ISSN: 1696-8352

Physical characterization of *Euterpe precatoria* Mart. seeds and the influence of ultrasound on seedling emergence

Caracterização física de sementes de *Euterpe precatoria* Mart. e a influência do ultrassom sobre a emergência de plântulas

Caracterización física de semillas de *Euterpe precatoria* Mart. y la influencia del ultrassonido sobre la emergencia de plántulas

DOI: 10.55905/oelv23n9-008

Receipt of originals: 8/1/2025
Acceptance for publication: 8/27/2025

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ABSTRACT

The irregular and slow seedling emergence of *Euterpe precatoria* Mart. is a challenge in seedling production. Therefore, this study aimed to characterize the physical aspects of the seeds and evaluate the potential of ultrasound to stimulate emergence. The seeds were treated using a total of 36 treatments (frequencies of 1 and 3 MHz; intensities of 0.5, 1.0, 1.5, and 2.0 W/cm², and times of 3, 5, 7, and 9 minutes) in a completely randomized research design. Morphological characteristics, viability, moisture content, and 1,000-seed weight were evaluated. The variables analyzed included emergence, speed index, and mean emergence time. Overall, the seeds had rounded shapes, with an average length of 15.09±0.24 mm, width of 12.45±0.83 mm, area of 144.34±4.02 mm^2, perimeter of 48.32±1.78 mm, circularity of 0.79±0.03 and roundness of 0.84±0.08. The viability was 97.00%, moisture content of 16.05% and weight of one thousand seeds of 923.55 g, characterizing them as large. The 1MHz-1.0W/cm² treatment at 5 and 7 minutes reached 86.00±5.29% and 93.00±1.00% emergence, respectively, with high-speed indexes of 0.58±0.02 and 0.61±0.01 seeds/day, respectively. In addition, low average emergence times of 37.55±1.07 and 38.51±0.67 days after 5 and 7 minutes of ultrasound treatment were obtained respectively. It is concluded that the use of ultrasound is promising to accelerate the emergence of *Euterpe precataria* Mart. seedlings, representing a green sustainable alternative for forest nurseries and restoration projects in the Amazon.

Keywords: Acai, Acoustics, Dormancy, Germination.

RESUMO

A emergência irregular e lenta das plântulas de *Euterpe precatoria* Mart. representa um desafio na produção de mudas. Portanto, este estudo teve como objetivo caracterizar os aspectos físicos das sementes e avaliar o potencial do ultrassom para estimular a emergência. As sementes foram tratadas utilizando um total de 36 tratamentos (frequências de 1 e 3 MHz; intensidades de 0,5; 1,0; 1,5 e 2,0 W/cm² e tempos de 3, 5, 7 e 9 minutos) em delineamento experimental inteiramente casualizado. Foram avaliadas as características morfológicas, a viabilidade, o teor de água e o peso de 1.000 sementes. As variáveis analisadas incluíram emergência, índice de velocidade e tempo médio de emergência. No geral, as sementes apresentaram formato arredondado, com comprimento médio de 15,09±0,24 mm, largura de 12,45±0,83 mm, área de 144,34±4,02 mm², perímetro de 48,32±1,78 mm, circularidade de 0,79±0,03 e circularidade de 0,84±0,08. A viabilidade foi de 97,00%, teor de água de 16,05% e peso de mil sementes de 923,55 g, caracterizando-as como grandes. O tratamento 1MHz-1,0W/cm² aos 5 e 7 minutos atingiu 86,00±5,29% e 93,00±1,00% de emergência, respectivamente, com índices de velocidade de 0,58±0,02 e 0,61±0,01 sementes/dia, respectivamente. Além disso, foram obtidos tempos médios de emergência baixos, de 37,55 ± 1,07 e 38,51 ± 0,67 dias após 5 e 7 minutos de tratamento com ultrassom, respectivamente. Conclui-se que o uso do ultrassom é promissor para acelerar a emergência de mudas de *Euterpe precataria* Mart., representando uma alternativa verde sustentável para viveiros florestais e projetos de restauração na Amazônia.

Palavras-chave: Açai, Acústica, Dormência Germinação.

