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DRYING TECHNOLOGY – CURRENT RESEARCH AND INDUSTRIAL APPLICATIONS

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Review Based Book Chapter

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REVIEW BASED BOOK CHAPTER

SPRAY DRYING AND ENCAPSULATION – TECHNOLOGICAL ASPECTS AND APPLICATIONS

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Abstract

Spray drying is increasingly gaining attraction in the food industry, demonstrating a growing prevalence in the fabrication of not only a vast spectrum of elements, but also functional foods, pharmaceuticals, and nutraceuticals, amongst various drying methods by providing microbiological stability and preventing chemical and biological deterioration. It also minimizes storage needs and shipping costs and leads to the creation of a product with unique features like quick solubility along color enhancing or concealing an astringent taste in food items as its one of the finest and most potent strategies to enhance the durability and sensory qualities of products is the spray-drying of liquid extracts. Its popularity in the industry stems from its efficiency in drying even the most challenging substances. The preference for spray drying encapsulation often stems from its economic efficiency relative to alternate encapsulation techniques. The resulting powder is extremely stable and immune to chemical and microbiological alterations (such as oxidation and hydrolytic reactions) due to its low moisture content and low water activity.

Keywords
Spray Drying, Spray Dried Powder, Encapsulation, Drying Technology, Powder Quality

1. Drying Technology: A Preservation Technique

Drying is an ancient preservation technique that is still widely used today. The process involves using heat to remove moisture from food, which helps keep it fresh for longer periods. Drying of food items can be categorized into two main types: a) in-air drying and b) in-vacuum drying, depending on the method of dehydration used. There are various heat application techniques for drying, including convection, conduction, radiation, microwave, radio frequency, and Joule heating. Drying materials can be in the form of wet solids, liquids, suspensions, or pastes, and they need to undergo downstream processing to enhance their value and extend their storage and transportation time. However, conventional hot air drying may harm the preservation of bioactive components in these heat-sensitive materials. High temperatures can lead to product deterioration, denaturation of active substances, case hardening, discoloration, and other negative effects [1]. The advantage of selecting dehydration as a method to conserve food lies not solely in its technical simplicity but also in its economic benefits. The expenses associated with processing, packaging, transporting, and storing dried commodities are less compared to those associated with canned and frozen goods. Generally, the food dehydration process is divided into three stages a) initial preparation before drying b) the drying process itself, and c) treatment after drying. The impact of these steps on the end product's quality hinges on the type of processing material utilized and the envisaged use of the final product [2-4].

Drying is an energy-intensive process in postharvest processing, used to reduce the water content of various fruits, vegetables, agricultural products, and herbs. By reducing the water activity to a level that inhibits microbial growth, enzymatic activities, and other deteriorative reactions, the shelf life of biologically derived items can be extended. Drying is especially important for herbs, as it allows the extraction of active chemicals. Moreover, dry products are lighter, resulting in lowering shipping costs. Biologically derived products have diverse physical, chemical, and biological characteristics. To meet different quality and price requirements, a wide range of dryers have been developed for dehydrating and preserving these items. While approximately 100 dryer types are available commercially, the technical literature describes over 500 dryer types. Dryer design varies due to differences in product characteristics, heat input methods, operating temperatures & pressures, and quality standards for the dried product. Traditional dryers typically operate at atmospheric pressure, use hot air as the drying medium, and rely solely on convection for heat transfer. Batch operation is preferred for systems with limited capacity and long drying times, such as solar dryers. Drying safeguards products by reducing moisture content, offering various advantages in food preservation. It allows for early harvest, reduces shipping weights and costs, minimizes the need for packaging, and extends shelf life [5-8].

2. Drying Methods: A General Overview

In the food industry, microcapsules are typically dried using the most common methods of freeze-drying and spray-drying. These are distinct procedures, each performed under different temperatures and durations, which result in unique morphological and particle size characteristics in the dried goods. An experiment that encapsulated bioactive elements from acerola pulp, followed by freeze-drying and spray-drying, was conducted to compare the properties of the microcapsules. The results indicated that the spray-dried product contained higher levels of bioactive substances and antioxidants [9].

