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Modeling Mineral Content and Acoustic Pressure in Agricultural Products Exposed to Ultrasonic Waves: A Case Study on Frequency Effects

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Abstract

Ultrasound technology is swiftly progressing and extensively utilized to optimize production operations, elevate product quality, and guarantee food safety. Low-frequency ultrasound alters physical qualities, whereas high-frequency ultrasound serves as an analytical instrument to evaluate the physicochemical characteristics of food, including acidity, hardness, sugar concentration, and maturity. High-frequency ultrasound produces pressure, shear, and temperature variations, resulting in cavitation effects that suppress microbial proliferation in food. Ultrasonic waves generate air bubbles and micro-vibrations in liquid mediums, hence improving mass and energy transfer. This is advantageous in processes such as freezing, cooling, and thawing by minimizing quality deterioration. This study examines the impact of ultrasonic waves at varying frequencies on the mineral composition of agricultural products. The findings underscore the influence of ultrasonic frequency on the physical and chemical properties of food, suggesting possible applications for the enhancement of food processing methods. The experimental results confirm that ultrasound technology is a feasible method to improve food quality and safety while maintaining nutritional integrity.

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1. Introduction

Exporting agricultural goods to other nations in order to compete in markets that are fiercely competitive and have a tendency to raise prices requires that the product be of high quality. There will be high-quality manufacturing, and the act of planting. After harvest, it is crucial to maintain the produce and give it to customers. Humidity is a crucial element that must be managed in order to preserve the quality of agricultural products. It is well recognized that humidity affects a product's weight, respiration rate, and microbial development.[1] In this study, ultrasonic waves—one of the methods used to regulate moisture content—were examined.[2,3]

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From ancient times to the present, ultrasonic waves have been frequently used in medicine. The term "ultrasound" refers to sound waves having frequencies higher than 20 kHz, above the range of human hearing. Ultrasound waves can be used to see images of different body parts, monitor growth, or identify infants in expectant mothers. using ultrasonic waves to examine anomalies in the breast, thyroid gland, veins in the arms, legs, and neck, as well as the abdominal organs. Ultrasound is an exception to this rule. Ultrasound cannot be used to evaluate the wind or bone organs. In order to remove brain tumors, ultrasonography was initially used as a diagnostic technique in 1942. Additionally, it is utilized in cosmetology and physiotherapy.[4] A property of ultrasonic waves is their ability to reflect waves, which can be used to survey the location of objects or equipment. Ultrasonic waves can also be employed to develop a device for humidity control.[5]

Throughout history, a multitude of research groups have examined the role of electromagnetic waves, mechanical waves, and ultrasonic waves in a variety of natural phenomena that are relevant to agriculture, food, and medicine. In particular, ultrasound has been extensively investigated for its potential applications in the processing of agricultural products, while electric field technologies have been investigated for their potential in the processing of food. Furthermore, these wave-based technologies are utilized to improve the quality and efficiency of agricultural processing techniques.[2,3,5-25] The most sustainable and effective use of the resources now available, as well as natural resources including land, water, and air, was deemed to be crucial in the future. Inadequate soil development techniques, poor soil management, and the current variable climate change are some of the reasons for these issues. Additionally, the likelihood of a natural fertility recovery has been diminished by the increased urbanization of industrialized areas. Moreover, frequent droughts, poor water management, water pollution, and groundwater depletion are problems in farming areas. Researchers search for cutting-edge farming technologies and propose a solution: implementing readily available technologies in regulated settings. One of the technologies is systematic farming without soil.[26,27] Soilless agricultural methods can produce year-round, consistently productive veggies that are fresh, clean, and sanitary, regardless of climate or season. The usage of such technology helps with post-harvest care, and humidity control is a concern during this growth. Additionally, the idea of soilless agriculture is one way to guarantee both economic and environmental sustainability.

The best cropping method for all nations with small acreages and quick environmental changes is soilless agriculture. According to Butler and Oebker,[28] cropping under different controlled conditions is currently employed as a vegetative-free strategy. This is also stated by R. M. M. Naz *et al.*,[29] Farran and Mingo-Castel,[30] Beibel,[31] and Reyes *et al.*[32] Although mostly associated with hydroponic and aeroponic techniques, the plant will thrive in both systems without soil. Plant roots can thrive in water that is rich in nutrients or in the misty air. With the support of ultrasonic technology, the crop-growing method known as aeroponics may grow plants without the use of soil by misting them with the nutrients they require. a plant's growth. An ultrasonic atomizer sprays the nutrient mist into the roots of aeroponic cultivation.

According to Avvaru *et al.*,[2] atomization is a technique for dividing liquid molecules into tiny droplets. For the majority of conventional aeroponic systems, a spring nozzle is used to spray pressure water onto the roots. However, several fields have developed atomizers with diverse spray patterns that test various kinds of liquids. Spray nozzles with small holes might result in issues like blocked nozzles and stagnant water supply, however this enables liquid droplets to be as small as 1 micron. A mesh filter is therefore utilized to prevent issues in order to prevent nozzle clogging. Although nozzle clogging is less likely in larger nozzles with larger mouths, considerable pressure is necessary to operate in this situation. To obtain the correct droplet size, it is necessary to choose the proper spray nozzle. The droplets are classified according to their size, which ranges from microns to thousands of microns pertaining to high-pressure spray nozzles with 0.635 mm and 0.4064 mm jet nozzles and 80 and 100 psi operating pressure pumps, droplets of 5-50 microns and 5-25 microns, respectively, are produced. Droplets are categorized as fine mists of 10 to 100 microns.

According to earlier studies, the ideal droplet size range for the majority of plants in an aeroponic system is typically between 30 and 100 microns. (Fig. 1). Droplet sizes smaller than 30 microns have a tendency to linger in the atmosphere like mist and saturate it. Plant growth is sporadic. Droplets bigger than 100 microns, however, typically fall to the ground before making it to the plant roots. Additionally, too-large droplets result in less oxygen being present in the aeroponics growing chamber. In order to suit the needs of the grower or farmers, the choice of aerosol nozzles should be made accordingly.

The operating frequency of ultrasonic mist sprayers is between 1 and 3 MHz. It needs to be driven by a unique electrical circuit. Thus, it has a highly intricate structure. The chemical composition of fertilizer solutions for plant growth is also impacted. In order to create and improve the ultrasonic mist maker to be suitable for the unique qualities of that agricultural product, this mathematical simulation will be employed as industrial improvement data. Wagner *et al.*[12] explored the association between the frequency of ultrasonic waves and the size of the aerosol by developing a test, which is another finding from the analysis of related studies. The findings showed that the droplet size was equal to 4.98 micrometers when using an ultrasonic frequency of 1.7 MHz, 0.47 micrometers when using an ultrasonic frequency of 3.3 MHz, and 0.48 micrometers when using an ultrasonic frequency of 4 MHz, indicating that the droplet size was relatively constant at frequencies greater than 3.3 MHz.

