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Physics-Guided Ultrasound-Based Seed Priming for *Lens culinaris*: Coupled Thermo-Acoustic Modeling and Resource-Efficient Seedling Development

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Abstract

Ultrasound-assisted seed priming has emerged as an effective strategy for improving germination; however, the physical mechanisms governing ultrasound–seed interactions and their implications for process sustainability remain insufficiently understood. This study presents an integrated thermo–acoustic–experimental framework for ultrasound-assisted germination of *Lens culinaris*, combining finite element multiphysics simulations, biological validation, and a resource-based sustainability assessment. The thermo–acoustic framework predicted the spatial distribution of acoustic pressure and temperature within the ultrasonic bath, identifying localized regions of high acoustic intensity while confirming that seed

temperatures remained below the threshold associated with thermal damage. Guided by these predictions, germination experiments involving ultrasound exposure times ranging from 5 to 30 min demonstrated consistently high germination rates (96–99%), increased mean seedling length from 16 to 46 mm, and up to a 2.9-fold increase in vigor index relative to untreated seeds. Short sonication promoted faster and more synchronized germination, whereas longer treatments enhanced post-germinative growth and seedling vigor. To quantitatively assess process sustainability, conventional germination parameters were integrated with resource-based indicators, including vigor productivity per unit energy ($\boldsymbol{VP_E}$), vigor productivity per unit water ($\boldsymbol{VP_W}$), seedling length efficiency ($\boldsymbol{SL_E}$), and an integrated sustainability index ($\boldsymbol{ISI}$). These indices revealed that the biological gains substantially outweighed the negligible increase in ultrasound energy consumption, demonstrating that there is higher biological productivity per unit resource input. By coupling physics-based modeling with biological performance and sustainability metrics, this work provides a predictive framework for optimizing ultrasound-assisted seed priming and establishes quantitative indicators for evaluating resource-efficient germination technologies.

Keywords: Acoustic cavitation, Seed vigor, Sustainable agriculture, Energy efficiency, Water-use optimization, Heat transfer

1 Introduction

Germinated seeds are especially promising due to their elevated levels of bioactive compounds, such as phenolics, flavonoids, γ–aminobutyric acid (GABA), and antioxidants, along with improved digestibility and nutrient bioavailability (Yılmaz Tuncel et al. 2025; Rico et al. 2021). Among these, *Lens culinaris* (lentil) stands out for its high protein content, low glycemic index, and its ability to enrich soil through nitrogen fixation (Riaz et al. 2024; Chamoun et al. 2024). Germination further enhances its nutraceutical profile, positioning lentils as a valuable component in health-promoting diets (Vidal et al. 2024; Onwuka et al. 2024).

However, unlocking the full potential of germinated seeds requires overcoming limitations in conventional sprouting methods, which often involve prolonged soaking, excessive water use, microbial risks, and inconsistent outcomes (Sergiacomo et al. 2025; Gilbert et al. 2023). These challenges underscore the need for innovative, resource-efficient techniques that ensure safety, uniformity, and scalability. In this context, ultrasound technology has emerged as a promising nonthermal, eco–friendly solution. By mechanically stimulating the seed coat, ultrasound-based seed priming enhances water uptake, enzymatic activity, and cell permeability, thereby promoting faster and more uniform germination (Pacheco et al. 2024; Huang et al. 2024; Wang et al. 2019; López-Ribera and Vicient 2017).

Ultrasound-assisted seed priming applies high-frequency acoustic waves in water to induce localized mechanical stress and thermal gradients, triggering physiological responses such as acoustic cavitation, sonoporation, and microturbulence (Liu et al. 2016; Dai et al. 2025). These effects can significantly enhance germination

performance, but excessive intensity or exposure may compromise seed structure and biomolecular integrity through oxidative or thermal damage (Qin et al. 2012; Wang et al. 2012; Hasanović et al. 2025). Optimizing acoustic parameters is therefore essential to maximize the benefits of ultrasound while safeguarding seed viability.

To optimize germination supported by ultrasound-based seed priming, modeling tools that simulate the thermo–acoustic environment offer a strategic advantage. Multiphysics simulations, especially those using the FEM, can predict acoustic pressure, heat distribution, and mechanical stress within complex geometries (Aguilar-Torres et al. 2026). These models help define safe and effective operating conditions that enhance ultrasound-based seed priming performance while minimizing potential damage of seeds.

This study proposes a two-stage ultrasound-based seed priming to enhance the germination of *Lens culinaris* seeds. First, a multiphysics simulation modeled the acoustic field generated at 40 kHz and 1.5 MPa, coupling acoustic and thermal equations to predict pressure, temperature, and stress profiles while keeping temperature conditions below the 40 °C damage threshold (Malek et al. 2022). In the second stage, the seeds were treated experimentally in a commercial ultrasound bath, followed by morphological assessment and analysis of energy and water consumption. This integrated thermo–acoustic–experimental framework provides a predictive and mechanistically guided basis for optimizing ultrasound-assisted germination, enabling improved food functionality alongside resource-efficient performance.

Accordingly, the manuscript is organized to contextualize this study within existing research and highlight its specific contributions. Section 1.1 reviews prior work on ultrasound-assisted germination. Section 1.2 outlines the development of the proposed two-stage method aimed at improving efficiency and sustainability. Section 2 details the seed characteristics, modeling framework, and experimental procedures, including the ultrasound—rinsing protocol and the evaluation metrics: germination rate, seedling growth, and resource use. Section 3 presents the outcomes, while Section 4 explores their implications for sustainable sprout production. Section 5 summarizes key findings and future directions.

1.1 Related works

Ultrasound technology has gained increasing attention as a sustainable method to enhance seed germination, particularly in legumes such as *Lens culinaris*. Numerous studies have demonstrated its potential to improve germination rates, seedling vigor, and biochemical activity, positioning ultrasound-based seed priming as a promising tool in functional food production and agricultural biotechnology. However, its effectiveness depends critically on treatment parameters, including frequency, acoustic intensity, and exposure duration.

Research on the mechanisms of ultrasound-based seed priming highlights three primary effects: acoustic cavitation, enzymatic stimulation, and microbial reduction. Cavitation generates localized mechanical stress that disrupts the seed coat, increasing porosity and facilitating water absorption, a process known as scarification (Foschi et al. 2023; Chiu 2021). This enhanced water uptake accelerates metabolic activation and promotes uniform germination. Ultrasound-based seed priming also stimulates

key enzymes such as amylase, lipase, protease, and peroxidase, which convert stored macromolecules into simpler compounds that support embryo development (Chen et al. 2023). Additionally, studies have shown that Ultrasound-based seed priming can reduce microbial load on seed surfaces, minimizing fungal and bacterial contamination during sprouting (Zhang et al. 2022; Chiu 2015). Ampofo and Ngadi (2020), further reported hormonal and gene expression changes that enhance antioxidant defenses and growth potential.

Specific studies on lentil seeds confirm the positive impact of Ultrasound-based seed priming. Aladjadjiyan (2011) observed that applying ultrasound at 42 kHz and 100 W for up to 3 minutes increased germination rates from 92% to 98%, with *Lens culinaris* responding more favorably than wheat. These findings underscore the species-specific nature of ultrasound optimization. Other studies have reported improvements in seedling length, root development, and germination energy, reinforcing the relevance of ultrasound for lentil-based functional foods.

The role of ultrasound parameters has been extensively examined. Chiu (2021) identified optimal frequency ranges (40–80 kHz) for enhancing germination, while Aladjadjiyan (2011) emphasized the importance of short exposure times—typically under 3 minutes—to avoid structural damage and reduced viability. Foschi et al. (2023) highlighted the risks of excessive acoustic intensity, which can lead to oxidative stress and impaired seedling growth. These studies collectively suggest that ultrasound efficacy depends on carefully calibrated treatment conditions tailored to each crop species.

Beyond *Lens culinaris*, Ultrasound-based seed priming has shown promise across a wide range of legumes and cereals, including soybeans, chickpeas, and peas. Nogueira et al. (2023) described Ultrasound-based seed priming as a green technology with potential to improve crop yields and resource efficiency. While macroscopic effects such as germination rate and seedling length are well documented by Gong et al. (2024) and Nogueira et al. (2025), the molecular mechanisms, particularly those involving gene regulation and metabolic pathway activation, remain underexplored. Future research should aim to bridge this gap by integrating molecular biology tools with ultrasound-assisted priming protocols.

