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Review Article

Effect of Spray Drying on Physico-Chemical and Functional Properties of Food Component Utilizing Different Carriers as Encapsulating Agents

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Abstract

A common method for preserving fruit and vegetable juices in powder form is spray drying. Achieving high-quality fruit and vegetable powders is the main goal, which necessitates optimising spray drying conditions. Sensitive bioactive compounds are harmed by high drying temperatures; however, carrier agents shield these compounds, and other spray-drying-related variables impact the product's physicochemical and microstructural characteristics. Encasing liquids into powders through spray drying is a popular and affordable method that can enhance product handling and preserve food constituents like lipids, carotenoids, tastes, and bioactive substances. In the food sector, encapsulation is the process of shielding food bioactives inside a tiny capsule for later release at specific locations. In addition to protecting delicate food ingredients, the carrier agents used for encapsulation may also preserve tastes and lessen volatility and reactivity. It's a technology that shows promise for maintaining nutritional value while enhancing the solubility and oxidative stability of the active ingredient. A thorough knowledge of the characteristics and influence of the carrier material is essential to achieving those goals. The present review focuses on the potential applications of different carriers as encapsulating agents in the preservation of functional bioactive compounds and food ingredients by spray drying technology. The process of spray drying wraps bioactive substances in porous particles. Heat-sensitive compounds can be used with this procedure because of its short drying time. Thus spray drying can be used as an essential tool in the encapsulation of a diverse range of food materials retaining their functional and nutraceutical characteristics.

Introduction

The health benefits of fruits and vegetables stem from their high nutritional content and health-promoting properties. Fruit and vegetable production is hampered primarily by their high perishability; postharvest spoiling quickly deteriorates quality and results in significant waste [1-3]. Because fruit and vegetable juice powders have a higher level of stability than their liquid counterparts, making them a viable way to cut costs associated with packaging, storing, and shipping while also minimising losses. Fruit and vegetable juices can be kept for weeks to months, while powdered products made from these juices can be kept for months or even years, depending on how they are packaged [4]. The powder form's flexibility opens up new markets and makes complex formulations possible. Furthermore, the pharmaceutical and cosmetic industries may find that the production of highly nutritious and consistently micro-structured fruit and vegetable powders satisfies their needs. The process of encapsulating solids, liquids, or gaseous materials in tiny, sealed capsules that have the ability to release their contents at precise times under particular circumstances is known as microencapsulation. Microencapsulated ingredients have made it possible to produce many products that were previously thought to be technically impossible. These ingredients are completely encased in a coating material, which either gives the original ingredient useful properties

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or removes those that are not needed [5].In food processing, encapsulation technology broadly refers to coating whole ingredients (such as raisins, nuts, and confections) as well as minute particles of ingredients (such as flavours, fats, and acidulants). These coatings can be achieved by macro-coating or micro-encapsulation techniques, respectively.

There are numerous drying methods that can be applied in an industrial setting. Chopda& Barrett [6] state that freeze drying, foam mat drying, and spray drying are the most effective techniques for producing fruit juice powder. The most cost-effective method of preserving quality through quick dehydration is spray drying. Through atomization in the drying chamber, it produces a large surface area in the form of fine liquid droplets, which results in the production of regularly and spherically shaped powder particles [7]. Although freeze-drying is thought to be the most effective method for preserving nutrients in powdered goods, its industrial use is limited by the high instrumentation costs, high energy consumption, and low throughput [8,9]. The conditions of the spray drying process, which include feed concentration, inlet and outlet air temperatures, feed flow rate, compressor air flow rate, drying air flow rate, atomizer type, and atomizer speed, all affect the quality of the finished product [10]. Low moisture content (< 5%) improves product stability during packaging and storage, while high bulk density lowers packaging and shipping costs and increases flowability [11]. The drying temperature and carrier agent have a significant impact on the physical properties of the powdered product, such as moisture content, bulk density, and particle size, as demonstrated by existing literature [12]. Therefore, additional study is required to optimise the spray drying of fruit and vegetable juices in order to determine the ideal conditions for particular types of samples. Additionally, recent efforts have been made to address the limitations of spray drying, which include the loss of heat-sensitive compounds, a wide distribution of particle sizes, and occasionally irregular microstructure. Combinations with other techniques, such as ultrasound-assisted spray drying, vacuum spray drying, ultrasound-assisted vacuum spray drying, and dehumidified air spray drying have been shown to possess advantages over conventional spray drying [13-15]. In the food sector, encapsulation is the process of shielding food bioactives inside a tiny capsule for later release at specific locations. The process of encapsulating a bioactive molecule into an outer shell—also known as a carrier material—is called encapsulation. In addition to protecting delicate food ingredients, the carrier agents used for encapsulation may also preserve tastes and lessen volatility and reactivity. It's a technology that shows promise for maintaining nutritional value while enhancing the solubility and oxidative stability of the active ingredient. By means of capping or coating, the carrier, an encapsulating agent (also referred to as exterior phase, wall material, shell, or matrix), protects an active agent from light, oxygen, pH, moisture, heat, shear, and other harsh conditions.

