Advancing Food Preservation: Harnessing Innovative Drying Technologies for Quality and Sustainability

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Abstract: ***Drying is a commonly used food preservation technique because it minimizes moisture - mediated deteriorative reactions and lowers moisture content to inhibit the growth of germs. While hot air convective drying and natural open - sun drying are widely used effective technologies, they have disadvantages such extended drying durations, color loss, and nutritional deterioration. For example, extended exposure to high temperatures during hot air drying results in nutritional degradation, taste alterations, and decreased antioxident capability. Recent studies have concentrated on reducing chemical and thurmal degradation while optimizing nutrition retention in an effort to address these issues. Cutting - edge and novel drying technologies have significant benefits for raising food quality. Innovative methods have been created to improve physicochemical characteristics by reducing drying time and heat degradation. The objective of these improvements is to enhance productivity while preserving nutritional value and prolonging shelf life. Ensuring product safety, quality, and acceptance is the primary objective of these innovations; they also aim to lower energy usage and the carbon footprint connected with drying process. Scholars have investigatigated methods including heat pump drying, high electric field drying, refractance window drying, and microwave or ultrasonic assisted drying. These techniques not only increase productivity but also maintain the final product's quality. This special issue offers a forum for the most recent developments in cutting - edge and novel drying methods. Through the resolution of issues related to food quality and customer requirements, these developments provide a competitive edge in the international market.***

Keywords: Advance in drying: hybrid drying techniques; pre - treatment; process analytical technology, drying techniques, freezing/drying points; drying period, Artificial and natural drying.

1. Introduction

Food items are dried by simultaneously applying heat and mass transfer to remove moisture [1]. Water is driven to evaporate by convection, conduction, and radiation of heat; vapours are expelled by forced air. Because fruits and vegetables have a high moisture content—more than 80%—they are particularly vulnerable to germs that cause spoiling. Dehydration preserves food for a far longer period of time than fresh goods by reducing water activity [2]. Fruits and vegetables should be preserved because they spoil easily. Vacuum drying, solar drying, air drying, fluidized bed drying, spouted bed drying, vacuum drying, and freeze - drying are some methods for doing this [3, 4, 6, 8]. the following fruits and vegetables— apple, black carrot [9], strawberries [11], carrot, garlic [12], guava [13], papaya, jackfruit [13], sweet potato [14], banana [15], and mushroom—are examples of studies done on the drying kinetics of these foods. To choose the ideal drying method and control the drying process, it is essential to understand drying kinetics.

The most economical method of extending the shelf life of food items is drying them. Dehydration is a common method used to preserve a variety of food goods, such as cereals, seafood, meat products, and all fruits and vegetables. The moisture content of food products can vary greatly; it can be as low as 35% in grains and as high as 90% or more in some fruits (water melon, for example, has a moisture content of 93%), which must be brought down to a suitable level to prevent the growth of microorganisms. Water activity, which is merely the amount of free water accessible for microbial development in solids, is typically used to describe this. Regarding water activity, the limitations for various microorganisms are mentioned [16]. The pre - and/or post - processing stages are crucial for improving product quality and lowering the drying load. Pre - treatment techniques that are frequently employed include soaking, blanching, salting, and osmotic dehydration. However, after food has dried, post - processing steps like coating, mixing, packaging, and so forth are as crucial.

Protein cakes that are effectively freeze - dried at high interest could take longer to reconstitute than powders that flow freely and are produced using alternative drying methods. Readers can refer to the previously mentioned points of view. Non - stop drying technology, which is no longer widely recognized in the biopharmaceutical industry, offers a number of features that could be investigated to address the issues related to conventional freeze - drying techniques [Pisano, R, 2019]. Numerous cutting - edge drying methods are examined in this work, including spin - freez drying, dynamic freeze - drying, active freeze - drying (spray freezing), spin - drying of suspended vials, Lynfinity® drying, PRINT drying, and MicroglassificationTM drying for biopharmaceuticals. Combining PAT with biopharmaceutical characterization techniques allows for a full assessment of both process and product CPPs and CQAs [Al - Hussein, A., Gieseler, H., 2012].

