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A Review Study of Influencing Factors and Conceptual Scaling Framework for Spray Drying Assisted by Ultrasonic Vibrating Mesh Atomizers

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Abstract. Spray drying is widely used in the pharmaceutical, food, and chemical industries for converting liquid feed into dry particulate products. However, conventional spray drying systems commonly generate broad droplet size distributions and exhibit limited capability for producing submicron particles. To overcome these limitations, ultrasonic vibrating mesh atomizers have recently attracted significant attention due to their ability to generate highly uniform droplets with relatively low energy consumption and improved atomization controllability. Previous studies have investigated the influence of individual operating parameters on ultrasonic spray drying performance, particularly using laboratory-scale systems such as the Büchi Nano Spray Dryer B-90. Nevertheless, existing literature remains fragmented, with limited efforts to systematically establish the relative importance of governing parameters or to develop a unified conceptual framework for scaling ultrasonic spray drying systems from laboratory to industrial applications. This study addresses this gap by conducting a systematic literature-based parametric analysis of spray drying systems assisted by piezoelectric vibrating mesh atomizers. Experimental studies employing the Büchi Nano Spray Dryer B-90 were critically reviewed to identify the dominant factors controlling droplet formation, atomization stability, and particle generation behaviour. The analysed parameters were classified into three principal categories: atomization parameters, fluid properties, and drying process parameters. The analysis demonstrates that mesh aperture size, ultrasonic vibration frequency, and spray throughput are the primary parameters governing droplet formation and particle size distribution. Fluid properties, including viscosity, surface tension, and feed concentration, strongly influence atomization stability through their effects on dimensionless parameters such as the Weber number and Ohnesorge number. In contrast, drying parameters, including inlet air temperature and gas flow rate, predominantly affect evaporation kinetics and particle morphology rather than the initial droplet generation process. The reviewed studies further indicate that ultrasonic atomization commonly operates within a regime characterized by moderate Weber numbers and relatively low Ohnesorge numbers, consistent with capillary wave breakup mechanisms. Based on these findings, a conceptual scaling framework is proposed in which atomization similarity, fluid dynamic similarity, and drying conditions must be simultaneously considered to achieve reliable scale-up of ultrasonic spray drying systems

Keywords : Vibrating Mesh Atomizer, Spray Drying, Ultrasonic, Scaling Technique

1. INTRODUCTION

Spray drying has long been recognized as one of the most versatile and widely used technologies for transforming liquid feed solutions into dry particulate products. The technique is extensively applied in various industrial sectors, including pharmaceuticals, food processing, biotechnology, and advanced materials engineering. Conventional spray drying systems typically employ pressure nozzles or rotary atomizers to generate droplets, which subsequently undergo rapid solvent evaporation within a heated drying chamber. Although these systems are well established for large-scale production, controlling droplet size distribution and producing submicron particles remain significant challenges due to the inherent limitations of traditional atomization mechanisms.[1]-[4]

In recent years, ultrasonic atomization technologies have attracted increasing attention as an alternative approach for generating highly controlled droplets. Among these technologies, the vibrating mesh atomizer has emerged as a particularly promising solution due to its ability to produce narrow droplet size distributions with relatively low energy consumption [5]-[7]. This atomization mechanism relies on the oscillation of a piezoelectric element coupled with a micro-perforated mesh, through which the liquid feed is forced under ultrasonic vibration. As a result, droplets are generated through capillary wave instabilities at the liquid–mesh interface, enabling precise control of droplet formation.[5]-[13]

A significant advancement in this field was the development of the Büchi Nano Spray Dryer B-90, which integrates a piezoelectric vibrating mesh atomizer into a laboratory-scale spray drying system. This technology enables the production of submicron particles and nanoparticles with improved control over particle size distribution compared to conventional spray drying systems [14]-[16]. These capabilities have made the system particularly attractive for pharmaceutical particle engineering, nanoencapsulation, and also the stabilization of bioactive compounds. Beyond its application as a laboratory-scale particle engineering tool, the Buchi B-90 platform also provides valuable insights into the fundamental physics of ultrasonic atomization and droplet formation. Because the atomization process is governed by well-defined dimensionless parameters such as the Weber number and Ohnesorge number, experimental results obtained using the Büchi B-90 system can be used to establish scaling relationships for spray drying processes. Maintaining similar dimensionless parameters allows the preservation of atomization mechanisms when transitioning from laboratory-scale equipment to pilot-scale or industrial-scale spray dryers. Consequently, research conducted using the B-90 system plays an important role in bridging the gap between fundamental atomization studies and the design of industrial spray drying equipment. By systematically investigating the effects of ultrasonic frequency, mesh geometry, feed properties, and operating conditions, researchers can develop scaling frameworks that enable consistent droplet formation across different process scales. Such knowledge is essential for the development of next-generation spray drying technologies capable of producing nanoparticles and highly engineered particles in industrial applications. Therefore, understanding the atomization mechanisms and scaling principles derived from studies using the B-90 system is crucial for advancing the design of industrial spray drying equipment. The insights gained from these studies provide a foundation for improving droplet control, enhancing particle engineering capabilities, and ultimately enabling the efficient production of advanced functional powders in large-scale industrial processes. [17]-[25]

Although numerous studies have investigated individual operating parameters in ultrasonic spray drying systems, existing research remains largely fragmented and application-oriented [26]-[28]. Most previous studies focused on formulation development, nanoparticle production, or optimization of isolated process variables using laboratory-scale equipment such as the Büchi Nano Spray Dryer B-90 (see Tabel 1). However, no previous review has systematically established a hierarchical relationship among atomization parameters, fluid properties, and drying conditions while simultaneously proposing a conceptual scaling framework based on dimensionless similarity principles for ultrasonic spray drying systems. Consequently, the fundamental relationships governing scale-up from laboratory-scale ultrasonic spray dryers to industrial-scale applications remain insufficiently understood.