This paper aims to review the current state of the art in spray-drying food ingredients to create microencapsulation and to provide the necessary theoretical and practical information about this process. Therefore, spray-drying applications for microencapsulation ends are covered in this paper from four angles. It begins by concentrating on a few theoretical facets of the spray-drying procedure. The use of spray drying for the microencapsulation of food ingredients is then covered in the paper. The third section outlines the requirements for encapsulating agents and provides descriptions of a number of wall materials that have demonstrated high encapsulation efficacy. The last section provides an overview of significant recent developments in spray-drying food ingredient microencapsulation. More stability, better defense against environmental elements including oxidation, light, and temperature, ease of handling and storage, and redispersibility in aqueous solutions are all advantages of a spray-dried powder form. The produced powders have long shelf life stability because of their high quality and typically low moisture content. A range of particle designs, such as single-core, irregular, multi-wall, multi-core, and composites, can be produced by spray drying encapsulation.

Spray drying

Using a liquid stream, a spray dryer separates the solvent into a vapor and the solute, or suspension, into a solid. Typically, a drum or cyclone is used to capture the solid. A nozzle is used to spray the liquid input stream into a hot vapor stream, where it is vaporized. As the moisture rapidly escapes the droplets, solids form. Spray drying is one of the many drying technologies that is frequently used to create quick powders. Its extensive use in the food and food-related industries is attributed to its many advantages, which include reduced volume and/or weight due to lower moisture content over liquid-based goods and extended shelf life. It is frequently modified with process parameters appropriate to a specific product. Since the late 1950s, spray-drying encapsulation has been used in the food industry to turn liquids into powders and give flavour oils some protection against oxidation and degradation. The most popular microencapsulation method in the food industry is spray-drying, which is generally employed to create dry, stable food flavours and additives. The procedure is affordable, flexible (offering significant variation in the microencapsulation matrix), adaptable to commonly used processing equipment, and yields high-quality particles. Because it requires little maintenance, spray drying is thought to be the most cost-effective drying method. Basic spray-drying involves three crucial steps: atomization, the interaction between the drying gas and droplets, and powder recovery. To put it briefly, the sample feed is atomized to create the droplet prior to its contact with a hot gas, which initiates the spray-drying process. An air filter, air heater, air distributor, two fluid nozzles, drying chamber, glass bottle collection, cyclone separator, and air compressor are all parts of the spray dryer. To control the spray drying temperature in the current investigation, distilled deionized water was added to the spray drier. Before the feed was introduced, the dryer ran under these settings for roughly twenty minutes. Once the input and output air temperatures were adjusted, the feed was pumped into the spray drier through the feed pipe. The airflow rate in the dryer was 1658 kg/dry air h. The temperature of the feed was 60 °C, the temperature of the air inlet was 168.5 °C, and the temperature of the air outlet was 101.8 °C. According to Masters [16], 1 m^3 of liquid is thought to create about 2×10^{12} homogenous droplets that are 100 microns in size and have a surface area of almost 60,000 m^2. The solvent in the droplets instantly evaporates as they come into contact with the hot air within the drying chamber, producing dry powdered goods. According to the study by Hammami& René [17], an industrial comparison revealed that because spray drying uses less electricity and dries faster than freeze drying, it is about four to five times more cost-effective than freeze drying. According to Santivarangkna, Kulozik, and Foerst [18], spray drying is four times more cost-effective than vacuum drying and eight times more cost-effective than freeze drying. Additionally, spray drying has the advantage of having a relatively short drying contact time (5 – 100 s), which helps to maintain delicate quality characteristics like nutrients, colours, and flavours [19].