1.2 Contribution

This work establishes an integrated physics-guided framework for ultrasound-based seed priming by coupling multiphysics modeling, experimental validation, and quantitative sustainability assessment. Its principal scientific contributions are summarized as follows:

1. Development of a predictive thermo–acoustic framework for ultrasound-based seed priming. A fully coupled FEM-based thermo–acoustic model was developed to resolve the spatial distribution of acoustic pressure and temperature within the ultrasonic priming system. The model identifies regions of enhanced acoustic energy localization, predicts the thermo–acoustic environment experienced by the seed, and

verifies that the selected operating conditions remain below critical thermal thresholds associated with embryo damage. This framework provides a physically grounded basis for rational selection and optimization of ultrasound operating conditions.
2. Experimental elucidation of the relationship between acoustic exposure and biological seed's response. The numerical predictions were systematically validated through controlled germination experiments performed over a range of ultrasound exposure times (5- to 30-minute). The results demonstrate that sonication duration differentially modulates multiple dimensions of seed performance, including germination kinetics, temporal synchrony, radicle elongation, and seedling vigor, revealing a non-linear dose–response relationship between acoustic stimulation and early plant development.
3. Evaluation of resource productivity in ultrasound-based seed priming oriented to germination. Beyond conventional germination descriptors, this study proposes a set of integrated resource-based productivity indicators that relate biological performance to water and energy consumption. These include VP_E, VP_W, SL_E, and an ISI. Collectively, these indicators can help to define biological productivity to be assessed within the context of resource utilization.

Overall, the proposed framework advances ultrasound-based seed priming from a predominantly empirical approach toward a predictive and quantitatively assessable process in which physical modeling, biological performance, and resource productivity are integrated into a unified optimization framework.

2 Materials and methods

This section outlines the materials, modeling framework, and experimental procedures used in the study. It begins with the characterization of the seed material and the definition of input parameters for simulation. A thermo–acoustic modeling approach is then presented to evaluate ultrasound propagation and thermal effects in *Lens culinaris* seeds. The two-stage germination protocol, comprising ultrasound-based seed priming and controlled rinsing, is described next. Finally, the variables used to assess germination performance, including germination rate, seedling growth, and resource consumption, are detailed along with the data collection methodology.

2.1 Seed material

Seeds of *Lens culinaris* were used as the plant material in this study. *Lens culinaris* is a widely cultivated legume recognized for its high protein content, dietary fiber, and diverse bioactive compounds, and it has gained increasing attention as a source of nutritionally enriched sprouts due to the enhanced bioavailability of vitamins and phytochemicals during germination. Untreated, food-grade lentil seeds were obtained from a commercial batch purchased in Querétaro, Mexico. Prior to experimentation, seeds were visually inspected and manually sorted to remove damaged, malformed, or discolored individuals in order to ensure uniformity. Only intact seeds with similar size and appearance were selected for the germination assays. No chemical or physical pretreatments were applied before the experiments, allowing the germination behavior

to reflect the natural physiological condition of the seeds. The use of commercially available seeds also aimed to ensure that conditions relevant to the practical sprout production and small-scale food applications were considered. The *Lens culinaris* seeds used are shown in Fig. 1.



Fig. 1: Commercial *Lens culinaris* seeds used as the experimental plant material.

2.2 Modeling parameters

Optimizing ultrasound-based seed priming in *Lens culinaris* requires a predictive framework to characterize the interaction between acoustic energy and seed tissues. A thermo–acoustic model was developed using the FEM to simulate ultrasound propagation and heat transfer within the seed matrix. The model incorporated experimentally derived parameters, including density ($\rho_s = 818$ kg/m^3), speed of sound ($c_s = 153.68$ m/s), elastic modulus ($E = 19.32$ MPa), acoustic impedance ($Z_s = 125.71$ kPa·s/m), thermal conductivity ($k_s = 0.30$ W/m·K), and specific heat capacity ($C_{ps} = 1825$ kJ/kg·K). Geometric parameters included the average seed length ($l = 4.50$ mm), width ($w = 4.50$ mm), and thickness ($th = 2.30$ mm). These values were obtained from Amin et al. (2004) and Bargale et al. (1994) and were used as input parameters for the FEM-based thermo–acoustic simulation.

By integrating these properties into the FEM framework, the model captured the localized distribution of mechanical stress and temperature, offering predictive insights into safe and effective ultrasound conditions. This approach supports the design of energy-efficient protocols that enhance *Lens culinaris* germination while minimizing structural and thermal damage. Specific modeling considerations are detailed in Section 2.3.

2.3 Thermo–acoustic modeling

To model ultrasound propagation in *Lens culinaris* seeds, the classical wave equation (Eq. 1) was resolved using the FEM, following the formulation by Blackstock (2000). This numerical framework describes the behavior of ultrasound signals across different media, including water and seed tissue.

$$c^2 \nabla^2 u - \frac{\partial^2 u}{\partial^2 t} = 0 \ , \tag{1}$$

where u represents the ultrasound signals, c is the speed of sound, t is the time, and ∇^2 represents the Laplacian applied to $u(x, y, z, t)$.

A simplified 2D geometry was defined to compute the acoustic field: water was represented as a rectangular domain and the seed as an elliptical inclusion. Figure 2 illustrates the configuration and variables considered.

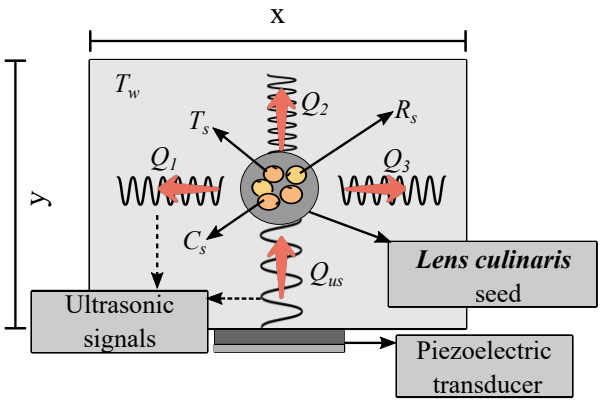


Fig. 2: Simulation geometry for the thermo–acoustic modeling of *Lens culinaris*.

From the defined geometry and wave equation, the model computes how ultrasound propagates through the transmission medium and interacts with the seed, accounting for key acoustic properties such as impedance, absorption, and density. To complement this, a thermal model was derived from the acoustic field, treating ultrasound signals as heat flux inputs that govern temperature evolution within the seed. This approach enables prediction of localized thermal effects induced by ultrasound exposure, supporting the evaluation of safe and effective germination conditions

The thermal model in Eq. 2, adapted from Aguilar-Torres et al. (2025), describes heat transfer within the seed during ultrasound exposure. It incorporates the input flux (Q_{us}) generated by the ultrasound signal and the output fluxes (Q_1, Q_2, and Q_3) representing heat dissipation. Key parameters include the seed's thermal resistance (R_s), thermal capacitance (C_s), internal temperature (T_s), and surrounding water temperature (T_w). Based on the energy balance equation ($Q_{net} = \sum Q_{in} - \sum Q_{out}$) and the simplified geometry showed in Fig. 2, the model assumes heat as the sole energy exchange mechanism, consistent with the first law of thermodynamics.

$$\frac{\partial T_s}{\partial t} = \frac{\alpha P}{\rho_s C_{ps} A} \frac{\partial \bar{\varepsilon}}{\partial t} - \frac{3k_s}{\rho_s C_{ps} A} \nabla T_f \ . \tag{2}$$

Note that for the model shown in Eq. 2, $\sum Q_{in} = Q_u = 2\alpha I = 2\alpha P \frac{\partial \bar{\varepsilon}}{\partial t}$, where $I = P\frac{\partial \bar{\varepsilon}}{\partial t}$, $Q_1 = Q_2 = Q_3 = \frac{1}{R_s}(T_s - T_{water})$, $\sum Q_{out} = Q_1 + Q_2 + Q_3 = \frac{3}{R_s}(T_s - T_w)$, $C_s = \rho_s C_{ps} A$, $R_s = \frac{e}{k_s}$, and $\Delta T_f = T_s - T_w$, where α is the seed's local acoustic absorption coefficient, I is the local sound intensity, P is the pressure generated by the ultrasound signal, $\bar{\varepsilon}$ is the particle velocity, $\sum Q_{out}$ is the sum of the heat fluxes

leaving the *Lens culinaris* seed, ρ_a is the seed density, C_{ps} is the seed specific heat, A is the transverse area of the seed, $e = \Delta V$ is the volume of the seed, k_s is the seed thermal conductivity, and $\Delta T_f = T_s - T_w$.