The objective of this study is to investigate the key parameters governing the scaling behaviour of spray drying systems assisted by a piezoelectric mesh atomizer. In recent years, vibrating mesh atomization has emerged as a promising technique for generating highly uniform droplets with narrow size distributions, which is particularly advantageous for producing submicron and micron-scale particles. However, despite the growing number of laboratory-scale studies, the fundamental parameters that control the scalability of ultrasonic spray drying systems remain insufficiently understood. Therefore, this study aims to conduct a comprehensive parametric analysis of the operational variables influencing droplet formation, atomization stability, and particle characteristics in spray drying processes assisted by piezoelectric mesh atomizers. Particular attention is given to identifying the relationships between atomization parameters, fluid properties, and drying conditions that govern the droplet formation mechanism and ultimately determine the particle size distribution. Furthermore, the study seeks to establish a conceptual scaling framework that links laboratory-scale experimental observations with potential industrial spray drying applications. By analysing the effects of key parameters such as mesh aperture size, vibration frequency, feed properties, and drying conditions, this work aims to determine the dominant variables controlling atomization performance and particle formation in ultrasonic spray drying systems. Ultimately, the findings of this research are expected to contribute to the development of scaling strategies for spray drying technologies employing piezoelectric mesh atomizers, thereby supporting the design of next-generation spray drying equipment capable of producing finely controlled powders in industrial-scale processes.

2. METHODS

This study employed a systematic literature-based parametric analysis to identify the key operational and physical parameters governing droplet generation and particle formation in spray drying systems utilizing vibrating mesh atomizers. Particular emphasis was placed on studies conducted using the Büchi Nano Spray Dryer B-90, as this system represents one of the most widely used laboratory-scale spray drying platforms employing ultrasonic vibrating mesh atomization.

The methodological framework was designed to extract, classify, and analyze experimental parameters reported in published research in order to determine the dominant variables influencing spray drying performance. By synthesizing findings from multiple studies, the research aims to establish a parameter hierarchy and develop insights into potential scaling strategies applicable to industrial spray drying systems. A comprehensive literature search was conducted using major scientific databases including Scopus, Web of Science, Google Scholar, and ScienceDirect. The search focused on peer-reviewed journal articles published between 2010 and 2024, corresponding to the period following the introduction of the Büchi Nano Spray Dryer B-90. The search keywords included combinations of; "nano spray dryer B-90", "vibrating mesh atomizer spray drying", "ultrasonic atomization spray drying", "nano spray drying particle engineering", and "B-90 spray drying parameters". Articles were included in the analysis if they satisfied the following criteria:

1. The study employed the Büchi Nano Spray Dryer B-90 as the primary spray drying equipment.
2. Experimental conditions and operating parameters were explicitly reported.
3. The study analyzed particle characteristics, droplet formation, or process performance.
4. The research was published in peer-reviewed scientific journals.

Studies were excluded if they did not provide sufficient information on process parameters or if they focused solely on formulation chemistry without reporting spray drying operating conditions. Then, the selected articles and relevant experimental parameters were systematically extracted and categorized into three major groups: Atomization Parameters, Feed and Fluid Properties, Drying Process Parameters. Although the present study synthesizes a wide range of experimental findings from the literature, certain limitations must be acknowledged. Differences in feed formulation, measurement techniques, and experimental setups across studies may introduce variability in reported results. Therefore, the conclusions derived from the parametric analysis should be interpreted as general trends rather than absolute predictive correlations. Nevertheless, by integrating results from multiple studies, the present methodology provides a comprehensive overview of the key parameters governing vibrating mesh spray drying systems and offers valuable insights for future development of industrial-scale ultrasonic spray drying technologies.

3. RESULTS

3.1 An Overview of Industrial Spray Drying Assisted by Ultrasonic Atomization

An industrial spray dryer is composed of several integrated components that work together to transform a liquid feed into dry powder through atomization and rapid solvent evaporation. The performance and efficiency of the spray drying process strongly depend on the proper design and operation of these components. In general, the system consists of a feed preparation unit, pumping system, atomization device, air heating unit, drying chamber, particle separation system, powder collection unit, and exhaust air system (see Figure 1). Each of these components plays a critical role in controlling the droplet formation, heat transfer, mass transfer, and powder recovery processes.[29], [30].

The feed preparation unit is responsible for storing and conditioning the liquid feed before it enters the spray dryer. Typically, the feed solution or suspension is stored in a feed tank equipped with an agitation system to maintain uniformity and prevent sedimentation of solid particles. In many industrial applications, the feed preparation stage also includes filtration and deaeration systems to remove impurities and entrapped air bubbles that could interfere with the atomization process. [30] The physical properties of the feed, such as viscosity, surface tension, and solids concentration, must be carefully controlled during this stage because they significantly influence droplet formation and drying behavior within the spray dryer.[4]

The feed pumping system transports the prepared liquid feed from the storage tank to the atomizer at a controlled flow rate and pressure. Industrial spray drying systems commonly use positive displacement pumps or high-pressure pumps depending on the type of atomizer used. The feed flow rate is a crucial operating parameter because it determines the amount of liquid introduced into the drying chamber and influences the residence time of droplets within the drying environment. Precise control of the pumping system is therefore necessary to ensure stable atomization and prevent operational problems such as flooding or incomplete drying [24], [31].

