying medium flow rate. Theoretically, the solid particles are denser than the drying medium. Hence, they will bring higher centrifugal force that direct them to the cyclone walls, where they collide with and lose their momentum. This magnitude of the centrifugal force can vary from 5 times gravitational force in large, low velocity unit to 2000 times gravitational force in small, high-pressure units [88]. In addition, the high value of both revolution and flow rate of the drying medium promotes the creation of swirling movement inside the cyclone chamber that increases the probability of the dried particles to strike the cyclone wall. As a result, they will get separated easily from the drying medium. Pressure drop between the inlet and outlet sections of a cyclone is another operating parameter that potentially affects the collection efficiency. In fact, the increase in air flow rate does not only enhance the separation efficiency of a two-stage cyclone separator, but also powerfully alters the stratification range. Furthermore, the centrifugal force also enables a complete separation of particles above 5.0 μm in the first cyclone, even if the pressure drop is low. However, when the pressure drop surpasses a certain value, there is no further effect on the cut-off particle size and the maximum particle size [89]. The pressure drop depends on the cyclone dimensions and its working conditions.

In addition to the aforementioned operating parameters, the dimensional geometry of a cyclone, such as cone length, body length, ratio of accept port to body diameter, and the roughness of its internal surfaces also influence the separation efficiency [90]. The main design parameter that determines the collection efficiency of a cyclone is its diameter. A small-diameter cyclone operated at a given pressure drop has a higher efficiency than that of a large-diameter one. Indeed, the reduction of gas-outlet duct diameter also potentially increases the powder separation efficiency. Depending on their geometric proportions, the friction loss through cyclones may vary from 1 to 20 inlet-velocity heads [91]

$$h_{vt} = 0.0030.\rho.V_c^2 \tag{19}$$

where h_{vt}, ρ and V_c are the inlet-velocity head (inches of water), gas density (lb/ft^3), and average inlet-gas velocity (ft/sec), respectively.

In practice, the pressure drops (Δp_{cv}) and the friction loss (F_{cv}) through a cyclone are most preferably stated in terms of the velocity head evaluated on the nearest inlet area (Equation 20). In addition, the cyclone friction loss, F_{cv}, is a direct indicator of the static pressure and power that a blower must provide. Although cyclone separators offer some advantages, namely low capital cost, ability to operate at high temperatures and ability to handle liquid mists or dry materials, they also suffer from remarkable shortcomings, such as high operating costs (due to pressure drop), low efficiencies for separating small particles (<5.0 μm), and difficulty to process "sticky" materials.

$$F_{cv} = \Delta p_{cv} + 1 - \left(\frac{4.Ac^2}{\pi \mathcal{D}_e^2}\right) \tag{20}$$

where F_{cv}, Δp_{cv}, A_c, and $\mathcal{D}_e$ are friction loss (inlet-velocity heads), pressure drop (inlet-velocity heads), cross-sectional (ft^2) and diameter of the gas exit (ft) of the cyclone, respectively.

4. Common Characteristics of Spray Drying Products

Moisture content (*MC*), water activity (a_w) and glass transition temperature (T_g) are the key parameters that determine the shelf life and storage conditions of food powders attained from the spray drying process. If the moisture content and water activity of the products are well below 6% and 0.3, respectively, then they are regarded as stable products [92]. Water activity (a_w) is one of the main parameters that influences the shelf life of spray-dried powder [93]. In fact, a larger water activity value also indicates a higher free water content in the powder products and hence shortens their shelf life [94-95]. The presence of an adequate amount of free water quickens not only the microbial spoilage, but also various chemical reactions, such as enzymatic, non-enzymatic browning, lipid oxidation, etc. Usually, the a_w values of the spray-dried granules range from 0.2 to 0.3 [95]. Practically, the recommended a_w values of a stable granule range between 0.2 and 0.6 [96-97]. Solubility is the ability of granules to completely dissolve in water to establish a homogeneous mixture or aqueous solution. This parameter is a basic requirement to assess the powder nature in an aqueous solution, as it is an indicator of powder reconstitution quality [93].