Emulsion-based methods use emulsifiers to keep droplets of the active ingredient in a continuous phase stable. When the solvent evaporates or solidifies, the droplets form nano-sized capsules. In order to precisely manage the encapsulation process, layer-by-layer construction depends on the sequential deposition of polymers onto a core material [20]. Polymer-based techniques of encapsulation originate from natural sources, natural and semi-synthetic polymers are great encapsulating materials. Compared to synthetic polymers, natural polymers have far fewer immunogenicity issues when used as encapsulating materials. As evidenced by the successful production of alginate-chitosan micro/nanoparticles at room temperature without the use of organic solvents, natural polymer encapsulation can be carried out without high temperatures, preventing the degradation caused by high temperatures [21]. The target component and the encapsulating materials combine to form an emulsion solution, which is subsequently used to create microcapsules through the freeze-drying process in encapsulation based on this technique. The main aim of freeze-drying encapsulation is heat-sensitive compounds [22].

Characteristics of carrier material

Choosing the right carrier material for the spray drying process is crucial since it affects the dried powder's characteristics and encapsulation effectiveness. The final product specification and the physicochemical behaviour of the ingredients were typically taken into account when selecting the material [23]. Because carrier agents affect the characteristics and durability of the food powders, adding them to the feed solution during the spray drying process is crucial. Examples of these agents include maltodextrins, gums, pectin, calcium silicate, and carboxy-methyl cellulose. The hydrolysis of starch yields maltodextrins, which offer a number of benefits including low cost and low viscosity at high solids ratios [24]. The majority of materials that are challenging to dry use maltodextrin. Gum Arabic is a naturally occurring hydrocolloid that comes from Acacia trees. Because of its low viscosity in aqueous solution and high emulsifying ability, gum arabic has been employed as an encapsulating agent in microencapsulation by spray drying. Furthermore, because of their large molecular weights, gum Arabic and maltodextrin are less hygroscopic. As a result, the finished powder has a lower moisture content because of its decreased hygroscopicity. Furthermore, the substance needs to be approved as "Generally Recognised as Safe" (GRAS) before it can be utilised in food applications [25]. A number of criteria can be used to simplify the qualities of the perfect carrier material. They should, in general, have low viscosity even at high concentrations, excellent emulsifying and diffusive abilities, and be highly soluble in the solvent. To lessen the stickiness effects of the powders, the carrier material for sugary and acidic spray-dried food ingredients should have a high molecular weight, glass transition temperature (Tg), and degree of crystallinity. Lastly, in order to shield the active ingredient from the environment, the material needs to be non-reactive and able to form films [26,27].

Type of carrier agent

Fruit and vegetable juice spray drying presents a number of difficult problems, including stickiness, wall deposition, and low yield. These problems are linked to the presence of low molecular weight compounds with low glass transition temperatures (Tg) (sucrose: 62 ºC, fructose: 5 ºC, glucose: 31 ºC), such as fructose, glucose, sucrose, malic acid, citric acid, and tartaric acid [10]. The carrier materials used in the spray drying process for food applications are mainly biomolecule-based substances (carbohydrate polymers, proteins, and lipids). Among all, carbohydrate polymers are mostly applied. More than 90% of the dry mass of the polymers is made up of sugar residues and/or their derivatives. They have the capacity to create useful modified materials that can be used to increase their needs and functions [28]. One of the most crucial components of spray drying is the carrier agent, as materials high in sugar, like fruit and vegetable juices, are very difficult to spray dry directly without one [29]. In spray drying, carrier agents are known to raise the Tg and yield percentage while lowering the stickiness and hygroscopicity of the powdered product. Gum arabic, maltodextrins, gelatin, starches, pectin, methyl cellulose, alginates, tricalcium phosphate, and their combinations are common carrier agents [30,31]. Alginate, modified starch, and inulin have also been extensively employed in microencapsulation processes. Cellobiose is an intriguing prospective carrier agent. Cellobiose is a disaccharide consisting of two (1,4)-β-D-glucopyranose units that are formed as a by-product during the refinement process of beet sugar manufacturing and as the primary product of cellulose's enzymatic hydrolysis [32]. Cellobiose is a potentially useful food additive since it is easily obtained on an industrial scale, water-soluble, and has a low sweetness. It is also not degraded by digestive enzymes in humans [33].