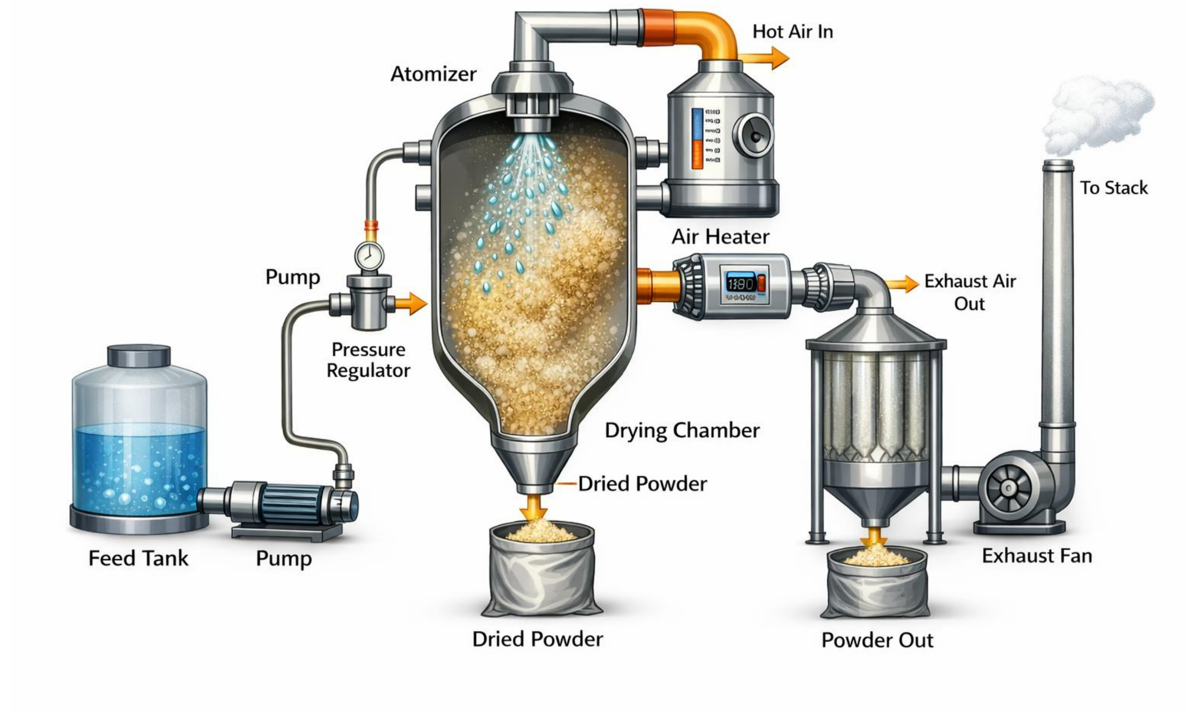


Figure 1 Schematic of industrial spray drying system

The atomizer is considered the most critical component of a spray dryer because it is responsible for converting the liquid feed into fine droplets. The droplet size generated during atomization largely determines the final particle size distribution and drying rate. Industrial spray dryers typically utilize three main types of atomizers: pressure nozzle atomizers, rotary atomizers, and ultrasonic or vibrating mesh atomizers. Pressure nozzles atomize the liquid by forcing it through a small orifice under high pressure, while rotary atomizers use centrifugal forces generated by a rapidly rotating disk to disperse the liquid. Ultrasonic atomizers, on the other hand, generate droplets through capillary wave breakup induced by high-frequency vibration. The selection of the atomizer type significantly affects the droplet size distribution and overall drying efficiency.[13], [32]

The air heating system supplies the thermal energy required for rapid solvent evaporation from the atomized droplets. Ambient air is first filtered to remove contaminants and then heated using various heating methods such as electric heaters, steam heat exchangers, or gas-fired burners. The heated air is subsequently introduced into the drying chamber as the drying gas. The temperature of the inlet air is one of the most important process parameters in spray drying because it directly influences the evaporation rate, drying kinetics, and final moisture content of the powder. Careful control of the air temperature is therefore required to achieve efficient drying while preventing thermal degradation of temperature-sensitive materials [33].

The drying chamber is the central vessel where the atomized droplets come into contact with the hot drying air, resulting in rapid evaporation of the solvent and formation of solid particles. Industrial spray drying chambers are typically designed as large cylindrical or conical vessels that provide sufficient residence time for the droplets to dry completely before reaching the chamber walls or outlet. Within the drying chamber, complex interactions occur between heat transfer, mass transfer, droplet evaporation, and particle formation. The geometry and size of the chamber play an important role in determining the flow patterns of the drying air and the residence time distribution of droplets. Following the drying process, the dried particles must be separated from the exhaust air stream using an appropriate particle separation system. The most commonly used separation device in industrial spray drying is the cyclone separator, which utilizes centrifugal forces to separate solid particles from the gas stream. As the air-particle mixture enters the cyclone, the swirling motion forces particles toward the outer wall of the cyclone, where they lose momentum and fall into a collection hopper [34]. Cyclone separators are particularly effective for recovering particles with relatively large diameters, while finer particles may require additional separation devices such as bag filters or electrostatic precipitators. The powder collection system is designed to collect and store the dried powder after separation from the air stream. In industrial spray drying plants, the powder is typically discharged from the cyclone separator into collection bins or storage silos. Automated discharge mechanisms are often used to enable continuous operation and prevent powder accumulation inside the system. Maintaining efficient powder collection is essential for maximizing product yield and minimizing product losses during the drying process. Finally, the exhaust air system is responsible for removing the humid air generated during the drying process from the system. This subsystem usually includes exhaust fans, ducts, and air filtration units to ensure stable airflow within the spray dryer and to prevent the release of fine particles into the environment. Proper design of the exhaust air system is important not only for maintaining process stability but also for meeting environmental and safety regulations in industrial operations [35].

The process converts liquid feed into dry particulate products through atomization followed by rapid solvent evaporation in a heated gas stream. Conventional spray drying systems typically rely on pressure nozzles or rotary atomizers to generate droplets. While these atomization methods are well established for large-scale production, they often produce relatively broad droplet size distributions and require high operating pressures or rotational energy to achieve fine droplet formation [36]. To overcome these limitations, ultrasonic atomization has emerged as an alternative approach for generating highly controlled droplets with narrow size distributions. In particular, vibrating mesh atomizers utilize piezoelectric actuators to excite micro-perforated meshes at ultrasonic frequencies, forcing liquid through micron-scale apertures and producing droplets through capillary-wave instability [37]. This mechanism allows droplet formation to be governed primarily by mesh geometry, vibration frequency, and fluid properties, enabling more precise control over droplet size compared with conventional atomizers.

3.2 Summary of Parametric Study in Spray Drying

A major technological advancement in this field is represented by the development of the Büchi Nano Spray Dryer B-90, which integrates vibrating mesh atomization with a laboratory-scale spray drying system. The B-90 platform has enabled the production of submicron particles and nanoparticles with significantly narrower size distributions than those produced by traditional laboratory spray dryers. Numerous studies have demonstrated its capability to generate droplets typically ranging from approximately 8–21 µm, resulting in dried particles in the range of several hundred nanometres to a few micrometres depending on feed composition and operating conditions. Consequently, the B-90 system has become a widely used experimental platform for nanoparticle production, nanoencapsulation of bioactive compounds, and pharmaceutical particle engineering.[18]