This study presents a novel approach by integrating numerical modeling, specifically the finite element method (FEM) via COMSOL Multiphysics, to analyze the effects of ultrasonic waves on moisture content and acoustic pressure in agricultural products. This study systematically evaluates the impact of different ultrasonic frequencies (20 kHz, 1.7 MHz, and 3.3 MHz) on moisture distribution and mineral content, unlike previous research that primarily relied on experimental methods. The results show that low-frequency ultrasound (20 kHz) penetrates deeper and increases moisture absorption, while higher frequencies affect the surface moisture retention. This study also shows a mathematical link between acoustic pressure and moisture absorption, aiding post-harvest tech and precision farming. Ultrasonic waves can control moisture and minerals in crops, and may be used to regulate greenhouse humidity, aeroponic farming, and food preservation. By extending ultrasonic technology beyond conventional food quality assessment, this study provides a framework for optimizing moisture control, enhancing product shelf life, and

Fig. 1: Aeroponic cultivation in enclosed environments.

improving agricultural efficiency. This research will enhance storage and processing technologies for agricultural products and promote innovations that sustainably improve efficiency and quality in the agricultural sector.

2. Problem formulation

2.1 Physical model

This research is a theoretical study by developing physical and mathematical models based on theoretical references and research related research using the finite element numerical method to find answers and explain the phenomena occurring within 2D models of agricultural materials considered porous. Considering the pressure and intensity of ultrasonic waves at different frequencies, the correctness of the program is checked. and the accuracy of the model with published research is also checked. This model has been computed through various equations through a computer program called COMSOL Multiphysics.

The development of physical models of agricultural products was obtained from a review of relevant research studies.[12] Wagner *et al.*[12] created the test. The results showed that when using ultrasonic frequencies at 1.7 MHz, the droplets were 4.98 μm in size, and when using 3.3 MHz, they found the droplets were 0.47 μm, and at the ultrasonic frequency of 4 MHz, the droplets were 0.48 μm. Tests showed that at frequencies greater than 3.3 MHz, the droplet sizes were quite similar. Therefore, this work has applied the above knowledge to develop a physical model as shown in Fig. 2 by calculating the pressure by using the ultrasonic frequencies of 1.7 and 3.3 MHz and the intensity of the resulting ultrasonic waves.

An axisymmetric two-dimensional biological model is used to figure out the total acoustic pressure and the amount of water in the biological tissue during the ultrasonic ablation process. The agricultural material tissue is complex and heterogeneous, but the model used in this study was built in an axisymmetric plane. To simplify the problem, the tissue is assumed to be homogeneous, uniform, and isotropic in the same layer, which means that there is no difference in the thermal and acoustic properties within any layer. The focused ultrasound ablation to the surface has a portion of the mechanical vibration at the biological tissue.

Table 1 shows the acoustic and thermal properties of the biological tissues used in the simulations. Because the general heat transfer application in COMSOL does not include the thermal effects of perfusion included in the Pennes' bioheat equation, the effects of perfusion were simulated in the muscle and fat tissues using the external heat source term (Q_{ext}) is equal to the resistive heat generated by the ultrasound ablation.

Table 1: Thermal properties and acoustic properties of the tissue.[33]

Tissue properties	Values
Tissue density (ρ)	1,090 $\frac{\text{kg}}{\text{m}^3}$
Heat capacity of tissue (C)	3,421 J/kg K
Heat capacity of blood (C_b)	3,617 J/kg K
Thermal conductivity of tissue (k)	0.49 W/m K
Density of blood (ρ_b)	1,049 $\frac{\text{kg}}{\text{m}^3}$
Blood perfusion rate (ω_b)	0.0001 s^{-1}
Tissue porosity (ε_p)	0.4
Acoustic absorption coefficient (α)	7.11 m^{-1}
Speed of sound (C_c)	1,588.4 m/s

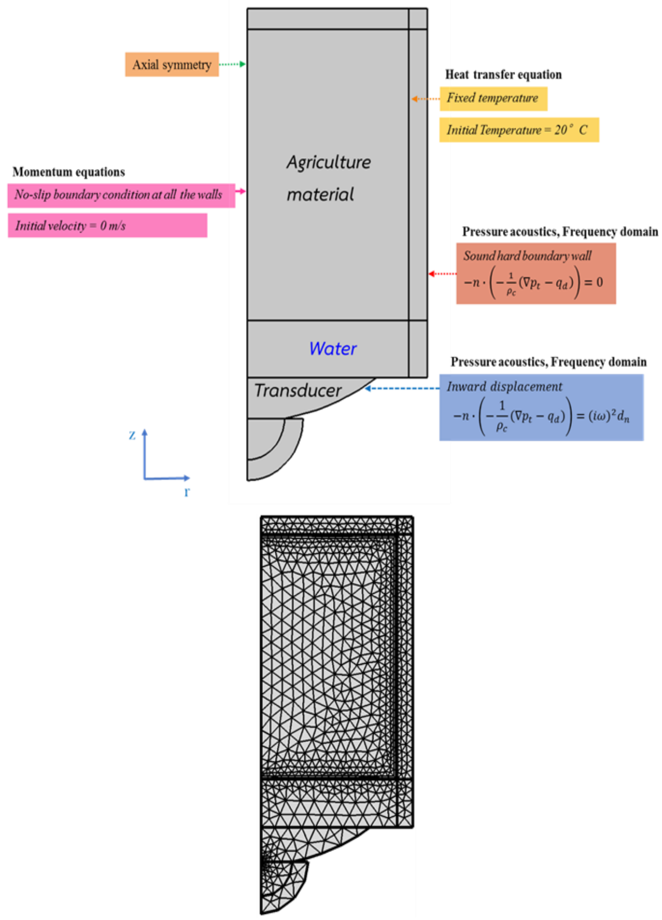

Fig. 2: Modeling boundary conditions and shape and number of elements used in the model in comsol multiphysics.

2.2 Analysis of the pressure acoustics

Ultrasound is a mechanical vibration of matter with a frequency above the audible range. The wave is propagating through the medium as a disturbance of the particles in the medium supporting the wave. Particles will oscillate around their mean positions in a 3D manner. In general, liquids, soft tissue, and gases produce only longitudinal waves. The factors of acoustic impedance are the properties of the wave and the object that the wave is progressing through. Ultrasound waves propagating in the biological tissue will be attenuated because of absorption and scattering. Sound pressure, or acoustic pressure, is the local pressure deviation from the ambient (average or equilibrium) atmospheric pressure caused by a sound wave. In air, sound pressure can be measured using a microphone, and in water with a hydrophone. The International System of Units of sound pressure is the pascal (Pa).