The right-hand terms of Eq. 2 represent the heat fluxes entering and leaving the seed system. Under initial equilibrium conditions ($T_s = T_w$ at $t = 0$), only the ultrasound-induced flux (Q_{us}) remains active, and no temperature gradient is observed—an indicator of the thermo–acoustic effect. Building on Eqs. 1 and 2, spatio-temporal simulations were conducted using the thermophysical properties of *Lens culinaris* seeds. These simulations revealed localized temperature gradients within the seed and surrounding medium, offering insight into how ultrasound modulates thermal behavior. This integrated modeling approach supports the use of ultrasound as a non-invasive strategy to influence seed physiology and enhance germination performance. A detailed characterization of ultrasound-based seed priming is presented in Section 3.

2.4 Simulation setup

The thermo–acoustic behavior of the system was modeled using the *Acoustic* and *Heat Transfer* modules of COMSOL Multiphysics^{TM}, implemented via the FEM. This computational framework enabled detailed analysis of ultrasound–seed interactions in *Lens culinaris*. The software allowed precise control over ultrasound pressure and frequency, as well as accurate definition of material properties and geometric configuration for both the transmission medium (water) and the seed. These settings supported the exploration of various propagation and absorption scenarios, offering insights into how ultrasound influences thermal and mechanical responses relevant to germination enhancement. The main factors considered to describe the ultrasound–seed interaction are presented below.

1. The simulation geometry consisted of a 5 cm × 5 cm rectangular domain representing the transmission medium (water), and a piezoelectric transducer with a 1.5 cm radius, matching the specifications of the ultrasound treatment system. A *Lens culinaris* seed was also included, using the dimensional parameters listed in Section 2.2.
2. The simulation incorporated the physical and acoustic properties of both media. For *Lens culinaris* seeds, the parameters in Section 2.2 were used. Water was defined with standard values: density of 1000 kg/m^3 at 20 °C, sound velocity of 1500 m/s, absorption coefficient of 0.01, and acoustic impedance of 150 kPas/m. These definitions ensured accurate modeling of ultrasound propagation and interaction within the aqueous environment.
3. The ultrasound source was defined as a piezoelectric transducer operating at 40 kHz. Based on a 60 W input and the acoustic properties of the medium, the resulting pressure was estimated at 1.5 MPa, corresponding to a sound intensity level of approximately 240 dB.
4. The domain was discretized using a tetrahedral mesh with element size $\frac{\lambda}{10}$, where λ is the wavelength at 40 kHz. This configuration ensured adequate resolution of ultrasonic fields and allowed geometric flexibility for modeling the spatial variations of the thermo–acoustic response.

5. The interaction between 40 kHz ultrasound and *Lens culinaris* seeds was modeled as a closed system, excluding environmental energy exchange. This assumption isolated internal thermo–acoustic dynamics, allowing focused analysis of ultrasound effects on seed and medium
6. Boundary conditions included a 40 kHz, 1.5 MPa pressure input at one surface, while the remaining boundaries were defined as perfectly matched layers to suppress reflections. At the seed–fluid interface, continuity conditions coupled acoustic and thermal fields, and adiabatic walls at the seed surface restricted heat dissipation through non-conductive layers.
7. Finally, a thermodynamic analysis was performed to evaluate ultrasound-induced temperature gradients in water and *Lens culinaris* seeds during 30 minutes of exposure. The simulation focused on the internal thermal response, ensuring seed temperature remained below 40 °C, the viability threshold reported by Malek et al. (2022) to prevent embryo damage.

2.5 Experimental procedure

The experimental methodology consisted of two sequential stages: (1) ultrasound pre-treatment of *Lens culinaris* seeds and (2) rinse-based germination under controlled conditions. The ultrasound-based seed priming stage was designed using thermo–acoustic finite element method (FEM) simulations to identify exposure conditions that minimize potential thermal and mechanical stress on the seeds. Following this pre-treatment, seeds were subjected to a controlled germination procedure that enabled systematic monitoring of germination performance as well as water and energy consumption.

1. **Ultrasound-based seed priming:** Thermo–acoustic FEM simulations were used as a predictive framework to guide the selection of ultrasound exposure parameters. Based on these results, lentil seeds were subjected to ultrasound treatments of 5, 10, 15, 20, and 30 min. After treatment, seeds were immediately rinsed with water to initiate the germination process. Germination outcomes, together with associated water and energy consumption, were recorded for each treatment condition.

   Ultrasound-based seed priming were conducted using an ultrasonic bath with a capacity of 1.5 L equipped with a 60 W piezoelectric transducer operating at a frequency of 40 kHz. For each treatment condition, 100 seeds were used. An untreated group was included as a control to provide a baseline for comparison with the ultrasound-treated samples. The *Lens culinaris* seeds treated in the ultrasonic bath used in this study are shown in Fig. 3.



Fig. 3: *Lens culinaris* seeds during ultrasound treatment in the ultrasonic bath.

2. **Seed germination:** Following ultrasound-based seed priming, seeds were transferred to a rinse-based germination system designed to provide periodic hydration while allowing monitoring of resource consumption. The rinse method was employed to supply regular moisture to the seeds while preventing excessive water accumulation, thereby supporting uniform hydration during the early stages of germination.

   The germination system consisted of multiple trays assigned to *Lens culinaris* samples, including both untreated (control) and ultrasound-based seed priming. Each tray measured 5.1 × 7.6 × 2.5 cm and was paired with a perforated drainer to facilitate the removal of excess water, resulting in an effective germination area of 38.76 cm^2 per tray. The trays were arranged on a base platform measuring 25 × 35 × 10 cm and equipped with an LED lamp (30 W) providing a photoperiod of 16 h light and 8 h dark. The germination system, including the trays, the enclosed chamber, and the LED illumination setup used in this study, is shown in Fig. 4.

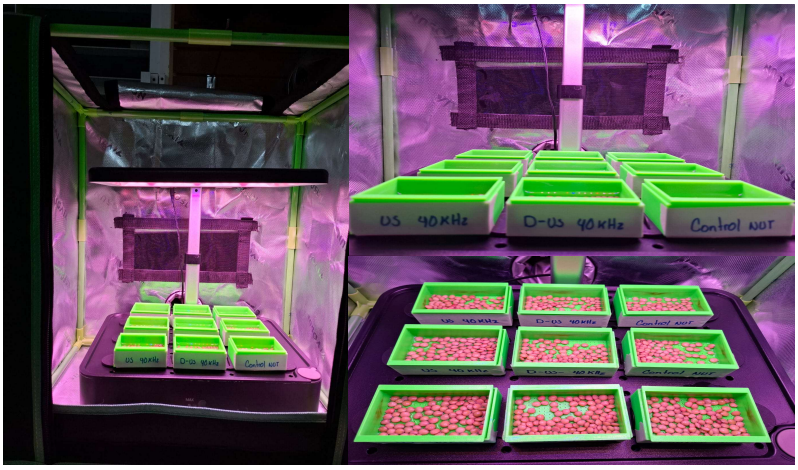


Fig. 4: Germination system composed of seed trays, an enclosed chamber, and an LED illumination source used during the germination experiments.

The entire setup was placed inside a controlled-environment chamber (50 × 35 × 53 cm; VIVOSUN) to maintain stable germination conditions. Seeds were rinsed manually twice every 24 h at 12 h intervals using tap water. Each rinsing cycle lasted approximately 10 s, after which the trays were allowed to drain freely.

The volume of drained water was recorded individually for each tray to estimate water consumption during the germination process. Energy consumption associated with illumination was monitored using a digital power meter connected to the LED lamp. Germination progress was evaluated every 24 h. A seed was considered germinated when the radicle was visibly protruding from the seed coat, whereas complete germination was defined as the stage at which both cotyledons were fully exposed.

2.6 Germination performance and resource consumption metrics

The physiological response of *Lens culinaris* ultrasound priming was evaluated through a multi-parametric framework encompassing germination performance indicators, kinetic descriptors, and resource consumption variables. All treatments were monitored at 24 h intervals under controlled and identical environmental conditions throughout the germination period. Germination was defined as the moment at which the cotyledons became visibly exposed following radicle emergence, in accordance with the criteria established by the International Seed Testing Association (2026).

