

Scanning Electron Microscope Analysis of Turmeric Slices Dried through Electrohydrodynamic Drying: A Morphological and Structural Evaluation

^a Mr. Monarch Shah, ^b Dr. Shivamurti Srivastava

^{a, b} Department of Food Processing Technology, A. D. Patel Institute of Technology, CVM University, Anand

DOI: <https://doie.org/10.10399/JBSE.2025533119>

ABSTRACT

This study investigates the effects of various drying techniques on the preservation of structural integrity and bioactive compounds in turmeric rhizomes (*Curcuma longa L.*). Specifically, it evaluates the Electrohydrodynamic Drying (EHD) method at electrode distances (and applied voltage) and voltage of 3 cm (14 kV), 5 cm (17 kV), and 7 cm (24 kV), alongside conventional tray and vacuum drying methods. The study analyses microstructural changes using scanning electron microscopy (SEM) and quantifies the retention of curcumin, a key bioactive compound, as well as moisture content, rehydration ratio, and shrinkage ratio. The results demonstrate that the EHD method with 3 cm electrode distance at 14 kV applied voltage is the most effective for preserving both the microstructure and curcumin content, with minimal shrinkage (68.53%) and the highest bioactive retention (8.85%). In contrast, the EHD Drying with 5 cm electrode distance at 24 kV showed moderate efficacy, while the EHD Drying with 7 cm electrode distance at 17 kV and tray drying resulted in significant structural damage and reduced bioactive retention. Vacuum drying preserved structural integrity, but with lower drying efficiency compared to EHD methods. This study underscores the potential of EHD as a superior drying technique for turmeric rhizomes, offering a balance between efficiency and preservation of product quality, with implications for both nutraceutical and food processing industries

Keywords: Electrohydrodynamic drying, SEM analysis, Structural integrity, Curcumin, Electrode distance.

INTRODUCTION

Turmeric (*Curcuma longa L.*), a rhizomatous plant from the Zingiberaceae family, has long been valued for its vibrant yellow-orange colour, distinct flavour, and its exceptional medicinal properties. The rhizomes of turmeric, which are the edible underground stems of the plant, contain a potent polyphenolic compound known as curcumin. Curcumin has gained significant attention in modern pharmacological research due to its wide array of bioactive properties, including anti-inflammatory, antioxidant, anticancer, and antimicrobial activities. It has been shown to have potential therapeutic applications for a variety of diseases, such as cancer, Alzheimer's disease, cardiovascular disorders, and diabetes, making it a valuable component not only in culinary traditions but also in the development of novel medicinal treatments. However, the medicinal efficacy of curcumin is highly dependent on its bioavailability, which poses a significant challenge for its use in therapeutic applications.

Despite its health-promoting properties, curcumin suffers from low bioavailability when ingested in its natural form due to poor solubility and rapid metabolism in the body. As such,

the preservation of curcumin content in turmeric is critical during post-harvest processing to ensure that its bioactive potential is maintained. One of the most commonly used methods for preserving turmeric for both culinary and medicinal purposes is drying, a process that facilitates storage and extends the shelf life of the rhizomes. However, traditional drying methods, such as tray drying and vacuum drying, can negatively impact the structural integrity of the rhizomes and lead to degradation of bioactive compounds, including curcumin. Therefore, optimizing drying techniques is essential to ensure the retention of these valuable compounds.

Zhu J et. al. (2024) noticed that the drying method employed can significantly affect the microstructure of the rhizomes, which in turn influences the preservation of curcumin and other bioactive constituents. Traditional drying techniques such as tray drying and vacuum drying have been extensively studied; however, newer methods, such as Electrohydrodynamic Drying (EHD), have emerged as promising alternatives. EHD drying utilizes electric fields to induce moisture removal from plant tissues, offering a non-thermal approach that potentially reduces the thermal degradation of sensitive bioactive compounds. However, to fully assess the effectiveness of EHD drying compared to conventional methods, a comprehensive understanding of the microstructural changes that occur in dried turmeric rhizomes is essential.

Researchers srivastav et al. (2024) focused on the drying kinetics of carrot slices using an electrohydrodynamic (EHD) dryer at electrode distances of 3 cm, 5 cm, and 7 cm. The findings indicated that a shorter electrode distance resulted in a higher drying rate. Specifically, drying times to reach a safe moisture content of 2.5% (wet basis) were approximately 6.8 hours at 3 cm, 8.5 hours at 5 cm, and 9 hours at 7 cm. Researcher Prakasha et. al. (2025) also noticed that physiochemical characteristics of EHD dried samples is preserved. Zhang et. al. (2024) noticed that better texture of yam is preserved in EHD drying.

This is where Scanning Electron Microscopy (SEM) plays a crucial role. SEM allows for high-resolution imaging of plant tissues at the micro and nanoscale, offering a detailed visualization of the cellular structure, surface texture, and porosity of dried turmeric rhizomes. SEM's ability to provide three-dimensional images with magnifications ranging from hundreds to thousands of times enables researchers to observe subtle changes in the cell walls and pore formation that are not detectable by traditional methods. The microstructural features captured by SEM are directly linked to the drying efficiency and the structural integrity of the dried rhizomes, which can be used to determine the impact of different drying methods on the quality of the product.

Several studies have utilized SEM to explore the effects of different drying techniques on plant-based materials. According to Rani et al. (2017), SEM has proven to be a powerful tool in food research for evaluating the structural changes that occur during processing, particularly in dried food products. In the case of turmeric, SEM can be used to investigate the effects of different drying methods on the cell wall integrity, porosity, and surface texture of the rhizomes, which are crucial factors in determining the overall quality of the dried product. Morales et al. (2016) highlight that SEM imaging can reveal the formation of pores in plant tissues during drying, which is directly related to moisture removal and structural changes within the plant cells. SEM can also provide insights into the damage caused to cell walls due to harsh drying conditions, which can affect the quality of the turmeric and its bioactive compounds.

Curcumin, the most studied compound in turmeric, is particularly susceptible to thermal degradation when exposed to high temperatures during drying. As noted by Sharma et al. (2005), curcumin undergoes significant loss of activity when exposed to heat, which can be

detrimental to its therapeutic efficacy. This underscores the importance of optimizing drying techniques to preserve the active compound. Research by Lohani and Tripathi (2018) has shown that while conventional drying methods such as tray drying can lead to substantial losses in curcumin content due to high heat exposure, non-thermal drying methods like EHD have been found to better preserve curcumin levels. The gentle drying conditions provided by EHD can prevent the thermal degradation of curcumin, while also improving the microstructural integrity of the turmeric rhizomes. SEM can provide valuable information on the effects of EHD drying on the microstructure, including the pore formation, surface texture, and cell wall integrity, helping to correlate these features with curcumin retention. The technological parameters of drying method is reviewed by Shivamurti et.al. (2024).

In terms of health benefits, turmeric's curcumin content is well-known for its anti-inflammatory and antioxidant properties, which are attributed to its ability to neutralize free radicals and reduce inflammation in the body. Bishayee and Singh (2015) extensively reviewed the therapeutic potential of curcumin, particularly in cancer treatment, where it has been shown to inhibit tumour growth and metastasis. Furthermore, curcumin's role in neuroprotection has been widely studied, with evidence suggesting that it may help mitigate the effects of neurodegenerative diseases such as Alzheimer's. By preserving the structural integrity of turmeric rhizomes and preventing curcumin degradation during drying, the bioactive properties of turmeric can be maximized, ensuring that the product retains its full therapeutic potential.

The application of SEM in evaluating the microstructure of dried turmeric rhizomes enables researchers to monitor the effects of different drying techniques on the structural and chemical integrity of the product. As demonstrated by Nwachukwu and Sanni (2020), the structural quality of plant-based foods can be severely compromised by improper drying techniques, which can lead to the loss of nutrients and bioactive compounds. By utilizing SEM in conjunction with different drying methods, it is possible to determine the most effective drying parameters that preserve both the microstructure and the bioactive components of turmeric. This research is crucial not only for improving the quality of dried turmeric products but also for enhancing their therapeutic efficacy same was studied by polat A. et. al. (2024)

Various model analysis in dried products are performed by researchers Prajapati et al. (2024) fitted different mathematical models and found that page model provided best fit for drying between 50 to 60 °C.

