***Review Article***

**Innovations in Spray Drying Technology: Enhancing Food Processing and Nutritional Preservation**

**ABSTRACT**

Spray drying is an unprecedented technique in the food industry which involves conversion of liquid foods into stable powdered form, allowing enhanced transportability, solubility and stability of temperature-sensitive bioactives. It involves atomization of liquid feed into fine droplets which are rapidly dried by hot air. One of the biggest advantage of this method is its ability to preserve nutrients like vitamins, antioxidants and probiotics because of which this technique is widely applied to dairy products, fruit and vegetable powders, flavour encapsulations and nutraceuticals. For the effective encapsulation and controlled release, it is very essential to select suitable wall materials like gum Arabic and maltodextrin. Compatibility with core materials, emulsification, solubility and viscosity are some of the factors upon which the quality of products depend. Efficiency of the technique is influenced by certain parameters like air temperature, feed composition and method of atomization. Many advancements like nano and electrostatic spray drying have helped in improving precision, energy use and minimizing thermal damage. Computational modeling and real-time monitoring optimize the drying conditions. Though spray drying technology has many benefits,high energy demand and degradation of heat sensitive ingredients are few challenges which require further research and optimization.

**KEYWORDS :-** Spray drying, Food processing, Maltodextrin, Encapsulation, Wall materials

**INTRODUCTION**

In food industry, spray drying is an indispensable method that is used extensively to change liquid food products into powders or granules with a long shelf life. It improves both ease of transport and storability for products. A long-standing development, known as spray drying, involves transforming a liquid feed into fine droplets which are then instantly dried using hot air. The final product is particles size and moisture content controlled (Gaiani et al., 2010). This method has been widely adopted because it can keep intact the functional and nutritional characteristics of heat-vulnerable natural product ingredients. Furthermore, stability and solubility is increased (Mishra et al., 2014).

Spray drying is used to produce milk powder, whey protein concentrates, and infant formulas. Among food products themselves, spray drying has also been employed, albeit limitedly to the making of fruit and vegetable powders and tea and coffee extracts as well as flavor encapsulations (Rawson et al., 2011).

Perishable fruit juices can, for example, be made into stable powdered forms by this method. This not only extends their shelf life but also conserves active compounds in them which are essential to human health (Santhalakshmy et al., 2015). One great advantage that spray drying possesses over traditional methods is its ability to preserve bioactive components such as vitamins, probiotics, and anti-oxidants by minimizing heat damage (Krishnaiah et al., 2014). By spray-drying technology, the oxidation and decomposition of heat, light and oxygen which is caused can be effectively blocked from getting into certain products (Dantas et al., 2024). Ways in which this technology is used within the food industry commonly include improving the shelf life of flavors as well as preservation of essential oils and functional ingredients. (Sobulska & Zbicinski, 2021)). In addition, microencapsulation increases the effectiveness of functional food preparations by providing a controlled release mechanism that is not possible through conventional methods (Wong et al., 2017).The precision of input air's temperature is an important factor that affects both the quality and efficiency in producing spray-dried powders. The temperature of output air, water content of feed solution, kind of carrier agents in use such as carrier oils, modified starches, maltodextrin, whey proteins or gum arabic also play vital role in the effectiveness of spray drying (Santhalakshmy et al. 2015). If these procedures are not controlled properly, the final product obtained will not be in desired form.

Spray drying technology is a boon to the food processing industries since it tansforms liquid food into shelf-stable powders with enhanced solubility and shelf life. By using this method,precise control over particle size,encapsulation and moisture is also ensured.