2.6.1 Germination performance indicators

The germination rate (G_r) was employed as a primary indicator of germination success, representing the proportion of seeds that successfully completed germination relative to the total number of seeds evaluated within each treatment (Reed et al. 2022). As defined by Eq. 3, G_r provides a measure of the overall germination performance of the seed lot and is expressed as a percentage.

$$G_r = \frac{N_g}{N_t} \times 100, \tag{3}$$

where N_g denotes the number of germinated seeds and N_t the total number of seeds evaluated in the corresponding experimental unit.

To incorporate both germination speed and cumulative germination performance, the germination index (G_I) was determined following Eq. 4 (Sedghi 2025). Unlike the germination rate, this index assigns greater weight to seeds that germinate earlier during the experimental period.

$$G_I = \sum_{i=1}^{n} \frac{G_i}{D_i}, \tag{4}$$

where G_i represents the number of seeds germinating on day i, D_i is the corresponding day of observation counted from the beginning of the experiment, and n is the total number of observation intervals.

Seedling vigour was evaluated through the vigour index (V_i), which integrates germination performance with early seedling growth (Chen et al. 2012). As shown

in Eq. 5, V_i was obtained by multiplying the germination rate by the mean seedling length.

$$V_i = G_r \times L, \tag{5}$$

where L corresponds to the mean seedling length [mm] measured at the end of the germination assay.

2.6.2 Germination kinetic descriptors

To characterise the temporal dynamics of germination beyond integrated performance indicators, three complementary kinetic descriptors were incorporated (Ranal and Santana 2006; Czabator 1962). These parameters provided a statistically robust assessment of germination speed, temporal uniformity, and synchronisation among germinating seeds. The mean germination time (MGT) was calculated as the weighted average number of days elapsed between the onset of imbibition and germination events within the seed lot. This parameter was determined according to Eq. 6.

$$\mathrm{MGT} = \frac{\sum_{i=1}^{n} D_i G_i}{\sum_{i=1}^{n} G_i}, \tag{6}$$

where D_i corresponds to the number of days elapsed from the beginning of the experiment to the i-th observation, and G_i is the number of seeds germinating on that day.

The coefficient of variation of germination time (CVt) was used to quantify the dispersion of germination events around the mean germination time. Following Eq. 7, CVt was calculated as:

$$\mathrm{CVt} = \frac{S_t}{\mathrm{MGT}} \times 100, \tag{7}$$

where S_t is the standard deviation of germination time. This parameter was estimated using Eq. 8:

$$S_t = \sqrt{\frac{\sum_{i=1}^{n} G_i \left(D_i - \mathrm{MGT}\right)^2}{\sum_{i=1}^{n} G_i - 1}}, \tag{8}$$

Lower CVt values indicate greater temporal homogeneity among germinating seeds and therefore a more uniform germination process. The synchrony index (Z) was employed to quantify the degree of temporal overlap among germination events. The Z index was calculated according to Eq. 9:

$$Z = \frac{\sum_{i=1}^{n} \binom{G_i}{2}}{\binom{N_g}{2}}, \tag{9}$$

where $\binom{G_i}{2} = G_i(G_i - 1)/2$ represents the number of co-germinating seed pairs on day i, and $\binom{N_g}{2} = N_g(N_g - 1)/2$ corresponds to the maximum possible number of simultaneous pairs within the germinated fraction. Values of Z range from 0, indicating completely asynchronous germination, to 1, indicating perfect synchrony. Together, MGT, CVt, and Z provided a comprehensive description of germination kinetics.

2.7 Water and energy consumption analysis

To evaluate the sustainability of the germination process, both water and electrical energy consumption were quantified throughout the experimental period. Water consumption was estimated according to the daily irrigation volume supplied to each treatment and the total duration of the experiment (Aguilar-Torres et al. 2026). The cumulative water consumption (W_{total}) was calculated using Eq. 10.

$$W_{total} = W_{daily} \times t, \tag{10}$$

where W_{daily} is the daily water volume supplied [L day^{-1}] and t is the total experimental period [days]. This equation determines the total amount of water required during seed germination and seedling development under each treatment.

The electrical energy consumed by the germination system (E_{system}) was estimated from the average electrical power demand of the experimental setup and the total operating time, as described in Eq. 11.

$$E_{system} = P_{system} \times t, \tag{11}$$

where P_{system} is the average electrical power of the germination chamber [kW] and t is the cumulative operating time [h]. This parameter represents the baseline electrical energy required to maintain the environmental conditions throughout the germination experiment.

Since ultrasonic priming introduces an additional energy input before germination, the electrical energy consumed during the ultrasound-based seed priming (E_{US}) was independently calculated using Eq. 12.

$$E_{US} = P_{US} \times t_{US}, \tag{12}$$

where P_{US} is the nominal ultrasonic power [kW] and t_{US} is the sonication time [h]. This equation estimates the electrical energy exclusively associated with the ultrasound-based seed priming.

The total electrical energy required for each treatment was determined by combining the germination system energy and the ultrasonic pretreatment energy according to Eq. 13.

$$E_{total} = E_{system} + E_{US}, \tag{13}$$

where E_{total} represents the total electrical energy demand [kWh] associated with each treatment.

This approach enables direct comparisons among treatments by considering both the operational energy of the germination chamber and the additional energy supplied during ultrasonic priming.

To compare resource utilization among treatments, water-use efficiency (WUE) and energy-use efficiency (EUE) were calculated by normalizing total resource consumption with respect to the final germination percentage, as expressed in Eqs. 14 and 15.

$$WUE = \frac{W_{total}}{Gr}, \tag{14}$$

$$EUE = \frac{E_{total}}{Gr}, \tag{15}$$

where Gr is the final germination percentage (%). These indicators quantify the amount of water [L $\%^{-1}$] and electrical energy [kWh $\%^{-1}$] required to obtain one percentage point of germination.

Lower WUE and EUE values indicate greater resource-use efficiency, since fewer resources are required to achieve the same germination performance.

To further evaluate the effectiveness of resource utilization, three biological productivity indicators were incorporated by relating seedling performance to the total energy and water consumed. The energy-based vigor productivity (VP_E) was calculated as:

$$VP_E = \frac{V_i}{E_{total}}, \tag{16}$$

where V_i is the vigor index and E_{total} is the total electrical energy consumed [kWh].

This indicator represents the amount of seedling vigor generated per unit of electrical energy supplied during the entire process.

Similarly, the water-based vigor productivity (VP_W) was determined according to Eq. 17.

$$VP_W = \frac{V_i}{W_{total}}, \tag{17}$$

where W_{total} is the cumulative water consumption [L]. This parameter quantifies the biological return obtained from each liter of water used during germination.

Finally, the seedling length productivity with respect to energy consumption (SL_E) was calculated as:

$$SL_E = \frac{SL}{E_{total}}, \tag{18}$$

where SL is the average seedling length [mm] at the end of the experimental period. This indicator evaluates the amount of seedling growth achieved per unit of electrical energy consumed, providing an integrated measure of biological productivity and process sustainability.

To obtain an integrated assessment of process sustainability, an ISI was proposed by combining biological performance with the corresponding water and energy requirements. The index was calculated according to Eq. 19.

$$ISI = \frac{VI \times Gr}{E_{total} \times W_{total}}, \tag{19}$$

The proposed index integrates the overall germination response with the associated resource consumption into a single sustainability metric. Higher ISI values indicate greater biological performance achieved with lower water and energy demands, thereby reflecting a more resource-efficient and sustainable germination process.

Overall, the proposed indicators complement conventional germination parameters by incorporating resource consumption into the evaluation of seed performance, enabling a comprehensive assessment of the sustainability and efficiency of where P_{US} is the nominal ultrasonic power [kW] and t_{US} is the sonication time [h]. This equation estimates the electrical energy exclusively associated with the ultrasound-based seed priming.

3 Results

This section presents the results of FEM simulations and experimental trials evaluating ultrasound-based seed priming germination for the *Lens culinaris*. Acoustic field distribution was characterized, and germination rates were compared between untreated seeds and those exposed to varying ultrasound durations under manual rinsing. Water and energy consumption were quantified to assess system efficiency. Scalability and potential applications in seed treatment and early cultivation are also addressed.