3. Methods and model

To find out what happens when biomaterials are exposed to acoustic energy during ultrasonic ablation, this study looked at how the acoustic pressure is spread out. The absorbed energy and its effects on temperature and fluid flow were evaluated. The computational model is shown in Fig. 3. Equations for momentum, continuity, and energy, as well as how acoustic waves travel, were used to look into the acoustic pressure field and fluid flow during ultrasonic ablation. Computer simulations were used to see how the type of biomaterial and the frequency of the sound waves used affected the flow field and heat transfer in the biological tissue around it during ultrasonic ablation.

Fig. 3: Computational model of ultrasonic interaction with bio-material tissue.

3.1 Equation for acoustic wave propagation analysis

The mathematical models illustrate the acoustics, and their variations and moisture content relate to the physical phenomena that arise from the interactions between ultrasonic ablation and biological tissues. To simplify the problem, the following assumptions are made:

1. The pressure acoustics are modeled in two dimensions.
2. The focused ultrasound interaction with the tissue proceeds in the open region.
3. The free space is truncated by a scattering boundary condition.
4. The model assumes that the acoustic properties of each biological tissue are constant.

To describe the ablation of focused ultrasound through a tissue, the focused ultrasonic ablation is calculated using pressure acoustics, which mathematically describes the interdependence of the ultrasonic ablation. The general form of pressure acoustics is simplified to demonstrate the ultrasonic ablation into the biological tissue as expressed by Eqs. (1)-(3):[4]

$$\nabla \cdot \left(-\frac{1}{\rho_c}(\nabla p_t - q_d)\right) - \frac{k_{eq}^2 p_t}{\rho_c} = Q_m \tag{1}$$

$$k_{eq}^2 = \left(\frac{\omega}{c_c}\right)^2 - \left(\frac{m}{r}\right)^2 \tag{2}$$

$$c_c = \frac{\omega}{k}, \quad k = \frac{\omega}{c} - i\alpha, \quad \rho_c = \frac{\rho c^2}{c_c^2} \tag{3}$$

where p_t is the acoustic pressure (N/m^2), ω is the angular frequency (rad/s), c_c is speed of sound (m/s), q_d is the dipole source term (W/m^3), Q_m is the monopole source term (W/m^3), and α is the acoustic attenuation coefficient in the biological tissue (dB/cm.MHz).

In the present study, the dipole source term and the monopole source term are assumed to be zero. The boundary condition for the pressure acoustics in the frequency domain is presented by Eqs. (4) and (5).

Sound hard boundary wall $$-n \cdot \left(-\frac{1}{\rho_c}(\nabla p_t - q_d)\right) = 0 \tag{4}$$

Intensity determined $$I = \frac{Q_m}{2\alpha} \tag{5}$$

3.2 Calculation procedures

The mathematical models were solved using the finite element method (FEM). An adaptive mesh methodology was employed to efficiently address the numerical model. COMSOL Multiphysics was used to solve the computational problem and analyze the tissue model's response after ultrasonic treatment.

To solve the thermal problem, the coupled effects of the pressure acoustics propagation and the unsteady bioheat transfer are investigated. The temperature distribution corresponds to the thermal properties of biological tissue. The absorbed energy from the mechanical wave (acoustic pressure) is converted to thermal energy, which increases the tissue temperature. In order to simulate the biological ablation, a model of unsteady heat transfer, as well as boundary conditions, is investigated. Heat transfer analysis on the tissue during biological ablation is modelled in a 2D tissue thermomechanical model constructed in an axis symmetric plane. To simplify the problem, the following assumptions are made

1. The biological tissue is a bio-material with constant thermal properties in the same layer.
2. There is no phase change of substance in the biological tissue.
3. There is no chemical reaction in the biological tissue.
4. The two-dimensional model with an axisymmetric plane is assumed.
5. Unsteady heat transfer is considered.
6. The contact surface between each tissue is assumed to be a smooth surface.
7. All the biological tissues are assumed to be homogeneous and isotropic.

3.3 Equations for heat transfer and flow analysis

Pennes' bioheat equation is used for calculating as shown by Eq. (6).

$$\rho C \frac{\partial T}{\partial t} = \nabla \cdot (k \nabla T) + \rho_b C_b \omega_b (T_b - T) + Q_{met} + Q_{ext} \quad (6)$$

where ρ is the biological tissue density (kg/m^3), C is the heat capacity of the biological tissue (J/kg K), k is the thermal conductivity of the biological tissue(W/m·K), T is the biological tissue temperature (°C), $\rho_b C_b \omega_b (T_b - T)$ is a source term accounting for blood perfusion, T_b is the temperature of the blood (°C) assumed to equal 36 °C, ρ_b is the density of the blood (kg/m^3), C_b is the heat capacity of the blood (J/kg K), ω_b is the blood perfusion rate (1/s), Q_{met} is the metabolic heat source (W/m^3) is neglected since it is small, and Q_{ext} is the external heat source (the acoustic pressure heat-source) (W/m^3).

The boundary condition for the heat transfer analysis: It is assumed that no contact resistance occurs between the internal tissues of the biological tissue. Therefore, the internal boundaries are assumed to be continuous. The heat transfer analysis excludes the surrounding space and is considered only in the biological tissue model. biological tissue, as shown in Fig. 3, is considered under the constant boundary condition. At the initial stage, the temperature distribution within the biological tissue is assumed to be uniform at 36 ℃. Therefore, the temperature boundary condition of 36 ℃ is applied to all the surface boundaries. The initial temperature of the tissue is 36 ℃. The movement of fluids in porous biological tissue is described by the Navier-Stokes equation (Eq. (7)) along with the incompressible continuity condition (Eq. (8)). Moisture migration is measured using a normalized moisture content model (Eq. (9)), while its transport is regulated by the diffusion-based mass transfer equation (Eq. (10)).

The Navier-Stokes equation, describing the motion of fluid substances such as liquids and gases.

$$\rho(u \cdot \nabla)u = \nabla \cdot [-p2I + \mu(\nabla u \cdot (\nabla u)^T + F) \quad (7)$$

Continuity equation

$$\rho \nabla \cdot (u) = 0 \quad (8)$$

Moisture content

$$M = \frac{M_t - M_e}{M_0 - M_e} \quad (9)$$

Mass transfer equation

$$\frac{\partial c}{\partial t} = \nabla \cdot \left(D_{eff} \nabla c\right) \quad (10)$$

3.3.1 Hypothesis

1. Consider a two-dimensional model.
2. Ignore the impact of wind speed on the environment.
3. Consider the properties of agricultural tissue materials as follows.