Maltodextrin (MD), Gum Arabic (GA), and a combination of maltodextrin and inulin (MD+Inulin) or a combination of gum arabic and inulin (GA+Inulin) were used in the spray drying of lychee juice [34]. Ascorbic acid, anthocyanins, and total phenolic compounds were successfully reduced by heat and oxidative means thanks to the carrier agents' combinations, which also increased Tg, bulk density, and solubility while

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reducing moisture and hygroscopicity. On the other hand, it was discovered that GA+Inulin was more effective in retaining anthocyanins, ascorbic acid, and total phenolic compounds, with decreased hygroscopicity and increased Tg.

In contrast, maltodextrin outperformed gum arabic and tapioca starch in terms of encapsulation efficiency and solubility, as well as better retention of anthocyanin and antioxidant activity in spray-dried black carrot powder [35. In addition, studies on purple sweet potatoes and guava juice powder have demonstrated that maltodextrin offers superior vitamin C protection [36,37]. The higher the concentration of maltodextrin, the more pigment was retained in the powdered spray-dried amaranthus betacyanin extract [38]. In contrast, with the increase of maltodextrin concentration (3% - 10%), lycopene and total carotenoids were reduced in watermelon juice powder [39]. Similarly, in spray-dried amla juice powder [12], increased concentration of carrier agent (maltodextrin 5% - 9%, w/v) reduced total phenolics and free radical scavenging activity. According to Tonon, Brabet, and Hubinger's [40] research, when the concentration of maltodextrin was increased from 10% to 30%, the yield percentage of spray-dried acai powder decreased by approximately 9.5%. This can be explained by the fact that higher feed viscosity produces more feed droplets, which dry more slowly and stick to the drying chamber to form wet powder. These findings indicate that there is no recommended concentration of carrier agents for spray drying that is generally applicable. The sample, the type of carrier agent, and the spray drying target determine the ideal concentration. Typically, a process of trial and error is used to determine the appropriate range of a given carrier agent for spray drying, taking into account the desired properties of the finished product. The atomizer's speed essentially determines the feed flow rate. A greater feed flow rate is produced by a faster pump. For the feed to evaporate the same amount of moisture from feed droplets, a higher flow rate feed requires more energy. According to Tonon, Brabet, and Hubinger [40], the process yield of spray-dried acai fruit powder was considerably decreased by the feed flow. Slower heat and mass transfer made possible by a higher feed flow rate made it challenging for the droplets to dry sufficiently. As a result, it created moist particles that adhered to the drying chamber wall. Drying air flow rate is also an important factor in spray drying because the energy needed for evaporation is changed depending upon the supply of drying air into the drying chamber. The drying air flow rate influences the rate of water evaporation. A lower drying air flow rate increases the droplet drying time and advances the circulatory systems [41]. The higher drying time causes a higher degree of water evaporation. Similarly, a higher drying air flow rate leads to less drying time, and insufficient drying and subsequently produces higher moisture content in the final product. The moisture content of tomato pulp powder increased, nevertheless, as per Goula and Adamopoulos [42], when the spray drying air flow rate was increased from 17.5 to 22.75 m^3/h.

The principal function of a spray dryer is atomization. The atomizer is considered the brains of a spray dryer, and selecting the appropriate atomizer is essential to successful spray drying and cost-effective production. Maximising the liquid feed's surface volume area is the atomizer's primary job in order to facilitate effective and efficient drying. The performance and design of the atomizer determine the final product's characteristics. In their 2000 study, Jumah, Tashtoush, Shaker, and Zraiy [43] examined how the pressure in the atomizer affected the characteristics of jameed powder. They discovered that increasing the pressure from 1.0 bar to 2.5 bar resulted in smaller particles and a larger surface area, which improved the drying process. The authors Tee, LuqmanChuah, Pin, AbdullRashih, and Yusof [44] noted that when the atomizer pressure rate was increased from 80 to 100%, the process yield and hygroscopicity increased while the particle size and moisture content decreased. The type of atomizer used in spray drying is also very important. There are many different kinds of atomizers; the most popular ones are rotary atomizers, pneumatic, hydraulic (pressure), and ultrasonic nozzles. Another significant factor in product characteristics is atomizer speed. Higher atomizer speeds (10,000 – 25,000 rpm) decreased the moisture content and microsphere size in orange juice powder, according to Chegini and Ghobadian's 2005 [45] study. The features of the concentrate before spraying, as well as the drying parameters (such as the type of tower spray drier, nozzles/wheels, pressure, agglomeration, and thermodynamic air conditions like temperature, relative humidity, and velocity), all affect these features.

