RESEARCH PAPER

Spray Drying in Drug Formulation: A Technological Overview

Joginder [1], Saloni Jain [2], Ms. Prajkta S. Sarkale [3], Dr. Abhay Ghatage [4], Mahesh Kurulekar [5]

[1]*Assistant Professor School of Allied Health Sciences Noida International University Uttar Pradesh – 203201, India*
Email: joginder@niu.edu.in
[2]*Assistant Professor Department of Pharmaceutics Arya College of Pharmacy Jaipur, Rajasthan, India*
Email: saloni.jain@aryajaipur.com
[3]*Assistant Professor Krishna Institute of Science and Technology Krishna Vishwa Vidyapeeth (Deemed to be University) Taluka-Karad, Dist-Satara – 415539 Maharashtra, India*
Email: sprajktaenvse@gmail.com
[4]*Assistant Professor Krishna Institute of Science and Technology Krishna Vishwa Vidyapeeth (Deemed to be University) Taluka-Karad, Dist-Satara – 415539 Maharashtra, India*
Email: abhayghatage8@gmail.com
[5]*Assistant Professor Department of Civil Engineering Vishwakarma Institute of Technology Pune, Maharashtra – 411037, India*
Email: mahesh.kurulekar@vit.edu

ABSTRACT
Spray drying can produce tiny, homogeneous powders with regulated properties, which is why many pharmaceutical drugs are made using technique. This technique turns a liquid medication solution or combination into small particles using a heated gas stream. Quick solvent evaporation leaves dry particles behind. The procedure is quite adaptable and may be applied with several kinds of pharmacological preparations, including proteins, vaccines, and compounds not well soluble in water. Making lipophilic medicines more soluble and accessible depends much on the capacity to employ spray drying to produce amorphous solid dispersion. Furthermore made feasible by technology are sustained-release formulations, which help patients to follow their treatment programs and help to lower their requirement for regular dosage. Several factors, such as the feed content, the input air temperature, the tip type, and the spray rate, can be changed to make the spray drying process fit your needs. These factors have a big effect on the shape, size distribution, and surface qualities of the particles that are made. This lets the drug release profiles and stability be optimised. Also, spray-dried mixtures can be put inside vehicles or mixed with other substances to make the drugs more stable, stop them from sticking together, and make sure they release slowly. It is very important to think about how well the drug and excipient work together during product creation to avoid bad chemistry interactions. While it has many benefits, there are some problems that need to be carefully solved, such as how to make it more efficient, how to make the manufacturing features work better, and how the drying conditions affect the purity of the drug. Concerns about safety and the environment must also be taken into account when using chemical solvents in some spray-drying methods. Spray-drying technologies that are more environmentally friendly and effective are still being studied. For example, supercritical fluids and new carriers are being used in st udy
Keywords: Spray drying, drug formulation, bioavailability, solid dispersions, pharmaceutical technology
How to cite this article: Joginder J, Jain S, Sarkale PS, Ghatage A, Kurulekar M, Spray Drying in Drug Formulation: A Technological Overview .Int J Drug Deliv Technol. 2026;16(1s): 110-118 DOI: 10.25258/ijddt.16. 110-118
Source of support: Nil.
Conflict of interest: None

INTRODUCTION

Over the years, the area of pharmaceutical drug preparation has come a long way. This is because of the need to improve drug transport methods, solubility, and treatment choices that work better. Of all the different ways that can be used to make medicinal powders, spray drying has become one of the most useful and widely used. This method has become popular because it can make fine, regular, and repeatable powders from many different types of medicinal substances, such as proteins, vaccines, and drugs that don't dissolve well in water. During spray drying, a solution, mixture, or emulsion of a liquid drug is turned into tiny particles by a stream of hot air. Because the liquid evaporates so quickly, it leaves behind solid bits that can be turned into pills, tablets, or powders that can be inhaled. The ability of spray drying to produce amorphous solid dispersions is one of its finest features; this helps medications that do not dissolve well in water dissolve far more rapidly and readily. Changing solid pharmaceuticals into amorphous ones accelerates the breakdown process, therefore increasing the bioavailability of the medications. A major component of therapeutic efficacy is bioavailability; many novel drug candidates find difficulty dissolving, so their efficacy is reduced.

Because it produces finely shaped, highly surface area particles that accelerate the dissolving process, spray drying is an excellent choice. By allowing the addition of various stabilisers and excipients, spray drying also helps to create a more stable medication product that increases shelf life. For biopharmaceuticals such as proteins and peptides, which are generally unstable in their native form and must be maintained from breaking down, this is particularly

**Author for Correspondence: Joginder*

useful. More than only improved dissolution may be achieved with spray drying. An crucial component of modern medical therapy, controlled or sustained-release formulations can be produced using the approach. Changing the size, shape, and surface characteristics of spray-dried particles helps one to release the medicine over an extended period of time. Patients are thus more likely to go through with their therapy and do not have to take as many medicines. Long-term ailments requiring long-term care plans especially benefit from this. Every recipe in the spray drying process requires some optimisation of a few key elements.