Table 1 Summary of key parametric studies using the Büchi Nano Spray Dryer B-90

No	Reference (Author–Year)	Material / Feed Solution	Mesh Size / Frequency	Inlet Temp (°C)	Feed Rate	Gas Flow	Key Parametric Variables	Particle Size / Result
1	Li et al., 2010 [38]	Model pharmaceutical compounds	Mesh 4–5.5 µm (~120 kHz)	90–120	20–40 mL/h	~100 L/min	Feed concentration, mesh size	Submicron particles (300 nm–2 µm)
2	Harsha et al., 2015 [39]	Drug-loaded nanospheres	Mesh 4 µm	100	25 mL/h	100 L/min	Polymer concentration, drug loading	High encapsulation yield (~83%) and controlled release behavior
3	Strob et al., 2018[40]	Submicron spray-dried particles	Mesh 5.5 µm	90–110	30 mL/h	100 L/min	Mesh aperture size, feed composition	Submicron particle formation suitable for drug delivery
4	Chopde et al., 2020 [14]	Bioactive compounds / nutraceuticals	Mesh 4–7 µm	80–120	20–50 mL/h	80–120 L/min	Feed concentration and viscosity	Nanoparticles <1 µm with improved bioavailability
5	Almansour et al., 2022 [41]	Pharmaceutical particles	Mesh 5.5 µm	100–120	25–40 mL/h	100–120 L/min	Drying temperature and mesh pore size	Particle engineering at submicron scale
6	Hwang et al., 2023 [42]	Cellulose nanocrystal suspension	Mesh 4 µm	100	30 mL/h	100–120 L/min	Gas flow rate	Gas flow had minimal influence on particle size
7	Bürki et al., 2011 [43]	Protein stabilization	Mesh 4 µm	100	20–30 mL/h	100 L/min	Stabilizer concentration	Stable protein nanoparticles
8	Lee et al., 2011 [44]	Protein nanoparticles	Mesh 4–5 µm	90–110	20–35 mL/h	100 L/min	Protein concentration	Narrow particle size distribution
9	Schmid et al., 2012 [45]	Pharmaceutical excipients	Mesh 5.5 µm	100	30 mL/h	100 L/min	Drying temperature	Improved powder stability
10	Gu et al., 2015 [46]	Amorphous solid dispersions	Mesh 4–5.5 µm	90–120	25–40 mL/h	100 L/min	Feed composition	Particle size 2–10 µm depending on formulation
11	Arpagaus et al., 2017 [47]	Nano-encapsulated bioactives	Mesh 4–7 µm	80–110	20–40 mL/h	100 L/min	Carrier composition	Enhanced encapsulation efficiency
12	Kyriakoudi et al., 2018 [18]	Saffron extract encapsulation	Mesh 4 µm	90–110	25–35 mL/h	100 L/min	Carrier type	Improved stability of bioactive compounds
13	Shehata et al., 2019 [48]	Drug nanoparticles	Mesh 4–5 µm	100–120	25–40 mL/h	100–120 L/min	Polymer ratio	Enhanced drug dissolution

No	Reference (Author–Year)	Material / Feed Solution	Mesh Size / Frequency	Inlet Temp (°C)	Feed Rate	Gas Flow	Key Parametric Variables	Particle Size / Result
14	Gómez-Mascaraque et al., 2020 [49]	Biopolymer nanoparticles	Mesh 5.5 µm	100	30 mL/h	100 L/min	Feed viscosity	Increased viscosity increased particle size
15	Baldelli et al., 2020[50]	Pharmaceutical formulations	Mesh 4–5.5 µm	100	20–35 mL/h	100 L/min	Spray throughput	High throughput reduced powder yield

The studies summarized in Table 1 highlight the key operational parameters influencing particle formation in nano spray drying systems using ultrasonic vibrating mesh atomizers. Most investigations report that mesh aperture size and feed composition are the dominant parameters controlling droplet formation and final particle size distribution. For example, Li et al. (2010) demonstrated that mesh apertures between 4 and 5.5 µm can generate droplets capable of producing submicron particles in the range of 300 nm to 2 µm [38] . Similarly, Strob et al. (2018) confirmed that mesh geometry strongly affects droplet size and particle formation during ultrasonic atomization [40]. In addition, several studies have shown that feed concentration and viscosity significantly influence particle size due to their effects on droplet shrinkage during solvent evaporation. In contrast, parameters such as drying gas flow rate appear to have a relatively minor influence on particle size, as demonstrated by Hwang et al. (2023), who reported that variations in gas flow mainly affected drying dynamics rather than droplet formation. A parametric study based on previously published experimental investigations using the Büchi Nano Spray Dryer B-90 indicates that several operating parameters significantly influence particle formation during spray drying [42]. Among these parameters, the mesh aperture size and the ultrasonic vibration frequency play a dominant role in controlling droplet generation. The piezoelectric mesh atomizer operates typically within a frequency range of 80–140 kHz [5], producing droplets with mean diameters between approximately 3 and 15 µm, which subsequently dry into particles with sizes ranging from 200 nm to several micrometers. In addition, process variables such as inlet temperature, feed concentration, and drying gas flow rate influence the evaporation kinetics and the morphology of the final particles. Most studies reported that variations in mesh size and feed concentration strongly affect particle size distribution, while drying gas flow rate has a relatively smaller impact on particle morphology. In table 2 we can adjust several parameters on Büchi Nano Spray Dryer B-90 to conducted an experiment to innovative model of spray drying system [17], [18].

Table 2 Summary of controllable parameter in Buchi B-90

Parameter	Typical Range in B-90
Piezoelectric frequency	80–140 kHz
Mesh pore size	4 – 7 µm
Inlet temperature	80 – 120 °C
Feed rate	20 – 50 mL/h
Gas flow rate	80 – 160 L/min
Particle size	200 nm – 5 µm

Experimental studies conducted using the Büchi Nano Spray Dryer B-90 have provided valuable insights into the relationship between atomization parameters, feed properties, and particle formation. By analysing the experimental findings reported in these studies, a conceptual scaling framework can be developed to identify the dominant parameters controlling droplet generation and particle formation in ultrasonic spray drying systems.

3.3 Estimated We–Oh Operating Regime for Ultrasonic Atomizer

In ultrasonic atomization systems, droplet formation is governed by complex interactions between acoustic energy, liquid properties, and operational conditions. Therefore, evaluating the influence of individual parameters is essential to establish a deeper understanding of the droplet generation mechanism and to identify optimal operating conditions for producing particles with controlled size distribution. The present parametric study focuses on several critical variables including ultrasonic vibration frequency, liquid feed rate, electrical input power, and liquid physical properties such as viscosity and surface tension. These parameters directly influence the atomization process, droplet size distribution, and the overall efficiency of spray drying systems employing piezoelectric mesh atomizers.