Ferrari, et al. [24] examine how the physical and chemical properties of spray-dried blackberry powder are affected by a number of carrier agents, including gum Arabic, maltodextrin, or a mixture of the two. By using maltodextrin, powders with lower moisture content, better reconstitution properties, and a decreased propensity to absorb moisture were produced. The powders containing maltodextrin or a combination of gum arabic and maltodextrin had the highest antioxidant activity and the best retention of anthocyanins. Higher wettability ratings were probably the result of the blackberry powder's smaller particles and more uneven surfaces when prepared with gum arabic.

Effect of carrier material on the physiochemical properties of spray-dried powder

Particle size distribution: After spray drying, the dry particle size distribution is formed, and this is an important powder characteristic because it affects the product's handling, transportation, and storage conditions. It can also be related to other properties like bulk density, dispersibility, angle of repose, rehydration capacity, flowability, and solubility [46]. According to Tonon, et al. [47], the polymeric structure of the carrier material influences the size of a dry powder particle. The smaller the particle size that can be produced, the shorter the polymeric chain. Pieczykolan and Kurek [48] investigated how various carrier materials affected the spray-dried chokeberry powder's particle size. According to the results, gum arabic produced mean particle sizes that were two to three times larger than those of the other samples, with the highest value being 53.09 µm. Next in order of appearance were gum guar (16.29 µm), pectin (17.35 µm), inulin (17.66

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μm), and beta-glucan (25.61 μm). The powder with the lowest bulk density and the widest range of particle sizes was the one that was carried by gum arabic. According to the findings, the dry powder's bulk density decreased for the larger-sized particles because the smaller particles did not occupy the spaces between the larger-sized particles; instead, the spaces were empty. In the meantime, Filho, et al. [46] investigated how the concentration of gum arabic affected the size of the powdered carotenoid molecules. The outcome demonstrated that the larger size of particles (greater than 10 mm) can be found when the concentration increases. The size of dry particles produced ranged from 1.82 to 40.91 mm (3% - 35% gum arabic). Typically, the inlet temperature is set at 100 °C or more. Due to their large surface area and close proximity to the drying gas, the atomized droplets dry quickly. Particle diameter can be decreased to less than 5 μm by spray drying [49].

Solubility: When assessing a product's wettability and dispersibility in an aqueous solution, the solubility of the spray-dried powder is crucial. Different carrier material types resulted in varying powder solubility; however, because of their physical structure, starch-based materials were highly soluble. The impact of inulin and gum arabic on the solubility of cagaita fruit powder has been investigated by Daza, et al. [50]. The outcome demonstrated that while both carrier materials are very soluble in water, gum arabic had a marginally higher solubility than inulin. Due to its high solubility, gum arabic was the primary carrier material used in the majority of the carrier materials; however, inulin has also been shown to share this property. Moreover, Silva, et al. [51] investigated the solubility of green tea powder using a novel carrier material called cashew gum in conjunction with maltodextrin in various formulations. Though the final product's solubility has been significantly reduced due to the increase in cashew gum concentration, both materials were previously recognised as highly soluble carriers. The author hypothesised that the insoluble green tea extract may have had an impact on the outcome. When using a high concentration of b-cyclodextrin instead of maltodextrin and gum arabic, Nadeem, et al. [52] reported that a higher solubility of powder was achieved in terms of carrier concentration. Abadio, *et al.* [53] came to the conclusion that the powder's moisture content decreased as the maltodextrin concentration rose. This was because there was less free water available for evaporation as a result of the feed's increased solids content. Additionally, they found that a higher percentage of maltodextrin resulted in a lower actual density of the product, which was explained by the reduced moisture content. They also discovered that the product's solubility was enhanced by lowering the maltodextrin concentration. They recommended a 10% maltodextrin concentration and slower atomization rates to produce free-flowing, well-soluble products.