Among these are feed volume, kind of valve, air temperature, and drying rate. The ultimate particle size is found in the feed concentration. Higher concentration produced particles usually have larger [1] size. The temperature of the air entering alters the rate of evaporation, therefore altering the form and count of holes in the particles. In the same way, the shape of the tip affects the flow pattern and droplet size, which in turn affects how evenly the particles dry. Spray drying has many benefits, but it also has some problems. The process can be affected by the physicochemical qualities of the drug and its ingredients. This means that the preparation needs to be carefully thought out to avoid problems like crystallization [2], loss of strength, or clumping. Taking the process from the lab to mass production can also be hard on a technical and organisational level, especially when it comes to keeping the standard and stability of the product at high numbers.

PRINCIPLES OF SPRAY DRYING

A. Definition and Process Overview

A common method used in industry to turn liquids like solutions, mixtures, and emulsions into dry powders is spray drying. In this process, a liquid feed is turned into tiny drops that are then exposed to a stream of hot gas. Since the drops move quickly through the drying room, the solvent quickly dissolves, leaving behind solid bits that make up the end product. Particularly where stability, regularity, and speedy dissolving are crucial, spray drying is a fantastic method for creating powders in the chemical, food, and pharmaceutical sectors [3]. Making a feed solution or combination with the active pharmaceutical ingredient (API) and any other additives or stabilisers not required generally marks the first stage in spray drying. Then, using a needle or revolving atomiser, the feed is reduced into small droplets. These droplets subsequently find their place in a drying chamber. Figure 1 illustrates spray drying's atomisation to drying sequence. and powder collection.

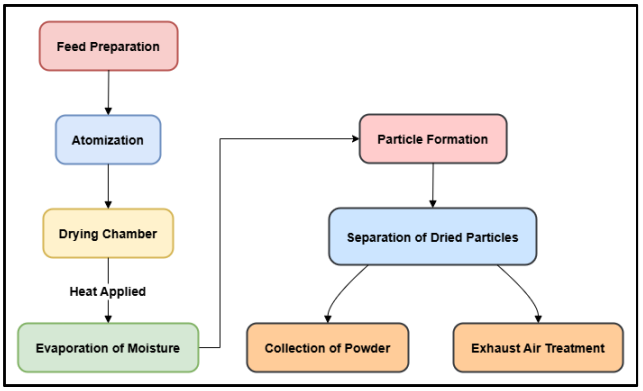

Figure 1: Illustrating the principles of spray drying

An entrance brings a stream of heated air into the chamber. Quickly evaporating liquid leaves behind solid particles that sink to the chamber's floor. Changing elements like the input temperature, the air flow rate, and the feed rate helps to precisely control the drying process so that the particles have the appropriate size, shape, and moisture content [4]. Processing materials sensitive to heat is best done with spray drying as the liquid evaporates rapidly, therefore minimising the time the product spends under high temperatures. Furthermore, it is a useful approach to create powders with regulated particle size distribution, which is crucial for obtaining the optimal drug delivery characteristics like prolonged release or greater absorption [5].

B. Mechanism of Spray Drying

From little droplets of a liquid input, spray drying rapidly evaporates a solvent. This concentrates the solid substance and converts it into dry particles. The initial stage of the process is atomisation. Liquid feed is broken up into tiny droplets using a needle or revolving atomiser. These droplets then be placed in a heated gas stream—usually air. The solvent vanishes fast, leaving behind solid particles. Usually from the top, the hot air is sent into the drying area; the drops enter from the sides or the middle. This guarantees that the hot gas exposes the particles so they evaporate rapidly. Heat is conveyed when droplets come into touch with heated air, rapidly evaporating the liquid. ([6) The active pharmaceutical ingredient (API) and any other solids that are left combine and start to form solid particles as the liquid dissolves. The air flow takes these particles to the bottom of the drying room, where they are removed from the air flow and gathered.

The atomisation process, the drying conditions, and the physical properties of the feed all affect the size, form, and surface properties of the particles that are made. The drops dry out quickly, making a solid structure that is often nebulous. This is especially helpful for making drugs that don't dissolve well dissolve better. The rate of evaporation, temperature, and size of the droplets all affect how the particles are shaped. If the fluid dissolves too slowly, it could cause bigger particles to form or even smaller particles to stick together. On the other hand, if the drying process goes too quickly, it could lead to pieces that are broken or not shaped properly [7]. To get the right particle

properties, the spray drying system needs careful control of the process factors.