This ensures that goods are safe and effective before being administered to patients. Section 4 provided justification for the usage of excipients related to the drying technique, and procedure components are necessary to preserve the balance of biopharmaceuticals. In addition to the aforementioned difficulties, various drying techniques may simplify validation processes and make a successful scale - up possible by applying a quality - by - design approach. This table enumerates various techniques for drying. Even though some of these technologies are referred to as bulk drying, single unit dosages can be produced using a powder/product filling machine [Wang, B., McCopy, T. R., 2015].

Traditional methods of drying

Numerous businesses work with various kinds of dried grains, leading to the development of numerous drier design solutions. The flow of energy used for moisture evaporation is a fundamental requirement for the drying process, which is why drying apparatuses are most frequently categorized based on how heat is transferred to the dried material.

Dryers that use energy fields, contact dryers, and convective dryers are available. The majority of them can function in batch and continuous modes. [Berrozo et al, 2014].

1) Air Drying Units:

Convective dryers, which employ convection to transmit heat from the drying gas to dried material, make up the majority of equipment used for drying grains. Among these devices are the most traditional solutions that were first presented to the industry, including tunnel and belt dryers, as well as bin, cabinet, and chamber dryers with forced and natural flow. The drying gas in each of these devices has the ability top travel both across and along the material to be dried. Direct rotery drum dryers, one of the earliest models of high - capacity drying equipment in use, are examples of convective dryers. [wae - hayee et al, 2020]

2) Contact dryers

The majority of heat in contact dryers is transferred to the material via conduction from the hot wall or belt, which is typically heated by steam, hot water, and sometimes electricity. Because the heat transfer coefficient from the heating medium to the appliance wall should have a high value, heated gases are rarely employed as a heat source [Hanifarianty et al., 2018]. There are two main types of dryers in this group: contect drum dryers and belt dryers [Burmenster et al., 2011].

3) Using energy field in dryers

Applying energy fields can greatly accelerate drying processes. Acoustic dryers employ ultrasound, dielectric dryers use high - frequency electric fields (such as those from radio and microwave frequencies), and radiant dryers use infrared or ultraviolet light. There are two main types of energy field dryers: batch operation and continuous belt designs [Pasichnyi et al., 2017].

Technologies for Biopharmacutical Drying: - Technologies for single Dose Drying:

Traditional Batch Freeze - Drying Method:

To freeze a solution, freeze - drying involves removing water molecules from it. In batch freeze - dryer, the two most typical components are a vaccum pump and a condenser. There are three steps to this process: freezing, drying, and then drying again [Wang, w, Roberts, C. J., 2018]. Vials that have been vaccum - sealed are kept in the drying chamber to partially dry. For crystalline additives below the eutectic point™ or for amorphous compounds below the frozen product's glass transition temperature (Tg'), products are frozen to temperatures between - 400^0 and - 600^0 C. Thermocouples and other Wi - Fi temperature sensors may be used in non - cGMP freeze - drying cycles to track the average product temperature [Broadwin, S. M., 1965]. Annealing can be utilized to complete a step beyond bulking chemicals crystallization and product consistency improvement. The three - step process of primary drying starts with the freezing of liquid water and concludes with the production of water vapor. When the vials are partially sealed, water vapor may transfer from the vials to the condeser. Longer shelf life and reduced chamber pressure can lead to sublimation, but the product's temperature must stay below its Tg' or Tm. The last phase of secondary drying is called desorption [Cover, J. A. W. M., 2012].

Technologies for Bulk Drying:

Active - freeze Drying:

Heat - sensitive bulk materails, such as solutions, suspensions, pastes, and wet materials, can be dried with minimal handling. Solids, utilizing the active - freeze - drying method with minimal handling [Struschkact et al., 2016]. The vaccum dryer, condenser, vaccum pump, collecting filter, and product collector comprise the gliding technique.