The vibration frequency of the ultrasonic mesh atomizer plays a dominant role in determining droplet size during ultrasonic atomization. The oscillatory motion of the piezoelectric actuator generates capillary waves on the liquid interface located above the mesh apertures. When the amplitude of these waves exceeds a critical threshold, the liquid disintegrates into droplets through the instability of the capillary wave crests. Theoretical analyses and experimental observations suggest that the droplet diameter produced by ultrasonic atomization is inversely proportional to the operating frequency. This relationship can be expressed using the Lang-type scaling law[51], [52]:

$$d = \left(\frac{8\pi\sigma}{\rho f^2}\right)^{1/3} \quad (1)$$

where:

d= droplet diameter
σ= surface tension of the liquid
ρ= liquid density
f= ultrasonic frequency

This relationship indicates that higher vibration frequencies lead to smaller droplet diameters due to the formation of shorter wavelength capillary waves. Consequently, frequency variation is one of the most effective approaches for controlling droplet size distribution in piezo electric mesh atomizer assisted spray drying systems.[51], [53]

The liquid feed rate significantly affects the stability of atomization and droplet generation efficiency. In piezoelectric mesh atomizers, liquid is supplied to the vibrating mesh surface where it forms a thin liquid film before passing through the micro-apertures of the mesh. The thickness of this liquid film is directly influenced by the feed rate [54]. At excessively high feed rates, the liquid layer becomes thicker and may dampen the vibration transmitted from the piezoelectric actuator. This damping effect reduces the effective acoustic energy reaching the liquid surface, leading to irregular droplet formation or increased droplet size. Conversely, lower feed rates generally promote more stable atomization conditions by allowing efficient energy transfer and uniform droplet ejection through the mesh apertures. Therefore, an optimal feed rate range must be determined to maintain a balance between droplet production rate and atomization stability.

The electrical input power supplied to the piezoelectric actuator determines the amplitude of ultrasonic vibration and the intensity of acoustic energy applied to the liquid. Higher input power increases the vibration amplitude, which enhances the capillary wave instability responsible for droplet formation. An increase in acoustic intensity generally leads to an increase in droplet generation rate and atomization throughput. However, excessive power input may introduce undesirable effects such as unstable atomization behaviour, droplet formation, or increased thermal loading of the piezoelectric element. Therefore, evaluating the influence of input power is essential for determining the energy-efficient operating conditions of the piezoelectric mesh atomizer system.[12], [55], [56]

Dimensionless analysis provides a fundamental framework for understanding droplet formation mechanisms and for developing scaling strategies in spray drying systems. In ultrasonic atomization, droplet generation is governed by the complex interaction between inertial forces, viscous forces, and surface tension forces acting at the liquid interface. These interactions can be quantitatively described using dimensionless parameters, particularly the Weber number (We) and the Ohnesorge number (Oh), which are widely applied in atomization studies [52], [57], [58]. The Weber number represents the ratio between inertial forces and surface tension forces and can be expressed as:

$$We = \frac{\rho u^2 d}{\sigma} \quad (2)$$

where ρ is the liquid density, u is the characteristic velocity of the liquid, d is the characteristic length scale (often the droplet diameter or nozzle dimension), and σ is the surface tension. In atomization processes, the Weber number indicates whether the inertial forces acting on the liquid are sufficient to overcome surface tension and promote droplet breakup. Moreover, The Ohnesorge number is defined as:

$$Oh = \frac{\mu}{\sqrt{\rho\sigma d}} \quad (3)$$

where μ represents the dynamic viscosity of the liquid. This dimensionless parameter characterizes the relative importance of viscous forces compared with inertial and capillary forces. In the context of ultrasonic atomization, the Ohnesorge number determines the extent to which viscous damping suppresses the growth of capillary waves on the liquid surface. Scaling of spray drying processes is traditionally based on maintaining similar thermal histories, residence times, and droplet size distributions between laboratory-scale and industrial-scale systems. However, when ultrasonic atomization is employed, additional parameters related to the vibrating mesh atomizer must be considered. Unlike conventional pressure nozzle atomizers, vibrating mesh atomizers generate droplets through capillary-wave-driven ejection induced by ultrasonic vibration. Consequently, droplet formation is governed not only by flow conditions but also by atomizer geometry, vibration frequency, and fluid properties.

The droplet formation mechanism in piezoelectric mesh atomizers, is typically associated with capillary wave breakup induced by high-frequency oscillations. When the ultrasonic vibration excites the liquid surface, capillary waves are generated. As the wave amplitude increases beyond a critical threshold, the crests of the waves detach from the surface, forming droplets. The stability of this mechanism depends strongly on the balance between the Weber and Ohnesorge numbers. Experimental investigations of ultrasonic atomization have shown that efficient droplet formation occurs within a specific region of the Weber–Ohnesorge parameter space. When the Ohnesorge number is too large, viscous forces dampen the capillary wave growth, preventing efficient droplet ejection [51], [59]. Conversely, when the Weber number is too small, surface tension dominates and inhibits droplet breakup. Therefore, maintaining an appropriate balance between these parameters is essential for stable atomization. Several published studies have confirmed the relevance of this dimensionless framework for vibrating mesh atomizers used in spray drying. Investigations using laboratory-scale nano spray dryers have demonstrated that mesh aperture size and fluid properties strongly influence droplet size and atomization stability [60]. Because these parameters directly affect the characteristic length scale and viscous properties of the liquid, they alter the corresponding Weber and Ohnesorge numbers. Consequently, the operating regime of the atomizer can shift between efficient droplet formation and unstable atomization depending on the fluid formulation and operating conditions.

The Weber–Ohnesorge framework provides a valuable guideline for maintaining dynamic similarity between laboratory-scale and industrial spray drying systems. If the Weber and Ohnesorge numbers remain within the same regime during scale-up, the fundamental droplet formation mechanism can be preserved. This principle suggests that scaling strategies for ultrasonic spray drying should focus on maintaining similar relationships between atomization geometry, fluid properties, and operating conditions rather than relying solely on geometric scaling. Furthermore, the dimensionless analysis highlights the dominant role of atomization parameters in determining droplet size distribution. Parameters such as mesh aperture size and vibration frequency define the characteristic droplet formation scale, while fluid properties such as viscosity and surface tension determine the atomization regime through their influence on the Ohnesorge number. Drying parameters, including inlet temperature and gas flow rate, mainly affect solvent evaporation and particle formation but do not directly control droplet generation. Therefore, the Weber–Ohnesorge framework offers a useful theoretical basis for interpreting experimental results obtained in ultrasonic spray drying studies and for developing scaling strategies for industrial spray drying systems. By maintaining appropriate ranges of these dimensionless parameters, it is possible to preserve droplet formation behaviour across different equipment scales and thereby achieve consistent particle characteristics in large-scale spray drying processes. Figure 2 shows The Weber–Ohnesorge regime map for ultrasonic vibrating mesh atomizer as framework of scaling technique in ultrasonic spray drying.