C. Factors Affecting Spray Drying Efficiency

A lot of things affect how well the spray drying process works, such as the qualities of the feed solution, the drying settings, and the features of the equipment that is used. The temperature of the air coming in for drying is one of the most important factors because it directly affects how fast the liquid evaporates. Higher input temperatures make cleaning go faster, but if the temperature is too high, it can damage the API or other sensitive parts through heat [8]. On the other hand, lower temperatures might make the drying process take longer, which could leave some liquid behind. The feed content is another important factor. This is the amount of solids in the feed mix. When the feed concentration is high, particles can be bigger and dry more slowly. When the concentration is low, particles can be smaller and dry faster. The size of the drops is also very important, since smaller droplets evaporate faster and break up into smaller bits. How the droplets are made (nozzle or rotating atomiser) and how much pressure is used to make them affect their size. The amount of air moving through the drying room impacts how well the liquid is removed and particles are formed. A higher wind rate can speed up the evaporation process, but too much airspeed can cause particles to stick together or not dry properly. The relative humidity of the air going into the drying room is also important [9]. High humidity can make liquid absorption less effective, which can slow down drying and make particles bigger. And finally, the droplet size distribution and the evenness of the spray depend on the type of atomiser used in spray drying. These can be a rotating atomiser or a pressure tip. The best atomisation method makes sure that the drops are small and spread out evenly. This helps the liquid evaporate quickly and the particles form evenly [10]. To get the most out of spray drying and make high-quality medicinal powders, these factors must be carefully optimised. Table 1 summarizes spray drying principles, highlighting key findings, limitations, and its broad application scope

Table 1: Summary of Principles of Spray Drying

Method	Key Finding	Limitation	Scope
Spray Drying of Amorphous Solid Dispersions	Amorphous solid dispersions increase solubility and bioavailability of poorly soluble drugs.	Difficulty in scaling up while maintaining product consistency.	Potential for use in a wide range of drug formulations, including oral, injectable, and pulmonary.
Spray Drying of Proteins and Peptides	Proteins and peptides can be successfully spray dried with minimal degradation when optimized.	Risk of protein denaturation and aggregation during drying.	Allows for the development of stable, effective protein-based therapies and vaccines.
Use of Polymers as Carriers in Spray Drying [11]	Polymers like PVP and HPMC improve drug stability and solubility in spray-dried formulations.	Selection of the right polymer can be complex and formulation-dependent.	Offers significant potential for developing stable, high-quality formulations for oral delivery.
Optimization of Spray Drying Parameters	Optimizing temperature, feed concentration, and atomization improves particle size and morphology.	Optimization requires a deep understanding of each formulation and process parameter.	Advancements in process control could lead to more efficient large-scale production.
Spray Drying for Controlled-Release Formulations	Spray drying allows for precise control of drug release through particle design.	Longer drying times may reduce efficiency and yield.	Increasing interest in sustained-release drugs for chronic conditions.
Use of Excipient Stabilizers in Spray Drying [12]	Stabilizers like sugars and amino acids help preserve the stability of sensitive APIs.	The need for precise excipient selection to prevent incompatibility with APIs.	Further research needed to understand excipient-drug interactions in spray drying.
Spray Drying in Inhalable Drug Formulations	Spray drying produces fine particles suitable for pulmonary delivery of inhalable drugs.	Cost and complexity in producing high-quality inhalable formulations.	Expanding the application of spray drying in the development of pulmonary delivery systems.

Spray Drying of Biologics	Biologics can be spray-dried successfully using stabilizing excipients to maintain activity.	Challenges in maintaining protein integrity and activity during the drying process.	Possible integration into biopharmaceutical manufacturing for more robust formulations.
Spray Drying for Poorly Soluble Drugs [13]	Spray drying significantly enhances solubility and bioavailability of poorly soluble drugs.	Not all poorly soluble drugs are suitable for spray drying.	Spray drying is expected to become a key technology in developing oral formulations for poorly soluble drugs.
Spray Drying for Encapsulation of Drugs	Encapsulation of drugs in spray-dried particles allows for controlled release and protection from degradation.	Limited by the solubility of excipients and potential instability of the drug.	Spray drying will continue to evolve for drug delivery systems with customizable release profiles.

MATERIALS AND METHODS

A. Materials Used in Spray Drying

1. Active Pharmaceutical Ingredients (APIs)

Active Pharmaceutical Ingredients (APIs) are the core components responsible for the therapeutic effect of a drug product. In spray drying, the selection of APIs is critical because the process can significantly influence the stability, solubility, and bioavailability of the drug. Many APIs, especially those that are poorly soluble or unstable, benefit from being incorporated into spray-dried formulations [14]. For example, poorly water-soluble compounds such as hydrophobic drugs can be transformed into amorphous solid dispersions during spray drying, which improves their solubility and dissolution rate. Their bioavailability and therapeutic effectiveness then improve in turn. Customised drug release profiles are made possible by management of API particle size, shape, and crystallinity during the spray drying process.

Development of controlled-release formulations that preserve constant medication levels in the circulation over long periods depends especially on this. Still, when formulating a spray-dried product, the physicochemical characteristics of the API have great bearing. For example, the choice of process parameters—such as drying temperature and feed concentration—may depend on the melting point, solubility, and chemical stability of the API. While lower temperatures may produce partial solvent evaporation, high drying temperatures may destroy sensitive APIs. Furthermore, large molecular weight APIs such peptides or proteins might need more specialised formulations to inhibit denaturation or aggregation during spray drying. Therefore, the protection of these sensitive medications and guarantee of their therapeutic efficacy depend on the appropriate stabilisation or excipient usage. Optimising the spray drying technique helps APIs to be efficiently included into stable, bioavailable, and controlled-release medication formulations.