Dynamic freeze - drying and spray - freezing technology: -

This approach consists of two main steps: spray freezing and dynamic bulk freeze drying. The first step is to spray freeze. The droplet length is determined by the viscosity, orifice diameter, nozzle frequency, and floating price.

Some estimates place the number of drops at 1000 to 5000 per second [IMA Life, 2019]. The freeze chamber is two - sided, cylindrical tank. The droplets need some time to make contact with N2 (I). Internal administration of sterile N2 (g). Occurs at a temperature between - 80°C and - 1000°C and 50°C. There are usually three hundred to one thousand uniformly sized ice spheres with a micrometer diameter inside each 1.5 meter block of ice.

The dynamic freeze - drying method known as "sprayed freezing" makes use of a rotating freeze - dryer that is the variable cost, frequency of the nozzle, and viscosity, as a rotating freeze - dryer that is positional inside an enclosed vaccum chamber that rotates on its longitudinal axis as the temperature rises to freeze the product is used in sprayed freezing, a dynamic freeze - drying process. The product's conductive heat switch has been finished and is now operational. The amount of water vapor that can pass through the drum depends significantly on the exits at both ends [Siow et al, 2018].

Ceaseless aseptic spray - freeze - drying innovation by IMA life: -

IMA **ways of life designed** the Lynfinity® spray - freeze after **obvious** changes. A temperature - controlled **bead** zone **strengths** the **item bolster** to **create** uniform **bead beneath** the **impact** of **recurrence** vibrations, which **begins** the **splashing** system's **improvement**. **Moo** temperatures are

kept up within the cooling fluid. Frozen **circles accumulate within the foot** of the chamber. Cascade **racks influence delicately** to **exchange solidified circles** through the drying chamber a **foreordained** pace. The **arrangement** chamber is **utilized** to **accumulate** a **tremendous** number of dried **circles [**Roser B., 1991].

Print® Technology: -

"PRINT" technology is frequently used to describe particle replication in non - wetting templates. This method, which is derived from lithographic techniques, is used in the semiconductor microelectronics sector. It's using micro - moulding - based particle layout and engineering [Garcia A. et al., 2012] it is feasible to produce monodisperse, individually formed micro - and nano - debris of hydrogels, polumers, APIs, and other substances. Employing roll - to - roll technology connected with cGMP procedures [Morton, S. W. et al., 2013]. preclinical and medical statements for pharmaceutical inhalation powders employing liquid organization may now be produced with nonpreventable particles. Perfluoropolyether is poured into a closed silicon drawer template that has specific forms of m, like 200nm - sized shapes and 5m - sized forms, located in between the PFPE mold's chamber's and a high ground potential polyethylene film. print® technology: It's common to refer to particle reproduction in non - wetting templates as "PRINT" technology. The integrated circuit this method, which is derived from lithographic techniques, is used in the microelectronics sector.

Aspects Of Drying Technology formulation: -

Biopharmaceutical products that are freeze - dried are frequently made using sugar, bulking agents, surfactants, amino acids, buffers, and tonics. Trehalose's high glass transition temperature (>100°C) and other characteristics may be advantageous to biopharmaceuticals during spray - drying. If a precise stabilizing effect of a 2: 1 protein - to - sugar ratio is demonstrated, then iysozyme may enhance the overall stability of iysozyme. Also, it has been demonstrated that spay - drying iysozyme with methanol as a co - solvent increased the product's EPF over that of the water - based solution. The fact that sucrose and trehalose can crystallize in both dry and cold condition is noteworthy, even if storage at higher temperatures and moisture content may cause that stability and form of the proteins to deteriorate [36].