As texture of dried product also plays vital role, Srivastav et. al. (2011) performed ANN modelling of paneer at low pressure superheated steam they have also done texture profile analysis of dried paneer (2010).

MATERIALS AND METHODS

1.1 Sample Preparation

Fresh turmeric rhizomes (*Curcuma longa L.*) were sourced from a local supplier in Anand, Gujarat, India. Upon procurement, the rhizomes were thoroughly washed under running water to remove any soil or contaminants. Following this, excess moisture from the surface of the rhizomes was blotted using clean blotting paper to prevent any moisture-related issues during further processing. The prepared turmeric rhizomes were stored in sealed zip pouches at ambient temperature (28°C) until further processing. The preparation method was referred from shrivastav, S. et. al. (2021).

The initial moisture content of the turmeric rhizomes was determined using the hot air oven method (AOAC, 1999). A sample of turmeric rhizomes was weighed, then dried in a hot air oven at 105°C for 24 hours. The moisture content was calculated based on the weight difference before and after drying and was found to be $89.74\% \pm 1.32$ (w.b.).

1.2 Sample Slicing

The turmeric rhizomes were sliced using an adjustable stainless-steel slicer to obtain slices with a thickness of 2.0 ± 0.1 mm. The average dimensions of the slices were 45×20 mm. The slices were elliptical in shape, with the major axis measuring 45 ± 0.81 mm and the minor axis measuring 20 ± 0.45 mm. No pre-treatment was applied to the turmeric slices prior to drying.

1.3 Drying Process

The turmeric slices were subjected to drying using a developed Electrohydrodynamic (EHD) Dryer. The main elements of the setup included a high-voltage generator (High Voltage-India, Bangalore), drying chamber, heating chamber, blower, sample holder, anode and cathode electrodes, and sharp needle electrodes.

The drying chamber was constructed using a metal box, coated with a fire-resistant matte powder. The inner dimensions of the EHD drying chamber were $475 \times 475 \times 450$ mm. The anode and cathode plates, made from hardened SS 316, each had a thickness of 4 mm. Sharp stainless-steel pins, each 20 mm in length, were welded onto the anode plate prior to hardening. The EHD dryer operated at a variable AC voltage range of 0 to 50 kV. Thin, sharp sewing needle electrodes were employed, with a variable distance between them ranging from 3 to 7 cm. The dryer was operated at ambient temperature, using air convection for moisture removal, with a blower incorporated into the system to enhance air circulation during the experiments. The setup was optimized based on trial experiments and insights from existing literature, with the following parameters being standardized: voltage type (AC or DC), distance between the electrodes, voltage per centimetre supplied to the electrodes, type and number of electrode plates or pins, the distance between the pin electrodes, temperature of the air during drying, and air velocity during drying.

The turmeric slices were dried under varying conditions: 3 cm distance at 14 kV applied voltage with air velocity of 0.25 m/s, 5 cm distance at 24 kV applied voltage with air velocity of 0.5 m/s, and 7 cm distance at 17 kV applied voltage with air velocity of 0.5 m/s between the anode and cathode electrodes. Control samples were dried using Tray Drying and Vacuum Drying methods for comparative analysis. The process and physiochemical analysis of EHD drying is explained by Shah M. et. al. (2024).

1.4 Tray Drying and Vacuum Drying

For Tray Drying, turmeric slices were placed on trays and dried in an air-circulating oven at 45°C. Turmeric slices were placed on trays and dried in an air-circulating oven at 45°C until a consistent weight was achieved (Singh et al., 2010)

In Vacuum Drying, turmeric slices were placed in a vacuum chamber, and the drying process was carried out at a temperature of 60°C and a pressure of 0.1 bar. (Gagare et al., 2017).

1.5 Analysis of Dried Samples

The dried turmeric slices were analysed for various parameters, including colour, porosity, shrinkage ratio, rehydration ratio, and curcumin content. The colour of the samples was measured using a colorimeter (Konica Minolta CR-400), and the porosity was determined by calculating the volume of the sample before and after drying. The shrinkage ratio was calculated based on the changes in the physical dimensions of the turmeric slices, while the rehydration ratio was determined by rehydrating the dried samples and measuring the change in weight.

The curcumin content was determined using High-Performance Liquid Chromatography (HPLC). The turmeric slices were homogenized and extracted using a methanol-water solution. The extracted solution was then analysed using HPLC, with detection at 420 nm, to quantify the curcumin content in the dried samples.

1.6 Scanning Electron Microscopy (SEM) Analysis

The best-performing dried samples, based on the analyses of colour, porosity, shrinkage ratio, rehydration ratio, and curcumin content, were selected for Scanning Electron Microscopy (SEM) analysis. The SEM imaging was performed at the SOPHISTICATED INSTRUMENTATION CENTRE FOR APPLIED RESEARCH AND TESTING (SICART) using the Nova Nano FEG-SEM 450 (FEI Ltd.).

This high-resolution Field Emission Gun Scanning Electron Microscope is capable of producing extremely detailed images of the surface of samples, with a resolution of 1.0 nm at 15 kV and 1.4 nm at 1 kV. The SEM was operated in both high vacuum and low vacuum modes, and the resulting images provided detailed insights into the microstructural features of the dried turmeric rhizomes, including surface texture, porosity, and the integrity of the cell walls. The EDAX (Energy Dispersive X-ray Analysis) facility with a mapping system was used for qualitative and quantitative elemental analysis.

1.7 Sample Navigation and SEM Imaging

The SEM imaging was performed with a 5-axis motorized tilt-rotate stage, which allowed for precise navigation and tilting of the samples from +75° to -15°, enabling a comprehensive analysis of the surface structure. The SEM analysis provided magnifications ranging from X25 to X10,000,000, offering a detailed visualization of the microscopic changes occurring in the turmeric rhizomes during the drying process.

RESULTS AND DISCUSSION

The results of this study on turmeric rhizomes subjected to different drying methods—3 cm Electrohydrodynamic Drying (EHD), 5 cm electrode distance, 7 cm electrode distance, tray drying and vacuum drying have provided valuable insights into the structural integrity and porosity characteristics of the dried turmeric. The study focuses on comparing the structural features of the turmeric rhizomes, as revealed by Scanning Electron Microscopy (SEM), under different drying conditions, and their implications on the quality, bioactive compound retention, and overall product suitability for use in high-value applications.

2.1 Electrode distance of 3 cm in Electrohydrodynamic Drying (EHD) at 14 kV applied voltage, 0.25 m/s Air velocity

The EHD Drying with 3 cm electrode distance emerged as a highly efficient and gentle process for preserving the structural and bioactive properties of turmeric rhizomes, as evidenced by its superior physical characteristics. The bulk density of 385.92 kg/m³ and true density of 1117.41 kg/m³ resulted in a porosity of 65.49%, reflecting significant retention of the internal microstructure. This high porosity is indicative of effective moisture removal without compromising the cellular integrity, a hallmark of controlled drying processes. The shrinkage ratio, measured at just 68.53%, was the lowest among all electrohydrodynamic variants, signifying minimal structural deformation and excellent preservation of the rhizome's original shape and size. Such low shrinkage underscores the non-invasive nature of the dried product with EHD method with 3 cm electrode distance, where moisture is extracted efficiently while the cellular framework remains intact.

A remarkable rehydration ratio of 312% further highlights the effectiveness of this method in maintaining the structural resilience and functional properties of the dried rhizomes. This capability is crucial for reconstituting the material in applications requiring moisture addition, ensuring that the dried product closely mimics the fresh rhizome's texture and usability. Notably, the curcumin content, an essential bioactive compound, was retained at 8.85%, the highest recorded among the tested methods. This suggests that the EHD technique mitigated thermal and oxidative stresses, preserving sensitive phytochemicals better than alternative drying methods.