RESUMEN
La emergencia irregular y lenta de *Euterpe precatoria* Mart. representa un desafío en programas de producción de plántulas. Este estudio tuvo como objetivo caracterizar previamente aspectos físicos de semillas y evaluar el potencial del ultrasonido para estimular la emergencia. Las semillas se distribuyeron en 36 tratamientos (Frecuencias de 1 y 3MHz; intensidades de 0,5, 1,0, 1,5 y 2,0 W/cm²; tiempos de 3, 5, 7 y 9 minutos) usando un diseño experimental aleatorizado. Se evaluaron características morfológicas, viabilidad, contenido de humedad y peso de mil semillas. Las variables analizadas incluyeron emergencia, índice de velocidad y tiempo medio de emergencia. Las semillas presentaron forma moderadamente redondeada, longitud de 15,09±0,24 mm, ancho de 12,45±0,83 mm, área de 144,34±4,02 mm^2, perímetro de 48,32±1,78 mm, circularidad de 0,79±0,03 y redondez de 0,84±0,08. La viabilidad fue de 97,00%, contenido de humedad del 16,05% y peso de mil semillas de 923,55 g, lo que las caracterizó como grandes. Los tratamientos de 1MHz-1,0W/cm² en 5 y 7 minutos alcanzarón emergencias del 86,00±5,29% y del 93,00±1,00%, respectivamente, con mayores índices de velocidades (0,58±0,02 y 0,61±0,01 semillas/día, respectivamente) y tiempos de emergencia promedio cortos (37,55±1,07 y 38,51±0,67 días despues de los tratamientos por ultrason por 5 y 7 minutos, respectivamente). Se concluye que el uso controlado de ultrasonido es prometedor para acelerar la emergencia de plántulas de *E. precatoria* Mart., representando una alternativa sostenible en viveros forestales y proyectos de restauración Amazónica.

Palabras clave: Acai, Latencia, Acústica, Germinación.

1 INTRODUCTION

Açaí (*Euterpe precatoria* Mart.), a member of the Arecaceae family, is native to the Amazon (Melo, 2022). This species displays a broad natural distribution, extending from Central America to northern South American. It is characterized as a solitary-stemmed palm with an elongated stem and no tillering, which restricts its propagation to seed germination (Ferreira et al., 2020). Germination is typically slow and irregular, limiting the efficiency of seedling production (Romayna *et al.*, 2020). The açaí plam can reach up to 20 meters in height, occasionally growing as tall as 35 meters (Melo, 2022).

The açaí production chain holds significant economic relevance for the Northern Region of Brazil. In 2023, the state of Acre reported a production value of R$ 411,000, with 181 tons harvested across 65 hectares, resulting in an average yield of 2,785 kg/ha. The municipality of Acrelândia was the main contributor. In the state of Amazonas, production reached R$ 220.9 million, with 105,211 tons harvested from 6,932 hectares and an average yield of 15,178 kg/ha, with Codajás standing out as the leading producer. The state of Pará in Brazil has the largest açaí production, with 1,576,302 tons harvested over 225,957 hectares, with a production value of R$ 7.78 billion, highlighting the municipality of Igarapé-Miri as the top producer (IBGE, 2024).

In this context, enhancing the early stages of the production cycle is essential, particularly seedling propagation in nurseries (Butzke, 2019). Seeds with uniform and efficient germination are more likely to develop vigorous root systems and healthy shoots, contributing to more productive and sustainable harvests (Chen *et al*., 2023).

Among emerging technologies that promote seed germination, ultrasound application has shown promising results in overcoming seed coat dormancy by facilitating water uptake and accelerating the germination process (Dávila *et al*., 2024). The exposure of seeds to ultrasonic waves is considered a low-cost, easy-to-apply, and environmentally safe alternative, as it does not produce polluting residues (Venâncio; Martins, 2019).

Based on the above, this study aimed to characterize the physical properties of *Euterpe precatoria* Mart. seeds and to evaluate the effect of ultrasound application on seedling emergence.

2 METHODOLOGY

The experiments were conducted between September 2022 and March 2023 at the Biophysics Laboratory facilities of the Bionorte Network complex and the nursery of the Federal University of Acre (UFAC), located in Rio Branco, Acre State in Brazil

(10°01'30"S, 67°42'18"W, at 160 m above sea level). According to the Köppen-Geiger classification, the local climate is tropical (Am), with a maximum temperature of 30.92°C, minimum of 20.84°C, annual precipitation of 1,806.94 mm, and relative humidity of 83% (Climate-data, 2025).

Ripe fruits were collected from adult plants located in the Zoobotanical Park of UFAC. The fruits were spread on paper sheets at room temperature (25±3 °C) for 24 hours to facilitate pulp removal. They were then manually depulped using a steel mesh sieve, washed with running water, and shade-dried for 24 hours.

Seed viability was assessed using the pH exudate test, following the methodoly resported by Theodoro *et al*. (2018), with two indicator solutions: (1) phenolphthalein and (2) sodium carbonate. One hundred seeds were individually immersed into cups containing 10 mL of hot distilled water (approximately 80 °C) for 10 minutes. Subsequently, one drop (approximately 50 mg) of each indicator solution was added and stirred with a glass rod. A pink coloration indicated viable seeds, while colorless solutions indicated non-viable seeds.