Grabowski et al. [98] observed the enhancement of sweet potato powder solubility with the increase in maltodextrin concentration used as the carrier agent. Powder with high solubility is usually preferred for food applications [97]. Hygroscopicity shows the ability of solid materials to imbibe moisture from the surrounding air. Therefore, this characteristic influences the storage conditions and stability of the powdered products. Commonly, powder samples with low hygroscopicity are more facile to handle, pack, and store [95]. The hygroscopicity index of a powder is acceptable if ≤ 20 g/100 g [99]. Glass transition temperature (T_g) is also a simple indicator of powder stability during storage [100]. At a temperature higher than T_g, the molecular excitement in the powder intensifies and leads to contribute thermodynamic, chemical, and structural transformations, especially stickiness and crystallization [101]. Nevertheless, storing powder products at temperatures below the T_g value can lead to longer storage times [95]. Generally, foods with high sugar content demonstrate a low glass transition temperature as a consequence of their low molecular weight [63, 102]. In addition, a higher value of moisture content leads to increase molecular mobility and hence, reduces the T_g of the product [103].

In practice, a higher value of glass transition temperature of food products inhibits the physicochemical and transport properties and thus expedites the deterioration rate [104]. Actually, powder stickiness as one of the technical issues related to spray drying is strongly related to the plasticization of the amorphous small sugar molecules, such as glucose, fructose, and sucrose [105-106]. Although it is economically viable, a rough approach to prevent powders stickiness is by spray drying at temperatures below T_g + 20°C [66]. Therefore, incorporation of carriers with high T_g can decrease the water plasticization of the particle's surface, which substantially reduces powder adhesion to the spray dryer's chamber wall [106]. The increasing molecular weight of the amorphous fractions by incorporation of carriers, such as maltodextrins and gum Arabic into the feed mixture, decreased the stickiness of powder to the surfaces in the spray dryer. An increase in carrier agent concentration or a decrease of dextrose equivalent (DE) of maltodextrins improves product yield and solubility, but leads to a significant reduction in moisture content, water activity, and bulk density [66].

In general, the increase in air inlet temperature induces the enhancement of powder's porosity and subsequently reduces powder's bulk density. Powders with a lower bulk density indicate they are more soluble in water. Fluidity is a measure of the ability of the sample to flow freely in a constant and symmetrical way that can be identified based on Hausner ratios (*HR*) and Carr's compressibility indices (*CI*) [107]. Theoretically, the smaller the possibility of interaction between the powder particle surfaces will result in their lower cohesion and lead to the better the flowability [108]. Iqbal & Fitzpatrick [109] observed that the enhancement of the powder's moisture content improved the cohesion between the powder granules, which consequently decreased the flowability. The flowability of fine particles can be categorized using HR as follows: (a) 1.0< HR< 1.1, the fine particles are able to flow freely; (b) 1.1< HR< 1.25, the fine particles are classified as medium-flowing powders; (c) An HR value between 1.25 and 1.4 is a clear indication of hard to flow powders; and (iv) If the HR of fine particles is higher than 1.4, they are extremely

difficult to flow. Additionally, the flowability can also be characterized using *CI* as follows: (a) 5< CI< 15 indicates that the fine particles possess exceptional flowability; (b) 15< CI< 24, good flowability; and c) CI > 25 is an indicator that the fine particles also suffer from poor flowability. The *HR* value can be calculated as $HR = \frac{T_d}{B_d}$, the CI can be estimated as $CI = 100 \times \left(\frac{T_d - B_d}{T_d}\right)$ with T_d and B_d are respectively the tap and bulk densities.

Granule size distribution predominantly controls the product's characteristics, such as solubility, agglomeration, and microstructure. Although someone can expect that the resulting powder granules have a relatively fine structure with no observable cracks or fractures, some granules may suffer from structural distortions on the surface that are likely due to direct exposure to heat, friction, rapid water evaporation, or inadequate feed concentration for complete encapsulation [110]. The wrinkled and concave external surface exhibits general characteristics of all spray-dried powders, which is probably due to irregular shrinkage and rapid hardening of smaller droplets and low moisture content in the course of the falling rate period of the drying process [111-112]. The powder granule size obtained from spray drying at 160ºC using an equal portion of maltodextrin and gum Arabic spreads broadly and ranges from 1.1 to 22.5 μm for green tea powder [110] and from 10 to 20 μm for barberry powder [113]. With regard to the powder's morphology, the use of a mixture of carrier agents comprised of 6% maltodextrin and 2% gum Arabic produced the smallest powder size [66]. The powders produced using maltodextrin with 20DE are larger, amorphous, and all are piled up with a strong attraction to each other. Meanwhile, when maltodextrin with low DE or gum Arabic is employed as a carrier agent, the granules produced were more spherical with smaller due to their larger molecular weight and higher T_g [66].