Packaging, validation, and scal up considerations for Drying Technology: -

Scale - up and phase changeover are the two methods most frequently used to transfer a pharmaceutical production technology from one location to another. Additional time is needed for freeze - drying in vials during fill - finish operations like filtering, compounding, and vial filling, among others. Even worse, lengthy loading, unloading, and vial inspection periods in the company's most expensive footprint - such as the controlled area for aseptic filling - have a negative impact on the productivity of individual processes and prolong stock and inventory turnover times. Spray drying, energy - freeze drying, and spray - freeze drying all remove these unnecessary ingredients. Additional certification is required for major packaging additives, fill - finish line equipment, sterilizing methods, fill quantity, freeze - drying cycles, capping, inspection, and container closing integrity and validation [36].

Pat's viability for drying technology: -

PAT is one of the QbD strategies for "Pharmaceutical Development" included in ICH Q8 (R2) ideas. It involves gathering, analyzing, and maintaining data. Optimizing and improving freeze - drying cycles is the main objective of the strategy. To determine the drying give - up point, measurements from the pirani gauge and capacitance manometer are combined with data from temperature sensors and shelf temperature. The previous secondary drying procedure has demonstrated that MS is highly sensitive to a 3% median cake moisture. In a freeze - dryer, it might be utilized to stop helium gas and silicon oil leaks [36].

Hybrid Methods of Drying:

The versatility of hybrid drying procedures has led to their recent rise in popularity. The use of multiple dryers for drying a specific product (multi - stage drying), the use of multiple heat transfer modes, different heat transfer methods, or multiple dryer processing are examples of hybrid drying approaches. Multi - stage drying is widely recognized method for improving drying efficiency.

Different multi - stage drying options for different feed qualities are described in figure. To obtain faster drying for particle matter, fluid bed variations or fluid bed in combination with another technology can be employed successively. But for liquid feedstock, the fluid bed drier usually comes after spray drying to bring the moisture content down to a manageable level, which is not possible by spray dryer alone [Kudra, T., et al., 2009].

The benefits of microwave drying include improved drying kinetics, exact control, quick start - up and shut - down periods, high - quality dried product, lower equipment footprints, and more. For quicker removal of the last vestiges of moisture, infrared drying is also helpful. In order to overcome the limits of uneven heating caused by focusing, corner and edge heating, inhomogeneous electromagnetic field, irregular shape, and non - uniform composition of material, these techniques are generally combined with other drying processes.

Nevertheless, these methods have comparatively large startup costs and call for expensive mechanical and electrical components [37].

Altered atmosphere drying: -

As was previously said, hot air is the drying medium used in the majority of drying techniques used for food dehydration. The majority of food products that are dried using convective air suffer from quality degradation as a result of unintended physical and chemical changes that take place throughout the drying process. The most frequent ones are the products' shrinkage as a result of case hardening and the browning response [38, 39]. Enzymatic or non - enzymatic processes may be the cause of browning. Polyphenol oxidase is the most prevalent enzyme found in fruits and vegetables, and it is responsible for these undesirable quality consequences. In dried food products, oxygen causes a number of undesirable properties. Perera [39] and O'Neill et al. [40] have talked about employing a heat pump to apply modified environment drying for specific food goods. Numerous experimental investigations using modified heat pump drying on a range of food product categories have demonstrated a significant improvement in product quality [41–43].

Drying with superheated steam: -

For some operations, superheated steam is a desirable drying medium because it can reduce net energy consumption if the exhaust, which is also superheated steam, is used elsewhere in the plant instead of being charged to the dryer. Because superheated steam is oxygen - free, combustion or oxidative processes are prevented. It also gets rid of the possibility of an explosion and fire. Superheated steam - dried items typically have a higher quality than those produced by traditional hot air dryers. Food products can also be pasteurized, sterilized, and deodorized with the use of superheated steam. This is especially crucial for pharmaceutical and food items, whose manufacturing must adhere to strict hygienic standards. Furthermore, under some circumstances, superheater steam drying can provide higher drying rates during both constant and declining rate periods. By containing released scents, dust, or other potentially dangerous materials, closed system superheated steam drying helps to reduce the likelihood of these risks. The condensate of the effluent steam contains the majority of the contaminants. However, the superheated steam drying process can also be used to encapsulate desirable chemical molecules. Mujumdar has written about the fundamentals, benefits, drawbacks, and various uses of superheated steam drying methods in a number of articles and books [43–46], such as the Handbook of Industrial Drying [38].