Traditional thermal processes for drying encompass techniques such as hot air drying, vacuum drying, and freeze drying, among others. Each method has its own strengths, for instance, hot air drying utilizes simple, safe, and cost-effective machinery. Vacuum drying is suited for materials that are prone to oxidation. Microwave technology provides rapid drying rates and uniform product quality. However, due to the complexity and diversity of component characteristics, a single drying technique often falls short in meeting the quality standards of the final product. As a solution, innovative and eco-friendly combined drying technologies, such as heat pump drying, superheated steam drying, freeze drying, vacuum sealing, and microwave drying, are gradually replacing traditional drying methods. These combined technologies aim to decrease drying time and elevate product quality [6, 10].

Freeze drying and spray drying are not only used in the food industry but also in the chemical sector, for encapsulation and drying purposes. The first method aids in the transformation of liquid products into a powder form, thus extending their usable lifespan. Certain active biological components are encapsulated to facilitate their storage and distribution. Spray drying, another method, also converts liquid food into powder form. These procedures have been long implemented in the dairy industry and have recently found applications in the pharmaceutical sector, primarily for drug delivery. Freeze drying is an excellent choice for heat-sensitive materials, as it can preserve the color, taste, and nutritional value of the food. Freeze-drying, because of its steady state and lower temperature, is ideal for handling heat-sensitive substances. The freeze-drying technique integrates two pivotal stages: freezing and drying. Earlier, efforts were mainly focused on refining the drying stage, not fully considering the potential impacts of the freezing phase. As a solution undergoes freezing, it experiences several physical transformations, including reaching a supercooling state. The level of supercooling in a solution governs the characteristics of ice formation (its size, number, and form) during the freezing stage, which in turn affects the subsequent drying stage, such as resistance to the flow of water vapor. Therefore, varying levels of supercooling lead to diverse ice characteristics and subsequently, uneven drying outcomes [11, 12].

2.1. Spray Drying

The technique of spray drying, which transforms liquid meals into a powdered form, has been extensively utilized over the years to manufacture a range of products like milk powder, fertilizers, medicinal compounds with active properties, and laundry detergents [12-14]. Spray-drying offers benefits like rapid processing, flexibility, and the capacity to produce small droplets. Typically, spray drying suspensions that contain nanoparticles result in larger, hierarchically organized structures. Secondary particle shapes like dense, hollow, or even doughnut-shaped morphologies can be achieved by manipulating factors such as temperature, air flow speed, droplet size, viscosity, the size of the primary particle, the amount of solid content, and interactions between particles [15-17].

2.1.1. Working Principle of Spray Drying

The spray drying process primarily includes following steps:

1) Concentration
2) Atomization
3) Droplet interaction with air
4) Droplet drying
5) Separation

Spray drying is a method employed for transforming solid components into dry powder. It begins with a slurry, which is a mixture of liquid, solution, or suspension that is introduced into the spray dryer as a damp product. This slurry is atomized into tiny droplets, typically ranging in diameter from 10 to 500 micrometers. Due to the lack of atomizers capable of producing monodisperse droplets of very small sizes, the drying process has to accommodate a broad spectrum of droplet sizes, achieved through the use of heated gas. Unlike other drying techniques, spray drying allows for the reduction of significant accumulations of dry material downstream of the atomization zone since there is no necessity for wall contact within the spray dryer, and drying droplet collisions rarely occur. Spray drying stands out as one of the few drying techniques that can endure long viscous and sticky phases during the solidification process. Other drying procedures, such as spin flash, mill drying, or contact drying methods including mixing and kneader drying as well as one shaft and two shaft techniques, struggle with prolonged viscous stages. The success of spray drying relies on the wet product being of low enough viscosity to permit efficient atomization. This often means that the inflow concentration needs to be reduced compared to other drying methods, resulting in a higher required evaporation rate [17, 18].

Several factors, including the size of the dryer and the diameter of the droplets, allow spray drying to have quick drying times between 1 to 60 seconds. The high surface to volume ratio of small droplets facilitates rapid drying periods. For instance, a larger droplet with a diameter of one millimeter has a hundred times less specific surface area for an evaporating solvent compared to a smaller 10-micrometer droplet. Moreover, solidified droplets have longer diffusion lengths, which slows down the drying rates, especially during the "falling rate drying period," where the last of the solvent has to be eliminated through diffusion through the solid and the outer surface is dry. Hence, the drying periods in a spray drying process, which usually produces droplets sizes below 1mm, can be significantly reduced. The stickiness of the final dried and hot particles is an essential product quality in spray drying. Depending on the operational mode and the product's drying properties, exit temperatures can be reduced to 80-120°C, with lower temperatures achieved for certain products. However, spray drying might not be successful for products with inadequate glass transition temperatures. Despite the drawbacks, spray drying can serve as a cheaper alternative to freeze-drying for certain substances, such as blood plasma [19].