The physical characteristics of the coating material have an important role in preserving the core from undesirable oxidation. Ubbink [114] classified the influential factors of product stability as viscosity-related and structure-related. In practice, feed viscosity controls the physical stability, while the particle structure determines the chemical stability of the spray dried product. The dynamic structure of the spray-dried products strongly depends on the density of glassy matrix, which is conversely associated to the molecular weight (MW) of the carrier agent used. The higher the density of the glassy matrix results in the slower the oxidation rate of the products [114]. In fact, the use of a higher inlet temperature and aspiration rate inherently produces powders that reassemble and create a dispersion more easily due to a uniform dispersion of the steric stabilizer on each particle. In addition, a high inlet temperature and aspiration rate lead to speed up the drying rate and subsequently improve homogeneous distribution of dextran in the particles [115]. However, the mechanism is highly complicated as the result of the interrelationship between MW of the carrier agent, T_g, and the density of the carrier agent matrix. From bioactive compounds retention, the resulting powder obtained at high inlet and outlet air temperatures and low homogenization rate demonstrated a higher value for both total and surface phenolic contents, and antioxidant activity [71, 102]. However, products without incorporation of carrier have a higher agglomeration tendency, which can reduce their direct exposure to the air and protect the bioactive compounds from deterioration [113, 116-117].

An elevated drying temperature may induce an enhanced oxidation in the spray drying of lipophilic core constituents, such as polyunsaturated fatty acids and cubosome [115, 118]. In the course of spray drying, when the particle temperature increases beyond a certain level (depending on the nature of the protein), the tertiary structure of protein begins to disintegrate and gradually alters the secondary structure [117]. In addition, micron size droplets leaving the atomizer also potentially suffer from high interfacial stresses caused by a very high surface area to volume ratio. Haque & Adhikari [119] found that stabilization of protein against thermal and interfacial stresses by incorporation of low-molecular weight sugars that function as protectants and stabilizing agent can significantly control protein denaturation in spray drying. Encapsulation efficiency that was calculated based on the total/surface phenolic content ranged widely from 29.79 and 99.73% [102]. Therefore, an appropriate choice of spray drying parameters allows the retention of the appearance, color and chemical composition of the products [120].

Based on their study on the propolis encapsulation, Baysan et al. [102] found that the moisture content and water activity of the products increased with the increase in the inlet air temperature and the decline of the outlet air temperature. On the other hand, Fazaeli et al. [66] noticed that a higher inlet air temperature triggers an increase in product yield and solubility and a decrease in bulk density, moisture content and water activity. The observed phenomena were likely caused by crust development that is resistant to heat and mass transfer and makes the removal of bound water from the sprays was more difficult. Furthermore, such enhancement of the inlet air temperature and homogenization rate together with the reduction of outlet air temperature caused the decline of the glass transition temperature of the products. An increase in homogenization rate results in a smaller spray size that consequently enhances the surface area [121]. However, increasing the surface area induces rapid crust development at high inlet

and outlet temperature, which retard moisture removal. An increase in compressed air flow rate improves product yield and bulk density, but leads to reduce moisture content, water activity and solubility [66].

5. Current and Future Potential Applications of Spray Drying

Today, the commercial applications of spray dryers are growing with greater reason. For instance, food industries apply spray drying for the transformation of fruit and vegetable juices into instant granules and blends, preparation of instant coffees and teas, drying of eggs and dairy products, ice cream blends, and encapsulation of flavors, colorants, and essential oils [122-124]. Much progress has been made over the past few years in the use of spray drying for biology. Many studies have demonstrated the equivalence of spray drying to other drying techniques for stabilizing biological materials. Moreover, investigations revealed that protein aggregation during spray drying was most likely caused by the air–liquid interface of the atomized spray and the exposure of the particle droplets to excess temperature T_g during dry powder collection [125]. The spray drying process has also been widely used as a vaccine stabilization process. When combined with aseptic filling technology, the spray drying process provides yield advantages over lyophilization due to the continuous flow nature of the spray-dried particles [126].