Moisture content was determined by oven drying (model Q316M4; brand QUIMIS) at 105±3 °C for 24 hours using four subsamples of approximately 5 g of seeds each. After drying, the samples were placed in a desiccator with silica gel and weighed using an analytical balance with a precision of 0.0001 g (brand Marte Cientifica, model ATY224). The calculation followed the Brazilian Rules for Seed Analysis (Brasil, 2009), and results were expressed on a wet basis.

Morphological analysis of the seeds was conducted using ImageJ® software (version 1.46). A total of 200 seeds were photographed in groups of ten on a white background. A ruler was positioned alongside the seeds to serve as a measurement scale. Images were captured with a 26x magnifying lens at 20 cm from the seeds. Image processing followed the steps described by Ferreira and Rasband (2012). The following morphological variables were analyzed: seed area (mm^2), perimeter (mm), circularity (0.0-1.0), length (mm), width (mm), and roundness (0.0-1.0).

To determine the thousand-seed weight, eight subsamples of 100 seeds each were weighed using an analytical balance with a precision of 0.0001 g. The number of seeds per kilogram and the thousand-seed weight were calculated accordingly following the criteria established by the Brazilian Rules for Seed Analysis (Brasil, 2009).

For seed asepsis, the experimental seed lot was submerged in a sodium hypochlorite solution (2% active chlorine) and magnetically stirred for 5 minutes. Afterward, seeds were placed on paper towels for 1 minute before ultrasound application.

The ultrasound treatment considered two factors. The first included two groups: one without ultrasound and one subjected to continuous ultrasound application at frequencies of 1 MHz and 3 MHz, with intensities of 0.5, 1.0, 1.5, and 2.0 W/cm² for each frequency. These were represented as follows: 1 MHz–0.5 W/cm²; 1 MHz–1.0 W/cm²; 1 MHz–1.5 W/cm²; 1 MHz–2.0 W/cm²; 3 MHz–0.5 W/cm²; 3 MHz-1.0 W/cm²; 3 MHz–1.5 W/cm²; and 3 MHz–2.0 W/cm². The experiments followed a completely randomized design in a 9 x 4 factorial scheme (total of 36 treatments), with the second factor represented by four ultrasound exposure times of 3, 5, 7, and 9 minutes. A total of 3,600 seeds were used, distributed in 144 experimental units, with four replicates of 25 seeds per treatment. For ultrasound application, five seeds were placed in a plastic cup with 15 mL of distilled water, positioned on clinical gel and the transducer of the device (Sonomed V - Carci®).

After treatment, seeds were sown at a depth of 2 cm in wooden boxes (50 cm x 45 cm x 25 cm) filled with autoclaved sand (120 °C for 1 h; 5 mm granulometry), irrigated, and monitored daily for 60 days. Emergence variables (Carvalho; Carvalho, 2009), Emergence Speed Index (Maguire, 1962), and Mean Emergence Time (Carvalho; Carvalho, 2009) were fitted to regression models to describe the response as a function of the interaction between factors and to identify trends and optimal performance points.

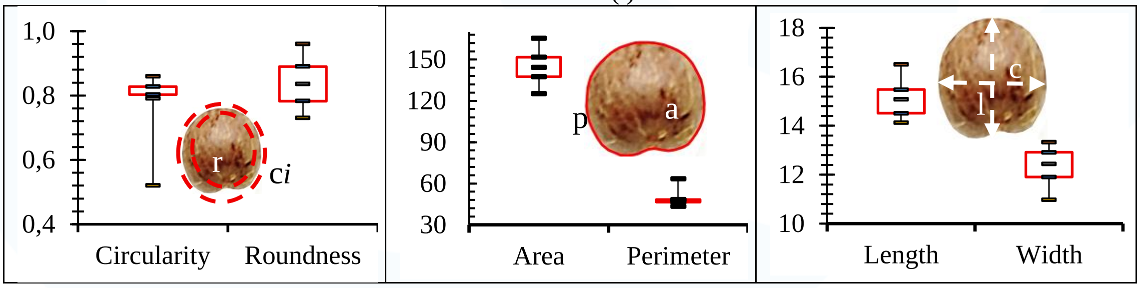
Experimental means were subjected to analysis of variance (ANOVA) with the F-test at a 5% significance level, using RStudio software (R Core Team, 2024) and the ExpDes.pt package. The experiments followed a completely randomized design (CRD). When significant differences were detected, residuals were assessed for normality. For the quantitative factor (ultrasound exposure time), a polynomial regression model was fitted to identify the most effective exposure durations for seedling emergence.