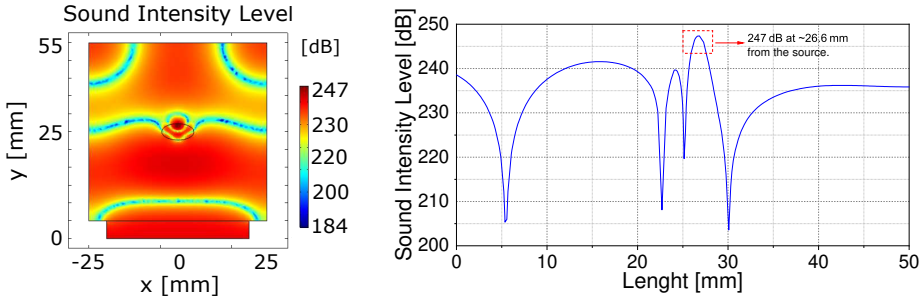
3.1 Effect of the acoustic field on seeds

The spatial distribution of the acoustic field in water and within the *Lens culinaris* seed was numerically approximated using FEM under 40 kHz and 1.5 MPa ultrasound irradiation. The resulting two-dimensional acoustic field, expressed as the Sound Intensity Level (SIL), quantifies the energy incident on the seed and facilitates evaluation of ultrasound-induced effects. Figure 5 depicts the spatial profile of the SIL extending from the ultrasound source through the transmission medium and into the seed structure.

As shown in Fig.5a, the spatial distribution of ultrasound signals reveals that the highest energy concentration occurs at the pericarp boundary of the *Lens culinaris* seed, where the maximum Sound Intensity Level (SIL) reached 247 dB (∼2 MPa). Within the seed, the average SIL was 230 dB (∼0.3 MPa). In comparison, the propagation medium exhibited a maximum SIL of 240 dB (∼1.5 MPa) and an average of 229 dB (∼281.8 kPa). This pattern indicates that 40 kHz ultrasound significantly affects the seed due to favorable acoustic properties and signal interaction with cellular structures. At this frequency, the seed's acoustic impedance and wavelength promote efficient energy transfer, while absorption enhances the conversion of acoustic energy into mechanical vibrations. These vibrations may trigger physical and chemical changes, particularly at the pericarp, facilitating imbibition by promoting rupture and enzymatic activation, thereby accelerating hydration and early germination.

Building on the spatial distribution analysis, Fig. 5b presents the longitudinal variation of the SIL along the system's central axis. The profile reveals distinct energy

peaks along the propagation path, with the highest SIL of ∼247 dB (∼2 MPa) occurring at approximately ∼26.6 mm from the ultrasound source, precisely at the pericarp boundary of the *Lens culinaris* seed, as previously identified in Fig.5a. These peaks correspond to the high-SIL zones (red/orange) in the spatial map, reinforcing the direct relationship between the axial and spatial dynamics of acoustic energy distribution within the system.

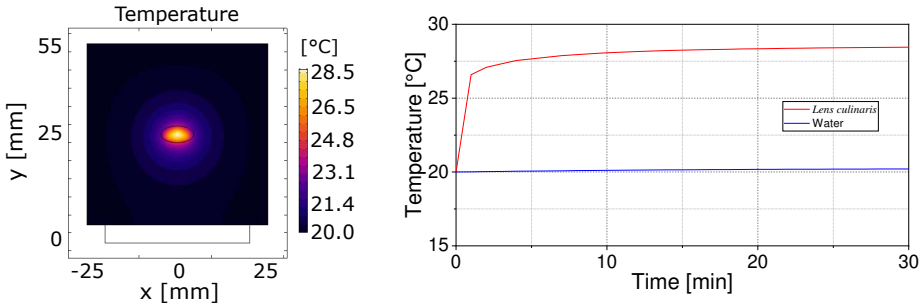


(a) (b)

Fig. 5: Distribution of the SIL generated by ultrasound at a frequency of 40 kHz and a pressure of 1.5 MPa on *Lens culinaris* seed: a) Spatial domain and b) Length distribution.

Based on the spatial distribution of the acoustic field generated at 40 kHz and 1.5 MPa, a spatiotemporal model was developed to assess thermal effects in the propagation medium (water) and *Lens culinaris* seeds. The analysis showed that ultrasound exposure did not induce temperature gradients exceeding 40 °C, a critical threshold beyond which embryo viability may be compromised. Establishing this thermal limit ensured that ultrasound-based seed priming remained non-detrimental to germination. Figure 6 shows the evolution of ultrasound-induced temperature gradients from $t = 0$ to $t = 30$ minutes, providing visual and quantitative insight into thermal dynamics within the system, consistent with the treatment durations described in Section 2.4.

Figure 6a displays the spatial distribution of ultrasound-induced temperature gradients after $t = 30$ minutes. Thermal analysis revealed a maximum temperature of 28.5 °C within the *Lens culinaris* seed and a minimum of 20.4 °C in the surrounding medium, indicating localized heating due to acoustic energy absorption. This thermal pattern aligns with the acoustic field distribution shown in Fig. 5a, confirming that the seed resides in a focal zone of elevated energy density. Figure 6b illustrates the temporal evolution of temperature, with the seed temperature rising from 20.0 °C at $t = 0$ to 27.6 °C at $t = 5$, 28.0 °C at $t = 10$, 28.2 °C at $t = 15$, 28.3 °C at $t = 20$, and reaching 28.5 °C at $t = 30$ minutes. In contrast, the medium remained at 20.4 °C, evidencing minimal thermal accumulation. These results show that seed temperature remained below the critical threshold of 40 °C, ensuring thermal safety throughout treatment, consistent with criteria established by Malek *et al.* (Malek et al. 2022).



(a) (b)

Fig. 6: Dynamics of temperature changes due to the interaction between the propagation medium and *Lens culinaris* seeds exposed to ultrasound-based seed priming at 40 kHz with 1.5 MPa: a) Spatial domain at $t = 30$ min and b) Time domain.

The thermo-acoustic analysis of *Lens culinaris* ultrasound-based seed priming enabled detailed characterization of heat generation and dissipation within both the propagation medium and seed structure. Localized thermal gradients were identified at the pericarp–embryo interface, confirming that temperature increases remained below thresholds that could impair embryonic viability. Integrating thermo-acoustic modeling with acoustic field simulations deepens our understanding of energy–seed interactions and provides a predictive framework for assessing biophysical responses. This approach strengthens the methodological rigor of ultrasound-based seed priming studies and supports the optimization of treatment parameters while preserving seed functionality.

3.2 Effect of ultrasound-based seed priming

Following FEM-based validation confirming that ultrasound irradiation at 40 kHz and 1.5 MPa d does not cause any harmful thermal or mechanical effects on *Lens culinaris* seeds, a controlled germination bioassay was undertaken. Seeds were subjected to ultrasound-based priming for exposure durations of 5, 10, 15, 20, and 30 minutes using a calibrated immersion bath system. Each experimental treatment comprised ten independent replicates (n = 10, 100 seeds replicate), totaling 1,000 seeds per treatment, thereby ensuring adequate statistical power and full experimental traceability.

Subsequent to ultrasound-based seed priming, they were transferred to the standardized germination system described in Section 2, which incorporated 12-hour hydration–rinsing cycles and a controlled photoperiod of 16 h light / 8 h darkness to simulate natural diurnal conditions. Germination progress was monitored continuously over an 8-day period, with daily quantification of germinated seeds employed to construct cumulative germination rate curves for all treatment durations (5, 10, 15, 20, and 30 min). A non-ultrasound-treated control group (NUST) was included as a baseline reference for comparative analysis. As illustrated in Fig. 7, control seeds attained a final germination percentage of 97% by day 8. Treatments of 10, 15, and

20 minutes yielded germination rates of 98%, with steady-state conditions reached on day 8 for the 10- and 15-minute groups and on day 7 for the 20-minute group. Although the 10- and 20-minute treatments exhibited germination dynamics broadly consistent with those of the control, the 15-minute treatment displayed a transient inhibition of early germination, converging with the remaining treatment groups only from day 3 onward. The 30-minute treatment demonstrated diminished germination performance, achieving a final rate of 96% by day 7, an outcome attributable to partial seed viability loss resulting from prolonged acoustic exposure. Of particular note, the 5-minute treatment yielded the highest overall germination rate (99%) alongside the most accelerated germination dynamics among all groups evaluated. These inter-treatment differences are further delineated in the inset panel of Fig. 7 to facilitate direct visual comparison.