**History of Spray Drying in Food Processing Industry**

The roots of spray drying in food processing can be traced back to the late 19th and early 20th centuries. Samuel Percy was awarded the first recorded patent for spray drying in 1872, marking a distinctive stage in the history of this technology (Schuck et al., 2016). Even so, it was not until the early 20th century especially in the dairy sector that significant advances in spray drying took place. Specialised equipment was developed for large-scale industrial production of milk powders (Gaiani et al., 2010). Spray drying did not confine itself to the dairy sector by the 1920s and 1930s, but moved into other areas of food production such as coffee and egg powders as well as vegetable extracts. During those decades, people were looking for ingredients with a longer shelf-life than the farm produce preserves they were using to eat at home (Rawson et al., 2011). The development of spray drying was greatly accelerated by the demands of the Second World War military for lightweight mass-produced, non-perishable foods with long shelf lives. Spray drying technology upgrades drove the mass production of powdered milk, instant coffee and dried soup bases (Meat Board of Denmark,1996) (Santhalakshmy et al., 2015). During this period, spray drying became recognized as the best alternative to drum drying and freeze drying because it could yield high-quality powders that were easily reconstituted (Krishnaiah et al., 2014). After the war, rapid industrialization and technological advances brought further improvements to spray drying including more advanced atomization techniques and a higher degree of control over process parameters. Such advances increased efficiency and the quality of spray-dried food products (Dantas et al., 2024).

In the latter part of the 20th century, spray drying was the very foundation of food production, kin to provide essential services and playing an indispensable role in encapsulated, powdered flavours and functional food ingredients from bioactive compounds that are known as caring compounds. This technology was especially valuable for preserving the original nutrients, including probiotics, vitamins and essential oils within foodstuffs. This was done through encapsulation of such products into a protective matrix of dried wall materials (Wong et al., 2017).Advances in carrier agents such as maltodextrin and arabic gum further enhanced the preservation of volatile and heat-sensitive compounds during spraying processes, allowing spray drying to be extended to various minerals and vitamins as well as cooling edible materials like dairy products or chocolates(Santhalakshmy et al., 2015).Recently, new techniques like nano spray drying and hybrid drying have brought about greater effectiveness in the precision of spray drying for food (McCormick et al., 2005.) These technical innovations have enabled better control over particle size and shape, as well as reducing the moisture content in food powders - all resulting benefits that vanish if we neglect keeping good quality standards up-to-date (Wong et al., 2017).In addition, the integration of computational modeling with real-time process control has helped us to optimize drying conditions with higher precision.

**Optimizing Spray Drying through wall material selection and functionality**

Spray drying is an excellent encapsulating and drying technique which is widely used in the food,pharmaceutical and chemical industries.This technique is acclaimed to convert liquid or semi-liquid feed into dry powdered form.The process consists of three primary components:-Atomization,drying and powder separation.In the atomization stage,transformation of the liquid feed into fine droplets takes place using a nozzle or rotary atomizer. These droplets are then subsequently introduced into a hot drying chamber, where dry particles are formed due to rapid moisture evaporation which occurs due to contact between droplets and hot air.Ultimately, with the use of bag filters,the dried powder is separated from the drying air and is collected for further use.

Selection of a suitable wall material is critical in spray drying since it helps to encapsulate sensitive food components in a better manner. It serves as a barrier that influences the stability, solubility, and, consequently, the final product's properties. Emulsification properties, ability to form a film, solubility, viscosity and compatibility with the core material are major characteristics of wall material (Gharsallaoui et al., 2007).

The emulsifying characteristics of wall material generally plays an important role in stabilizing the core component of the structure, which is essential for the efficient encapsulation.For example, sugar beet pectin, extracted from sugar beet pulp,exhibits strong emulsifying properties (due to a high protein content and acetylation level) that provide effective encapsulation of oils and hydrophobic compounds prior to spray drying (Nik Abd Rahman et al., 2024).

Spray drying and the characteristics of the final product are also greatly influenced by the solubility and viscosity of the wall material. Due to its good solubility and low viscosity, maltodextrin is often mixed with other materials having preferred viscosity to increase the solid content of the feed solution. This produces a homogeneous particle with good flow properties, which leads to effi­cient atomization when spray-dried, without clogging (Assadpour & Jafari, 2019).

The choice of wall material determines the physical and chemical properties of spray-dried product. The type of wall material and concentrations also influence particle size distribution, surface morphology, encapsulation efficiency and shelf-life stability. High sugar beet pectin concentration improves the encapsulation efficiency as well as oxidative stability of encapsulated oils (Tonon et al., 2009).

To sum up, it is imperative that the wall material be chosen wisely so that the spray drying can achieve maximum efficiency and the encapsulated food product is of high-quality. The various characteristics contributing to desirable effects, such as emulsifying ability, solubility, viscosity, compatibility, and protective functions must be evaluated for their applications in food processing (Jafari & Samborska, 2021).