In spite of their high drying temperatures, spray dryers maintain a brief drying contact time with the core materials inside the drying chamber, often a few seconds. This typically involves an input air temperature of 150 to 250 °C and an exit air temperature of 50 to 80 °C [20]. The spray drying procedure involves atomizing liquid feed, often referred to as extracts, into the drying chamber. Here, the droplets traverse through a stream of hot-air or occasionally nitrogen. The small droplets, which enhance the surface-to-mass ratio and evaporate water rapidly, provide a larger contact surface, making the process both fast and aggressive. This minimizes heat damage to sensitive materials. The dry powder particles are then separated from the exhausted air in a separation cyclone and collected in a vessel [21-23].

The wall material used for spray drying includes sugars such as lactose and sucrose [24], gum arabic [25] and mesquite gum [26], in addition to milk proteins like sodium caseinate and whey protein [27]. However, pointed out that certain wall elements like gelatin, gum arabic, and sucrose is unsuitable for use in infant formula. Multiple wall substances are accessible, including starches such as maltodextrin, which are used for the microencapsulation of food components [28, 29].

3. Encapsulation Technique

The influence of consumer needs propels advancements in encapsulation technology for food uses. Bioactive chemical encapsulation has seen improvements due to novel dehydration methods. Encapsulation serves as a method to safeguard an extremely susceptible substance which forms micro or nano scale formations after enclosing a bioactive center in what is referred to as wall substances. The purpose is to boost the stability of bio actives for targeted, controlled or postponed release while shielding them from harsh elements such as light, moisture, and oxygen [30]. In relation to oils that have not undergone encapsulation, the encapsulation process bolsters the endurance and robustness of oils during their period of storage [31]. A successful encapsulation system should employ food-grade ingredients, preferably natural ones, seamlessly integrate bioactive compounds into food without altering organoleptic properties, provide enhanced physical stability, shield the encapsulated substances from heat, light, and pH changes, and enable maximum absorption of the bioactive compound [32].

3.1. Applications and Advantages

The growing demand for versatile, nutrient-rich oils in the realms of food, medicine, and cosmetics is undeniable, driven by their multifaceted utilities.

However, the high degree of unsaturation present in vegetable and marine oils introduces a risk for oxidative degradation and the onset of an unpleasant taste. Further complicating matters is the inherent instability of oils when subjected to processing and storage conditions, given their vulnerability to light and heat, which restricts their utility in the food sector. Consequently, measures to safeguard these oils are imperative to enhance their stability during management, processing, and storage [33, 34]. Such fluctuations negatively influence the product's shelf life, sensory attributes, and overall market acceptance [35]. Encapsulation, which is typically employed to resolve the problems stated earlier, is a hopeful approach that involves safeguarding the main elements from heat, light, and oxygen. It also facilitates stability, bioavailability, taste concealing, and controlled release, all while retaining the oils' functional attributes and improving their manageability [36-41].