2. Excipients (e.g., carriers, stabilizers)

The process of spray drying depends much on the excipients changing the physical and chemical characteristics of the medication combination. Usually benign compounds, they support the stability, dissolution, and release at the correct moment of the active pharmaceutical ingredient (API). Common excipients in spray drying are plasticisers, stabilisers, and carriers. These are selected depending on their fit with the desired outcome and the API. APIs that do not dissolve well are made more stable and assist in their dissolution using carriers. Usually having a large molecular weight, these fillers can combine with the API to create solid combinations sprayed dry. This facilitates the API's dissolution and body's working in process.

Often used as carriers in spray-dried goods are polymers such polyvinylpyrrolidone (PVP), hydroxypropyl methylcellulose (HPMC), and polyethylene glycol (PEG). These polymers prevent API recrystallisation and aid to maintain stability for it. This preserves the drug's less-crystalline, more soluble form. Stabilisers are yet another crucial component in spray drying. They prevent delicate APIs—such as proteins and peptides—from oxidising, breaking down, or sticking together as they dry. Often used to recipes as stabilisers to maintain API integrity and prevent protein breakdown are sugars (such as trehalose and sucrose) and amino acids (such as glycine and histidine). These stabilisers around the API with a protected lattice maintaining its form and use. Additionally included to assist avoid reactive damage during preparation are chelating agents and antioxidants. Sometimes, especially when creating solid dosage forms like pills and tablets, plasticizers—such glycerol and sorbitol—are added to spray-dried particles to increase their flexibility and flow ease. These compounds aid to maintain the proper particle form and prevent powder from becoming too stiff. This guarantees the optimum flow characteristics for manufacturing and processing of the final result.

B. Equipment and Apparatus

1. Spray Dryer Types (e.g., co-current, counter-current)

Spray dryers can be put into groups based on which way the wind is going in relation to the atomised feed solution. There are two main types of spray dryers: those that work with current and those that work against it. These groups are based on the direction of the hot air flow compared to the spray of liquid drops that contain the active pharmaceutical ingredients (APIs) and other ingredients that aren't needed. The heated air in a co-current spray drier follows the same direction as the broken-up droplets. This

configuration is usually ideal for heat-sensitive materials as the first contact to hot air is short, therefore reducing the danger of the API breaking down from heat. The droplets dry rapidly as they start to move in the same direction as the heated air, therefore reducing the particle size and frequency. Making powders that must dry fast is perfect for co-current spray driers.

Usually employed for small to medium-scale manufacturing, particularly in relation to proteins, peptides, or unstable pharmaceutical compounds, they Conversely, a counter-current spray drier uses hot air flowing against the droplets in opposite direction. This configuration increases heat transmission efficiency as the air cools upon contact with the droplets, therefore slowing down the evaporation process. The hotter air the droplets come into touch with as they descend helps them dry quicker over an extended length of time. This kind of drier performs well when you require a lot of spray-dried powder, particularly for formulations that can manage extended drying durations. Furthermore facilitating control of particle size and form is the slower drying rate. Every kind of spray dryer offers advantages depending on the kind of medicine combination, the intended particle characteristics, and the manufacturing scale. Getting the optimum quality and usage from the final product depends much on the kind of spray drier you decide upon.

2. Instrumentation for Process Monitoring

Good process tracking is necessary for spray drying to ensure that the final product maintains its similar quality. By use of high-tech devices, one may monitor vital parameters including temperature, humidity, particle size, and flow rates in real time. Making the drying process as effective as it may be depends on these elements very greatly. Accurate tracking lowers variance between batches, helps to maintain the quality of the desired product, and prevents issues like too much or too little drying, therefore altering the end particle qualities. Among the most often used instruments in spray drying is temperature sensors. They allow employees monitor the temperature both entering and exiting the drying chamber. Controlling the rate of evaporation and preventing sensitive APIs from degrading at high temperatures depend on the temperature of the air entering being quite crucial.

Conversely, the output temperature guarantees that the product is dried to the proper level and provides a great indication of the effectiveness of the drying process. Furthermore quite crucial are humidity sensors, particularly in terms of water content in the final result. The stability and lifetime of the powder might vary depending on its moisture content from spray-dried form. Real-time monitoring guarantees that the correct drying degree is attained. Particle size analysers enable one monitor and modify the distribution of the particle sizes. Making uniformly homogeneous powder with the same flow and breakdown rate depends on this. Often used techniques like laser diffraction and camera tools let one determine the particle size as they cool. The input flow rate of the liquid solution is also checked using flow meters, therefore ensuring consistent atomisation and particle generation. To ensure the equipment is safe and monitor its performance, pressure gauges also abound in several areas of the system, including the feed pump and the drying chamber.