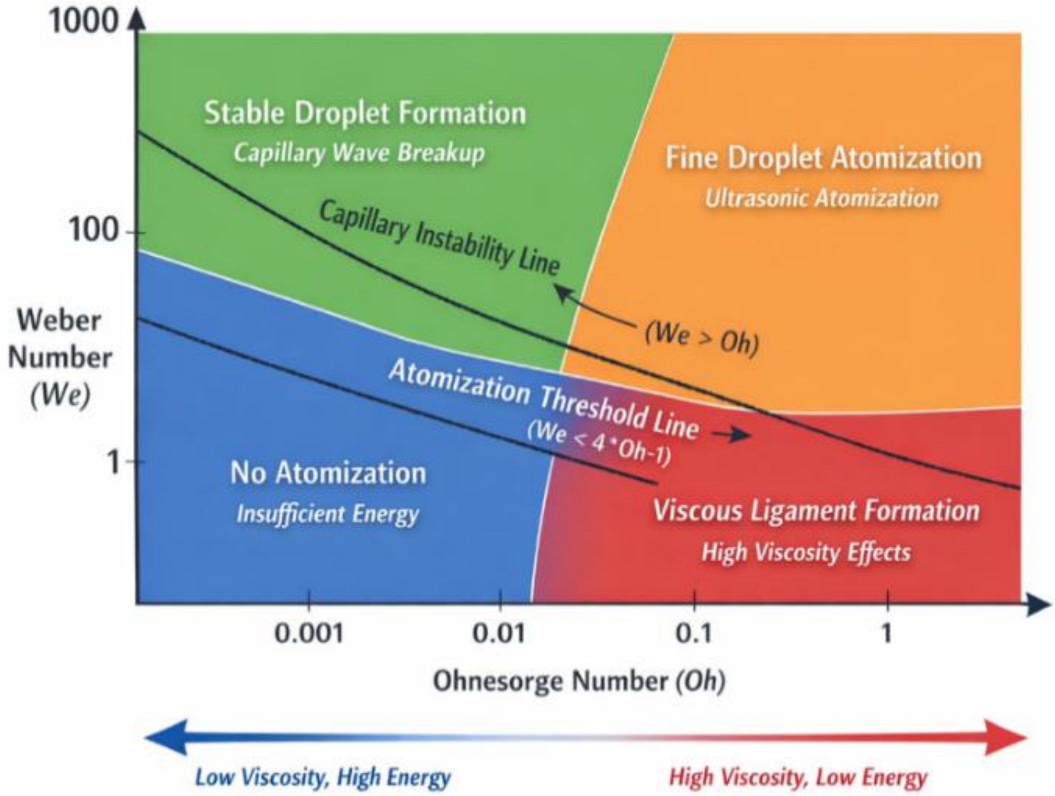


Figure 2 The Weber–Ohnesorge regime map for ultrasonic vibrating mesh atomizer

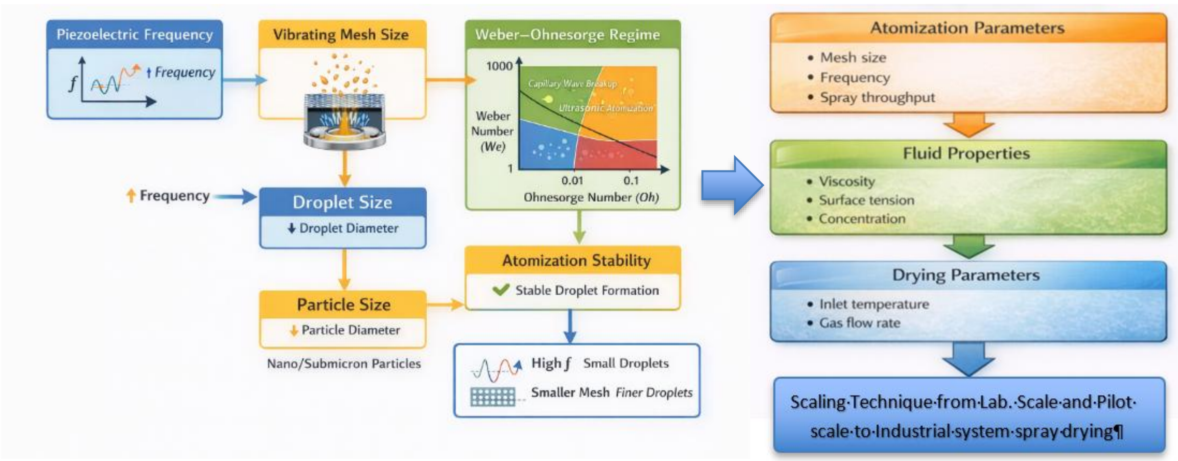
Based on operating conditions commonly reported in the literature for the Büchi Nano Spray Dryer B-90, approximate Weber and Ohnesorge ranges can be estimated to characterize the atomization regime associated with ultrasonic vibrating mesh atomization. Typical droplet diameters reported for the B-90 system range from approximately 8–21 µm, while atomization frequencies are commonly around 100-140 kHz [7], [12]. Assuming water-like fluid properties with density of approximately 1000 kg/m³, surface tension of 0.072 N/m, and viscosity ranging between 1–10 mPa·s depending on feed composition, estimated Weber numbers are typically within the range of approximately 1–10, while Ohnesorge numbers generally range from 0.01–0.1 [52]. These values are consistent with capillary-wave-driven atomization regimes reported in ultrasonic atomization studies [37]. The moderate Weber number regime indicates sufficient inertial force to overcome surface tension and initiate droplet detachment, whereas relatively low Ohnesorge numbers suggest that viscous damping remains limited and does not suppress capillary wave growth. Consequently, these dimensionless ranges support the interpretation that stable droplet generation in the Büchi B-90 system primarily occurs through capillary wave breakup mechanisms.