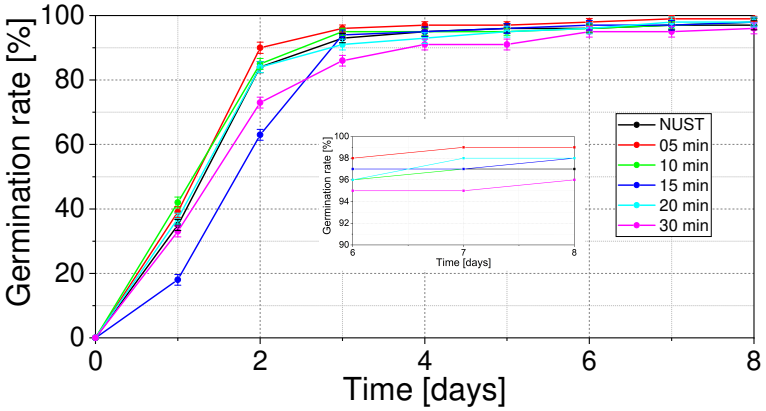


Fig. 7: Germination rate of *Lens culinaris*: without ultrasound treatment (NUST) and 5 min, 10 min, 15 min, 20 min, and 30 min of ultrasound-based seed priming.

The germination outcomes confirm that ultrasound-based seed priming exerts time-dependent effects on *Lens culinaris* seeds. Treatments of 10, 15, and 20 minutes yielded a consistent germination rate of 98 %, representing a marginal but reproducible improvement over the non-ultrasound-treated control (NUST: 97%). The 5-minute treatment produced the highest germination rate among all groups evaluated (99%), surpassing both the control and all longer-duration treatments. Conversely, the 30-minute treatment exhibited a slight reduction in germination performance (96%), suggesting that prolonged acoustic exposure may compromise seed viability. Even marginal gains in germination rate can have meaningful agronomic implications, particularly in medium- to large-scale *Lens culinaris* cultivation, where incremental improvements in seedling establishment directly influence final crop yield.

Beyond final germination percentages, the temporal dynamics recorded in Table 1 provide critical insight into the physiological response to ultrasound. The G_I, which weights early-germinating seeds more heavily, revealed that the 5-minute treatment

produced the highest value (67.060), exceeding both the control (63.343) and all longer-duration treatments, indicating that brief acoustic stimulation accelerates the onset of germination, likely through enhanced water imbibition facilitated by ultrasound-induced transient increases in seed coat permeability. This interpretation is further corroborated by the reduction in mean germination time (MGT) from 1.856 days in the NUST group to 1.778 days in the 5-minute treatment. In contrast, the 15-minute treatment exhibited the highest MGT(2.286 days) and the lowest G_I(51.575), corroborating the transient germination inhibition observed in the cumulative germination curves prior to day 3. This paradoxical response, in which an intermediate exposure duration underperformed relative to both shorter and longer treatments, may reflect a hormetic phenomenon. Under this interpretation, moderate acoustic stress could transiently suppress metabolic activation before seeds recover and resume normal germination kinetics. Similar biphasic responses have been reported in ultrasound-assisted seed priming of various leguminous species and have been attributed to temporary membrane perturbation or transient oxidative stress that is subsequently mitigated through antioxidant defense mechanisms.

Table 1: Germination parameters of *Lens culinaris* seeds following ultrasonic treatment at 40 kHz and 1.5 MPa at different exposure durations.

Treatment	G_r [%]	G_I [–]	MGT [days]	CVt [%]	Z [–]	l_{min} [mm]	l_{max} [mm]	l_{mean} [mm]	V_i [–]
NUST	97.0±1.4	63.343	1.856	50.402	0.388	5	45	16	1552
05 min	99.0±0.7	67.060	1.778	52.421	0.419	10	60	34	3366
10 min	98.0±1.1	67.268	1.827	62.411	0.381	10	40	23	2254
15 min	98.0±1.2	51.575	2.286	45.735	0.338	15	50	30	1940
20 min	98.0±1.5	64.186	1.939	60.991	0.373	20	65	38	3724
30 min	97.0±1.6	59.500	2.186	65.820	0.301	30	70	46	4462

CVt and Z reported in Table 1 provide complementary evidence regarding the homogeneity of the germination process. The 15-minute treatment, despite its elevated MGT, exhibited the lowest CVt(45.735%), indicating that once germination was initiated it proceeded with high temporal uniformity, whereas the 30-minute treatment displayed the highest CVt(65.820%), reflecting progressively greater temporal dispersion with extended exposure duration. This divergence implies that prolonged acoustic irradiation introduces heterogeneous physiological states among seeds within the same lot, potentially attributable to non-uniform distribution of mechanical energy or cumulative cavitation-induced microstructural damage. Z reinforces this interpretation: the 5-minute treatment achieved the highest synchrony ($Z = 0.419$), while the 30-minute group registered the lowest value ($Z = 0.301$), collectively indicating that brief ultrasound exposure promotes not only faster but also more coordinated germination, whereas prolonged exposure fragments the germination process temporally, producing heterogeneous seedling cohorts.

While brief treatments optimize germination speed and synchrony, the radicle length parameters and vigor index presented in Table 1 demonstrate that longer exposure durations exert a pronounced stimulatory effect on post-germinative growth.

Mean radicle length (l_{mean}) increased substantially across all ultrasound treatments relative to the control (l_{mean} = 16 mm), with the 20-minute group producing the longest radicles among short-duration treatments (l_{mean} = 38 mm) and the 30-minute group exhibiting the highest overall value (l_{mean} = 46 mm), suggesting that sustained acoustic energy delivery may stimulate auxin biosynthesis or cell wall loosening processes in the embryonic root, facilitating more vigorous early root development. The V_i, which integrates G_r and l_{mean} into a single composite indicator of seedling productive potential, revealed the most pronounced treatment effects observed in this study: all ultrasound-treated groups substantially exceeded the control (V_i = 1552), with values ranging from 1940 (15 min) to 4462 (30 min), representing increases of 1.25- to 2.88-fold over the untreated group. Notably, the 5-minute treatment yielded a V_i of 3366, a 2.17-fold increase over the NUST group, demonstrating that even the shortest exposure duration tested produces seedlings of considerably higher productive potential.

Considered collectively, the parameters presented in Table 1 reveal a complex, non-linear dose-response relationship between ultrasound exposure duration and seed performance. Short exposures (5 minutes) optimize germination rate, speed, and synchrony, making this treatment particularly suitable for applications where uniform and rapid crop establishment is the primary agronomic objective. Longer exposures (20–30 minutes), despite introducing greater temporal heterogeneity in germination, confer substantially higher post-germinative vigor, which may prove advantageous under challenging field conditions where early root establishment is critical for seedling survival. The 10-minute treatment represents a balanced compromise, achieving 98% germination with favorable MGT, G_I, and Z values alongside a V_i of 2254, a 1.45-fold improvement over the control, and may therefore offer the most practical agronomic benefit by combining enhanced germination performance with moderate vigor improvement at a brief exposure duration. These findings are consistent with the growing evidence that ultrasound-assisted seed priming enhances germination performance in leguminous crops. Previous studies have attributed these effects primarily to acoustic cavitation and mechanical microstreaming, which increase membrane permeability, accelerate enzymatic activation, and stimulate embryonic metabolism. The present study extends this mechanistic understanding by demonstrating that ultrasound exposure duration is not merely an operational parameter but a key determinant of the biological response, selectively influencing different dimensions of germination performance. Consequently, precise control of treatment duration should be considered an essential requirement for the effective translation of ultrasound-assisted priming to large-scale agricultural applications.

The enhanced germination dynamics and post-germinative vigor documented in Table 1 prompted further investigation into the structural modifications induced by ultrasound at the seed coat level. Fracture analysis was performed on representative samples from the NUST group and the 5- and 10-minute treatments, selected on the basis of their contrasting germination profiles: the 5-minute group for its superior G_r (99.0±0.7%), G_I (67.060), and synchrony index (Z = 0.419), and the 10-minute group as the shortest exposure achieving a consistent 98% germination rate with a favorable V_i of 2254. As shown in Fig. 8, untreated seeds (Fig. 8a,d) exhibited no evidence of

pericarp detachment, rupture, or surface damage, consistent with their baseline germination performance. In contrast, seeds subjected to 5-minute ultrasound exposure (Fig. 8b,e) displayed a well-defined pericarp fracture localized within the region delimited by the dashed circle, suggesting that acoustic cavitation induced concentrated mechanical stress sufficient to disrupt seed coat integrity. The 10-minute treatment (Fig. 8c,f) exhibited a comparatively less pronounced but more spatially extensive fracture pattern, with visible branching along the seed surface, indicative of a broader distribution of acoustic energy across the pericarp. Collectively, these observations confirm that ultrasound irradiation at 40 kHz induces measurable mechanical modifications to the seed coat, with fracture morphology and spatial extent dependent on exposure duration, providing a structural basis for the enhanced water imbibition and accelerated germination dynamics reported in Table 1.