Microencapsulation provides a high productivity process by which the granules or sprays are overlaid with either organic or inorganic constituents. The core material is situated inside the coating layer. Microencapsulation studies of several vitamins based on spray drying have been widely studied, such as α-tocopherol, ascorbic acid (vitamin C), folic acid, and B12 [127]. This process is targeted to control the liberation of the core materials at an expected duration and establishing their concentration in the preferred environment [128-129]. In the interest of producing microcapsules, two aqueous solutions are utilized, where one of them carries the core materials and the other one bears the coating materials. The two solutions are atomized into the drying air inside the drying compartment, and coating substances are subsequently solidified on the core materials during the evaporation of the moisture, thus creating microencapsulated products [67, 130]. Encapsulation provides numerous advantages, two of which are the protection of the products from undesirable thermal deterioration and enhanced final product functionality. However, it is necessary to bear in mind that the actual spray-dried materials are not completely encapsulated. The exclusive spray drying applications in the food and non-food sectors are presented in Table 2.

The latest advances in spray-drying technology include the development of a novel heatless spray-drying technology. This technology offers an energy-efficient alternative to conventional heat-based spray-drying methods that could potentially degrade highly valuable products. However, the scale-up of this technology to its commercial scale is currently in progress, and one of the applications is for food flavoring and nutraceuticals manufacturing. Other latest initiations include the potential to produce nano-sized powders with distinctive properties and the utilization of superheated steam and carbon dioxide to sterilize products while spray-drying.

6. Advantages and Disadvantages of Spray Drying

In comparison to other drying processes for the production of powdered products, such as oven drying, fluidized bed drying, pneumatic drying, vacuum drying, freeze drying, etc., spray drying offers some remarkable advantages [11]: (1). It is easy to change the drying conditions, adjust product quality standards, and continue operations that allow high throughput with excellent flexibility to be fully automated, (2). Excellent heat and mass transfer mechanisms that facilitate rapid drying rate and short operation, (3). A relatively uniform morphology, controlled-sized, high-solubility dried, and hollow-structured products can be obtained, thus lowering their bulk density, (4). The reconstitution makes the spray-dried products look as fresh as their original ones, showing high product quality, (5). The spray-dried products can be packaged and transported more easily, (6). Suitable for both thermally labile and thermally resistant foods (7). Fewer and/or no moving parts are directly exposed to the product, minimizing corrosion problems, (8). Versatility to handle various characteristics of feedstock, with the only mandatory requirement being that it be capable of being pumped (solution, slurry, paste, gel, suspension, or melt).

However, the spray drying process also suffers from some considerable shortcomings, namely (1). The equipment is complex and requires a large area, (2). High capital and overhead costs (the equipment requires a significant initial and ongoing maintenance investment), (3). Only works for feeds that can be atomized, (4). Being a convection dryer, its thermal efficiency is relatively low, generally only around 30% to 40% and (5). The technology remains less developed [17]. Among those drawbacks, high installation costs and the removal of residual aromatic compounds remain the most important weaknesses to consider [17].

Table 2. Applications of spray drying in food and non-food products derived from agricultural produce.