Obstructing the drying of streams:

For particle materials with extremely high drying loads, piercing stream dryers are a unique substitute for flash dryers [48, 49]. However, research on ISD is still incomplete or restricted to a few number of uses. The intense collision of opposing streams in these kinds of dryers produces a zone that provides extremely large heat, mass, and momentum transfer [50].

Make contact with sorption drying:

Two methods exist for achieving contact - sorption drying: first, wet material can come into contact with heated inert particles, which will remove moisture through heat exchange; second, wet material can come into contact with heated sorbent particles, which will transfer moisture from the wet solids to the sorbent particles, thereby achieving drying. Utilizing adsorbents with a strong attraction to water, such zeolites, can improve drying efficiency. In order to achieve heat and mass transfer, a typical contact - sorption drying process entails thoroughly mixing wet solid particles with sorbent particles, followed by the separation of these two media. After regeneration, the sorbent particles are put back into the dryer. Molecular sieves, zeolites, activated carbon, and silica gel are examples of common inert sorbent particles, also known as carriers, employed for this function. The drying of different grains and fruit pieces are the common uses for contact - sorbent drying. The fruit pieces can also be dried with sugar granules added, which will cause the fruit to taste sweeter and absorb moisture from the wet solids. The contact - sorption drying mechanism has been covered in further depth by Kudra and Mujumdar [51]. Mujumdar and Rahman [52].

Artificial techniques for drying:

Convective drying: Using heat in drying apparatus, the convective method of drying is utilized to extract water from food ingredients. In order to provide heat to the meal and remove moisture, hot air is let to travel through the product [53].

Anthocyanin concentration and antioxidant capacity decreased when strawberries were dried in an experimental hot air tunnel dryer at temperatures of 60, 70, 80, and 90°C with an air flow of 1 m/s parallel to the sample. When dried at 70 to 90°C, it was also noted that the area, parameter, and fertile diameter remained same. Nevertheless, the strawberries' parenchymal tissue's area, perimeter, feret diameter, and fractal dimensions were all reduced by drying at 60°C [54]. A convective tray dryer is shown. An investigation was conducted to determine the impact of pre - treating strawberries with alkaline ethyl oleate on their oven - drying process.50, 55, and 65°C were used for drying, and 1.2 m/s of air velocity was used [55]. The pre - treated strawberries were shown to have a faster rate of drying and a shorter drying period. In comparison to the sample that had not been pre - treated, the pre - treated samples likewise exhibited superior rehydrating qualities. Research has been conducted on a variety of fruits and vegetables, including jack fruit [56], ginger [57], mushrooms [58], mango [3], and convective drying method combined with osmotic drying method.

Drying by radiation:

The loss of food's heat - sensitive ingredients is caused by a lengthy drying process at high temperatures. Electromagnetic radiation with a wave length of one millimeter to one meter and a frequency range of 300 MHz to 300 GHz is known as microwave radiation. Microwave radiation travels across space via an electric and magnetic field. The advantage of microwave heating is that it takes less time and heat to evaporate moisture from food [6]. Since there is less water available as the drying process progresses, scorching is an issue when using a microwave. The main benefit of utilizing a microwave is that it may be used in conjunction with other drying methods, such vacuum drying [10]. The method of microwave - vacuum drying was used to prepare button mushrooms [58]. The mushroom was cut to a thickness of 614 mm, and the microwave's power ranged from 115 to 285 W with a pressure range of 6.523.5 KPa. When compared to convective air drying, they found that microwave drying preserves greater rehydrating qualities and requires 70–90% less drying time. Figure 3C shows a microwave dryer that has been vacuumed. An additional technique for eliminating moisture from food is infrared heating. Askari et al. [6] state that the wavelength range of infrared is between 0.75 and 1000 μm. Food exposed to infrared radiation developed an accumulation of charges in its electronic state as well as in its vibrational and rotational states at the molecular and atomic levels. As a result, the temperature of the food heated up without affecting the air around it. A variety of agricultural products, such as carrots [11], sweet potatoes [14], and tomatoes [59], have been dried using infrared drying.