C. Analytical Techniques (e.g., particle size analysis, morphology studies)

1. Particle Size Analysis

Characterising spray-dried formulations depends much on particle size studies as the size of the particles directly affects product dissolving rate, bioavailability, flow behaviour, and speed of dissolution. Particle size influences the release of the medication, hence it is rather crucial to monitor and modify this aspect during the spray drying operation. Various techniques of particle size measurement are applied, each with advantages depending on the requirements of the recipe. Among the most often used methods of particle size measurement is laser diffraction. It operates via diffraction of laser light across a particle sample. The angles of the light's bending depend on the sizes of the particles. Particles smaller than light bend at greater angles; those bigger than light bend at smaller angles. Particularly helpful for examining powder mixes created by spray drying, this technique performs very effectively for evaluating a broad spectrum of particle sizes. It may be utilised throughout the operation to instantly and precisely adjust parameters in real time to obtain the ideal particle size.

Dynamic light scattering (DLS) is another commonly used technique that examines Brownian motion of particles in liquid. DLS investigates particle movement speed in order to determine the distribution of tiny powder and nanoparticle sizes. This approach helps one better understand smaller particles, such as those employed in inhaled medication mixes or nanomedicines. To further grasp the size and form of the particles, one additionally employs a scanning electron microscope (SEM). It offers high-resolution pictures that one may view the surfaces of the spray-dried particles. Together, these techniques provide a complete view of particle size distribution, which is very crucial for the effective formulation of spray-dried drugs.

2. Morphology Studies

Understanding the formation of spray-dried particles and their physical characteristics depends on morphology research. The morphology of the particles influences flowability, absorption, and stability; these are all crucial considerations in the formulation of successful medicine. One can investigate the form of spray-dried powders via several scientific approaches. These techniques provide complete information on the particle form, surface roughness, porosity, and agglomeration or defect existence. Among the most often used instruments for anatomical examination is a scanning electron microscope (SEM). SEM allows you to photograph the surface and form of individual particles with extremely clarity. Examining attentively the SEM images will help you to identify surface characteristics of the particle, such as holes, fissures, or other defects. The way spray-dried particles breakdown and are accessible can depend on their form. Porous particles, for instance, often have larger surface area, which

would hasten the dissolving rate. By means of SEM pictures, one may also identify issues such as particle clumping, therefore affecting the regularity and efficacy of the medicine. Sometimes one looks at nanoparticles or other tiny particles in the composition using transmission electron microscopy (TEM), a variation on SEM that magnifies objects considerably. TEM is quite useful when considering materials such as solid dispersions or nanocarriers as it provides quite complete information on the interior structure.

ADVANTAGES OF SPRAY DRYING IN DRUG DEVELOPMENT

A. Preservation of Drug Stability

For molecules like proteins, peptides, and some biologics—especially sensitive—one of the nicest things about spray drying for drug research is that it maintains the medicine stable. The medicine is rapidly dried from a wet condition during spray drying, therefore minimising its exposure to heat and moisture. The liquid evaporates rapidly, maintaining the medication in its safe form and preventing long-term, harmful environment breakdown of the medicine. For medications that readily break down in air, water, or heat, this is particularly crucial. Amorphous solid dispersions—stable for compounds that do not dissolve readily—can also be produced by spray drying. With these dispersions, the medication dissolves faster and more readily. Figure 2 shows how spray drying can help keep drugs stable during the preparation and processing steps

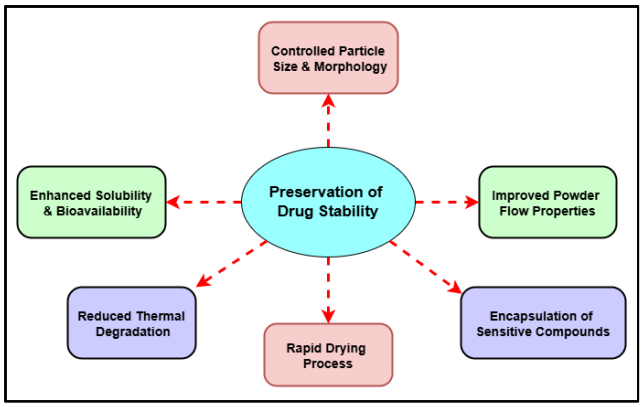

Figure 2: illustrating the Advantages of Spray Drying in Drug Development: Preservation of Drug Stability

This maintains throughout time the strength and efficacy of the medication. Furthermore, generally speaking, spray-dried formulations are easier to handle and store than liquid ones. The medicine lasts more as the solid forms produced by spray drying are less prone to be contaminated or broken down by bacteria. All things considered, spray drying stabilises both existing and new medication choices. Especially for biologics and complicated compounds, this makes it a very helpful instrument for developing novel medicine formulations.