- Agricultural tissue is a biological tissue. It is a saturated porous material.
- Agricultural tissue has the same properties in all directions (isotropic) and is incompressible.

4. Consider the properties of the fluid as follows: Since it is an incompressible fluid, no status changes, and the properties are constant throughout consideration.
5. Results depend on time in the case of moisture content analysis (time dependence).

3.3.2 Boundary conditions

The scope of the analysis begins with the emission of ultrasonic waves from the source. The wave travels through the probe, and the fluid enters the agrimaterial tissue modeled as a porous material. Ultrasonic characterization has the following scope conditions. Below will be designated as the receiving part. The left boundary condition of the model is symmetrical around the axis, meaning that axial symmetry analysis is actually simulated in 3D, but to reduce computation time. and reduce the complexity, which will be analyzed to only one part from around the axis, which is the cylinder. In other words, the modeling is analyzed in a 2D format.

In this study, the frequencies of 20 kHz, 1.7 MHz, and 3.5 MHz are chosen. These frequencies are used globally in a wide range of applications, especially humidifying with ultrasonics. Ultrasonic ablation was simulated in bioligical tissue models using the finite element method (FEM). In a COMSOL® Multiphysics heat transfer model, the ultrasonic power patterns that were made were used to add heat to Pennes' bioheat equation. In order to fully explain the biological effects of ultrasound ablation, we need to do a systematic study of how the patterns of ultrasound ablation affect biological tissues.

Therefore, this study shows how to use computers to figure out the acoustic pressure and moisture level in biological tissue that has been exposed to ultrasound. The study looks at the sound pressure that is put on biological tissue during ultrasonic ablation in various settings. The FEM numerical simulation via COMSOL™ Multiphysics is applied to model the temperature distribution and deformation of biological tissue. The phenomenon of ultrasonics in biological tissues is described using pressure acoustics.

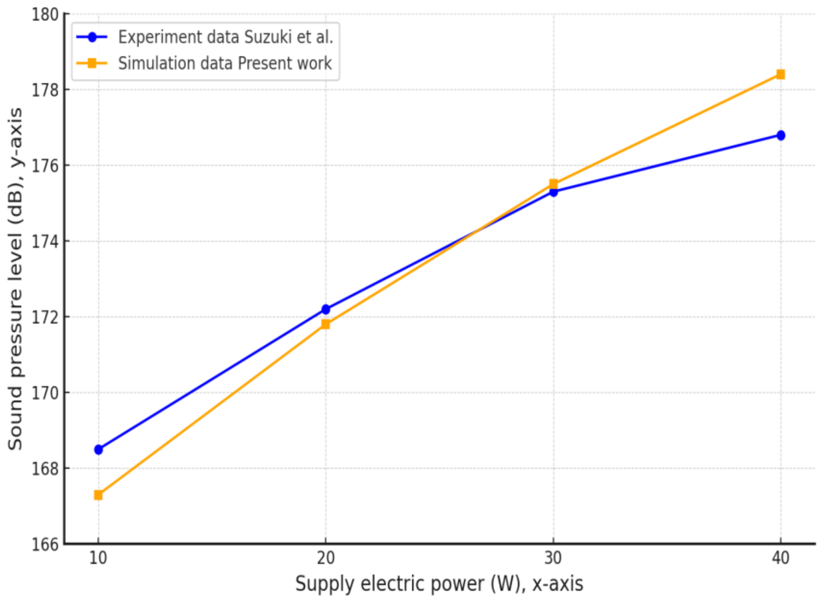

Fig. 4: The validation results of the calculated sound pressure level versus obtained by Suzuki *et al.*[34]

4. Results and discussion

This research is a study on simulating humidity control of agricultural products. Using energy from ultrasonic waves defines the model to be symmetrical around an axis in 2 dimensions and allows the agricultural material tissue to have the same properties as the agricultural material tissue. However, the surface of agricultural material tissue is a tissue that has continuity properties both thermodynamically and electrically. Within the tissue, it is defined as a local thermal equilibrium tissue, which means it is thermally balanced in the solid and liquid phases.

The numerical results obtained by Suzuki *et al.*[34] were compared to the straightforward case of the simulated results in order to validate the model proposed here. Consequently, in order to facilitate comprehension of the study as a fundamental case and to evaluate the model's precision, agricultural materials were investigated and modeled as porous materials. The ultrasonic power input is 20 W, and the results are compared to the investigation of Suzuki *et al.*[34] Fig. 4 illustrates the simulation outcomes. This favorable comparison reinforces our confidence in the precision of the current numerical model, particularly in its ability to accurately depict the complex processes that transpire during the interaction between an ultrasonic wave and tissue that has been heated through electromagnetic induction from an external source.

When the simulation results are compared to the results of Suzuki *et al.*, it is observed that at 20 W ultrasonic power, there seems to be a trend where sound pressure increases along the x-axis when the ultrasonic power is higher. The sound pressure trend of Suzuki *et al.* had a sound pressure was less than 2 dB lower than the result of this simulation. Therefore, the model was developed to further study the results of the simulation. The results obtained were quite similar to those of Suzuki *et al.*[34] at ultrasonic power in the range of 10-30 W.

This research is a theoretical study on the use of ultrasonic waves to control the humidity of agricultural products. It aims to conduct a study to understand the phenomenon of ultrasonic waves occurring in various situations. and understand the influence of various factors involved, such as the frequency of waves. The study aims to provide guidelines and recommendations for product quality management using ultrasonic technology. Therefore, the use of ultrasonic waves at an initial frequency of 20 kHz was simulated, and frequencies of 1.7 and 3.3 MHz were selected. Based on research by Wagner *et al.*,[12] it was found that if the frequency was higher than 3.3 MHz, the size of the aerosol was not much different.

This study expands on prior findings. It focuses on determining how the distribution of moisture content varies when exposed to various ultrasonic frequencies. Furthermore, it investigates the acoustic pressure produced by the ensuing waves. The intensity of the resulting ultrasonic waves remains constant over time. The wave pressure and the intensity of the ultrasonic waves are constant and do not change over time. As shown in Figs. 5-7, the left figure represents the pressure of the ultrasonic wave, Pa, and the right figure represents the intensity of the ultrasonic wave in W/m^2 at the frequencies of 20 kHz, 1.7 MHz, and 3.3 MHz, respectively.