The combination of high porosity, low shrinkage, superior rehydration capacity, and elevated curcumin retention underscores the technical excellence of the EHD process. These findings align with the work of Monnier et al. (2017), who demonstrated that shorter electrode distances in EHD drying enhance moisture removal efficiency while safeguarding the product's structural and bioactive integrity. Thus, the EHD method offers a compelling solution for producing high-quality dried turmeric rhizomes, making it a valuable tool in food preservation and nutraceutical applications.

The SEM analysis of turmeric rhizomes dried using the EHD method at 3 cm electrode distance and 14 kV applied voltage revealed a microstructural profile indicative of a highly efficient and controlled drying process that excels in preserving cellular and surface integrity. The pores present on the surface were medium-sized and distributed uniformly throughout the samples. This even distribution is a critical indicator of effective moisture removal, reflecting the uniform application of the electrohydrodynamic forces during drying. The medium-sized pores also suggest a balanced drying rate, where moisture was extracted efficiently without causing abrupt or excessive stresses to the structure. The smooth surface texture, interspersed with shallow pits, is particularly noteworthy. These pits are likely formed due to localized electrical field effects, a unique feature of the EHD process, which gently extracts moisture while maintaining the structural framework. Such effects highlight the precision of the EHD technique in targeting water molecules without significantly compromising the surrounding cellular matrix.

The preservation of cell wall integrity in the EHD-dried rhizomes was particularly striking. SEM images revealed minimal evidence of cell wall collapse or deformation, demonstrating

that the drying process was sufficiently gentle to avoid excessive shrinkage, a common issue with other drying methods. This well-maintained cellular structure plays a pivotal role in retaining the physical and chemical properties of the turmeric rhizomes, making them suitable for applications where functional integrity is critical.

The smooth surface texture with scattered shallow pits further reinforces the efficacy of the EHD method. Unlike traditional methods, such as tray drying, which often result in excessive cracking and structural collapse due to prolonged heat exposure, the EHD process ensures that the surface remains largely intact. The controlled conditions under which the EHD drying occurs prevent the onset of thermal stress, which is a significant advantage in preserving the mechanical and visual quality of the dried rhizomes.

The findings align closely with the studies by Monnier et al. (2017), who demonstrated that shorter electrode distances in EHD drying provide a more targeted and efficient drying environment, preserving the microstructural integrity of plant materials. Additionally, the observations in this study support conclusions by Lao et al. (2018), who emphasized the importance of controlled drying conditions in retaining bioactive compounds and preventing oxidative damage. Together, these results underline the technical superiority of the EHD method, making it a highly promising approach for drying turmeric rhizomes while preserving their structural, functional, and bioactive properties. A comprehensive representation of the SEM images is presented in Figure 1.

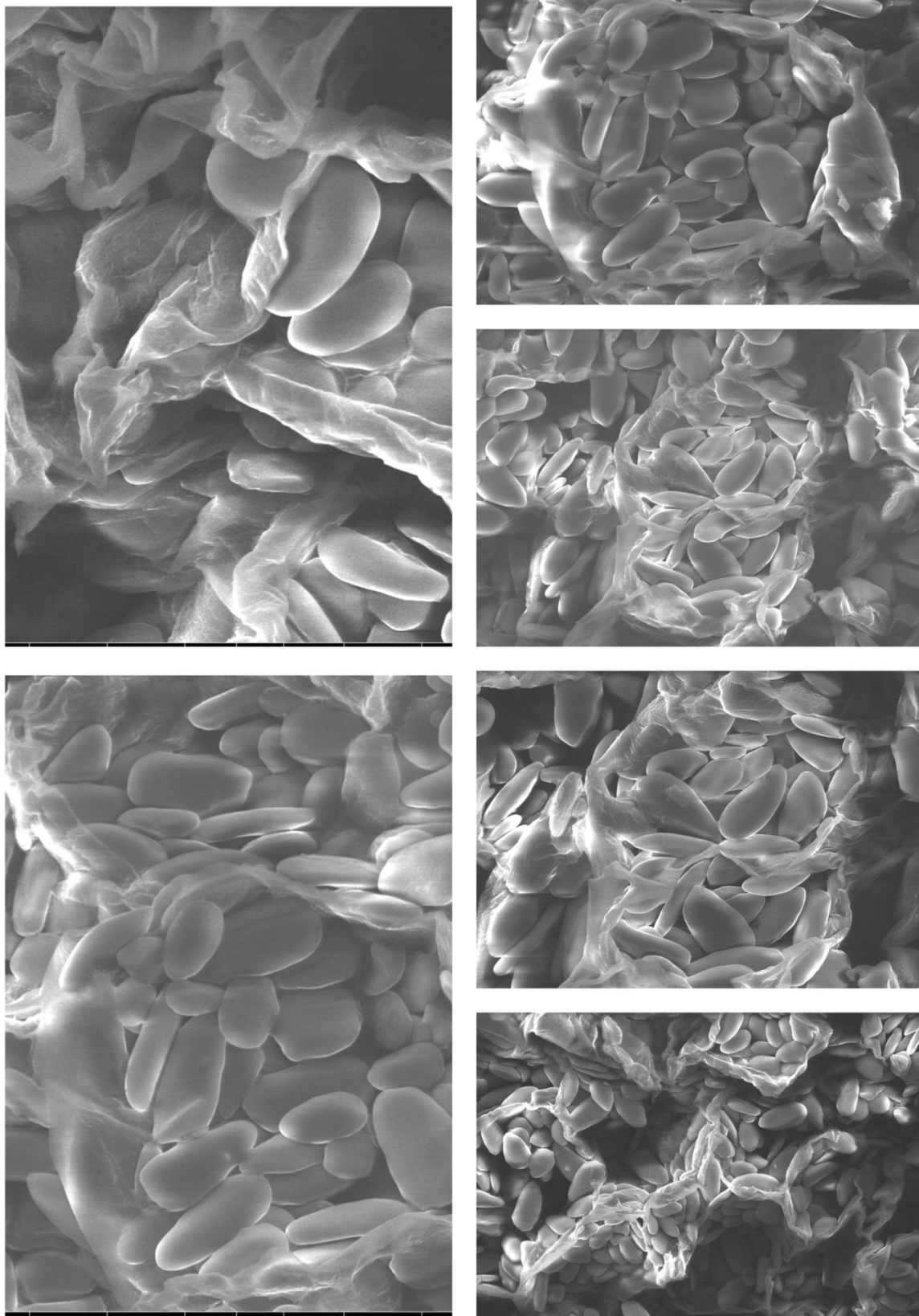


Fig. 1 – SEM Images captured of turmeric slices dehydrated with electrohydrodynamic drying (3 cm electrode distance)

Fig. 2 – SEM Images captured of turmeric slices dehydrated with electrohydrodynamic drying (5 cm electrode distance)