Applications	Performance and Product Properties	Optimum condition	References
Food products			
Corn products	Y: 36.19, S: 94.7, MC: 1.97, PD: 31.02, ρ: 0.79, a_w: 0.13, W: 128.05	SC: 48% (w/w) pulp, IAT:172°C, PS: 0.56 L/h	Marques et al. [131]
Corn starch	resistant starch (RS) 23.08%; relative crystallinity 23.00 ± 0.28 %	PS: 400 L/h, IAT: 160ºC, FR: 15%, SS: 1%	Shang et al. [132]
Oat starch	Slightly higher AC (34.44 %) than the native oat starch (31.75 %)	PS: 0.6 L/h, IAT: 170ºC, OAT: 50ºC	Shen et al. [133]
Dairy products (whole milk, skim milk, whey protein)	Y: 30 – 40, S: 94.7, MC: 5.35, PD: 15 – 25, a_w: 0.176 – 0.356	SC: 6.5 – 16.0 % (w/w), IAT:150–250°C, OAT: 149.8°C	Linke et al. [15]; Koca et al. [134]
Edible protein products	Y: 30 – 40, S: 94 – 98, MC: 0.0778, PD: 0.495, OHC: 1.16, FC: 127.08, FS: 96.99, WHC: 2.25, a_w: 0.176 – 0.356	SC: 25% (w/v), IAT:185°C, OAT: 90°C, pH: 7	Zhao et al. [135]
Edible oil products	EE = 91.3, Y: 12.99, PD: 10 – 15, ρ: 0.648 – 0.811, MC: 3.49 – 4.79	SC: 10 – 20% (w/v), IAT:180°C, OAT: 90°C, PS: 6 mL/min	Zhang et al. [136]
Egg-based products	Y: 56.27, MC: 5.85, PD: 10 – 15	SC: 10 – 20% (w/v), IAT: 200°C, OAT: 85°C, PS: 1.4 L/h, AS: 20,000	Medina-Torres et al. [137]
Flavoring and bioactive nutraceuticals compounds	EE: 26 – 96	SC: 10 – 20% (w/v), IAT: 150 – 170°C, OAT: 85°C, PS: 1.4 L/h	Furuta et al. [138]; Farouk et al. [139]
Fruit and vegetable products	EE: 78 – 85, MC: 3.19, pH: 3.4, Total phenolic content: 903 mg GAE/g	SC: 25-45% (w/v), IAT: 145°C, OAT: 48 – 76°C, PS: 1.4 kg/h, AS: 11,300	Sarabandi et al. [140]; Ghalenoe et al. [141]; Khaire & Gogate [142]
Infant foods	pyridoxine hydrochloride (0.99), DL-a-tocopheryl acetate (8), L-carnitine (20.4) mg/100 g DM	SC: 10 – 20% (w/v), IAT: 148.7°C, OAT: 85°C, PS: 342.4 mL/h, AS: 2,0000	Lee et al. [143]; Masum et al. [144]
Instant coffee and tea	EE: 82 – 99, Total phenolic content: 322.06 mg GAE/g, epigallocatechin gallate: 11.4%, PD: 8.3	IAT: 136°C, WM: 10.3%, AS: 6.8	Dao et al. [110]
Meat and fish products	EE = 67 – 83.77	IAT: 180°C, OAT: 90°C WM: 10%, PS: 4 mL/min, and NS: 5 s	Rahim et al. [146]
Sugar products	EE = 99, Y: 12.99	SC: 6.5 – 16.0 % (w/w), IAT:150 – 160°C, OAT: 84– 85°C	Sobulska & Zbicinski [147]
Wheat based products for bakery purpose	EE = 99, Y: 95	IAT:150°C, OAT: 115°C	Guraya et al. [148]; Tafti et al. [149]
Non-food products			
Antibiotics, vaccines, vitamins, yeast and tannin products	Y: 7 – 69, AAO: 21 to 51.4, MC < 6.3, ρ: 0.09 – 0.3, a_w: < 0.5, HR: 1.09 – 1.57	SC: 9.1 – 16.7% (w/v), IAT:180°C, OAT: 40°C, PS: 5 mL/min	Teixeira et al. [150]; Tomaro-Duchesneau et al. [151]
Detergents, soaps and surface-active agents	EE = 91.3, Y: 12.99, PD: 60.48, ρ: 0.37, HR: 1.27, MC: 3.49 – 4.79	SC: 40% (w/v), IAT:250 – 300 °C, OAT: 90 - 100°C, PS: 4 kg/h, pH: 7 – 8	Siwayanan et al. [152]
Dyestuffs, pigments	Y: 50.5 – 62.4, PD: 60.48, MC: 5.8 – 9.4, a_w: 0.269–0.317, CR:70.2 – 100	SC: 40% (w/v), IAT:100°C, OAT: 40°C, PS: 4 g/min	Souza et al. [153]
Enzymes, hormones, and amino acids	CR:80	IAT:130°C, pH 6.4 – 7.2	Pinto et al. [154]
Fertilizers	EE: 92 – 136, SD: 488 – 534, PD: 5 – 15, CR < 50	SC: 40 – 50% (w/v), IAT:180°C, OAT: 40°C, PS: 10 mL/min	Franca et al. [155]
Pesticides, herbicides, fungicides and insecticides	EE: 5-52, PD: (8.29– 11.35, a_w: 0.19-0.26, CR < 0.1042	SC: 40 – 50% (w/v), IAT:140°C, OAT: 85°C, PS: 1.1 L/h	Ahsaei et al. [156]