The simulation results showed that the highest total acoustic pressure of the ultrasonic waves was 0.862032 Pa at 20 kHz, 1675.64 Pa at 1.7 MHz, and 5694.80 Pa at 3.3 MHz. Ultrasonic waves at high frequencies have high ultrasonic pressure values. The intensity of ultrasonic waves varies at different wave frequencies. From the simulation results, it was found that the highest ultrasonic intensity (maximum Intensity magnitude) is 5.58225×10^{-4}, 1615.58, 25158.7 W/m^2 at 20 kHz, 1.7 MHz and 3.3 MHz, respectively. Sonic at highfrequencies has a high intensity of ultrasonic waves.

From the simulation results of Figs. 8-10, the maximum

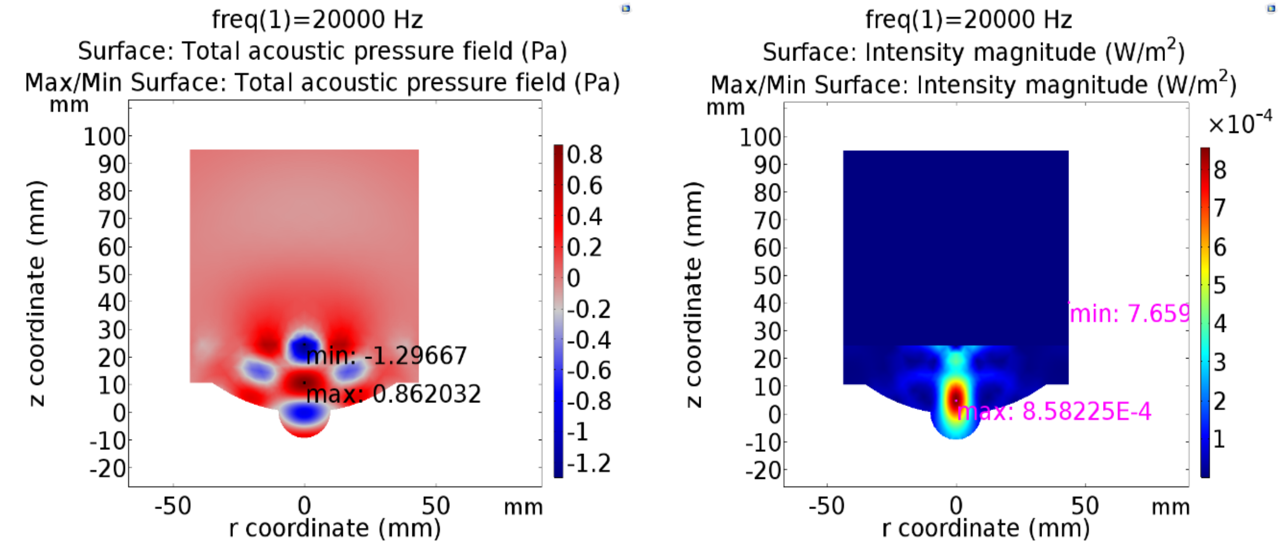

Fig. 5: Ultrasonic pressure values Pa (left figure) and ultrasonic intensity magnitude W/m^2 (right figure) at a frequency of 20 kHz. (The color contrast ratio used in the visualization is unitless.)

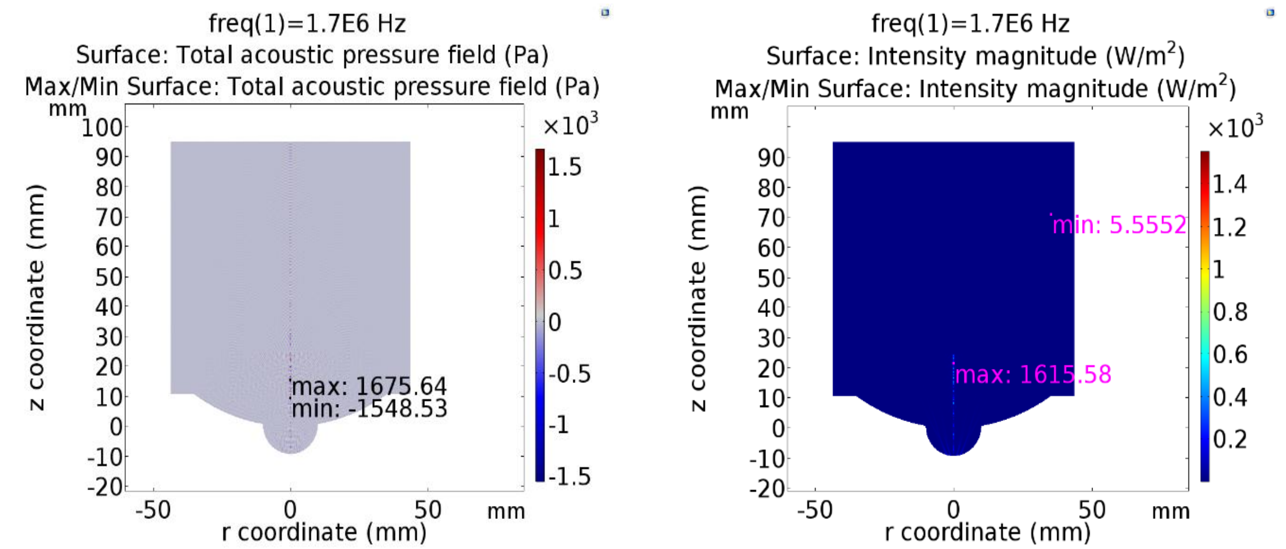

Fig. 6: The total acoustic pressure field (left figure) and the ultrasonic intensity magnitude (right figure) at a frequency of 1.7 MHz.