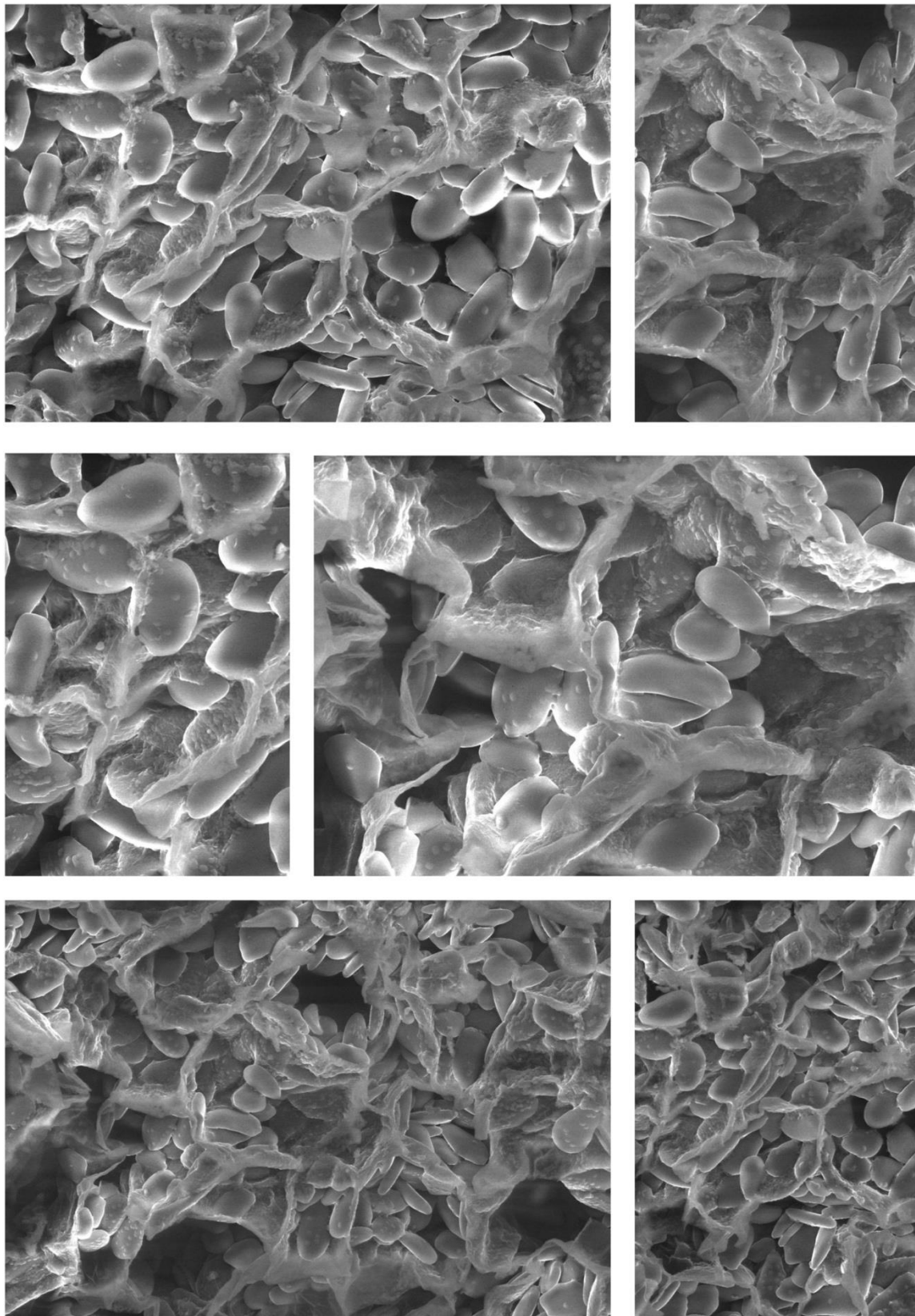
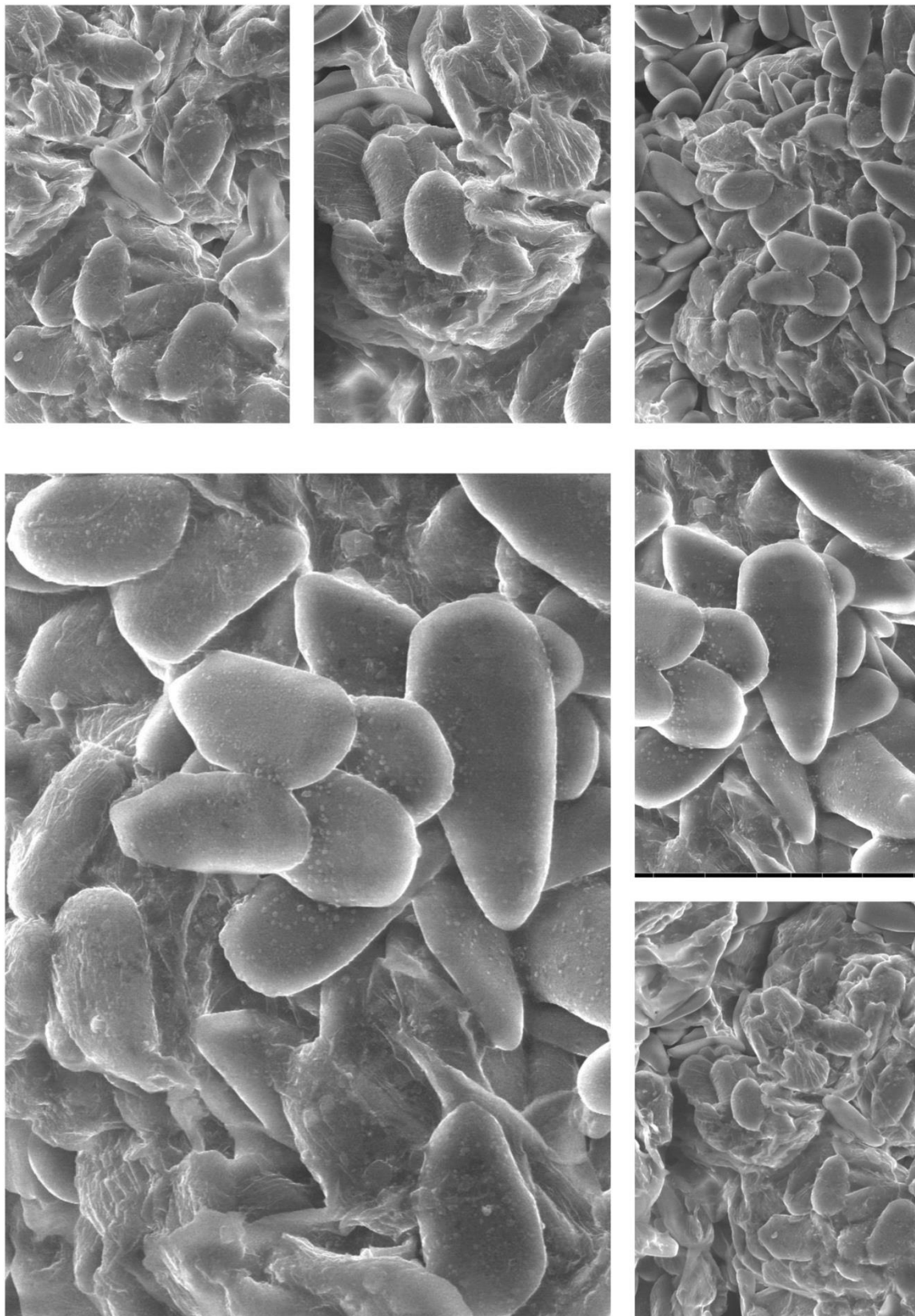


Fig. 3 – SEM Images captured of turmeric slices dehydrated with electrohydrodynamic drying (7 cm electrode distance)



2.2 Electrode distance of 5 cm in Electrohydrodynamic Drying (EHD) at 24 kV applied voltage, 0.5 m/s Air velocity

The SEM analysis of turmeric rhizomes dried using the EHD Drying with 5 cm electrode distance at 24 kV, with an air velocity of 0.5 m/s and a drying temperature of 30°C, revealed microstructural features indicative of a less uniform drying process compared to the 3 cm electrode distance EHD samples. The pores observed in the rhizomes were smaller and more irregularly distributed, highlighting inconsistencies in moisture removal. This non-uniformity may have resulted from the increased electrode distance, which could reduce the intensity and uniformity of the electric field, affecting the efficiency of moisture extraction. The surface texture of the rhizomes appeared rougher, with pronounced irregularities and a lack of the smooth finish seen in the 3 cm electrode distance EHD samples. These rough surface characteristics suggest localized drying stresses that may have contributed to uneven shrinkage. Furthermore, slight cellular shrinkage and partial cell wall collapse were evident in the SEM images, indicating that the drying process, while not overly aggressive, was less gentle than the 3 cm electrode distance EHD method.