3 RESULTS AND DISCUSSIONS

3.1 PHYSICAL CHARACTERIZATION

The seeds exhibited average dimensions of 15.09±0.24 mm in length and 12.45±0.83 mm in width, indicating a moderately rounded shape, with a mean area of 144.34±4.02 mm², perimeter of 48.32±1.78 mm, circularity index of 0.79±0.03, and roundness of 0.84±0.08. These values suggest a slightly irregular form, a common characteristic in palm seeds (Figure 1).

Figure 1. Boxplots of the quantitative values obtained in the analysis of biometric parameters of 200 seeds of *Euterpe precatório* Mart. Variation in circularity (ci), roundness (r), area (a), perimeter (p), length (c) and width (l).



Source: Authors

According to Aguiar and Mendonça (2003), seeds of *Euterpe precatoria* are described as globose, with a thin seed coat composed of three cellular layers, the outermost being thick-walled, although structural variations may occur among individuals. Lima *et al*. (2018) conducted a study in the municipality of Anorí (Amazonas State, Brazil) and described seeds of *Euterpe oleracea* Mart. as nearly round, with mean dimensions of 9.46 mm in length and 10.62 mm in width, classifying them as large seeds.

Regarding physiological quality, the seed lot showed a viability of 97%, exceeding the minimum standard of 80% required by Brazilian legislation for various species (Brasil, 2013). The seed moisture content was 16.05%. According to Costa (2015), seeds of E.

precatoria tolerate moisture levels ranged from 11% to 25% without significant loss of germination capacity, which can range from 95% to 69%. In contrast, Lima *et al*. (2018) reported that *E. oleracea* seeds analyzed in their study had an initial moisture content of 42%, a value considerably higher than that observed in our study (16,05%).

The seed lot contained 1,117 seeds per kilogram, with a thousand-seed weight of 923.55 g, classifying them as relatively large seeds according to the criteria established by the Brazilian Ministry of Agriculture (Brasil, 2009).

3.2 EMERGENCE

The treatments after regression analysis exhibited distinct statistical behaviors with respect to emergence of *Euterpe precatoria* Mart. after ultrasound application (Table 1). The control (without ultrasound application) maintained a constant average emergence rate of 81% and was not included in the regression analysis due to the absence of variation over time.

The combinations of 1 MHz–1.0 W/cm², 1 MHz–2.0 W/cm², 3 MHz–0.5 W/cm², and 3 MHz–1.0 W/cm² followed quadratic polynomial models, with coefficients of determination (R^2) greater than 0.80 and statistically significant effects, indicating the presence of an optimum point in terms of application time and intensity to maximize emergence, followed by a subsequent decline. Among these treatments, 1 MHz–2.0 W/cm² stood out due to its strong fit ($R^2 = 0.94$), indicating high efficacy in stimulating emergence, while 3 MHz–0.5 W/cm² presented a perfect fit ($R^2 = 1.00$), showing a highly consistent response according to the equation $y = 1.38x^2 + 14.00x + 54.38$. By interpolation of the regression curve, the maximum emergence value (E) would reach 89.88% after an exposure time of 5.07 minutes.

In contrast, both 1 MHz–0.5 W/cm² and 1 MHz–1.5 W/cm² treatments did not present statistically significant effects. The former exhibited a decreasing linear model with a low coefficient of determination ($R^2 = 0.23$) and no statistical significance (ns), suggesting only a slight decreasing trend in emergence. Although the 1 MHz–1.5 W/cm² treatment showed a good fit (R^2 = 0.84), the lack of statistical significance limits the interpretation of its effects.

Furthermore, the 3 MHz–1.5 W/cm² treatment followed a negative linear model, with a moderate coefficient of determination (R^2 = 0.47) and statistically significant effects, indicating a reduction in emergence over time. Lastly, the 3 MHz–2.0 W/cm² treatment demonstrated a marked linear decrease in emergence, with a high coefficient of determination (R^2 = 0.99) and strong statistical significance, reinforcing the risk of adverse effects under high-intensity ultrasound conditions.

Table 1. Statistical mathematical model with agronomic interpretation for the quantitative factor of ultrasound exposure time, with different combinations of frequency and intensity factors, based on experimental data on emergence (%) of *Euterpe precatoria* Mart., obtained through regression analysis.