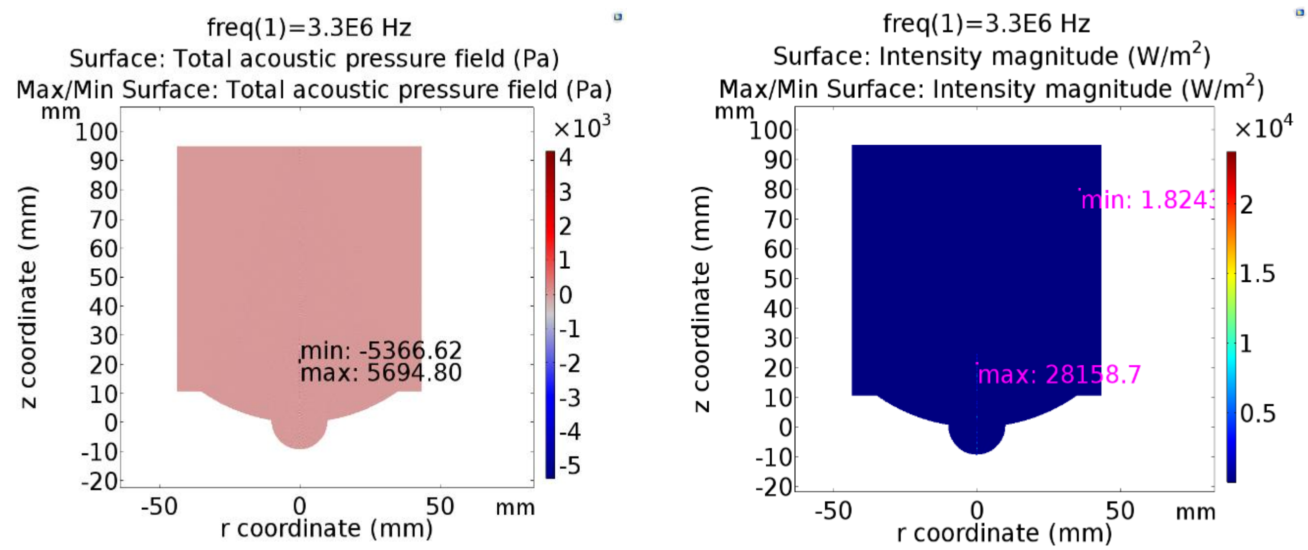

Fig. 7: The total acoustic pressure field (left figure) and the ultrasonic intensity magnitude (right figure) at a frequency of 3.3 MHz.

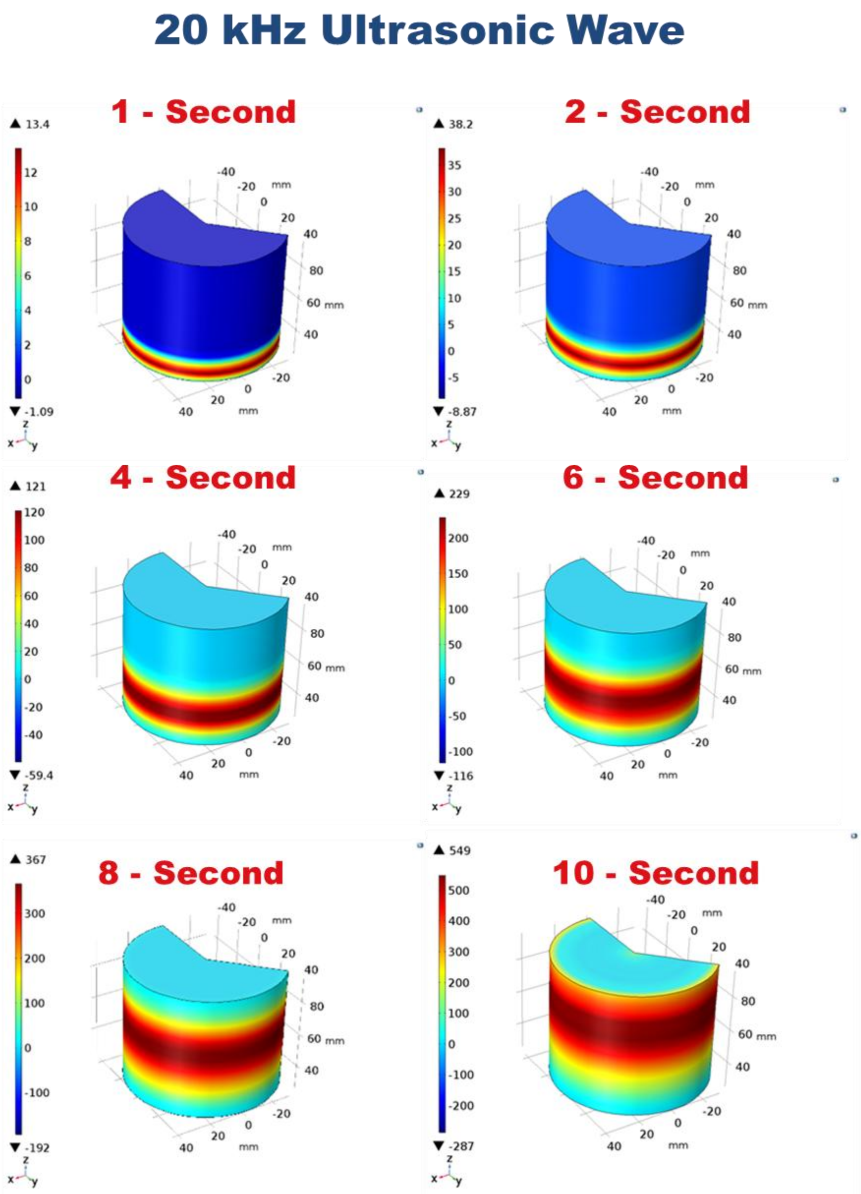

Fig. 8: Moisture content distribution at 20 kHz ultrasonic wave at 1, 2, 4, 6, 8 and 10 s.

dispersion of moisture content at ultrasonic wave moisture content of 20 kHz, 1.7 MHz, and 3.3 MHz is plotted as a moisture content curve compared to the time shown in Fig. 11. Fig. 11 illustrates the correlation between moisture content (%) and time (s) at three distinct frequencies 20 kHz (depicted in blue) and 1.7 MHz, 3.3 MHz (shown in orange), which shows a comparison of the effects of ultrasonic frequencies on the moisture absorption processes of a material over time. The moisture content rises with time for three frequencies, exhibiting a comparable trend. This indicates that, irrespective of the frequency employed, the material consistently absorbs moisture over the observed duration. Initially (from 0 to around 6 seconds), both frequencies exhibit essentially equal outcomes, with moisture content increasing from roughly 0% to about 20%. Approximately six seconds later, a little divergence occurs between the two trajectories. The 20 kHz signal has a marginally elevated moisture content compared to the 1.7 MHz and 3.3 MHz frequencies, while the disparity is minor. Over a duration of 12 seconds, the disparity in moisture content at the conclusion is negligible, with the 20 kHz curve registering approximately 55%, while the 1.7 MHz and 3.3 MHz curves exhibit end values slightly below 55%.