Osmotic drying:
This method involves putting the food to be dried in a hypertonic solution, which creates a concentration difference and drives the food's water content out of the sample and into the solution. Additionally, there is a diffusion of the solutes from the fluid into the fruit and vegetable tissue [60]. the mechanism of osmotic dehydration. Sodium chloride and other mono - and disaccharides are among the most widely utilized osmotically active solutes. Because the process can be carried out at room temperature, it is more beneficial than other traditional drying methods like hot air or vacuum drying because it uses a lot less energy to complete the operation [61]. Alam et al. 's [62] investigation focused on the impact of anola's osmotic drying on its quality.

New Developments in Drying Technology:
The process of removing water from a solid cell that contains water by immersing it in a concentrated aqueous solution is known as osmotic dehydration (Ponting, 1973). Food dehydration's primary goal is to reduce the water content of food in order to speed up distribution and storage and reduce the rate of chemical reactions. Foods are submerged or soaked in a saline or sugar solution to cause osmotic dehydration. Three different kinds of counter mass transfer phenomena are the result of this (Ponting, 1973). The osmotic solution absorbs water from the food tissue in the first place, transfers solutes from the food tissue to the osmotic solution in the second place, and then leaches the food tissue's own solutes— sugars, organic acids, minerals, and vitamins—into the osmotic solution in the third place. The third transfer is numerical in nature. Comparing the third transfer type to the first two, it is numerically insignificant, but crucial to the product's composition. The differential in the osmotic pressure of fluids on either side of the semi - permeable cell membranes acts as its driving force. According to Dabhake and Khedkar (1980), cabinet drying is a considerably faster method of drying raw mango pieces than sun drying. Mehta and Tomar (1980) found that drying papaya and guava slices in an air circulation dryer produced high - quality results. In an experiment utilizing sun dehydration for fruit and vegetable products, Kalra and Bhardwaj (1981) came to the conclusion that dehydration model - II, which operates at a high temperature of 70–75 ℃, is more efficient than dehydration model - I, which operates at a low temperature of 50–55 ℃. According to Bhutani and Sharma (1988), a cross flow dehydrator dries apricots more quickly than an open sun drying method. Fruits treated with alkali took less time to dry. Sugars and organic acids, two low - molecular - weight components of cell sap, selectively permeate into the surrounding solution with increasing osmotic pressure. Only a limited portion of other cell components cross the membrane. Osmo - active compounds diffuse countercurrently to the diffusion of water and low - molecular - weight molecules from the tissue structure during osmotic dehydration. For this reason, the complicated flow of water, chemicals dissolved in cell sap, and osmo - active compounds distinguishes osmotic dehydration from conventional drying. This has a major impact on the process's overall outcome in terms of nutrition, preservation, and organoleptic qualities (Lenart, 1992). The cell's water activity is decreased by the removal of water and the production of osmoactive chemicals (Lewicki and Lenart, 1992). In order to prevent heat damage to food texture, color, and flavor, food tissues are typically submerged in a concentrated solution of osmo - active substances at moderate temperatures, such as sucrose, fructose, glucose, glycerol, starch syrup, and sodium chloride (Torreggiani, 1993). As a result, by adding the appropriate amount of an active ingredient, preservative, nutritional solute, or sensory quality enhancer into the food tissue, the procedure allows for the de - watering and direct formulation of a product (Ponting, 1973; Raoult - Wack, 1994). Dehydration by osmotic mea Another technique for food preservation that makes it possible to obtain organoleptically. (Sitkiewiez et al., 1996). The impact of sun drying, bin drying, vertical continuous drying, vertical cylindrical drying, and funnel cylindrical drying on the quality of pistachio nuts was investigated by Nejad et al. (2002). They found that bin drying is a commercial approach that yields nuts of high quality. In an experiment on the impact of several drying techniques on the nutritional makeup of dehydrated aonla, Pragati et al. (2003) showed that the osmo - air drying process was the most effective due to its superior nutrient retention after ninety days of holding. Removing moisture reduces many of the moisture - mediated degradation responses and stops the growth and reproduction of microorganisms that would cause decay (Krokida and Marianos - Kouris, 2003; Araujo et al., 2004). In their investigation into the organoleptic and chemical analysis of osmotically processed apricot halves and wholes, Sharma et al. (2006) found that lye dipping combined with a 70° Brix syrup concentration produced a higher - quality product. In their study of the physiochemical characteristics of sliced peaches during osmotic pretreatment and dehydration, Sahari et al. (2006) found that after six hours, the solutions of 50% sucrose, 60% glucose syrup, and their combination with salt (40 percent sucrose, 20% glucose syrup, and 3% NaCl) removed more water from the fruit. Black mulberry samples that had been pretreated were artificially dried by air. open sun drying and solar drying. According to Taser et al. (2007), pretreatment combinations did not significantly alter the assessed color values of mulberries during any of the drying trails. Drying is the process of eliminating a significant amount of water from a product to significantly lower the reactions that cause the product to deteriorate (Doymaz, 2008). According to Sharma et al. (2011), apricot and plum fruits work well for dehydrating fruit - based powder, chutney mixes, ready - to - serve dry mixes, and dried pickles. According to Raquel et al. (2011), who investigated three distinct pear drying techniques—solar stove, solar dryer, and tunnel dryer—the drying times for solar and solar dryer revealed a reduction of more than 40%, and when compared to conventional open - air sun drying, this reduction rose to more than 60% in the drying tunnel.