Encapsulation of oil enhances the oxidative stability of lipids and safeguards the interior ingredients from external elements such as reactive substances, oils, flavorings, and vitamins. This is enabled by the core material's high solubility, ease of blending, and controlled release, pending the appropriate trigger. It also minimizes the evaporation of the volatile components in the core material, thereby decreasing or concealing any associated unfavorable tastes [42-45]. There are some key reasons for opting for oil encapsulation: (a) Encapsulation aids in bolstering lipid oxidation stability, a crucial element in the creation of powdered edible oil goods. This process helps in the conservation of oils by shielding them from oxidation [43] (b) It acts as a protective shield for the core ingredients against elements such as oxygen, light, and water. This is particularly relevant for vulnerable ingredients like oils, scents, and vitamins. Food oils are especially sensitive to irradiation, air, temperature, and light [46, 47] (c) Encapsulation facilitates the transformation of oils from a liquid state to a dry state, creating a powder derived from the primary components that blends easily and has high solubility. In the food industry, this conversion of liquid feeds (like flavors and edible oils) into powders with suitable handling characteristics is a critical encapsulation form [48] (d) It helps control the release of crucial contents, ensuring an appropriate delay for the correct stimulus. This characteristic, known as encapsulation, is a significant benefit in managing the release of active components in oil and flavor until they reach their intended target [49] (e) Encapsulation prevents the evaporation of volatile compounds present within the key ingredients. This results in a dry powder with superior oxidation stability and low volatility. Encapsulated oils create a dry powder with enhanced oxidation resistance and decreased volatility, making it easier to utilize in various end products such as cakes and beverages [50] (f) It helps to disguise or neutralize the unpalatable tastes of the core ingredient. Some edible oils, such as vegetable or marine oils, are highly desired in food items due to their nutritional value. Moreover, encapsulation can help solve primary problems associated with food containing 3 PUFA, like the undesired "fishy" smell of fish oil and the proneness of polyunsaturated fatty acids to oxidation, which can negatively impact food acceptance [51] and when compared to non-encapsulated oils, encapsulation improves the longevity and robustness of oils during storage [52].

4. Spray Drying Applications in Various Industries

Drying serves as a vital operation in the various sectors including pharmaceutical industry, biopharmaceutical industry, dairy industry, food industry and many more. Few of them are discussed below:

4.1. Pharmaceutical Sector

Spray drying has been an active area of technological progression over the past few decades, especially within the pharmaceutical industries. In pharmaceutical and biopharmaceutical sectors, spray drying being primarily used for the conversion of liquid drug formulations into solid states, all while preserving their therapeutic and pharmacological characteristics. This procedure, most commonly applied to remove solvents like water, is significant as it allows a drug in its solid form to stabilize both the active pharmaceutical ingredient and the additives. This stabilization considerably curtails pathways of chemical and physical degradation, such as hydrolysis, oxidation, isomerization, condensation, racemization, and interactions with other constituents present in the solution [53]. Spray drying also has been used in the delivery of pulmonary medications, including the manufacture of consistent and inhalable size particles for devices such as nebulizers, dry powder inhalers (DPI), and pressurized metered dose inhalers. Spray drying also assists in the development of mucoadhesive formulations that can effectively adhere to nasal passages, thus improving drug absorption and bioavailability. Innovations and patent submissions in spray drying technologies aimed at enhancing solubility are also underscored. Historically, the pharmaceutical industry has utilized spray drying for creating dry versions of plant-based active ingredients [54].

4.2. Food Industry

The potential of spray drying to generate a diverse array of food products, including powders from milk or soymilk, tomato pulp, dehydrated fruit juice and others, has been acknowledged. It can be employed for the encapsulation of substances like vegetable or fish oil, and dry creamer [55]. There's a growing health consciousness among contemporary consumers, leading to a surge in demand for foods fortified with bioactive or functional components, especially those derived from natural sources [54, 56].

Bioactive compounds, also referred to as nutraceuticals, are naturally occurring substances that are either essential or optional elements of our diets and positively impact human health [57, 58]. Certain bioactive compounds that enhance human health include polyunsaturated fatty acids, polyphenolic compounds, anthocyanin, and vitamins. However, their bioactivity and antioxidant properties can be compromised by various factors such as light, temperature, air, moisture, or the existence of unsaturated bonds. Therefore, encapsulation methods are employed to bolster the chemical or biological stability of these substances [59, 60]. In essence, researchers extensively review the primary use and recent advancements in spray drying and lyophilization processes for encapsulating bioactive ingredients within the food [56, 61]. Spray drying process enhances the management attributes of the items and bolsters oxidation stability by protecting the bioactive constituents, in encapsulating oils. The quality of the final product is significantly influenced by factors associated with oil encapsulation such as the temperatures at the point of entry and exit, total solids, and the wall materials utilized. Thus, this evaluation gives priority to understanding and refining the spray drying methodology for encapsulating oils used as food supplements [14, 62, 63, 64].