Glass transition temperature (Tg): One of the most important physical characteristics of powdered material is its glass transition temperature (Tg). It is described as the material's temperature at which it transitions from an amorphous, glassy state to a sticky, rubbery state. The food products that result from spray drying procedures with rapid heat exchange are usually not thermodynamically stable. They go through a transition that results in physical changes like sticking and lumping, especially when high sugar and acid ingredients are used. This causes low recovery, problems with storage, and a decline in product quality. In order to address the sticky behaviour that the powder would exhibit during the transition process, high molecular weight carrier materials with high Tg are incorporated into the feed medium. Maltodextrin and gum arabic are two common carrier materials applied in food applications; their Tg value ranges are 137 to 206 °C and 126 to 194 °C, respectively (Shishir, Samborska, Goula) [54]. A low powder was recovered when a novel carrier material made of orange by-product was investigated using spray-dried pomegranate peel extract. However, when it was swapped out for a mixture of maltodextrin and skim milk powder, the healing process improved [55]. Combinations of carrier materials (maltodextrin + gum arabic, maltodextrin + gelatin, maltodextrin + chitosan, maltodextrin + bicyclodextrin + gum arabic) were applied in the spray drying of the phenolic compounds of plum powder [56]. The Tg of the spray-dried powder has been successfully raised by all carriers, which has improved the powder recovery. Kingwatee et al. studied different formulations of carrier materials (maltodextrin + inulin + gum arabic) at 20% total concentration. The author recorded the highest Tg (98.39 °C) of lychee juice powder when a combination of inulin and gum arabic was used. However, when gum arabic and maltodextrin were mixed and added to the feed solution, Fazaeli et al. observed the highest Tg (76.40 °C) and black mulberry powder recovery. The Tg value increases when a combination of carrier materials is applied, according to both of the results. Lastly, the impact of carrier material concentration on date powder Tg has been studied by Moghbeli, et al. [57]. The outcome demonstrated a correlation between an increase in Tg and a rise in carrier material concentration. Overall, the outcome shows that the carrier material plays a critical role in influencing how well a spray drying operation performs.

Control release profiles and encapsulation efficiency: The purpose of the control release profiles and encapsulation efficiency calculation was to show how well the carriers worked as wall materials during the spray-drying encapsulation process. The longest total release time of microencapsulated curcumin (4 hours) was observed by Lucas, et al.[58] when gum arabic was used as the carrier material. This was followed by alginate (2 hours) and modified chitosan (35 minutes). The amount of antioxidants that are encapsulated using those carriers is measured by the encapsulation efficiency, which is 97.6%, 97.0%, and 93.8%, respectively. As a result, the current carrier has shown to be an effective wall material with minimal variations. In the meantime, Kaderides and Goula's investigation into a new orange-by-product carrier material revealed that, depending on process variables, the encapsulation efficiency of pomegranate peel powder ranged from 85% to 99%. Moreover, there was a noticeable distinction in the spray-dried green tea due to the combination of the carrier materials (maltodextrin and cashew gum). The findings indicated that higher maltodextrin concentrations were associated with higher encapsulation efficiency and

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higher powder retention in the encapsulated powder. Lastly, compared to the combination of maltodextrin and gallic acid, the use of aloe vera as wall material plus gallic acid produced superior control release profiles [59-61].

Conclusion

An established and widely used method in many fruit and vegetable products is spray drying. For the production of fruit and vegetable powder, the most common spray drying conditions are an inlet air temperature of 120°C to 180°C and a maltodextrin concentration of 7% - 20%. Excellent qualities were present in the products, including low moisture content, low hygroscopicity, small particle size, high bulk density, and high glass transition temperature. Using carrier agents, such as maltodextrin or a combination of gum arabic and maltodextrin, improved the protection of the bioactive compounds. Higher drying inlet temperatures generally resulted in lower moisture content, water activity, bulk density, and bioactive compounds while increasing yield, Tg, solubility, hygroscopicity, and particle size. In contrast, the addition of a carrier agent enhanced the protection of bioactive compounds, yield, solubility, and bulk density with reduced moisture and hygroscopicity. According to the reviews, it is highly encouraging that a recent study was able to develop new products and compete with existing carrier materials in terms of ideal carrier characteristics. It would be advantageous to continue developing innovative carrier material in order to lower costs, offer an alternative, and boost spray drying technology's effectiveness. The spray drying technique enabled the encapsulation of active compounds within nano-sized structures, offering numerous advantages such as enhanced stability, controlled release, and improved bioavailability.

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