4 Disscussion

4.1 Interpretation of Parameter Hierarchy

Vibrating mesh atomizer which is used in the Büchi Nano Spray Dryer B-90, droplet generation typically occurs within a regime characterized by moderate Weber numbers and relatively low Ohnesorge numbers. This regime corresponds to the capillary wave breakup mechanism, where ultrasonic vibration induces surface instabilities that lead to controlled droplet detachment. Experimental studies using the B-90 system have reported droplet diameters ranging from approximately 8 to 21 µm, producing dried particles in the submicron to micron range. Maintaining similar Weber and Ohnesorge numbers during process scale-up ensures dynamic similarity in atomization behaviour, enabling consistent particle size distribution across different spray drying scales [38].

The schematic diagram illustrates the fundamental scaling framework governing droplet and particle formation in spray drying systems employing a piezoelectric vibrating mesh atomizer (see Figure 3.a). In such systems, droplet generation is primarily controlled by the interplay between ultrasonic vibration frequency, mesh aperture size, and the fluid dynamic regime characterized by the Weber and Ohnesorge numbers. The atomization process begins with the oscillation of the piezoelectric actuator, which generates high-frequency mechanical vibrations. These vibrations are transmitted to the liquid layer above the vibrating mesh, inducing capillary waves on the liquid surface. When the amplitude of these waves exceeds a critical instability threshold, droplets are ejected through the micro-scale mesh apertures. Consequently, the vibration frequency plays a crucial role in determining the wavelength of the capillary waves and ultimately the droplet diameter. Higher frequencies generally produce shorter wavelength disturbances, resulting in smaller droplets. In addition to the vibration frequency, the geometry of the vibrating mesh strongly influences droplet formation. The mesh aperture size acts as a geometric constraint that limits the droplet size during the atomization process. Smaller mesh openings typically generate finer droplets due to the restricted liquid flow through the micro-orifices. Therefore, the combination of ultrasonic frequency and mesh aperture size provides an effective mechanism for controlling droplet size distribution in ultrasonic spray drying systems[37], [61], [62].



(a) (b)

Figure 3 (a) Fundamental scaling framework governing particle formation in spray drying systems (b) Parameter influence hierarchy for ultrasonic spray drying system

The parameter hierarchy illustrated in Figure 3.b highlights the relative importance of different groups of variables influencing the performance of ultrasonic spray drying systems. The parameter hierarchy presented in Figure 3(b) was developed through qualitative comparative analysis of trends repeatedly reported across the reviewed experimental studies. These parameters were ranked according to the consistency and magnitude of their reported influence on droplet formation, particle size distribution, and atomization stability. Atomization parameters were classified as having the highest influence because they directly govern droplet generation mechanisms. Fluid properties were categorized as secondary parameters due to their indirect influence through modification of viscous and capillary effects. Drying parameters were considered tertiary because their primary role is associated with solvent evaporation and particle morphology rather than initial droplet formation. Although the hierarchy is conceptual and literature-based rather than statistically weighted, it provides a systematic interpretation of the dominant scaling mechanisms governing ultrasonic spray drying systems.

The diagram categorizes the governing parameters into three main levels: atomization parameters, fluid properties, and drying parameters. This hierarchical structure reflects the fundamental mechanism of spray drying, in which droplet generation precedes solvent evaporation and particle formation. Consequently, parameters that control droplet formation tend to exert the strongest influence on the final powder characteristics. At the highest level of influence are the atomization parameters, which include mesh aperture size, vibration frequency, and spray throughput. These parameters directly control the droplet generation mechanism in vibrating mesh atomizers. Several studies have demonstrated that the geometry of the atomizer plays a dominant role in determining droplet size. For instance, experimental investigations by Li et al. (2010) and Arpagaus et al. (2017) showed that smaller mesh apertures in vibrating mesh atomizers produce smaller droplets and consequently smaller particles during spray drying[38], [63] . This relationship occurs because the mesh opening limits the size of the liquid ligaments ejected during atomization. Similarly, ultrasonic vibration frequency influences the wavelength of capillary waves formed on the liquid surface. According to Lang's capillary wave theory, droplet diameter is inversely related to ultrasonic frequency, meaning that higher frequencies generally lead to smaller droplets [51]. Therefore, atomization parameters represent the primary scaling variables when designing spray drying systems using ultrasonic atomizers. The second level in the hierarchy consists of fluid properties, including viscosity, surface tension, and feed concentration. These parameters influence droplet formation indirectly by altering the balance between inertial, viscous, and surface tension forces within the liquid. Several researchers have reported that fluid rheology significantly affects atomization stability. For example, Gómez-Mascaraque et al. (2020) and Wang et al. (2022) observed that higher viscosity tends to increase droplet size because viscous forces dampen the capillary wave instabilities responsible for droplet detachment [64], [65]. Similarly, surface tension influences the energy required for droplet breakup, while feed concentration affects the shrinkage behaviour of droplets during drying. These relationships are commonly described using dimensionless parameters such as the Weber number and Ohnesorge number, which characterize the balance of forces governing atomization processes. At the lowest level of influence are the drying parameters, which include inlet air temperature and drying gas flow rate. Although these parameters are essential for controlling evaporation kinetics and final moisture content, their influence on droplet formation is generally limited. Several studies using nano spray dryers have demonstrated that variations in inlet temperature primarily affect drying rate rather than droplet size distribution. For example, research conducted by Bürki et al. (2011) and Baldelli et al. (2022) reported that inlet temperature had minimal impact on particle size but significantly affected residual moisture and product yield. Gas flow rate also plays an important role in determining particle residence time within the drying chamber, which can influence particle morphology and agglomeration behaviour.[43, 50]

The stability of droplet formation can be interpreted using the Weber–Ohnesorge regime map, which describes the balance between inertial, viscous, and surface tension forces during atomization (see Figure 2). For ultrasonic atomization systems, stable droplet generation typically occurs within a regime characterized by moderate Weber numbers and relatively low Ohnesorge numbers. In this region, capillary wave instabilities dominate the droplet formation mechanism, enabling controlled droplet detachment from the vibrating mesh surface. This scaling framework is particularly relevant to experimental studies conducted using the Büchi Nano Spray Dryer B-90, which employs a piezoelectric vibrating mesh atomizer operating at ultrasonic frequencies of approximately 100 kHz. Experimental investigations have reported droplet diameters typically ranging from 8 to 21 µm, producing dried particles in the submicron to micron range (approximately 300 nm to 5 µm). These particle sizes are primarily governed by the initial droplet diameter and the solid fraction of the feed solution during solvent evaporation. From a process scaling perspective, maintaining similar Weber and Ohnesorge numbers across different operating scales ensures dynamic similarity in the atomization process. This implies that particle formation in spray drying systems scaling up spray drying systems, parameters such as feed viscosity, surface tension, droplet diameter, and characteristic velocity must be adjusted to preserve the same dimensionless regime. By maintaining this similarity, the droplet formation mechanism and resulting particle size distribution can remain consistent across laboratory-scale and pilot-scale spray drying systems.[38], [39]