* Yield (Y, %)), moisture (MC, %), water activity (a_w, -), solubility (S, %), particle density (PD, g/mL), density (ρ, g/mL), wettability (W, s), solid concentration (SC, %), inlet air temperature (IAT, ºC), outlet air temperature (OAT, ºC), feed flow (PS, L/h), feed rate (FR, %), starch suspension (SS, %), amylose content (AC, %), encapsulation efficiency (EE, %), wall material (WM, %), needle speed (NS, s).

7. The Economics of Spray Drying

The economy of spray drying improves with the increase in its capacity, especially due to three parameters: (a) there is no significant difference in labor requirements regardless of the size of the equipment, thus reducing the cost per mass as the throughput increases; (b) a large capacity spray dryer is usually constructed as a single unit, thus significantly reducing the rate of increase of the first cost and payback cost as its throughput increases; and (c) the superiority of continuous operating mode becomes more evident at large throughputs [157]. Regardless of the size of the spray drying equipment, only one man is recommended to be assigned to operate the dryer. Therefore, the labor component of the total cost becomes negligible as the size of the drying equipment increases [158]. In addition, spray

drying also has a low maintenance requirement because it only has two moving parts: the main circulating fan and a high-pressure pump or centrifugal disc for atomization, and the technique naturally contributes itself to continuous operation [159]. Surprisingly, differences in the temperature increments also do not significantly determine the operating costs [160]. However, changes in solid concentrations cause much more appreciable cost variations than do differences in temperature. The incorporation of deflocculants and dispersants in the feed has made the spray of feed containing high solid concentrations possible.

When comparing spray dryers with other kinds of drying equipment, there is a critical capacity for a specific application [158]. However, the appropriate critical point varies for each type of application. Fortunately, the advancement of equipment design by spray dryer manufacturers in the past decade has successfully brought down this critical point capacity. The design, arrangement and installation of a spray dryer, for example by doubling the investment cost would not significantly influence the overall economics. Although combining burners with fire either using oil or natural gas would increase the investment cost by around 10%, this strategy would likely reduce operating costs due to the use of cheaper fuel. An important fact to consider is that for certain applications, the products of fuel combustion are hazardous to the dried products, and thus indirect heating would be needed. As long as the inlet drying air temperature can be achieved by the use of steam coils at the corresponding operating pressure, this situation causes no problem. In addition, its investment cost would not be higher than that for the spray dryer with direct fire heating equipment. Nonetheless, for higher inlet drying air temperatures, there is a considerable rise in investment and operating costs. Indeed, this rise would be even larger if the system required a temperature higher than 600°F.

Furthermore, the type of product collection equipment used in the spray dryer may significantly influence the cost of spray dryer installations [161]. For instance, a single bank of high-efficiency cyclone collectors without secondary collectors can be a better choice [86, 87]. But if cloth bag collectors are used, or when stainless steel is an obliged collector material, the cost of the collector may be close to 50% of the total dryer installation. If cloth bag collectors' lives are short enough, the operating cost at the exit end of the system may be another important factor to be considered [162]. In some cases, spray drying can remove the need for other processes both before and upon drying. A clear example can be found in the conventional spray drying of ceramic bodies, which requires eight separate unit operations with many handlings between each. These unit operations consist of ball milling, blunging, filtering, tray drying, grinding, milling, classifying, and the final pressing [163]. The application of spray drying gets rid of the requirement for all but ball milling, blunging, drying, and pressing. In certain conditions, the savings in the drying operation itself are overshadowed by the savings in the removal of unnecessary equipment.