Frequency and intensity		Statistical model (Y)	Coefficient of determination (R^2)
Control (no ultrasound)		81.00 (constant)	-
1MHz	0.5W/cm²	$-2.51x + 85.53$	0.23 ns
	1.0W/cm²	$-1.63x^2 + 18.50x + 38.63$	0.81 *
	1.5W/cm²	$-2.75x^2 + 14.05x + 65.25$	0.84 ns
	2.0W/cm²	$-2.94x^2 + 25.20x + 30.99$	0.94 ***
3MHz	0.5W/cm²	$-1.38x^2 + 14.00x + 54.38$	1.00 *
	1.0W/cm²	$-1.38x^2 + 12.20x + 57.18$	0.99 ***
	1.5W/cm²	$-2.30x + 81.30$	0.47 *
	2.0W/cm²	$-7.05x + 99.05$	0.99 ***

ns: not significant. x: *time in minutes. *: regression significance at the 5% probability level (p<0.05). ***: regression significance at the 0.1% probability level (p<0.001).*
Source: Authors

Treatments with different ultrasound exposure times were evaluated using Tukey's test at 5% probability, as shown in Table 2. The Controle Group (no ultrasound treatment) showed emergence rate of 81.00±3.42%. In the other treatments, the response to ultrasound varied, providing both positive and negative effects.

At 3 minutes of exposure, the emergence values ranged from 76.00±2.83% to 84.00±2.83%. Despite the numerical variation, no statistically significant differences were observed among treatments (absence of grouping letters), indicating that at this short exposure duration, ultrasound does not induce substantial physiological effects on the seeds.

At 5 minutes of exposure, the treatments of 1 MHz–0.5 W/cm², 1 MHz–1.0 W/cm², and 3 MHz–0.5 W/cm² exhibited the best results, with emergence rates of

86.00±6.22%, 86.00±5.29%, and 90.00±3.46%, respectively, all statistically superior to the other treatments. In contrast, 3 MHz–2.0 W/cm² showed the poorest performance, with only 63.00±1.00% emergence, suggesting that under these conditions, ultrasound had a negatively affect on seed emergence.

At 7 minutes of exposure, the treatment of 1 MHz–1.0 W/cm² (93.00±1.00%) achieved the highest mean emergence, being statistically superior to all other treatments. Conversely, 1 MHz–0.5 W/cm², 3 MHz–1.5 W/cm², and 3 MHz–2.0 W/cm² displayed marked reductions (70.00±6.63%, 56.00±7.12%, and 51.00±2.52%, respectively), confirming that prolonged exposure can lead to adverse effects.

At 9 minutes of exposure, 1 MHz–2.0 W/cm² (17.00±3.41%) clearly demonstrated the detrimental impact of extended exposure times. Similarly, 3 MHz–2.0 W/cm² (35.00±5.97%) and 3 MHz–1.0 W/cm² (56.00±2.31%) exhibited significantly lower emergence rates compared to other treatments. In contrast, 1 MHz–0.5 W/cm² maintained an emergence level of 79.00±5.74%, statistically comparable to the control (without ultrasound), indicating greater tolerance to prolonged exposure durations.

Table 2. Mean ± standard error of emergence (%) of *Euterpe precatoria* Mart. seeds as a function of ultrasound exposure time, and different combinations of frequency and intensity.

Frequency and intensity		Ultrasound Exposure Time			
		3 min	5 min	7 min	9 min
Control (no ultrasound)		81.00±3.42	81.00±3.42^{ab}	81.00±3.42^{ab}	81.00±3.42^{a}
1MHz	0.5W/cm^2	82.00±5.77	86.00±6.22^{a}	70.00±6.63^{bcd}	79.00±5.74^{a}
	1.0W/cm^2	81.00±2.52	86.00±5.29^{a}	93.00±1.00^{a}	72.00±2.83^{ab}
	1.5W/cm^2	76.00±2.83	84.00±6.93^{ab}	81.00±1.15^{ab}	78.00±5.74^{ab}
	2.0W/cm^2	83.00±8.06	75.00±9.71^{ab}	72.00±6.93^{abcd}	17.00±3.41^{d}
3MHz	0.5W/cm^2	84.00±2.83	90.00±3.46^{a}	85.00±2.52^{ab}	69.00±3.00^{ab}
	1.0W/cm^2	81.00±1.91	85.00±1.90^{ab}	74.00±2.58^{abcd}	56.00±2.31^{bcd}
	1.5W/cm^2	76.00±2.83	72.00±3.73^{ab}	56.00±7.12^{cd}	66.00±9.59^{ab}
	2.0W/cm^2	78.00±4.76	63.00±1.00^{b}	51.00±2.52^{d}	35.00±5.97^{cd}
F Test:			4.91		
Coefficient of variation:			13.65%		

Lowercase letters next to the mean values (± standard error) indicate statistical differences between ultrasound exposure times by Tukey's test at 5% probability (p<0.05). Values followed by the same letter do not differ statistically from each other, different letters indicate a significant difference, and the absence of letters indicates non-significance between factors.