**TABLE 1:- Role of Wall Materials in Spray Drying of Fruits and Vegetables: Concentration and Functional Benefit**

| **Fruit/Vegetable** | | **Wall Material(s)** | **Concentration (%)** | | **Health Benefits** | | **Reference** | |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Black Soybean | | Maltodextrin, Gum Arabic | 10% Maltodextrin, 10% Gum Arabic | | Enhanced stability of anthocyanins, potential antioxidant benefits | | Zhang, W. et al,.2024 | |
| Carrot | | Arabic Gum | 11.9% | | Protection against oxidation, maintenance of provitamin A activity | | Correa-Filho et al,.2019 | |
| Pomegranate Juice | | Prebiotic Fibers, Maltodextrin | Not specified | | Preservation of antioxidant activity | | Miravet, G. et al,.2016 | |
| Gac Fruit Aril | | Maltodextrin | 20-30% | | Retention of antioxidant properties | | Tuyen, C. K. et al,.2014 | |
| Fish Oil (as a model for ω-3 LC-PUFAs) | | Gelatin, Gum Arabic | Not specified | | Enhanced stability and bioavailability of ω-3 fatty acids and carotenoids | | Zhu, Y., et al,.2024 | |
| Origanum onites | | Maltodextrin, Gum Arabic | Not specified | | Extended shelf life, preservation of antimicrobial properties | | Balci‐Torun, F. 2024 | |
| Caucasian Blueberries | | Maltodextrin, Gum Arabic | Not specified | | Improved stability of anthocyanins, potential antioxidant benefits | | Girgin, S., et al ,. 2024 | |
| Pomegranate Seed Oil | Gum Arabic, Maltodextrin | | | 15% oil with varying GA:MD ratios | | Enhanced stability and preservation of essential fatty acids, antioxidant properties | | Mangope, K., et al,.2024 |
| Fruit and Vegetable Juices | Various wall materials | | | Not specified | | Enhanced stability and controlled release of active compounds | | Speranza, B., et al,.2017 |

**Technical aspects of spray drying:**

Spray drying is a knotty process which transforms liquids into powdered form and the quality of this powdered food product depends on various decisive factors. Though the humidity of the spray is a key factor, there are several other important factors like inlet and outlet air temperatures constituents of the feed material mechanism of atomization rate of airflow and the carrier agents chosen (Gaiani et al., 2010). When all these factors become favourable in all respects, then the conditions of drying, fixedness of the product and prolongation of functional and nutritional properties of the powder is enriched (Mishra et al., 2014).

The inlet air temperature is one of the important parameters in the spray drying process because it is directly related to moisture evaporation. Elevated temperatures decrease the drying time, which improves the flowability of the powder and reduces the time for processing (Schuck et al., 2016). Nevertheless, high temperature treatment can destroy heat sensitive nutrients, such as vitamins, antioxidants and probiotics that influence the quality and efficacy of final product (Santhalakshmy et al., 2015). In contrast, a low temperature at the inlet may cause an inadequate drying process, as it may cause food product moisture levels above the acceptable values, raising the risk of microbial contamination and lower stability of the product (Rawson et al., 2011). Likewise, the outlet air temperature is critical in determining the resulting moisture content and bulk density of the powder. This is needed to prevent stickiness, clumping and to maintain powder stability (Comerford et al., 2016).

Another important parameter in the spray drying process is the concentration and overall composition of the feed solution, which can affect the drying behavior of the entire process. The presence of proteins, lipids, and sugars affects the viscosity, solubility, and drying kinetics ((Dantas et al., 2024).

Increasing the solid content improves drying rate and yield, although viscosity tends to increase at higher solids contents, making atomization and fluidization more difficult (Sobulska & Zbicinski, 2021)). This atomization so far is a highly significant factor influencing the particle size distribution, impacting the powder flowability and solubility. Rotary, pressure nozzle, and ultrasonic are among various atomization methods that can be used based on the required properties of the final powder (Wong et al., 2017). Example of a good atomization is the formation of droplets in a consistent manner using a pneumatic nozzle or a rotary nozzle which can lead to uniform drying, finally providing a good powder.