2. Conclusion and Future Directions

Currently, the most common drying technology for biopharmaceutical goods is batch freeze - drying. A growing number of alternative drying technologies have demonstrated promise. opportunities for producing solid biopharmaceuticals without sacrificing the products' efficacy, safety, or quality. The biopharmaceutical industry will benefit greatly from these prospective drying technologies since they will help mitigate risks related to drug supply during pandemics like COVID - 19 and save time, energy, and associated costs associated with producing life - saving medications. Even though some alternative techniques provide continuous manufacturing at lower operating costs, choosing drying technologies must take into account how CPPs—such as temperature, shear, etc. — affect product CQAs. Despite drying technology' As though While several drying technologies, including PRINT®, MicroglassificationTM, Spin - freeze - drying, Spray - freeze - drying, and Spray - drying, have demonstrated promising results for the stability of certain proteins and inhaled biopharmaceuticals, their effects on a variety of parenteral biopharmaceuticals remain to be investigated. Sufficient stability data obtained through product - specific research is needed to transition from traditional freeze - drying to continuous manufacturing. To guarantee product stability, formulation components must be chosen carefully considering the product and the drying method in addition to CPPs. Furthermore, little is known about the molecular process underlying the solid - state interaction of biopharmaceuticals with particular excipients. When used in conjunction with PATs, several advanced characterisation techniques can provide a more thorough and rapid analysis for comprehending and assessing the product - process relationship. As Although the majority of alternate drying techniques can be very beneficial when used with PATs, more research is needed to determine whether these techniques are feasible to implement on a commercial scale. Certain alternative drying processes have a bigger advantage in terms of scale - up, packaging, and validation aspects when it comes to simplifying the validation of multiple fill finish unit operations. While some scale - up issues need to be resolved, the biopharmaceutical industry has shown promise for the commercial scale operation of certain alternative drying technologies.

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