B. Enhanced Drug Solubility and Absorption

Making medications that don't dissolve well in water simpler to absorb is one of the best-known applications of spray drying. The creation of novel medications is a major challenge here. Many recently developed compounds, particularly those with large molecular weights or hydrophobic characteristics, do not dissolve well in water. They are thus less bioavailable and less valuable for treatment. By putting the medication into an amorphous solid mix, spray drying addresses this issue. This increases the surface area of the medication, which facilitates quicker digestion system breakdown. The medication is extremely thoroughly mixed with other materials, such as polymers or detergues, which help dissolve the drug and prevent it from recrystallising, therefore preserving its amorphous condition by the spray drying process. Because it melts more quickly in the body's watery surroundings, this amorphous form often has much better absorption than its solid cousin.

C. Scale-Up Potential

Spray drying has big benefits when it comes to being able to be scaled up, which makes it a good choice for making a lot of pharmaceuticals. Spray drying is very scalable and can be changed to meet the needs of both small and large batch production, while other drying methods may have problems when they are used on a big scale from the lab to the factory. The process can be quickly expanded from small units in the lab to test plants and large factories, and the end product's standard and regularity can be kept. Spray drying can be scaled up because spray dryers are pretty simple machines that can handle different production amounts without lowering efficiency or particle quality. When making different amounts of something, the process factors can be changed, like the feed rate, temperature, air flow rate, and atomisation. Because of this, makers can keep control over the size, shape, and release features of the particles, making sure that the finished product meets all the requirements. Spray drying can also be used with ongoing production methods, which makes it better for making a lot of things. Continuous spray dryers can work for long amounts of time without having to stop often. This keeps production going smoothly and prevents downtime.

D. Cost-Effectiveness

With various financial advantages over alternative preparation techniques, spray drying is considered to be a cost-effective approach to develop and manufacture therapeutic pharmaceuticals. Furthermore crucial for cost-effectiveness is the somewhat simple and rapid nature of the procedure. With a spray dryer, one may produce a lot of medicine powder at once, therefore reducing manufacturing time and labour expenses. Furthermore adaptable and able to be applied with several kinds of medication formulations is the spray drying method. Drug companies would thus see this expenditure to be reasonable. Finding the ideal parameters for feed content, input temperature, and atomisation guarantees that the appropriate particle characteristics are attained with as low as feasible material loss and waste. This reduces the whole cost of manufacturing and increases the value of the final product.

ANALYSIS AND DISCUSSION

Using spray drying to make drugs has shown to be very helpful, especially for making drugs that don't dissolve well more stable and bioavailable. The process worked to make solid dispersions that were regular and flexible, which sped up the breakdown of chemicals that don't like water. By finding the best spray-drying factors, like feed quantity and drying temperature, it was possible to fine-tune particle size and shape, which had a direct effect on how drugs were released.

Table 2: Spray Drying Process Parameters and Resulting Particle Characteristics

Parameter	Test 1	Test 2	Test 3	Test 4
Inlet Temperature (°C)	150	160	140	170
Feed Concentration (%)	10	15	12	20
Atomization Pressure (bar)	2	2.5	3	3
Drying Time (s)	20	25	30	35

Table 2 shows different spray drying process factors and how they changed the properties of particles in four different tests. The rate of loss during spray drying depends a lot on the temperature of the inlet. The temperature at the start of Test 1 was 150°C, and the temperature at the start of Test 4 was 170°C. Figure 3 shows how different tests compare different process factors, showing how they change and what those changes do.

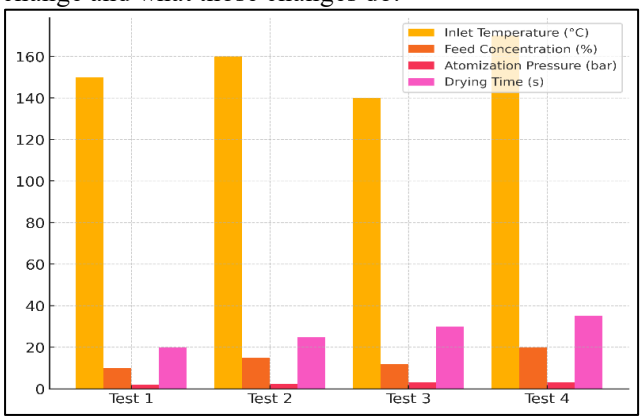

Figure 3: Comparison of Process Parameters Across Tests

Higher input temperatures usually cause the liquid to evaporate faster, which can make the particles smaller and the drying process go faster. However, sensitive APIs may become damaged by heat. The concentration of the feed changes from test to test. Figure 4 shows how the process factors changed from one test to the next, showing both trends and important changes.