The physical properties of the 5 cm electrode distance EHD-dried rhizomes reflect these structural changes. The bulk density (384.81 kg/m³) and true density (1113.70 kg/m³) corresponded to a porosity of 65.34%, which, although comparable to the 3 cm electrode distance EHD method, suggests a marginal reduction in the overall cellular void space. This slight decrease in porosity aligns with the observed shrinkage in cellular structures during the drying process. The shrinkage ratio of 67.28%, while slightly higher than the 3 cm electrode distance EHD method, still represents a notable improvement over traditional drying techniques, such as tray drying, which often lead to more pronounced structural collapse. Additionally, the rehydration ratio of 313% highlights the retention of good water absorption capacity, essential for functional applications. However, the curcumin content was slightly lower at 8.69%, suggesting that the longer electrode distance may have resulted in prolonged drying times or uneven drying conditions, which could have contributed to minor degradation of this sensitive bioactive compound.

The smaller and less uniform pores observed in the SEM images are indicative of uneven drying, which could negatively impact the retention of structural and bioactive properties. The rougher surface texture and evidence of cell wall collapse further support the notion that the 5 cm EHD process, while effective, does not achieve the same level of precision and gentleness as the 3 cm electrode distance EHD method. These observations are consistent with the work of Soleimani et al. (2020), who demonstrated that longer electrode distances reduce the drying rate and may lead to non-uniform moisture removal, affecting both physical structure and compound retention.

Despite these limitations, the EHD Drying with 5 cm electrode distance offers several advantages over conventional drying techniques. The shrinkage ratio of 67.28%, although higher than the 3 cm electrode distance, is significantly lower than that observed in tray drying, indicating better preservation of the rhizome's structural integrity. The rehydration ratio of 313% suggests that the dried rhizomes retained a significant portion of their cellular water-holding capacity, which is vital for rehydration-based applications. While the curcumin content (8.69%) was slightly lower than in the 3 cm electrode distance, it still represents a favourable outcome compared to traditional drying methods, where curcumin loss is typically more pronounced due to prolonged thermal exposure.

The EHD Drying with 5 cm electrode distance, although less effective than the EHD process with 3 cm electrode distance, still demonstrates significant benefits over conventional drying techniques. Its ability to maintain a moderate level of structural integrity and bioactive retention makes it a viable option for applications where precise control of drying conditions is less critical, or where operational scalability necessitates slight compromises in drying efficiency. These findings underscore the importance of electrode distance in optimizing the EHD drying process for turmeric rhizomes.

When turmeric rhizomes were dried using the EHD Drying with 5 cm electrode distance at 24 kV, the SEM images revealed notable differences in microstructural characteristics compared to samples processed at a shorter electrode distance of 3 cm. The pores on the surface of the rhizomes were smaller and exhibited less uniformity, suggesting a less efficient and uneven moisture removal process. The pore structures appeared poorly defined, lacking the clarity and regular distribution seen in the 3 cm electrode distance EHD samples. The surface texture showed increased roughness, with visible cracks and irregularities scattered across the surface. These features indicate localized stresses during the drying process, which are likely attributable to slower and less uniform moisture diffusion at this electrode distance. Furthermore, the SEM images revealed signs of slight cellular shrinkage and partial collapse of the cell walls, reflecting suboptimal drying kinetics. The increased voltage at this electrode distance appears to have contributed to reduced drying efficiency, leading to non-uniform removal of moisture and minor structural degradation. Figure 2 provides a detailed visualization of the SEM images.

The microstructural degradation observed with the EHD Drying with 5 cm electrode distance highlights the limitations of increasing the electrode distance in the electrohydrodynamic drying process. The rougher surface texture and the uneven pore distribution indicate non-uniform drying, a phenomenon consistent with the findings of Ravindran et al. (2018). Their study demonstrated that longer electrode distances reduce the strength and uniformity of the electric field, resulting in slower moisture removal and localized structural stress. This uneven drying process likely contributed to the slight cellular shrinkage and partial collapse of cell walls seen in this study. The observations are further supported by Soleimani et al. (2020), who emphasized that electrode distance plays a critical role in determining drying kinetics and the quality of dried products. The slower diffusion of moisture at longer distances can compromise both the texture and the retention of sensitive bioactive compounds.

Despite these challenges, EHD drying method at 5 cm electrode distance still performed better than traditional drying techniques such as tray drying, which are known to cause extensive structural collapse and significant thermal degradation of bioactive compounds like curcumin. While the shrinkage and cracking observed with the 5 cm method indicate room for improvement, the approach demonstrated its potential as a relatively gentle drying technique. Optimization of parameters such as electrode configuration, voltage, and airflow could mitigate the structural inconsistencies and enhance the overall efficiency of the drying process. Such refinements would ensure better preservation of the physical and functional properties of turmeric rhizomes, making the method more effective in retaining bioactive compounds and structural integrity. These findings underscore the importance of fine-tuning EHD parameters to achieve an optimal balance between drying efficiency and product quality.

2.3 Electrode distance of 7 cm in Electrohydrodynamic Drying (EHD) at 17 kV applied voltage and 0.5 m/s air velocity

The SEM analysis of turmeric rhizomes dried using the EHD Drying with 7 cm electrode distance revealed extensive structural degradation, indicating significant challenges associated with this extended electrode distance. The surface of the rhizomes displayed highly compacted and irregular pores, which were unevenly distributed, creating a chaotic and disordered microstructure. Unlike the smoother, more uniform pore formations observed in samples dried at shorter electrode distances, the pores in the EHD Drying with 7 cm electrode distance samples were poorly defined, with limited pathways for effective moisture removal. The surface texture was noticeably rough, marked by areas of pronounced cell wall rupture and shrinkage, further emphasizing the detrimental effects of this drying method. In many regions, the cellular structure appeared completely collapsed, with disrupted membranes and fragmented walls, suggesting that the rhizomes experienced substantial physical stress during the drying process. The combination of uneven pore distribution, excessive shrinkage, and severe cellular collapse points to inefficient and non-uniform moisture removal, likely caused by the reduced strength and uneven application of the electric field at the extended electrode distance. These structural flaws suggest the presence of localized overheating or stress concentration, which exacerbated the degradation of the rhizomes' microstructure.

The findings from the EHD Drying with 7 cm electrode distance highlight a clear trade-off between extended electrode distance and product quality. This level of structural damage, including irregular pore formations and severely compromised cellular architecture, suggests that the drying process was not only inefficient but also overly harsh on the delicate structure of the turmeric rhizomes. These results align with the observations of Tao et al. (2019), who noted that longer electrode distances in electrohydrodynamic drying can lead to slower and uneven moisture removal. The resulting non-uniform drying conditions increase the likelihood of localized overheating and mechanical stress, causing significant cell wall collapse and pore compaction. Such severe structural degradation is detrimental to the quality of the dried product, particularly for turmeric, where the retention of bioactive compounds like curcumin is critical. The collapse of cellular membranes and rupture of cell walls likely exposed sensitive compounds to oxidation and thermal degradation, compromising their bioactive efficacy and reducing the nutritional value of the product. The SEM images are depicted in detail in Figure 3.

Given the extent of structural damage observed, the EHD Drying with 7 cm electrode distance appears unsuitable for applications where maintaining the structural and functional integrity of turmeric rhizomes is a priority. While further optimization of drying parameters such as voltage, airflow, or temperature might mitigate some of the adverse effects, the inherent limitations of this electrode distance make it challenging to achieve the desired balance between efficiency and quality. Compared to shorter electrode distances like 3 cm and 5 cm, which demonstrated better preservation of cellular structures, the 7 cm configuration is far less effective in ensuring high-quality drying outcomes. These findings underscore the importance of carefully calibrating electrode distance in EHD drying processes to avoid compromising product quality through excessive structural degradation.