4.2 Scaling Implications

The scaling of ultrasonic spray drying systems assisted by vibrating mesh atomizers requires a fundamentally different approach compared with conventional pressure-nozzle or rotary-atomizer spray dryers [36]. In conventional spray drying systems, scale-up is generally performed by preserving thermal residence time, drying kinetics, and air-flow distribution within the drying chamber. However, in ultrasonic spray drying systems, the atomization mechanism itself becomes the dominant factor governing particle formation because droplet generation is controlled by capillary-wave instabilities induced by ultrasonic vibration [59]. Consequently, maintaining atomization similarity during scale-up is essential to preserve droplet formation behavior and final particle characteristics.[24]

The present parametric analysis indicates that atomization parameters, particularly mesh aperture size and ultrasonic vibration frequency, represent the primary scaling variables in vibrating mesh atomizer-assisted spray drying systems. These parameters directly determine the wavelength of capillary waves formed at the liquid–mesh interface and therefore control the initial droplet diameter generated during atomization. Since the final particle size distribution strongly depends on the initial droplet size, preserving similar atomization conditions across different process scales becomes critical for maintaining consistent powder characteristics. Unlike conventional spray dryers, where droplet size can often be adjusted through pressure variation, vibrating mesh atomizers are constrained by the geometric characteristics of the mesh and the operating ultrasonic frequency.

Dimensionless analysis further demonstrates that dynamic similarity during scale-up can be achieved by maintaining appropriate Weber number and Ohnesorge number regimes. The Weber number represents the balance between inertial and surface tension forces, whereas the Ohnesorge number characterizes the relative influence of viscous damping during capillary-wave formation. Experimental studies reviewed in this work suggest that stable ultrasonic atomization typically occurs within moderate Weber numbers and relatively low Ohnesorge numbers, corresponding to capillary-wave-driven droplet breakup mechanisms. Therefore, industrial-scale ultrasonic spray drying systems should be designed such that fluid properties, characteristic velocity, and atomization geometry preserve similar Weber–Ohnesorge operating regimes observed in laboratory-scale systems such as the Büchi Nano Spray Dryer B-90.

The scaling implications also indicate that increasing production throughput in ultrasonic spray drying systems cannot rely solely on enlarging atomizer dimensions, as commonly performed in conventional spray dryers. Excessive increase in liquid throughput may destabilize the thin liquid film above the vibrating mesh, reduce acoustic energy transmission efficiency, and alter the capillary-wave breakup mechanism. Consequently, industrial scale-up may require parallelization strategies using multiple vibrating mesh atomizers operating simultaneously rather than simple geometric enlargement of a single atomizer unit. Such modular scaling approaches could maintain atomization stability while increasing production capacity.

Fluid properties also become increasingly important during process scale-up because viscosity and surface tension strongly influence the atomization regime. Feed formulations with higher viscosity may suppress capillary-wave growth due to increased viscous damping, leading to unstable droplet formation or broader droplet size distributions. Therefore, maintaining similar rheological properties between laboratory-scale and industrial-scale feed systems is essential for preserving atomization behavior. In addition, drying conditions such as inlet temperature and gas flow rate must be adjusted to accommodate increased solvent evaporation demands at larger process scales while avoiding thermal degradation or particle agglomeration.

Overall, the proposed scaling framework suggests that successful scale-up of ultrasonic spray drying systems should prioritize atomization similarity rather than purely geometric similarity. Maintaining consistent relationships among ultrasonic frequency, mesh geometry, fluid properties, and dimensionless force balances provides a more reliable basis for preserving droplet generation behavior and achieving controlled particle formation across different operating scales. Consequently, the present framework offers a conceptual guideline for the future development of industrial ultrasonic spray drying technologies capable of producing highly engineered submicron and micron-scale powders with improved process controllability.

4.3 Limitations of the Conceptual Scaling Framework

Although the proposed conceptual scaling framework provides useful theoretical insight into the dominant mechanisms governing ultrasonic spray drying systems, several limitations should be acknowledged. First, the framework is primarily derived from literature synthesis rather than direct experimental validation under controlled scaling conditions. As a result, the proposed parameter hierarchy should be interpreted as a conceptual guideline rather than an absolute predictive model. Second, the reviewed studies employed different feed formulations, experimental configurations, and measurement techniques, which may introduce variability in the reported atomization behavior and particle characteristics. Third, the present framework focuses mainly on droplet generation mechanisms associated with vibrating mesh atomizers and does not fully account for industrial-scale complexities such as turbulent airflow interaction, multi-droplet collision phenomena, or large-scale thermal non-uniformity. Therefore, future work should focus on systematic experimental validation and computational modeling to quantitatively verify the proposed Weber–Ohnesorge scaling framework across different operating scales.

5. CONCLUSION

This study presents a comprehensive review and conceptual parametric hierarchy for ultrasonic spray drying systems assisted by piezoelectric vibrating mesh atomizers. Unlike previous studies that primarily focused on isolated process variables or formulation-specific applications, the present work systematically integrates atomization parameters, fluid properties, and drying conditions into a unified scaling-oriented framework. The analysis demonstrates that atomization parameters, particularly mesh aperture size, ultrasonic vibration frequency, and spray throughput, constitute the dominant variables governing droplet generation and particle size distribution through capillary-wave-driven breakup mechanisms.

Fluid properties such as viscosity, surface tension, and feed concentration were identified as secondary scaling parameters because they influence the atomization regime through the Weber and Ohnesorge dimensionless numbers. In contrast, drying parameters primarily affect evaporation kinetics and particle morphology rather than the initial droplet generation process. The proposed Weber–Ohnesorge scaling framework therefore provides a theoretical basis for maintaining atomization similarity during process scale-up from laboratory-scale to industrial-scale ultrasonic spray drying systems.

The novelty of this study lies in the development of a conceptual parameter hierarchy combined with a dimensionless scaling framework specifically for ultrasonic vibrating mesh atomizer-assisted spray drying systems. This contribution advances the understanding of ultrasonic spray drying engineering and provides a systematic foundation for the future development of industrial-scale spray drying technologies capable of producing highly controlled submicron and micron-scale particles.

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