Airflow rate is another important factor of heat and mass transfer during spray drying process. High airflow rates increase the removal of moisture and are associated with better particle formation, but can lead to higher operating costs and energy consumption (Schuck et al., 2016). Thus, an optimization of the airflow should be conducted in order to reach a trade-off between energy consumption and quality of the end-product and to avoid problems of powder agglomeration and non-uniform dryings (Gaiani et al., 2010).

It is also common for spray drying to incorporate carrier agents such as maltodextrin, gum arabic and whey proteins to improve powder stability and rehydration properties (Santhalakshmy et al., 2015). In addition, these carriers are especially helpful in encapsulating labelized bioactive materials due to the their property of prevention from oxidation and minimizing stickiness, which is major importance in the high sugar food products (Rawson et al., 2011).

Existing technological innovations in spray drying, including computational simulation and real-time monitoring, have largely contributed to enhancing the scout to control and optimize the aforementioned parameters. Automation of artificial intelligence and machine learning technologies has created more accurate forecasts of powder characteristics, considerably improving the ability to control drying conditions. Additionally, hybrid emerging models of drying technologies, such as spray-freeze drying and microwave-assisted spray drying, have been developed to enhance efficiency and maintain nutritional and functional characteristics of heat-sensitive products.

**Application of Spray Drying in Food processing industries**

Spray drying technology is widely used in food processing industry since it enables to transform liquid food into stable powdery form. The powdered food obtained using spray drying technology has longer shelf life and it does not contain the inconsistencies of moisture content found in other foods (Gharsallaoui et al., 2007).

This process involves atomising a liquid feed into droplets, which are then dried rapidly by hot air. The result is a powder with controlled moisture content and particle size (Selvamuthukumaran et al., 2017). This technology is used in various fields of food processing industries like in dairy industry, food and vegetable processing industry, flavour preservation and nutraceuticals. It has the ability to preserve the bioactive compounds present in foodstuffs as well as other essential functional properties (Banozic et al., 2021).

Spray drying technology is most widely used in dairy industry as it enables the production of milk powder, whey protein concentrates and infant formula products (Gharsallaoui et al., 2007).This process enhances the stability and solubility of the products as well as preserves the essential nutrients present in the product. It also reduces the loss of nutrients, especially antioxidant and vitamins (Azhar et al., 2021).The stability and dispersibility of these powders can be enhanced by adding carrier agents such as maltodextrin and gum Arabic and because of this reason these carrier agents are used as key ingredients in a wide variety of food products (Banozic et al.,2021).

One of the thousand virtues of this technology is that it helps in encapsulation of flavours, essential oils and functional ingredients and protects the product from oxidation, high temperature or light exposure (Gharsallaoui et al., 2007). This technology has been proven to be invaluable in the beverage industry particularly in the manufacturing of instant coffee, tea extracts and powders which immediately provide their flavour. The aroma also remains maintained for long periods since these products are not exposed to air or moisture (Selvamuthukumaran et al., 2017).

Microencapsulation helps in prolonging the shelf life of volatile compounds as well as helps in regulating their controlled release which ultimately helps in improving their efficacy in the final product. (Azhar et al., 2021).The nutraceutical and functional food industries have also benefited from spray drying, especially in preserving probiotics, vitamins, and bioactive peptides (Banozic et al., 2021).For example, probiotic bacteria must be protected from its surroundings that includes environmental factors such as heat and humidity and spray drying is vital to ensure their survival in dairy products and dietary supplements (Gharsallaoui et al., 2007).

Spray drying in addition is a method generally applied to produce plant based proteins (Selvamuthukumaran et al., 2017).In the last decade, spray drying has also played a role in reducing food waste by transforming surplus or discarded food materials of various types into valuable powdered ingredients (Banozic et al., 2021).Such a sustainable development can turn food waste including fruit peels, coffee husks and trimmings from vegetables into high nutrition powders suitable for use in functional food formulations (Azhar et al., 2021).It helps to reduce the amount of waste generated while adopting a circular economy approach in the food business that makes use of resources efficiently. Furthermore, recent advances in spray drying technology such as nano spray drying and hybrid drying techniques further enhance the efficiency and applicability of the process. Among these is greater control attained through live process monitoring and computational modelling, resulting in greater product yields, improved energy efficiency and preservation of heat- sensitive materials (Selvamuthukumaran et al., 2017). The integration of spray drying with other drying techniques such as freezing and microwave assisted drying results in enhancement of the quality of product as well as shortening of processing times ultimately reducing the cost of energy use (Azhar et al., 2021).