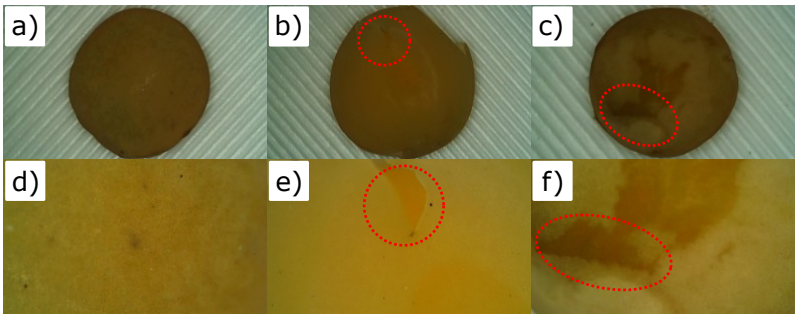


Fig. 8: Pericarp fractures in *Lens culinaris* seeds induced by ultrasound treatments. a) Untreated seed showing intact pericarp; b) 5–minute treatment; c) 10–minute treatment. d–f) Zoomed views of respective seeds, illustrating fracture details.

The structural modifications observed in the seed coat following ultrasound exposure are further reflected in the early developmental outcomes of the resulting seedlings. As illustrated in Fig. 9, representative seedlings from each treatment group exhibit marked differences in growth response that corroborate the quantitative parameters reported in Table 1. The NUST group displays comparatively smaller and morphologically heterogeneous seedlings, consistent with its diminished V_i and reduced l_{mean}. In contrast, all ultrasound-treated groups exhibit a progressive tendency toward greater radicle elongation and improved developmental uniformity with increasing exposure duration, a pattern directly reflected in the radicle length and V_i values reported in Table 1. Seedlings from the longest exposure treatment exhibited markedly greater vigor and homogeneity, consistent with the highest V_i recorded across all groups. These results suggest that sustained acoustic stimulation promotes more consistent early establishment by enhancing the physiological conditions for embryonic growth. Taken together, the visual evidence presented in Fig. 9 reinforces the quantitative findings of this study and underscores the positive influence of ultrasound priming on early seedling performance in *Lens culinaris*. . This condition establish

a coherent link between seed coat structural modification, accelerated germination dynamics, and enhanced post-germinative vigor.

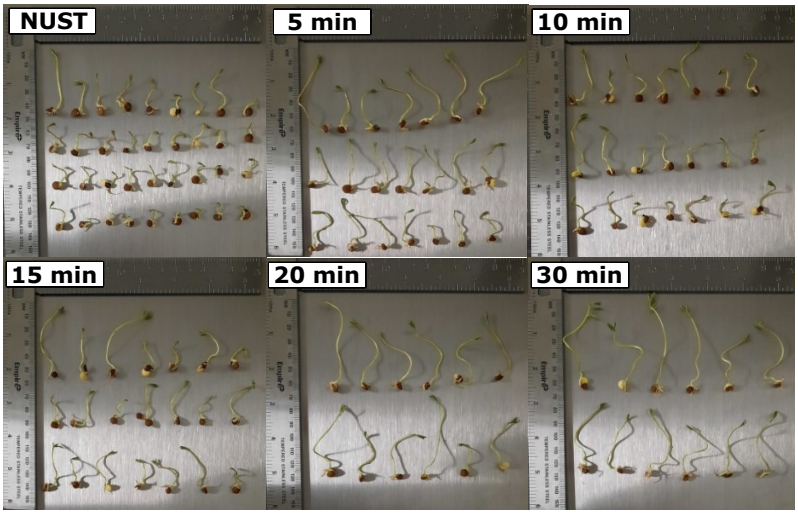


Fig. 9: Representative *Lens culinaris* seedlings showing shorter, less uniform growth in untreated seeds, and greater elongation with improved homogeneity under ultrasound treatments.

These results demonstrate the value of integrating multiphysics simulation with experimental validation as a rigorous framework for investigating ultrasound effects on seed physiology. The FEM-based acoustic–thermal coupling model confirmed that irradiation at 40 kHz and 1.5 MPa generated a spatially controlled acoustic pressure field without producing deleterious thermal gradients. The predicted temperature distribution remained well below levels associated with thermal damage, indicating that heating did not contribute significantly to the observed biological responses. Consequently, the improvements in germination rate, germination dynamics, synchrony, and post-germinative vigor can be attributed primarily to the mechanical effects of acoustic stimulation. The structural evidence derived from seed coat fracture analysis provides a mechanistic link between ultrasound-induced pericarp modifications and the observed physiological improvements, while the seedling development patterns further corroborate the quantitative parameters reported in Table 1. Collectively, these findings position ultrasound pre-treatment as a physically controllable, non-chemical seed priming strategy with demonstrated efficacy in *Lens culinaris* and clear potential for integration into precision agriculture and sustainable crop production systems.

3.3 Water and energy consumption

The results presented in Tables 2 and 3 provide a comprehensive framework for evaluating the sustainability of ultrasound-assisted germination by integrating resource

consumption with biological performance. Table 2 shows that the electrical energy demand of the germination system remained constant across all treatments (3.840 kWh), as it was determined exclusively by the LED illumination and controlled environmental conditions, which were identical for all experimental units. In contrast, ultrasound-based seed priming introduced a marginal increase in total energy consumption, ranging from 3.840 kWh in the control (NUST) to 3.870 kWh in the longest exposure treatment (30 min). This represents an increase of less than 1%, indicating that the energetic cost associated with sonication is negligible compared to the baseline energy demand of the germination system.

Similarly, water consumption was identical across treatments (4.0 L per experimental unit), since irrigation was standardized throughout the experimental period. This experimental design allows isolating the effect of ultrasound-based seed priming on biological performance and efficiency indicators without confounding variability in resource supply. Consequently, differences observed in sustainability metrics are primarily driven by variations in germination response and seedling development rather than by changes in resource input.

Table 2: Electrical energy and water consumption associated with the germination system and ultrasonic pretreatments.

Treatment	E_{system} [kWh]	E_{US} [kWh]	E_{total} [kWh]	W_{daily} [L·day^{-1}]	W_{total} [L]
NUST	3.840	0.000	3.840	0.5	4.0
05 min	3.840	0.005	3.845	0.5	4.0
10 min	3.840	0.010	3.850	0.5	4.0
15 min	3.840	0.015	3.855	0.5	4.0
20 min	3.840	0.020	3.860	0.5	4.0
30 min	3.840	0.030	3.870	0.5	4.0

Table 3 integrates these resource inputs with germination performance through a set of efficiency and productivity indices. WUE and EUE exhibited minimal variation among treatments, reflecting the constant nature of water supply and the low relative contribution of ultrasonic energy to the total energy budget. These results indicate that traditional efficiency metrics based solely on resource normalization are not sufficient to capture the functional improvements induced by ultrasound-based seed priming.

In contrast, the biological productivity indicators showed marked sensitivity to ultrasound-based seed priming effects. VP_E increased from 404.2 VI·kWh^{-1} in the non-sonicated control to 1153.0 VI·kWh^{-1} in the 30 min treatment, while VP_W followed a similar trend, increasing from 388.0 to 1115.5 VI·L^{-1}. Likewise, SL_E increased from 4.17 to 11.89 mm·kWh^{-1}. These results indicate that ultrasound-based seed priming substantially enhances the biological output obtained per unit of resource consumed, despite the negligible changes in absolute energy and water inputs.

ISI further consolidates these trends by simultaneously accounting for germination performance and resource consumption. ISI values increased progressively with ultrasonic exposure time, reaching a maximum in the 30 min treatment (27959.56), followed

Table 3: Resource-use efficiency, biological productivity, and integrated sustainability indicators of ultrasound-assisted germination of *Lens culinaris* seeds.