Source: Authors

Among the treatments evaluated, 1 MHz–1.0 W/cm² and 3 MHz–0.5 W/cm² were the most effective in promoting seedling emergence of Euterpe precatoria Mart. The treatment at 3 MHz–0.5 W/cm² resulted in an emergence rate of 90.00 ± 3.46% after 5 minutes of exposure, with a high coefficient of determination ($R^2 = 0.94$). Meanwhile, the 1 MHz–1.0 W/cm² treatment achieved the highest emergence rate of 93.00±1.00% at 7 minutes of exposure, also exhibiting a high coefficient of determination ($R^2 = 0.99$). When compared to previous studies, these results surpass the average emergence rate of 86.5% reported by Guilherme *et al*. (2018) for seeds sown in sand, with or without the application of biostimulants. Similarly, the outcomes obtained in the present study are superior to those reported by Firmino (2013), who found mean emergence rates of 66.35% for manually depulped seeds and 61.78% for mechanically depulped seeds, both cultivated in trays with washed sand as a substrate.

Furthermore, the emergence rates observed in this study exceeded those reported by Amoêdo (2006), with 60.9% seedling emergence after 45 days using seeds that had been soaked for approximately 4 hours, manually depulped, treated with 5% sodium hypochlorite for 10 minutes, and germinated in Gerbox boxes under controlled conditions. In addition, the results of this study also outperformed those obtained by Smiderle *et al*. (2015), who studied Euterpe oleracea seeds using two seed sizes (large: 85 g/100 seeds and small: 58 g/100 seeds) and two substrates (clean sand and sawdust). The authors observed a germination rate of 66.80%, which was lower than the rates achieved with ultrasound treatments in our study.

3.3 EMERGENCE SPEED INDEX

The treatments underwent regression analysis of the Emergence Speed Index of *Euterpe precatoria* Mart., show in Table 3. The control treatment (without ultrasound application) showed an Emergence Speed Index of 0.46 seeds/day. The treatments of 1 MHz–0.5 W/cm², 1 MHz–1.0 W/cm², 1 MHz–2.0 W/cm², and 3 MHz–1.0 W/cm² fitted regression models with high coefficients of determination ($R^2 \geq 0.99$) and statistical significance, indicating a significant influence of ultrasound on seedling emergence dynamics.

The treatment of 1 MHz–0.5 W/cm² fitted a cubic model perfectly ($R^2 = 1.00$; $p < 0.01$), demonstrating a highly consistent response characterized by an initial acceleration in Emergence Speed Index, followed by a decrease after long exposure durations within the tested range. Similarly, the 1 MHz–2.0 W/cm² treatment also followed a cubic model, highlighting the importance of precise control of both intensity and exposure duration. The 3 MHz–0.5 W/cm² treatment showed a negative slope in the linear fit ($R^2 = 0.94$; $p < 0.001$), indicating a progressive reduction in Emergence Speed Index as exposure time increased, with a strong statistical fit.

The treatments of 1 MHz–1.5 W/cm² and 3 MHz–1.5 W/cm² did not show statistical significance, despite being fitted to a quadratic model (1 MHz–1.5 W/cm², $R^2 = 0.47$) and a negative slope in the linear model (3 MHz–1.5 W/cm², $R^2 = 0.44$), respectively. The lack of statistical significance limits interpretation, suggesting that under these conditions, the treatments did not result in a consistent effect on Emergence Speed Index. Finally, the treatment of 3 MHz–2.0 W/cm² was adjusted to linear model with a high coefficient of determination ($R^2 = 0.98$), demonstrating a strong trend of reduced Emergence Speed Index with increasing exposure time, indicating adverse effects under more intense ultrasound conditions.

ISSN: 1696-8352

Table 3. Statistical mathematical model with agronomic interpretation for the quantitative factor of ultrasound exposure time, in different combinations of the frequency and intensity factor, based on experimental data of the Emergence Speed Index (seeds/day) of *Euterpe precatoria* Mart., obtained through regression analysis.

Frequency and intensity factor		Statistical model (Y)	Coefficient of determination (R^2)
Control (no ultrasound)		0.46 (constant)	-
1MHz	0.5W/cm²	$0.01x^3 – 0.17x^2 + 0.89x – 0.86$	1.00 **
	1.0W/cm²	$-0.02x^2 + 0.23x – 0.09$	0.99 ***
	1.5W/cm²	$-0.01x^2 + 0.03x + 0.39$	0.47 ^{ns}
	2.0W/cm²	$-0.01x^3 + 0.12x^2 – 0.58x + 1.45$	1.00 *
3MHz	0.5W/cm²	$-0.03x + 0.65$	0.94 ***
	1.0W/cm²	$-0.01x^2 + 0.11x + 0.19$	0.99 *
	1.5W/cm²	$-0.02x + 0.36$	0.44 ^{ns}
	2.0W/cm²	$-0.03x + 0.54$	0.98 ***

^{ns}: not significant. *x*: time in minutes. *: regression significance at the 5% probability level (p<0.05). **: regression significance at the 1% probability level (p<0.01). ***: regression significance at the 0.1% probability level (p<0.001).
Source: Authors

The results of the treatments evaluated the Emergence Speed Index as a function of ultrasound exposure time, as shown in Table 4. These data were analyzed using Tukey's test at a 5% probability level. The control treatment (without ultrasound application) exhibited an Emergence Speed Index of 0.46 seeds/day.