The frequencies (20 kHz and combined 1.7 MHz/3.3 MHz) signify distinct techniques for assessing moisture content via ultrasonic methods. These strategies can influence the distribution or detection of moisture within a substance. Low-frequency ultrasound (20 kHz) penetrates materials more deeply. The marginally elevated moisture content observed at longer intervals may result from the signal's deeper penetration, capturing moisture from within the material's interior. Higher-frequency ultrasound (1.7 MHz and 3.3 MHz) exhibits reduced penetration depths while demonstrating enhanced sensitivity to surface or near-surface wetness. The nearly comparable response to the 20 kHz signal implies that

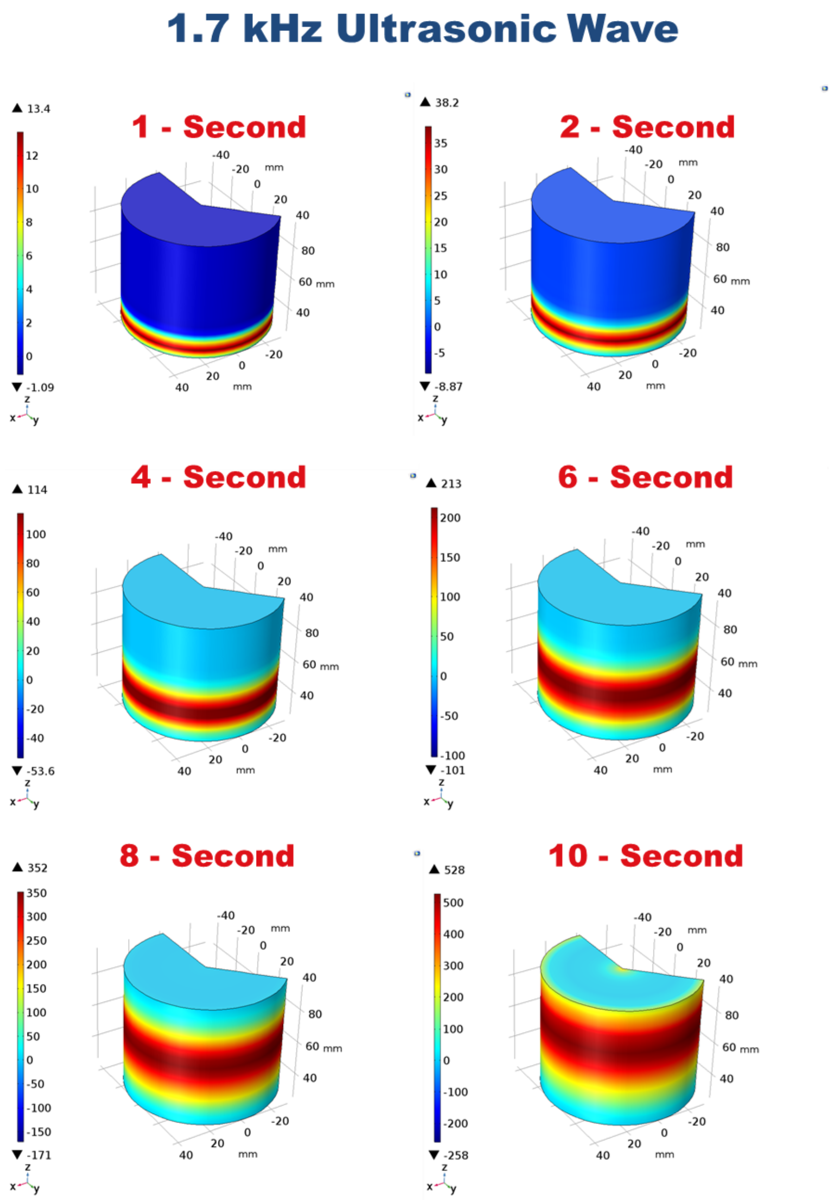

Fig. 9: Moisture content distribution at 1.7MHz ultrasonic moisture content at 1, 2, 4, 6, 8, and 10 s.

the material's surface is collecting moisture similarly. However, the somewhat reduced readings may reflect either diminished penetration or a constraint in sensitivity at higher frequencies.

The moisture absorption process throughout time exhibits a steady and uniform increase in moisture content for the material, free from sudden variations or irregularities. The slight variation between the two frequency responses over time suggests that moisture interaction within the material may vary according to depth or specific material properties. Higher frequencies may be less effective in identifying deeper strata than lower frequencies.

The increase in moisture content aligns with diffusion theories, in which moisture gradually permeates the material, saturating both the surface and internal layers at different rates. The 20 kHz frequency, demonstrating greater penetration, suggests increased moisture content with time, indicating moisture that has infiltrated deeper into the material. Ultrasonic frequencies, both low and high, are commonly utilized in non-destructive testing to evaluate moisture content in various materials.

The choice of frequency depends on the material's properties, thickness, and required measurement depth. Both low-frequency (20 kHz) and high-frequency (1.7 MHz, 3.3 MHz) signals can be effectively employed to assess moisture content in a material over time. The greater moisture content detected by the 20 kHz signal after around 6 seconds may indicate that the lower frequency is more adept at penetrating the material to detect moisture. The distinction, however minor, may be crucial in circumstances where substantial moisture infiltration or the moisture content of bulk materials is vital.