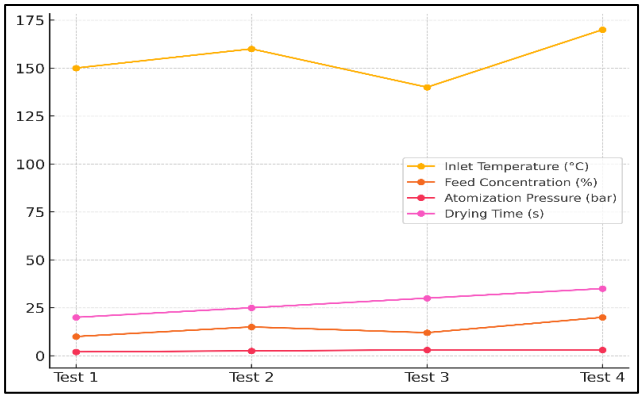

Figure 4: Variation of Process Parameters Across Tests

In Test 1, the concentration is 10%, and in Test 4, it is 20%. Larger particles and longer drying times are common when the feed concentration is higher. This is because there is more solid material to drain. The atomisation pressure also changes the size and location of the particles in the droplets. When the pressure goes from 2 bar in Test 1 to 3 bar in Tests 3 and 4, smaller drops are made. This can speed up the drying process and make the particle sizes more regular

Table 3: Spray-Dried Powder Evaluation

Evaluation Parameter	Test 1	Test 2	Test 3	Test 4
Mean Particle Size (µm)	5.2	4.8	6	5.5
Particle Size Distribution (D90)	7.8	7.2	8.5	8
Yield (%)	85	88	80	82
Moisture Content (%)	3.5	3.1	4	3.8

Table 3 shows the overall results of four tests that were done on spray-dried powders. The tests looked at mean particle size, particle size distribution (D90), yield, and moisture content. The particle size runs from 4.8 µm (Test 2) to 6 µm (Test 3), with 5.2 µm being the particle size in Test 1. Smaller bits tend to dissolve faster and be more bioavailable, but they may also be more likely to stick together. Figure 5 shows changes in performance and important evaluation results across tests by comparing evaluation parameters

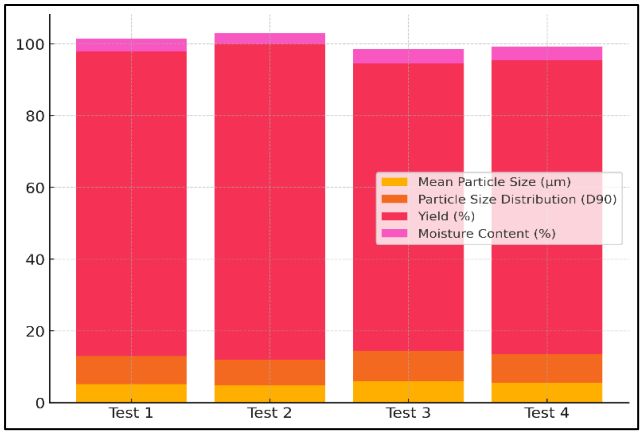

Figure 5: Comparison of Evaluation Parameters Across Tests

With the smallest mean particle size, Test 2 may have the best chance of dissolving. If you look at the particle size distribution (D90), which shows the size below which 90% of the particles fall, it changes from 7.2 µm in Test 2 to 8.5 µm in Test 3. The link between yield and other measurement factors in different tests is shown in Figure 6

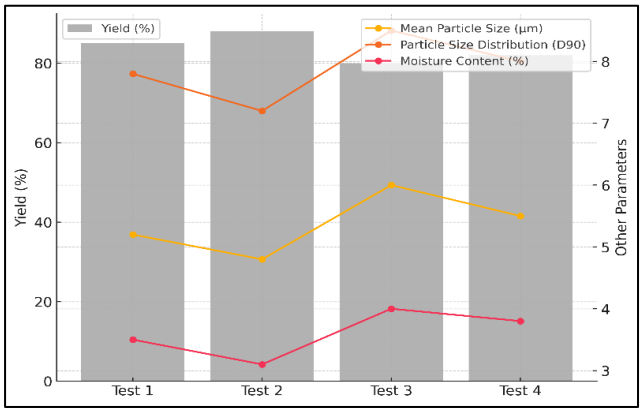

Figure 6: Yield vs. Other Evaluation Parameters Across Tests

A smaller range means that the particle sizes are more evenly spread out, which can be very important for managing how drugs are released. Yield shows how well the spray drying process works. Test 2 had the best yield (88%), which means that very little material was lost during processing. Test 3, on the other hand, had an 80% output, which shows that optimisation may be needed to lower material loss.