For treatments with 3 minutes of exposure, numerical variations were observed ranging from 0.33±0.01 to 0.55±0.05 seeds/day. Notably, the treatments of 1 MHz–0.5 W/cm² (0.54±0.04 seeds/day), 1 MHz–2.0 W/cm² (0.54±0.06 seeds/day), and 3 MHz–0.5 W/cm² (0.55±0.05 seeds/day) presented the highest mean values and were statistically significant compared to the other treatments. However, the 3-minute exposure time was not sufficient to induce significant physiological changes.

With 5 minutes of exposure, the treatments of 1 MHz–0.5 W/cm² (0.54±0.05 seeds/day) and 1 MHz–1.0 W/cm² (0.58±0.02 seeds/day) maintained the highest mean values, again with statistical significance. The 1 MHz–1.0 W/cm² treatment demonstrated the highest performance at this exposure time, indicating a positive sensitivity to the ultrasonic stimulus. At 7 minutes, 1 MHz–1.0 W/cm² reached its peak performance (0.61±0.01 seeds/day), being statistically superior to all other treatments.

In contrast, the treatments of 3 MHz–1.5 W/cm² (0.28±0.03 seeds/day) and 3 MHz–2.0 W/cm² (0.30±0.01 seeds/day) exhibited significant reductions in Emergence

Speed Index, suggesting a possible shift from a beneficial effect to the onset of physiological stress due to prolonged exposure. At 9 minutes, a marked reduction was observed in several treatments, particularly for 1 MHz–2.0 W/cm² (0.12±0.02 seeds/day), which was statistically lower than all other treartments, indicating adverse effects caused by prolonged exposure combined with high ultrasound intensity. The treatments of 3 MHz–0.5 W/cm² (0.34±0.02 seeds/day) and 3 MHz–1.0 W/cm² (0.34±0.01 seeds/day) also showed reduced performance. Conversely, the treatments of 1 MHz–0.5 W/cm² (0.48±0.05 seeds/day), 1 MHz–1.0 W/cm² (0.47±0.03 seeds/day), and the control (0.46±0.03 seeds/day) maintained similar behavior and were statistically superior, demonstrating greater tolerance to prolonged ultrasound exposure.

Table 4. Mean ± standard error of the Seed Emergence Speed Index (seeds/day) of *Euterpe precatoria* Mart. as a function of the time of exposure to ultrasound, considering different combinations of frequency and intensity.

Frequency and intensity		Ultrasound exposure time			
		3 min	5 min	7 min	9 min
Control (no ultrasound)		0.46±0.03[ab]	0.46±0.03[abc]	0.46±0.03[b]	0.46±0.03[a]
1MHz	0.5W/cm²	0.54±0.04[a]	0.54±0.05[a]	0.36±0.04[bc]	0.48±0.05[a]
	1.0W/cm²	0.43±0.04[ab]	0.58±0.02[a]	0.61±0.01[a]	0.47±0.03[a]
	1.5W/cm²	0.42±0.05[ab]	0.45±0.02[abc]	0.41±0.02[bc]	0.41±0.02[ab]
	2.0W/cm²	0.54±0.06[a]	0.49±0.07[abc]	0.47±0.05[ab]	0.12±0.02[d]
3MHz	0.5W/cm²	0.55±0.05[a]	0.52±0.04[ab]	0.46±0.01[b]	0.34±0.02[abc]
	1.0W/cm²	0.42±0.01[ab]	0.47±0.01[abc]	0.46±0.02[b]	0.34±0.01[abc]
	1.5W/cm²	0.33±0.01[b]	0.36±0.04[c]	0.28±0.03[c]	0.30±0.04[bc]
	2.0W/cm²	0.43±0.03[ab]	0.39±0.01[bc]	0.30±0.01[c]	0.23±0.04[cd]
F test:			5.03		
Coefficient of variation:			15.75%		

Lowercase letters next to the mean values (± standard error) indicate statistical differences between ultrasound exposure times by Tukey's test at 5% probability (p<0.05). Values followed by the same letter do not differ statistically from each other and different letters indicate a significant difference.
Source: Authors

For comparison, Guilherme *et al*. (2018) reported an average Emergence Speed Index of 0.59 seeds/day for *Euterpe precatoria* Mart. seeds treated with the biostimulant Stimulate® (containing 0.005% IBA, 0.009% cytokinin, and 0.005% gibberellin) without additional substrate treatment. The proximity of these values indicates that the 1MHz-1.0W/cm² treatment provided equivalent or slightly more efficient performance.