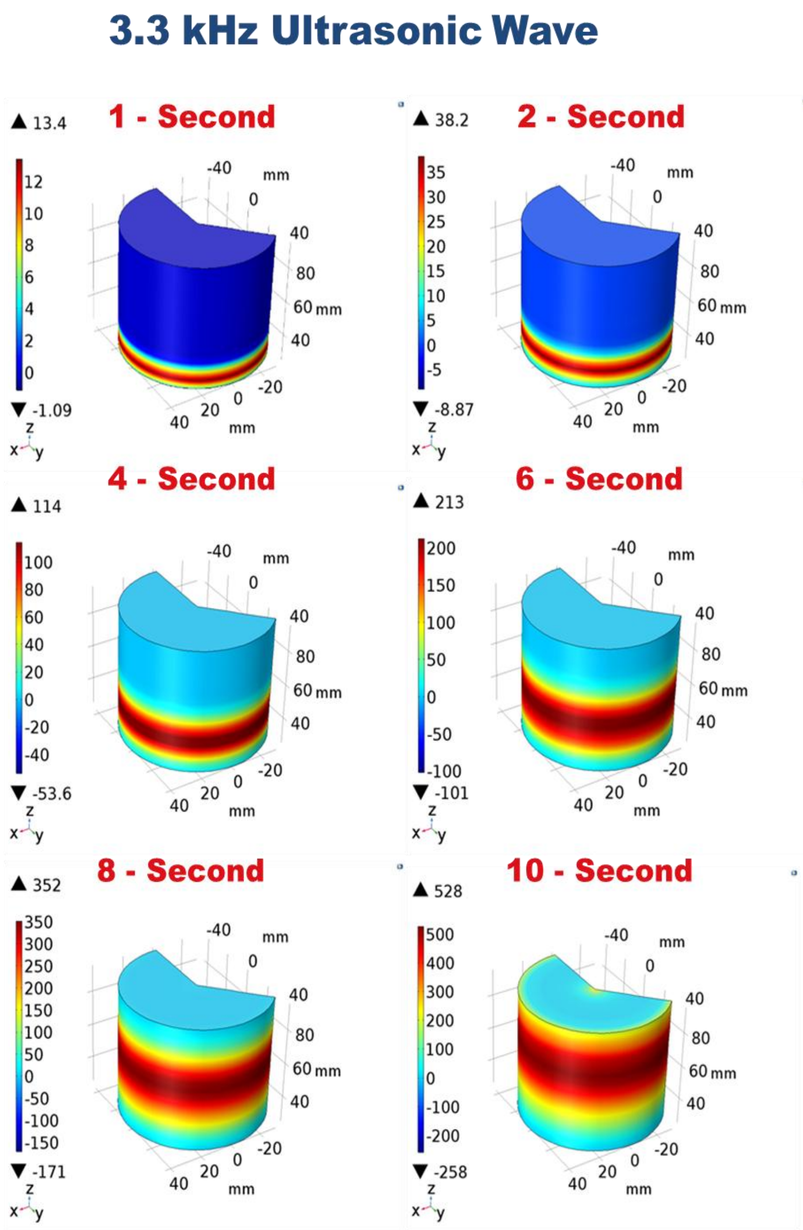

Fig. 10: Moisture content distribution at 3.3MHz ultrasonic moisture content at 1, 2, 4, 6, 8, and 10 s.

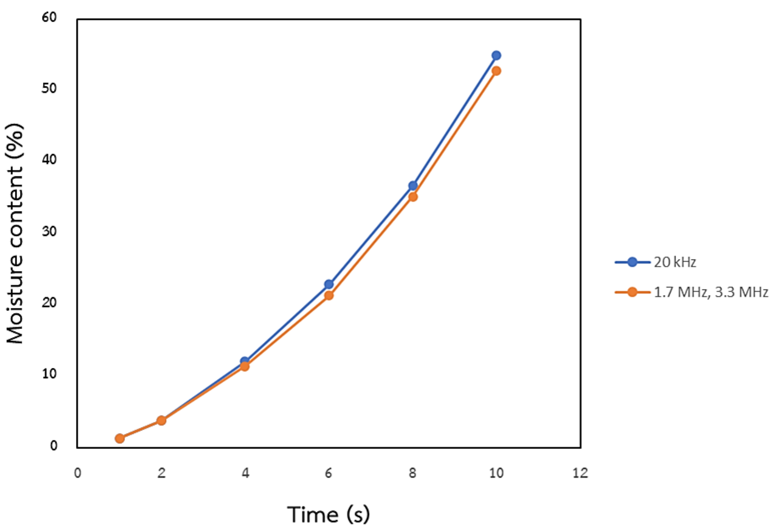

Fig. 11: Maximum dispersion of moisture content at ultrasonic moisture content of 20kHz, 1.7 MHz, and 3.3MHz at 1, 2, 4, 6, 8, and 10 s.

5. Conclusion

The size of the ultrasonic frequency affects the level of atomization of different sizes. From the model created as a result of the research, the results of the study were extended. To determine how these three frequencies affect moisture distribution in biological materials. From the results obtained from the model High-frequency ultrasonic waves have high pressure and intensity. The moisture distribution was not different at frequencies of 20 kHz, 1.7 MHz, and 3.3 MHz, but in the case of frequencies lower than 20 kHz, the moisture distribution was higher at 1.7 and 3.3 MHz. By employing high-frequency waves to vibrate the water molecules in agricultural products, ultrasonic waves can be employed to either increase or decrease their moisture content. This process aids in the evaporation or retention of moisture. The absorption of nutrients or minerals can be enhanced through the use of ultrasonic vibrations at various frequencies, which can aid in the extraction of minerals from agricultural products. As a result, selecting the appropriate ultrasonic wave technique is an alternative that will enhance the efficiency of controlling moisture and minerals in agricultural products, thereby enhancing the quality, safety, and shelf life of the products during the production process and storage until they are consumed.

This study's findings are consistent with prior research regarding the use of ultrasonic waves in moisture management and the processing of agricultural materials. The numerical results from this study, which investigated the effects of ultrasonic waves at frequencies of 20 kHz, 1.7 MHz, and 3.3 MHz on moisture distribution and acoustic pressure, align with previous research in the field. A significant comparison can be made with the research conducted by Suzuki *et al.*,[34] which confirmed a numerical model of ultrasonic power input at 20 W. The simulation results of this study demonstrate a comparable trend in sound pressure distribution, exhibiting minor variations of less than 2 dB relative to the findings of Suzuki *et al.* The minor discrepancy arises from variations in computational modeling methods and the boundary conditions applied in the simulations. The consistency of the results supports the validity of the numerical methodology utilized in this study.

Wagner *et al.*[12] examined the effect of ultrasonic frequency on the distribution of droplet sizes in mist generation. Their findings demonstrated that droplet size remained stable beyond 3.3 MHz, exhibiting minimal variations at elevated frequencies. This study confirms the observation that moisture content distributions at 1.7 MHz and 3.3 MHz are nearly identical, thereby supporting the hypothesis that frequencies exceeding 3.3 MHz produce consistent atomization behavior.

Ruiz *et al.*[35] performed numerical characterizations of ultrasonic mist generators utilized in evaporative cooling. Their study established a direct correlation between ultrasonic intensity and moisture diffusion, a trend corroborated by our results. Our simulations indicated that the highest ultrasonic intensity occurred at 3.3 MHz, resulting in a more uniform moisture content distribution, aligning with the findings of Ruiz *et al.* regarding ultrasonic-enhanced moisture diffusion. Previous studies by Avvaru *et al.*[2] and Rajan and Pandit have emphasized the significance of ultrasonic atomization in enhancing fluid distribution within porous agricultural materials.[36] This study supports the conclusion by demonstrating that ultrasonic waves enable moisture penetration at lower frequencies (*e.g.*, 20 kHz), while higher frequencies improve surface-level moisture distribution.

The alignment of our findings with prior research indicates that the finite element models created in this study effectively represent the essential principles of ultrasonic interactions with agricultural materials. This agreement enhances the reliability of our methodology and highlights the potential of ultrasonic technology in agricultural applications, particularly in moisture management and quality preservation. Future studies should further explore the influence of additional environmental factors, such as air velocity and relative humidity, to refine the predictive capability of these models.

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Conflict of Interest

There is no conflict of interest.

Supporting Information

Not applicable.

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