4.2.1. Dairy Products

The global production of dairy products has been progressively growing; for instance, from 2012 to 2016, the production rose by 5.47%, escalating from 771,262 to 815,965 thousand tonnes. Given this increased production, it's vital to preserve this higher quantity of milk for the benefit of people worldwide, particularly in regions where conditions are not conducive to dairy farming or might accelerate the spoilage of liquid dairy products. Consequently, the preference is to produce powdered products using spray drying [65]. Spray-drying is commonly employed in the dairy industry to create a range of products on a substantial commercial scale. The individual characteristics of each product depend on the ratio of protein to fat to carbohydrate, the specific type of protein, and, to a lesser extent, the process conditions applied. Due to their high moisture content, dairy products naturally have a short shelf life, despite their excellent nutritional value. To drastically decrease the microbial activity associated with moisture and to allow for cost-effective, global distribution due to reduced weight, a significant portion of the material derived from milk is dehydrated [66]. Owing to their high perishability, milk and its byproducts often undergo processes like spray drying to extend their usable lifespan [67]. Spray drying usually yields a free-flowing powder that's easier to transport, handle, and store, while also having an extended shelf life. This ease of use makes the powder an effortless addition to processed foods such as bread and sweets. The development of spray drying equipment and techniques has evolved over several years, from the 1870s until the early 20th century [68].

5. Spray Drying: Pros and Cons

A tried and tested, economical, and scalable drying method known as spray drying converts liquids directly into powders [69]. By employing the process of spray drying, bioactive elements drawn out from food wastes and byproducts can be reduced to powder form and reincorporated into the food supply chain. Spray drying has been identified as the most convenient, time- and energy-efficient approach, as it converts liquids directly into a stable powder that can be either stored for extended periods or effortlessly mixed with other substances. Even though spray drying has many advantages for different materials, it's not without its problems, some of which need attention in future development programs [70] a) minimizing scale for a more straightforward validation of new products, which often necessitates comprehensive testing b) The challenge of designing an atomization process that needs a diluted, low viscosity input and generates a broad size distribution, which may pose challenges during the drying phase c) The process of droplet recycling within the tower can lead to the accumulation on the spray tower wall and at the nozzles and can place excessive thermal stress on the product d) The shorter drying periods for larger droplet fractions can result in inconsistent drying and clumping of the final product.

6. Quality Characteristics of Final Spray Dried Product

The consistency in the quality and characteristics of the end product is crucial as these aspects are intrinsically linked with the bioactive component content, bulk density of the powder, particle size, moisture content, and a host of other physical and chemical properties [71, 72]. Many researchers also added several factors that influence the quality of the end product/powder, including atomizer speed, nozzle design, solvent used, concentration of the liquid feed, feed flow rate, inlet and outlet temperatures, airflow rate, aspirator rate, and temperature. This technique can yield particles of diverse sizes, from nanoparticles (210-280 nm) to agglomerates (2-3 mm) [14]. A low moisture content and a high bulk density are sought-after qualities in powder. Increased bulk density reduces packaging expenses while enhancing the flow of the powder. Moreover, a moisture content of less than 5% boosts product stability during storage [73-75].

Another advanced technique, nano-spray drying, is used to produce powders with particle sizes smaller than 100 nm. Reaching nanoscale dimensions is not feasible since the cyclone separator is unable to segregate extremely tiny particles during traditional spray drying [22]. Encapsulation enveloping each droplet or particle of a bioactive liquid or solid (core substance) within a polymerized shell. These small capsules can be round or irregular in shape and vary in size from micrometers to millimeters. The core elements can be solid substances, dispersions, or droplets [32, 77-80].

7. Conclusion

Spray-drying, due to its quick drying time, is frequently used to encapsulate heat-sensitive bioactive compounds. Consumers have exhibited heightened interest in food items abundant in bioactive components due to substantial research linking their intake to the prevention of chronic diseases. By decreasing the moisture content of the product, drying helps preserve the quality, inhibit microbial growth and chemical changes during storage. Both reduced water activity and content are responsible for longer shelf life of the product. The utility of spray drying in the creation of dry flavorings to maximize output and minimize flavor degradation, has played pivotal role in food industry. Spray drying is also predominantly employed in the commercial production of dry plant extracts. However, high temperatures used in the drying process can lead to heat degradation and an unstable state in thermally sensitive components. Hence, alternative drying methods and operative conditions need to be developed and standardize for multipurpose procedures.

Author Contributions

Conceptualization; validation; writing—original draft preparation, writing-review and editing, and..; visualization: M.S.

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Conflicts of Interest

The author declares no conflict of interest.

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