**Table2-: Spray-Drying Conditions, Carrier Agents, and Physicochemical Properties of Spray-Dried Fruit Extracts**

| **No.** | **Fruit Extract** | **Spray-Drying Conditions** | **Carrier Agent** | **Physicochemical Properties** | **Effect on Product Yield & Properties** | **References** |
| --- | --- | --- | --- | --- | --- | --- |
| 1 | Acai (Euterpe oleracea Mart.) Juice | Airflow rate: 73 m³/h; Compressor air pressure: 0.06 MPa; Feed flow: 15 g/min; Inlet temp: 140±2°C; Outlet temp: 78±2°C | Maltodextrin 10 DE, Maltodextrin 20 DE, Arabic gum, Tapioca starch | Antioxidant activity: 1165.84 ± 35.29 μmol TE/g juice-dried powder (maltodextrin 10 DE) | Temperature and water activity negatively affected anthocyanin stability. Antioxidant activity decreased with increasing water activity at 25°C but was higher at 35°C. | Tonon et al., 2010 |
| 2 | Acerola Pomace | Feed rate: 0.49 kg/h; Peristaltic pump rate: 1.23 kg/h; Aspirator flow rate: 5.51 × 10⁴ kg/h; Inlet temp >194°C | Maltodextrin, Cashew tree gum | Hygroscopicity: 34.72 ± 1.93 g absorbed water/100 g powder after 7-day storage at 25°C, 90% RH | Higher inlet temperature improved powder stability, reducing moisture content and hygroscopicity. | Moreira et al., 2008 |
| 3 | Gac (Momordica cochinchinensis) Fruit | Drying air flow rate: 56±2 m³/h; Compressor air pressure: 0.06 MPa; Feed rate: 12–14 ml/min | Maltodextrin | Total carotenoid content (TCC): 2.8 mg/g (10% maltodextrin); Total antioxidant activity (TAA): 0.14 mmol TE/g powder (120°C, 10% maltodextrin) | Moisture content, color, TCC, and TAA were significantly affected by maltodextrin concentration and inlet air temperature. | Kha et al., 2010 |
| 4 | Mango Juice | Inlet temp: 160°C; Outlet temp: 70–75°C; Liquid feed: 10 ml/min; Drying air flow rate: 0.7 m³/min | Maltodextrin, Arabic gum, Waxy starch | Stickiness: 0.15 kg-f (maltodextrin + 9% cellulose); Solubility: 90% (maltodextrin + 0% cellulose) | Stickiness decreased with increasing cellulose concentration for all drying aids. Solubility decreased with increasing cellulose concentration. | Phing, P. L., & Saleena, L. A. K. (2022) |
| 5 | Orange Juice | Atomizer pressure: 5±0.1 bar; Feed rate: 1.8±0.1 g/min; Inlet temp: 110–140°C | Maltodextrin | Powder hygroscopy: 0.04 g/g solids (140°C, DE 6, orange juice solids/maltodextrin solids: 0.25) | Higher inlet air temperature and maltodextrin concentration reduced hygroscopicity and caking. | Goula et al., 2009 |

**Recent Advances in Spray Drying**

In recent years, with the growing need for improved efficiency, sustainable food processing technology also increasingly come to bear environmental considerations.

The drying of bioactive compounds, improved particle morphology and control over the drying conditions as well as more careful production management can result in lower capital equipment costs in slow circuits.

Emerging techniques such as nano spray drying, vibration-assisted drying, pulse combustion drying and electrostatic spray drying have provided more precise control over powder properties yet with reduced thermal degradation of heat-sensitive ingredients (Schuck et al., 2016).