There are other conditions where the essential advantages of a spray dryer make the overall operating costs negligible. As a case in point, the control of product quality in spray drying is generally so good that enormous savings could be achieved by the remarkable reduction of rejects. However, the degree of these unconventional strong points will strongly depend on the particular implementations, and there will be no spray dryer equipment manufacturers who are able to handpick the advantages of spray drying.

The figures demonstrated here show that spray drying is not always costly and can still be an attractive drying method, especially for large-scale applications. Nevertheless, when attention is focused only on a few cost components, limited economic considerations are not always appreciable for spray drying.

8. Some Problems Associated with Spray-Drying Process

Disregarding the diverse strengths demonstrated by spray-drying technology, when standard spray-dryers are employed, their yields are greatly dependent on the equipment's operating capacity. The yields are high in larger-scale spray-dryers since the fraction lost is very little compared to the total production volume [164]. In contrast, the fraction lost is considerably higher in both laboratory and bench-scale spray dryers, where their yields reach about 20 to 70% [165]. In general, the low yield is mainly ascribable to the loss of the product adhering to the drying chamber wall and the quantity being relatively constant. Furthermore, fine particles (<2 μm) are commonly carried over by the exhaust air due to the low separation cyclone efficiency [89].

There are also some serious worldwide issues found during the application of spray drying for powder-form product manufacturing. In particular, low-quality powder and powder consistency, bearding, sub-standard hygiene, maintenance wear and tear, and safety [166, 167]. Product build up and wear part misalignment potentially cause the formation of low-quality powder and powder consistency, while nozzle bearding is the main cause of low productivity. Industrial experiences reveal that both products build up and nozzle bearding may be affected by dryer configuration, the use of a wider spray angle, improper powder formulation, and nozzle design [168]. Product build-up drips on the chamber and becomes seared particle deposits that reduce powder quality [169]. Similarly, the misalignment between the swirl chamber and orifice due to the use of traditional nozzles may induce inconsistent spray performance and reduce powder quality. Nozzle bearding demands for a more frequent cleaning up and causes

short run times, which slow down production and trigger low productivity. Meanwhile, radial O-ring scratch due to fitting together the component parts and complicated O-ring groove design are respectively the main contributors to reduced safety and product hygiene due to the difficulty of cleaning up the unreachable contaminants [170]. Accordingly, the high production costs may be the result of outdated dismantling procedures, broken threads, and unprotected sealing faces. Therefore, the advanced design of the nozzle can be a tough challenge for spray drying technology [168].

9. Conclusion

Spray drying is the most widely applied drying method to manufacture dried powder for agricultural produce due to its superior capabilities in terms of thermal efficiency and product quality. Considering that this technology has a very wide range of applications, this review focuses the consideration to some aspects related to its potential applications in the food industry. Apart from that, this paper also reviews several non-food applications, such as in the pharmaceutical, cleaning product, and fertilizer sectors. Some operating parameters that greatly affect the physical characteristics of the dried products, such as feed flowrate, carrier agent, and inlet temperature for the operating dryer, are also reviewed. This paper also found that water content, water activity, and glass transition temperature are the main parameters that really determine product quality in terms of shelf life and storage conditions of food powder obtained from the spray drying process. The economic aspect of the spray drying operation is also elaborated. In addition, safety and technical issues related to the implementation of spray drying for food applications are also discussed for further development. Hence, efforts are currently undergoing to fulfill the gap between academia and industry, especially those who do work together coherently.

9. Declarations

9.1. Author Contributions

Conceptualization, A.C.K. and D.H.W.; methodology, T.C.P.; software, M.A.; validation, T.D.K.; formal analysis, T.D.K.; investigation, D.H.W.; resources, T.C.P., M.D., and M.A.; data curation, D.H.W.; writing—original draft preparation, A.C.K.; writing-review and editing, A.C.K. and T.C.P.; visualization, M.A.; supervision, A.C.K.; project administration, M.D. and M.A.; funding acquisition, A.C.K. All authors have read and agreed to the published version of the manuscript.

9.2. Data Availability Statement

Data sharing is not applicable to this article.

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9.4. Institutional Review Board Statement

Not applicable.

9.5. Informed Consent Statement

Not applicable.

9.6. Declaration of Competing Interest

The authors declare that there is no conflict of interests regarding the publication of this manuscript. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, and redundancies have been completely observed by the authors.

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