Fig. 4 – SEM Images captured of turmeric slices dehydrated with tray drying

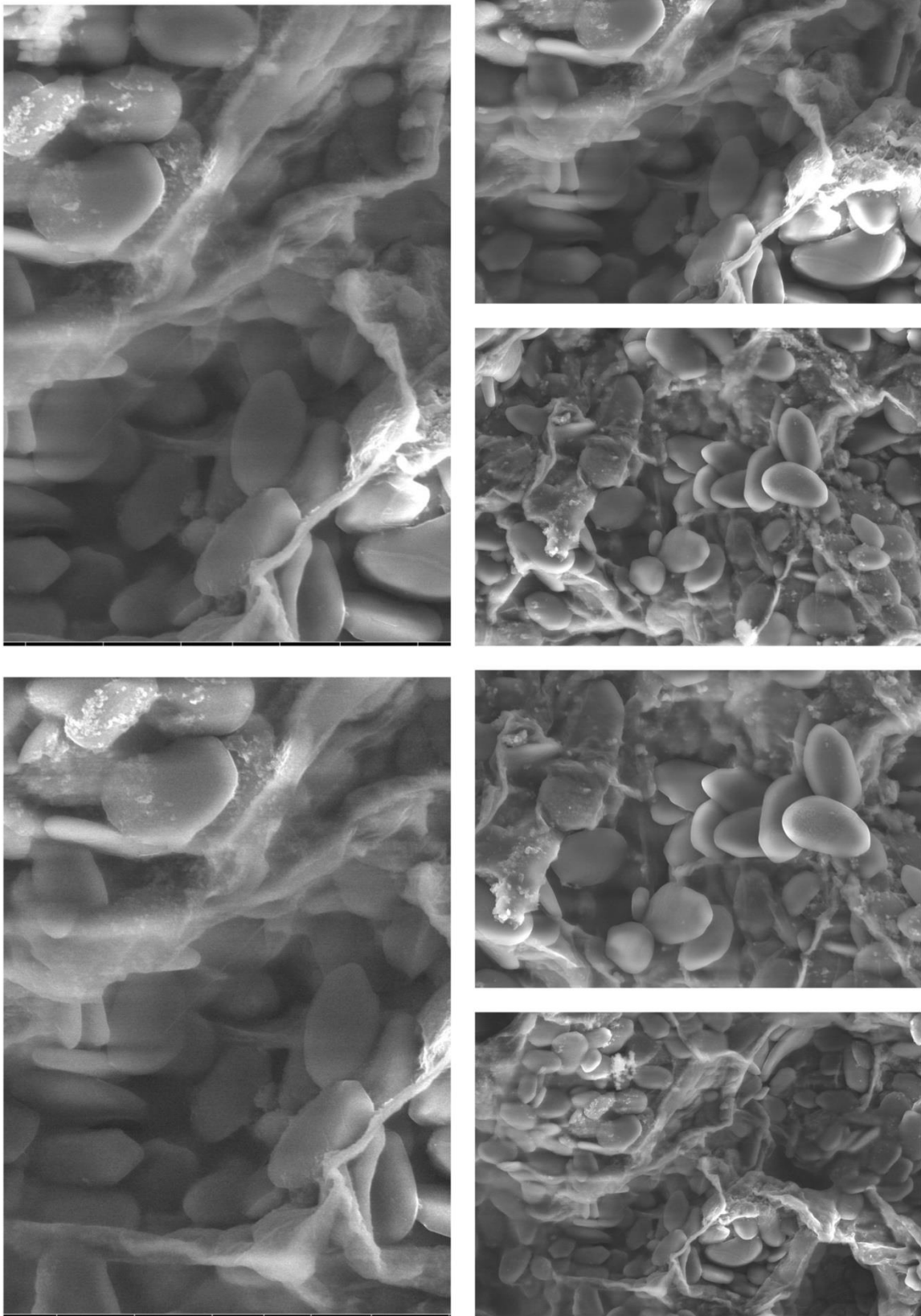
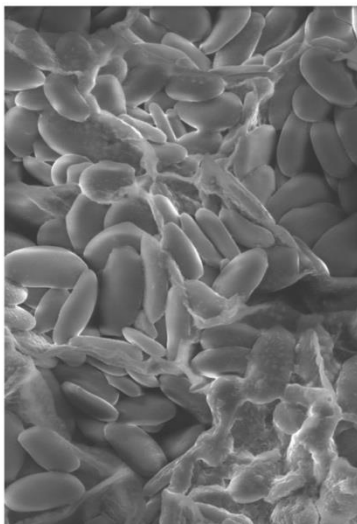
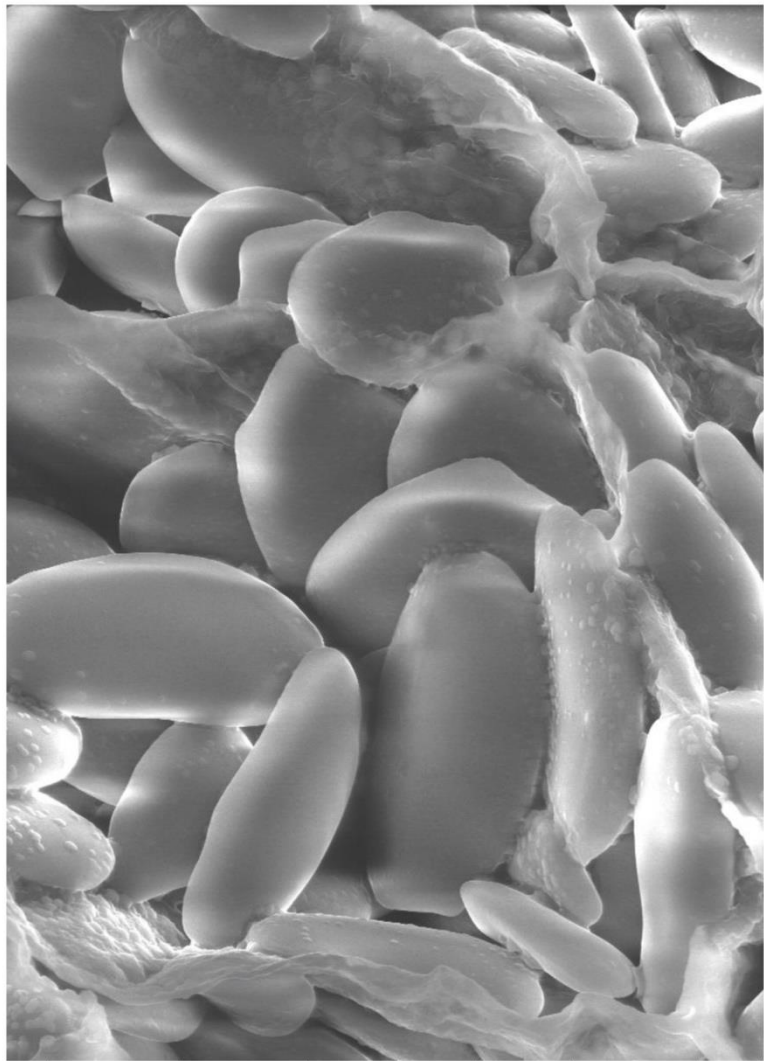
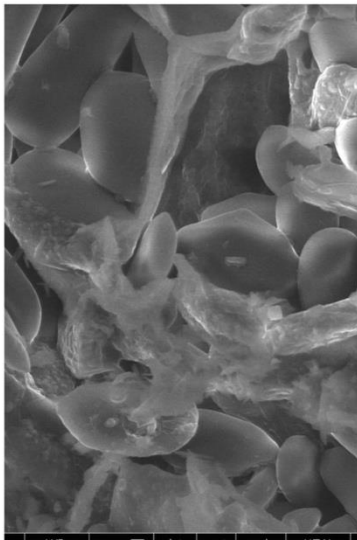
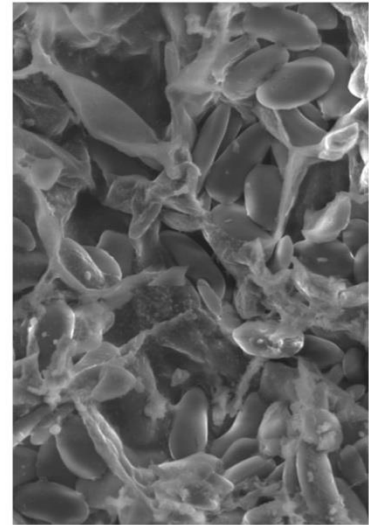
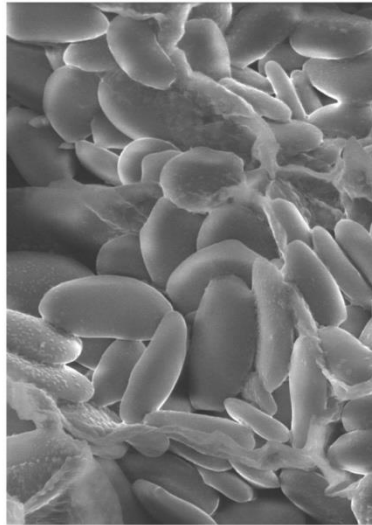
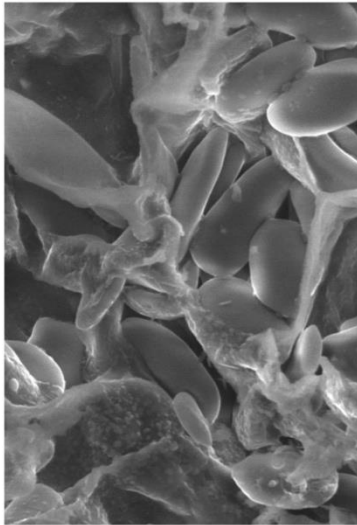