The most significant advancement in spray drying is nano spray drying which facilitate improved solubility and biological availability. This mode of spray drying depends on the electrostatic forces and special nozzles to produce particles in nanometer range which makes it ideal for encapsulating substances like vitamins or enzymes which can be sensitive. Till now more than hundred such companies have been established worldwide.

Though spray drying is valued in all the sectors related to drying, it is relatively more valued in nutraceutical and pharmaceutical industries because of its ability of producing powders with impressive dispersibility and controlled release. (Sobulska & Zbicinski, 2021).

Pulse combustion spray drying is another notable innovation that improves energy efficacy and boosts up the drying process while preserving integrity of the product at the same time.

By proper utilization of the controlled pulsating combustion this technology creates a highly aggressive drying environment that is rich in heat and mass transfer. This leads to quicker drying rates and reduces energy consumption.

Because this technology may be used to create premium milk or whey powders with exquisite solubility and reconstitution the dairy sector has benefited greatly from it. (Schuck et al., 2016).

Electrostatic spray drying (ESD) is another innovative system which is used to increase the encapsulation of those bioactive constituents which are sensitive. As a result, by using this method the uniformity of particles increase agglomerations are reduced and hence superior powders with quicker floatability and longer shelf life is obtained. Since electrostatic spray drying may shield these delicate substances from oxidation while maintaining their flavor characteristics, it is now often used especially for the microencapsulation of flavors, essential oils, and functional components (Dantas et al., 2024). Furthermore, because to developments in material science, powders capacity to rehydrate has improved recently.

The latest innovation in spray drying technology mainly focuses on the improvement of energy efficiency and enhanced control over particle properties.mPulse combustion(PC) spray drying,which is still in development for the purpose of food processing,includes pulsating flow of gas to improve heat and mass transfer,thus offering potential energy savings and the ability to handle high viscosity feed solutions (Dantas et al.,2024)

Classic carriers like maltodextrin and gum arabic have been supplemented or replaced with new biopolymeric carriers which give better rehydration performance such as prebiotic fibres, whey protein isolates from cow’s milk or plant-based hydrocolloids made by only chemical engineering (Sobulska and Zbicinski, 2011). These alternative carriers not only improve stability themselves but can also enhance the nutritional content of finished products.

**Advantages of Spray Drying**

Food processing and the method of spray drying which has gained worldwide acceptance is highly efficient. It has several advantages over traditional drying methods such as drying by sunlight or baking. This process turns liquid foods into stable powders, so their shelf life can be longer. Improved handling and greater solubility are other byproducts of such work. There's a key benefit to spray drying compared with freeze drying and drum drying: It's cost-effective and easily scalable; it can dry continuously and rapidly. That makes it ideal for large-scale food production scenarios. (Cal & Sollohub 2010).

The big advantage of spray drying is its ability to protect heat-sensitive chemicals such as vitamins, anti-oxidants and probiotics so they don't suffer from the drying process. Since the moisture in a spray drying chamber quickly dries up, elements from food products only experience high temperatures for a short time. This in turn improves the effectiveness and efficiency of bioactive compounds (Trends of Spray Drying 2017). Furthermore, such an approach allows finely tuned control over particle size, density and moisture content. These are important factors in modifying the solubility and flow properties of food powders (Cal & Sollohub 2010). Another benefit of spray drying is that it is highly effective at wrapping volatile or heat-sensitive ingredients, such as flavours, essential oils and functional additives. This encapsulation lets these ingredients avoid oxidation or moisture absorption and keep away degradation, which improves their stability and life expectancy (Sosnik & Seremeta 2015). This particular feature is especially important for the manufacture of instant coffee, tea extract, dairy powders and nutraceuticals, where maintaining both the taste and biological activity of the substances involved is a priority (Trends of Spray Drying 2017).

There is the fact that this kind of technology can produce custom-made food powders with specific functional properties. By controlling factors such as inlet temperature, feed composition and air flow rate, manufacturers can control major powder characteristics such as solubility, dispersibility and bulk density. Such customization is especially important in applications intended for infants' diets, sports supplements or specialized dietary products. (Cal & Sollohub 2010). For industry compared to freeze drying, spray drying is energetically more efficient. Without the high energy costs or lengthy drying times of freeze drying, it can also be done continuously and rapidly. This can greatly reduce operating costs while maintaining higher production efficiencies (Sosnik & Seremeta 2015).