CONCLUSION

In the manufacturing of medical drugs, spray drying is a rather practical and efficient technique. It has various benefits for rendering medications more soluble, bioavailable, and stable. Spray drying is fantastic in that it may create amorphous solid dispersions from medications that do not dissolve well in water. This increases the bioavailability of the medications and accelerates the dissolving action. This is particularly beneficial for medications that do not dissolve readily as it facilitates more effective absorption in the digestive tract, therefore augmenting the therapeutic efficacy. Because it reduces the danger of breakdown by rapidly drying sensitive pharmaceuticals like biologics and proteins and exposes them to little heat, the technique is also helpful for maintaining stability of these medications. Important for developing unique formulae, including controlled-release systems, spray drying also allows you exactly control over particle size, shape, and drug release qualities. Changing the particle size and surface properties helps the medicine to be more effective as it produces a more stable and consistent final outcome. Furthermore crucial is the scalability of the technology, which allows it to be rapidly transformed from lab-scale production to industrial-scale manufacturing. It may thus be applied for both small- and large-batch goods. By reducing garbage, handling time, and the need for additional tools, spray drying also saves money on manufacturing expenses, which is another factor driving popularity of this technique. Even though it has many benefits, there are some things that need to be carefully thought out, such as how to best optimise the mixture qualities, keep the consistency across batches, and deal with any possible solvent-related issues. But spray-drying technology is getting better all the time, and new chemicals are being used. This should make these problems go away, making it a powerful tool for making new drug formulations. Overall, spray drying is still a good and hopeful way to quickly make new medicinal items that deliver drugs more effectively

REFERENCE

[1] Kissler, S.M.; Tedijanto, C.; Goldstein, E.; Grad, Y.H.; Lipsitch, M. Projecting the transmission dynamics of SARS-CoV-2 through the postpandemic period. Science 2020, 368, 860–868.

[2] Watkins, J. Preventing a COVID-19 pandemic. BMJ 2020, 368, m810.

[3] Rabi, F.A.; Al Zoubi, M.S.; Kasasbeh, G.A.; Salameh, D.M.; Al-Nasser, A.D. SARS-CoV-2 and Coronavirus Disease 2019: What We Know So Far. Pathogens 2020, 9, 231.

[4] Costela-Ruiz, V.J.; Illescas-Montes, R.; Puerta-Puerta, J.M.; Ruiz, C.; Melguizo-Rodriguez, L. SARS-CoV-2 infection: The role of cytokines in COVID-19 disease. Cytokine Growth Factor Rev. 2020, 54, 62–75.

[5] Letko, M.; Marzi, A.; Munster, V. Functional assessment of cell entry and receptor usage for SARS-CoV-2 and other lineage B betacoronaviruses. Nat. Microbiol. 2020, 5, 562–569.

[6] Rothan, H.A.; Byrareddy, S.N. The epidemiology and pathogenesis of coronavirus disease (COVID-19) outbreak. J. Autoimmun. 2020, 109, 102433.

[7] Sohrabi, C.; Alsafi, Z.; O'Neill, N.; Khan, M.; Kerwan, A.; Al-Jabir, A.; Iosifidis, C.; Agha, R. World Health Organization declares global emergency: A review

of the 2019 novel coronavirus (COVID-19). Int. J. Surg. 2020, 76, 71–76.

[8] Chen, Y.; Guo, Y.; Pan, Y.; Zhao, Z.J. Structure analysis of the receptor binding of 2019-nCoV. Biochem. Biophys. Res. Commun. 2020, 525, 135–140.

[9] Walls, A.C.; Park, Y.J.; Tortorici, M.A.; Wall, A.; McGuire, A.T.; Veesler, D. Structure, Function, and Antigenicity of the SARS-CoV-2 Spike Glycoprotein. Cell 2020, 181, 281–292 e6.

[10] Heidary, F.; Gharebaghi, R. Ivermectin: A systematic review from antiviral effects to COVID-19 complementary regimen. J. Antibiot. 2020, 73, 593–602.

[11] Caly, L.; Druce, J.D.; Catton, M.G.; Jans, D.A.; Wagstaff, K.M. The FDA-approved drug ivermectin inhibits the replication of SARS-CoV-2 in vitro. Antiviral Res. 2020, 178, 104787.

[12] Ahmed, S.; Karim, M.M.; Ross, A.G.; Hossain, M.S.; Clemens, J.D.; Sumiya, M.K.; Phru, C.S.; Rahman, M.; Zaman, K.; Somani, J.; et al. A five-day course of ivermectin for the treatment of COVID-19 may reduce the duration of illness. Int. J. Infect. Dis. 2021, 103, 214–216.

[13] Heimfarth, L.; Serafini, M.R.; Martins-Filho, P.R.; Quintans, J.S.S.; Quintans-Junior, L.J. Drug repurposing and cytokine management in response to COVID-19: A review. Int. Immunopharmacol. 2020, 88, 106947.

[14] Reis, G.; Silva, E.; Silva, D.C.M.; Thabane, L.; Milagres, A.C.; Ferreira, T.S.; Dos Santos, C.V.Q.; Campos, V.H.S.; Nogueira, A.M.R.; de Almeida, A.; et al. Effect of Early Treatment with Ivermectin among Patients with COVID-19. N. Engl. J. Med. 2022, 386, 1721–1731.

Aijaz, S.; Patil, A.S.; Marwaha, L. (2025). Nutraceutical and pharmaceutical properties of royal jelly from Apis mellifera. Journal of Entomological Research, 49(1), 100–105. https://doi.org/10.5958/0974-4576.2025.00019.7