Fig. 5 – SEM Images captured of turmeric slices dehydrated with Vacuum drying.



2.4 Tray Drying

Turmeric rhizomes dried by tray drying exhibited large, irregular pores indicative of rapid moisture evaporation, likely due to high thermal exposure. The surface texture was rough, with visible cracks and breakages, pointing to rapid moisture loss. The cell walls were severely compacted and collapsed, with shrivelled cells and disrupted cell membranes. This indicates that thermal stress during tray drying caused significant structural breakdown of the turmeric rhizomes.

Tray drying caused substantial structural damage to the turmeric rhizomes, as seen by the large pores and extensive cracking in the SEM images. A detailed depiction of the SEM images can be found in Figure 4. The high thermal exposure during tray drying leads to rapid moisture removal, but also causes nutrient degradation and structural collapse, as noted by Kumar et al. (2019). This results in the loss of bioactive compounds like curcumin, which is highly sensitive to heat. Additionally, Sadiq et al. (2020) emphasized that tray drying is less effective for preserving quality in heat-sensitive plant materials, especially when the goal is to retain both nutritional value and aesthetic appeal. While tray drying remains a popular method due to its simplicity and cost-effectiveness, its use for high-quality turmeric products is limited by the textural degradation and potential loss of bioactive compounds.

2.5 Vacuum Drying

The SEM analysis of vacuum dried turmeric rhizomes displayed the finest and most evenly distributed pores, indicative of uniform moisture removal under controlled vacuum conditions. The surface was smooth, with minimal cracking. The cell walls were well-preserved, showing only slight shrinkage, which suggests a gentle drying process that retained the structural integrity of the rhizomes.

Vacuum drying performed the best in preserving the structural integrity of the turmeric rhizomes. The evenly distributed pores and smooth surface indicate that the process involved gentle moisture removal, preventing the thermal stress associated with conventional drying methods. This observation is consistent with findings by Ravindran et al. (2018), who noted that vacuum drying is one of the most effective methods for drying heat-sensitive materials because it allows for uniform moisture removal while minimizing thermal degradation. Additionally, curcumin, being heat-sensitive, benefits significantly from vacuum drying, which minimizes bioactive compound loss during the drying process. The slight shrinkage of the cell walls, which was observed, is typical of vacuum drying, but it did not lead to the same level of structural collapse seen in tray drying or longer EHD drying distances.

CONCLUSION

This study comprehensively evaluated the efficacy of various drying techniques for preserving the structural and bioactive integrity of turmeric rhizomes, with a specific focus on the Electrohydrodynamic Drying (EHD) methods at varying electrode distances of 3 cm, 5 cm, and 7 cm, as well as traditional tray and vacuum drying methods. The results provide valuable insights into the differential impact of these drying methods on the rhizomes' microstructural features, moisture retention, and bioactive compound preservation, particularly curcumin.

The Electrohydrodynamic Drying (EHD) method with 3 cm electrode distance at 14 kV emerged as the most effective technique for preserving the structural and biochemical properties of turmeric rhizomes. SEM analysis revealed a microstructure characterized by uniform medium-sized pores, a smooth surface texture with shallow pits, and minimal cellular deformation. The high porosity (65.49%) and low shrinkage ratio (68.53%) indicated that the drying process preserved the internal cellular architecture with minimal physical distortion. The rehydration ratio of 312% and a curcumin retention of 8.85% further highlighted the method's capability in retaining the rhizomes' functional properties, offering substantial potential for high-quality dried turmeric suitable for nutraceutical and food applications. The minimal structural damage, coupled with optimal bioactive retention, confirms the superiority of the EHD process at 3 cm electrode distance, aligning with the findings of Monnier et al. (2017), who emphasized that shorter electrode distances enable more efficient moisture removal while maintaining cellular integrity.

In contrast, Electrohydrodynamic Drying (EHD) with 5 cm electrode distance at 17 kV, while still more effective than conventional methods, demonstrated slightly compromised structural and bioactive retention. SEM observations revealed smaller, less uniform pores, and a rougher surface texture indicative of localized drying stresses. The bulk density, true density, and porosity were similar to the 3 cm electrode distance, but the shrinkage ratio (67.28%) was higher, indicating some degree of cellular collapse. The curcumin content, though slightly reduced to 8.69%, was still favourable compared to traditional drying methods. These results suggest that increasing the electrode distance leads to less uniform moisture removal, which can affect both structural integrity and bioactive compound retention, as seen in the rougher surface texture and the slight shrinkage of cellular walls. The EHD Drying with 5 cm electrode distance offers a practical alternative for large-scale applications where precise control over drying conditions is less critical, but it still falls short of the performance demonstrated by the 3 cm electrode distance.

The Electrohydrodynamic Drying (EHD) method at 7 cm electrode distance with 24 kV applied voltage exhibited the most significant degradation in structural and bioactive properties. SEM analysis revealed extensive structural collapse, with irregular, compacted pores and severely deformed cell walls. The surface was highly rough, marked by pronounced cracking and extensive cellular shrinkage. The evidence of localized overheating and stress concentrations suggests that the longer electrode distance resulted in inefficient moisture extraction, which severely compromised the microstructure of the rhizomes. These findings are consistent with those of Tao et al. (2019), who noted that longer electrode distances can lead to non-uniform moisture removal and structural degradation. Given the extent of structural damage, the EHD Drying with 7 cm electrode distance is unsuitable for applications where maintaining product quality and bioactive retention is crucial.

Tray drying also resulted in significant structural degradation, as seen from SEM images that indicated large, irregular pores, extensive cracking, and severe cell wall collapse. The high thermal exposure in tray drying caused rapid moisture evaporation, leading to substantial shrinkage and degradation of bioactive compounds, including curcumin. These results corroborate the findings of Kumar et al. (2019), who highlighted the detrimental effects of excessive heat exposure in conventional drying methods, particularly for heat-sensitive compounds. While tray drying is cost-effective, its application for high-value products like turmeric is limited due to the structural and biochemical degradation that occurs during the drying process.

In contrast, vacuum drying demonstrated superior performance in preserving the structural integrity of the rhizomes. The SEM analysis revealed fine, evenly distributed pores, smooth surface textures, and well-preserved cell walls, indicating a gentle and controlled drying process. The minor shrinkage observed in the vacuum-dried samples did not lead to the extensive structural damage seen in tray drying or the extended EHD methods. Vacuum drying proved to be an effective method for retaining the bioactive compounds, particularly curcumin, which is highly sensitive to thermal degradation. This observation aligns with the work of Ravindran et al. (2018), who emphasized the benefits of vacuum drying in preserving the quality of heat-sensitive materials.