Treatment	WUE [L·%$^{-1}$]	EUE [kWh·%$^{-1}$]	VP_E [VI·kWh^{-1}]	VP_W [VI·L^{-1}]	SL_E [mm·kWh^{-1}]	ISI [–]
NUST	0.0412	0.0396	404.2	388.0	4.17	9798.44
05 min	0.0404	0.0388	875.4	841.5	8.84	21666.71
10 min	0.0408	0.0393	585.5	563.5	5.97	14343.64
15 min	0.0408	0.0393	503.2	485.0	7.78	12329.44
20 min	0.0408	0.0394	964.8	931.0	9.84	23636.79
30 min	0.0412	0.0399	1153.0	1115.5	11.89	27959.56

by 20 min (23636.79) and 05 min (21666.71). The control treatment exhibited the lowest value (9798.44), confirming that ultrasound application significantly improves the overall sustainability of the germination process. The consistent increase in ISI suggests that the improvement in germination percentage and seedling vigor outweighs the minimal increase in energy demand associated with ultrasound treatments.

Overall, the combined analysis of Tables 2 and 3 demonstrates that the sustainability enhancement observed in ultrasound-based seed priming is not attributable by reductions in water or energy consumption, but rather by a substantial increase in biological efficiency. In other words, ultrasound acts as a performance-enhancing pretreatment that improves the conversion efficiency of inputs into biological output, thereby increasing system sustainability without altering the resource baseline. This distinction is critical, as it shifts the interpretation of sustainability from a resource minimization perspective toward a productivity-centered framework.

These findings highlight the relevance of integrating biological and physical metrics into a unified assessment framework, as conventional efficiency indicators alone may underestimate the benefits of physical seed priming technologies. The proposed methodology provides a scalable approach for evaluating sustainability in seed germination systems and can be extended to other physical or physico–chemical preconditioning techniques.

4 Discussion

The present study demonstrates that the effectiveness of ultrasound-based seed priming in Lens culinaris is governed not solely by sonication time but by the interaction between the thermo-acoustic environment generated during treatment and the physiological response of the seed. Although previous studies have consistently reported improvements in germination following ultrasonic treatments, optimization has largely relied on empirical adjustment of operational variables such as exposure time, frequency, and power. By integrating thermo-acoustic finite element simulations with experimental validation, the present work provides a mechanistic basis for interpreting how the spatial distribution of acoustic energy influences biological performance, thereby complementing conventional empirical approaches.

The numerical simulations revealed a heterogeneous acoustic field characterized by localized regions of elevated pressure generated by wave interference, attenuation,

boundary reflections, and impedance discontinuities within the ultrasonic reactor. Consequently, seeds experience spatially variable mechanical stimulation rather than a uniform acoustic environment. Because cavitation intensity and acoustic microstreaming depend primarily on local pressure amplitudes, the biological response should be interpreted not only as a function of treatment duration but also of the spatial distribution of acoustic energy. This observation provides a plausible explanation for the variability reported among previous studies employing similar operating frequencies under different reactor configurations, highlighting reactor geometry as an important factor influencing treatment performance.

The simulated pressure distribution was consistent with the structural alterations observed on the seed coat following sonication. Localized fractures identified by microscopy agree with the mechanical stresses expected from transient cavitation and acoustic microstreaming, phenomena capable of generating localized pressure gradients and shear forces that increase seed coat permeability without necessarily causing irreversible tissue damage. Although cavitation activity was not directly quantified, the agreement between numerical predictions and structural observations supports the hypothesis that controlled mechanical disruption facilitated water imbibition during the initial stages of germination. Future studies incorporating passive cavitation detection, acoustic emission analysis, or high-speed optical imaging would provide direct experimental evidence linking acoustic phenomena with structural modifications of seed tissues.

The thermo-acoustic simulations further demonstrated that the selected operating conditions maintained temperatures well below levels commonly associated with embryo damage or metabolic impairment. These predictions indicate that the treatment operated predominantly under non-thermal conditions, allowing the observed improvements in germination dynamics and seedling development to be attributed primarily to the mechanical effects of ultrasound. The non-linear response observed among sonication times is consistent with a hormetic mechanism, in which moderate acoustic stress transiently suppresses metabolic activation before recovery of normal physiological activity. The greater seedling vigor obtained after longer exposure times, despite comparable final germination percentages, further suggests that ultrasound-based seed priming exerts its principal influence on post-germinative development rather than on germination capacity itself. These findings reinforce the importance of evaluating multiple physiological descriptors instead of relying exclusively on germination percentage when assessing treatment effectiveness.

The incorporation of resource-based productivity indicators provides an additional perspective for evaluating ultrasound-based seed priming beyond conventional biological descriptors. Unlike germination percentage or seedling growth alone, the proposed indicators (VP_E, VP_W, SL_E, and ISI) relate biological performance to the energy and water required to achieve that response. The results demonstrate that the sustainability benefit does not arise from reducing resource consumption but from increasing biological productivity per unit of resource invested. This distinction is particularly relevant because sustainable process intensification should be assessed not only in terms of resource savings but also according to the biological value generated

from those resources. Accordingly, these indicators provide a complementary framework for comparing seed priming technologies from both biological and engineering perspectives.

Several limitations should be acknowledged. The study was conducted using a single crop species, one ultrasonic frequency, and a specific reactor configuration, limiting direct extrapolation of the results to other crops and operating conditions. Furthermore, although the proposed mechanisms are supported by numerical simulations and structural observations, physiological processes such as enzyme activation, reactive oxygen species signaling, aquaporin regulation, hormonal responses, and gene expression were not directly evaluated. Integrating physiological and molecular analyses with direct cavitation characterization would provide a more comprehensive understanding of the mechanisms through which mechanical stimulation is translated into metabolic activation during germination. Likewise, evaluating seed-associated microbial communities before and after treatment may provide valuable information regarding the influence of ultrasound on seed health and food safety, particularly for edible sprouts.

Overall, the results indicate that ultrasound-based seed priming should be interpreted as a multiphysics process in which acoustic energy distribution, rather than exposure time alone, governs the magnitude of the biological response. Understanding these interactions provides a more robust basis for interpreting treatment performance and supports future efforts to optimize operating conditions using predictive rather than exclusively empirical approaches.

5 Conclusions

This study established a physics-informed methodology for evaluating ultrasound-based seed priming by integrating thermo-acoustic FEM modeling, experimental validation, and resource-based productivity assessment within a unified framework. Rather than relying exclusively on empirical optimization, the proposed approach enables treatment performance to be interpreted through the interaction between acoustic energy distribution and biological response, providing a predictive basis for process design.

Experimental results demonstrated that ultrasound-based seed priming substantially improved early seedling development while maintaining consistently high germination percentages. Although the final germination rate remained largely unchanged, ultrasound promoted greater seedling elongation, enhanced vigor, and improved germination synchrony, indicating that its principal benefits are associated with post-germinative development rather than germination capacity alone.

A further contribution of this work is the introduction of quantitative resource-based productivity indicators for evaluating process sustainability. By relating biological performance to energy and water requirements, the proposed metrics (VP_E, VP_W, SL_E, and ISI) provide a complementary assessment framework showing that the sustainability advantage of ultrasound-based seed priming arises from greater biological productivity per unit of resource invested rather than from reduced resource consumption. These indicators facilitate objective comparison among seed conditioning technologies from both engineering and biological perspectives.

Although demonstrated using *Lens culinaris*, the proposed methodology is readily transferable to other crop species and physical seed conditioning technologies. Future studies integrating direct cavitation measurements together with physiological and molecular analyses will further strengthen the mechanistic understanding of ultrasound–seed interactions and support the development of predictive, resource-efficient seed conditioning strategies for sustainable agricultural production.

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Declarations

Contributions

Daniel Aguilar-Torres: Methodology, Data accuracy, Simulation, Conceptualization, Formal analysis, Writing - Original Draft, Writing - Review & Editing. Omar Jiménez-Ramírez: Conceptualization, Funding acquisition, Methodology, Validation, Supervision, Writing - Review & Editing. Juan Carlos Paredes-Rojas: Conceptualization, Writing - Review & Editing. Omar Gustavo Alvarado-Mancilla: Writing - Review & Editing. Rubeén Vázquez-Medina: Methodology, Validation, Supervision, Funding acquisition, Writing - Review & Editing. All authors discussed the results and contributed to the final manuscript.

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Conflict of interest/Competing interests

The authors declare no conflict of interest.

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable

Data availability

Data will be made available on request.

Materials availability

Not applicable

Code availability

The code will be available on request.

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