New technologies such as nano-spray drying and electrostatic spray-drying have further enhanced energy efficiency making it possible to produce ultrafine powders with even greater bioavailability and improved function (Trends of Spray Drying 2017). Sustainability is another major advantage of spray drying. It reutilizes the waste from food and reduces waste. Transforming excess or abandoned food materials into high-valued powdered ingredients is a method that contributes to the optimal utilization of resources in the food industry. Such an approach dovetails with today's drive for sustainable food production and implementation of a circular economy (Cal & Sollohub 2010).

**Challenges and Limitations of Spray Drying**

Although spray-drying is a widely used and effective technique for food processing, there are several challenges and limitations that affect its efficiency, cost effectiveness and practical reliability. One of these is its high energy demand. A great deal of thermal energy is required by the process to remove moisture from the feed solution which is why larger operations may eventually lose money on it (Sosnik & Seremeta, 2015). Moreover, it is very difficult to maintain precision with respect to processing parameters-temperature humidity and feed concentration during large-scale industrial operations (Cal & Sollohub, 2010).

Spray drying also fails to effectively preserve heat-sensitive bioactive compounds. Although high temperatures are sustained for only a short time, rapid drying still exposes essential nutrients like vitamins, probiotics and antioxidants to heat. So even now this loss of nutrition and quality resides (Trends of Spray Drying, 2017). For those industries specializing in the functional foods and nutraceuticals this is a particularly serious situation since maintaining ingredient stability determines product effectiveness (Cal & Sollohub, 2010).

Moreover, certain food powders present problems of stickiness and wetting. Ingredients with a high sugar, protein or fat content can give sticky residues during drying which may adhere to the chamber walls. This will be harmful to operational field and require frequent maintenance (Sosnik & Seremeta, 2015). In order to address this problem, manufacturers often add carrier agents such as maltodextrin or gum Arabic but this raises production costs and can change the sensory characteristics of the final product (Trends of Spray Drying, 2017).

Moreover, spray-dried powders often have low bulk density and poor flow properties making it hard to store or to handle them. If the particle size becomes too small it can also increase the possibility of an explosion of flour both of which create safety problems in the food industry. Thus, additional processing steps such as agglomeration or granulation must be taken adding a further complexity and cost to manufacturing processes (Cal & Sollohub, 2010). While the microencapsulation of some bioactive ingredients is quite efficient, other materials are not so easily processed by spray drying technology. The method's effectiveness relies on such factors as choice of carrier material, drying conditions and the nature of the core compound. For example, a highly volatile compound may decompose due to exposure to high temperatures and oxygen while being spray dried (Trends of Spray Drying, 2017).

Furthermore, environmental influences play a considerable role in the outcome of spray drying. The high amounts of energy consumption and water use that characterize food processing forces us to have mixed feelings about this technique's environmental friendliness.

**CONCLUSION**

Spray drying as a technology has become crucial to food processing industry providing a highly productive method for converting liquid food products to stable, transportable and long shelf life powders. Its advantages over traditional drying methods include fast processing speed, improved retention of heat-sensitive biological active compounds and improvement of the solubility and functionalities of food ingredients.Innovations revolving around spray drying technologies such as nano spray drying, electrostatic spray drying and hybrid drying methods have significantly affected energy efficiency, optimizing particle morphology and overall protection of bioactive compounds. Such innovations are increasing the scope of spray drying beyond its traditional bases in dairy and fruit powders to become a leading technology in the encapsulation of flavours, probiotics, essential oils, and functional food ingredients. Yet there are hurdles especially with high energy consumption, sticky issues related to sugar or high protein formulations and the risk of losing some heat-sensitive nutrients during processing but keeping these challenges aside, spray drying remains an important tool for the food industry.With ongoing researches targeting the refinement of the process parameters, the development of innovative carrier materials and the incorporation of real-time monitoring and computational modelling, it is likely that spray drying will continue to be a cornerstone of contemporary food processing pushing the envelope of high-value functional food and nutraceutical production.

Disclaimer (Artificial intelligence)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc.) and text-to-image generators have been used during the writing or editing of this manuscript.

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