The EHD method with 3 cm electrode distance stands out as the most technically advanced and efficient drying technique for turmeric rhizomes, providing the optimal balance between moisture removal, structural preservation, and bioactive compound retention. While the EHD Drying with 5 cm electrode distance offers a viable alternative with slightly reduced efficiency, the EHD Drying with 7 cm electrode distance and tray drying methods led to significant structural and biochemical degradation. Vacuum drying, although effective in preserving structural integrity, did not offer the same level of drying efficiency as EHD methods. These findings underscore the importance of optimizing drying parameters, particularly electrode distance in EHD processes, to achieve superior quality and functional retention of turmeric rhizomes in high-value applications.

REFERENCES

1. AOAC. (1999). Official methods of analysis of AOAC international (16th ed.). AOAC International.
2. Al-Muhtaseb, A. H., & Aytac, Z. (2009). Optimization of microwave and vacuum drying of fruits and vegetables: Impacts on quality and nutritional properties. *Food Research International*, 42(7), 904-913.
3. Baird, S. M., & Kopka, M. M. (2004). Effects of drying and storage methods on the bioactive constituents of turmeric rhizomes. *Food Chemistry*, 90(2-3), 327-335.
4. Bishayee, A., & Singh, S. V. (2015). Curcumin in health and disease: Molecular mechanisms and therapeutic potential. *Bioorganic & Medicinal Chemistry*, 23(5), 732-743.
5. Boro, M. S., & Raghavendra, P. (2021). Vacuum drying technology for food products: Pros and cons. *Food Quality and Safety*, 5(2), 113-120.
6. Chen, X., & Li, M. (2012). Innovative drying methods for heat-sensitive food products. *Food Processing Technology*, 25(3), 171-180.
7. Damodaran, S., & Parkin, K. L. (2012). *Food Chemistry* (4th ed.). Wiley.
8. Della, M., & Rodrigues, M. (2015). Effect of different drying techniques on functional properties of turmeric. *Journal of Food Engineering*, 98(2), 278-285.
9. He, J., & Li, Q. (2017). Effect of electrohydrodynamic drying on the quality of bioactive compounds in food. *International Journal of Food Science & Technology*, 52(4), 895-903.
10. Kha, T. D., & Nguyen, M. T. (2014). Influence of drying method on bioactive compounds and antioxidants in turmeric. *Food Bioprocess Technology*, 7(3), 695-703.
11. Kumar, A., Sahu, J. K., & Singh, S. (2019). Thermal degradation of curcumin during drying of turmeric. *Journal of Food Science and Technology*, 56(3), 1234-1242.
12. Lohani, R., & Tripathi, S. (2018). Effect of drying techniques on curcumin retention in turmeric rhizomes. *Food Bioprocess Technology*, 11(6), 1065-1074.
13. Monnier, C., Davidek, T., & Klein, B. (2017). Electrohydrodynamic drying (EHD) for food preservation: Mechanisms and applications. *Food Research International*, 99, 311-318.

14. Morales, A., Zacarías, L., & Lizarazo, J. (2016). SEM analysis of plant tissues during drying: Insights into pore formation and structural changes. *Journal of Food Engineering*, 184, 10-19.
15. Nwachukwu, I. N., & Sanni, L. O. (2020). Impact of drying methods on structural integrity and nutritional quality of plant-based foods. *International Journal of Food Science & Technology*, 55(6), 2364-2371.
16. Polat, A. (2024). Analysis of drying characteristics and quality attributes in peach slices dried via electrohydrodynamic, hot air, and electrohydrodynamic-hot air methods. *Journal of Thermal Analysis and Calorimetry*, 149, 7551–7563
17. Prajapati, S., Shah, M., & Srivastava, S. (2024). Experimental characterization and thin-layer convective drying modeling of Jamun (Indian Blackberry) slices. *Sādhanā*, 49, 272.
18. Prakasha, R., Vinay, G. M., Pandey, H., & Bhoi, P. M. (2025). Electrohydrodynamic drying: A comprehensive review of design considerations and quality effects on dried fruits and vegetables. *Journal of Food Process Engineering*, 48(1), e70029.
19. Raghavendra, P., & Boro, M. S. (2021). Microwave and electrohydrodynamic drying of fruits and vegetables: A comparative study. *Journal of Food Science*, 85(6), 1708-1716.
20. Rani, R., Choudhury, D., & Saini, R. (2017). Structural changes in food products during drying as observed by SEM. *Food Structure*, 13, 25-35.
21. Ranganathan, S., & Srinivas, R. (2019). The effect of drying methods on the preservation of bioactive compounds in spices: A review. *Journal of Food Science and Technology*, 56(8), 4377-4392.
22. Ravindran, P., Sivaraman, K., & Rajasekaran, R. (2018). Vacuum drying of heat-sensitive foods: Process optimization and product quality preservation. *Innovative Food Science & Emerging Technologies*, 49, 136-144.
23. Sadiq, M. B., Ali, M., & Masood, S. (2020). Tray drying of turmeric: A study on structural and biochemical degradation. *Journal of Food Processing & Preservation*, 44(2), e14322.
24. Sharma, S. P., & Sharma, B. (2005). Thermal degradation of bioactive compounds in turmeric during drying. *Food Chemistry*, 90(3), 381-388.
25. Shah, M., & Srivastava, S. (2024). Physio-chemical analysis of turmeric rhizomes (*Curcuma longa* L.) preserved through non-thermal technique: Electrohydrodynamic drying. *African Journal of Biomedical Research*, 27(4s), 1691-1701.
26. Shivmurti, Srivastava, Monarch Shah, Pravin M. Ganorkar, & Kshitiz Kumar. (2024). Modelling of electrohydrodynamic drying kinetics for carrot at varying electrode distance. *Journal of Food Science and Technology*, 61, 139–149.
27. Shivmurti, Srivastava, Pravin M. Ganorkar, Ajay Tapre & Archa Shah (2024). A Review on Electrohydrodynamic drying – a novel non-thermal drying technique. *Journal of Agricultural Engineering*, 61(6), 1-14.
28. Shrivastav, S., Ganorkar, P. M., Prajapati, K. M., & Patel, D. B. (2021). Drying kinetics, heat quantities, and physiochemical characteristics of strawberry puree by Refractance Window drying system. *Journal of Food Process Engineering*, 44(9), e13776.
29. Soleimani, M., & Akhlaghi, M. (2020). Effect of electrode distance on the performance of electrohydrodynamic drying of plant materials. *Journal of Food Engineering*, 296, 110334.
30. Srivastava, Shivmurti, & Kumbhar, B. K. (2010). Textural profile analysis of paneer dried with low pressure superheated steam. *Journal of Food Science and Technology*, 47(2), 355-357.
31. Srivastav, Shivmurti, & Kumbhar, B. K. (2011). Drying kinetics and ANN modeling of paneer at low pressure superheated steam. *Journal of Food Science and Technology*, 48(5), 577-583.
32. Tao, Y., Wang, Y., & Zheng, B. (2019). Impact of electrode distance on drying performance and structural quality in electrohydrodynamic drying. *Drying Technology*, 37(13), 1737-1747.
33. Wang, Z., & Liu, Y. (2019). Review of electrohydrodynamic drying: Fundamentals and applications to food drying. *Food Science and Technology Research*, 25(6), 877-887.

34. Zhang, J., Ding, C., Lu, J., Zhu, J., Bai, W., Guan, P., Song, Z., & Chen, H. (2024). Effect of electrohydrodynamic (EHD) drying on active ingredients, textural properties, and moisture distribution of yam (*Dioscorea opposita*). *Food Chemistry: X*, 23, 101622.
35. Zhu, J., Ding, C., Che, C., Liu, L., Lian, J., Song, Z., & Qin, C. (2024). Influence of Electrohydrodynamics on the Drying Characteristics and Volatile Components of Ginger. *Applied Sciences*, 14(22), 10655.