3.4 MEAN EMERGENCY TIME

Among the treatments involving ultrasound application, distinct patterns were observed, indicating that exposure time, frequency, and intensity significantly Mean Emergency Time of *Euterpe precatoria* Mart., as demonstrated by the regression models fitted to the data in Table 5. The control treatment (without ultrasound application) exhibited a constant mean emergence time of 46.01 days and did not fit any mathematical model.

The treatment of 1 MHz–0.5 W/cm² showed a significant cubic regression model ($R^2 = 1.00$; $p < 0.01$), as the 3 MHz–2.0 W/cm² ($R^2 = 1.00$; $p < 0.001$) treatment. Both indicate an initial acceleration of emergence followed by a peak and a subsequent pronounced increase in emergence time, suggesting a non-linear response to exposure duration. The 1 MHz–1.0 W/cm² treatment fitted a statistically significant quadratic polynomial model ($R^2 = 0.91$; $p < 0.001$), suggesting the existence of an optimal exposure window in which ultrasound application effectively reduced the mean emergence time. In contrast, the treatments of 1 MHz–1.5 W/cm² ($R^2 = 0.76$) and 1 MHz–2.0 W/cm² ($R^2 = 0.87$), although fitted the quadratic and linear models respectively, did not show any statistical significance, limiting interpretation. The lack of significance indicates that, under these specific conditions, ultrasound application did not yield consistent effects on seedling mean emergence time.

The 3 MHz–0.5 W/cm² treatment, despite being statistically significant ($R^2 = 0.79$; $p < 0.01$), was fitted to a positive slope in the linear model, indicating a delay in mean emergence time as exposure increased—an adverse effect on germination dynamics. Conversely, 3 MHz–1.0 W/cm² fitted a negative slope in the linear model ($R^2 = 0.85$; $p < 0.05$), showing that longer exposure durations progressively reduced the mean emergence time under this specific condition. The 3 MHz–1.5 W/cm² treatment was fitted to a quadratic model with a high coefficient of determination ($R^2 = 0.99$; $p < 0.001$), indicating an increase in mean emergence time with prolonged ultrasound exposure, thereby evidencing a detrimental response to sustained ultrasonic treatment.

Table 5. Statistical mathematical model with agronomic interpretation for the quantitative factor of ultrasound exposure time, in different combinations of the frequency and intensity factor, based on data on the Mean Emergence Time (days) of *Euterpe precatoria* Mart., obtained through regression analysis.

Frequency and intensity		Statistical model (Y)	Coefficient (R^2)
Control (no ultrasound)		46.01 (constant)	-
1MHz	0.5W/cm^2	$-0.40x^3 + 6.64x^2 - 32.07x + 86.34$	1.00 **
	1.0W/cm^2	$0.79x^2 - 10.72x + 73.30$	0.91 ***
	1.5W/cm^2	$-0.69x^2 + 4.21x + 42.68$	0.76 ^{ns}
	2.0W/cm^2	$-0.81x + 41.44$	0.87 ^{ns}
3MHz	0.5W/cm^2	$0.2x + 39.02$	0.79 **
	1.0W/cm^2	$-1.96x + 55.06$	0.85 *
	1.5W/cm^2	$0.91x^2 - 11.28x + 84.11$	0.99 ***
	2.0W/cm^2	$-0.54x^3 + 9.84x^2 - 56.35x + 142.29$	1.00 ***

^{ns}: not significant. *x*: time in minutes. *: regression significance at the 5% probability level (p<0.05). **: regression significance at the 1% probability level (p<0.01). ***: regression significance at the 0.1% probability level (p<0.001).
Source: Authors

As shown in Table 6, the control group (without ultrasound application) exhibited a mean emergence time of 46.01±1.52 days.

After 3 minutes of ultrasound treatment, a wide variation in mean emergence times was observed, ranging from 38.97±0.49 to 58.35±0.52 days. The lowest mean times were recorded for the treatments of 1 MHz–0.5 W/cm² (38.97±0.49 days) and 1 MHz–2.0 W/cm² (40.63±0.82 days). Both treatments were statistically lower than the others, indicating an initial beneficial effect of ultrasound within short times. In contrast, the treatment of 3 MHz–1.5 W/cm² (58.35±0.52 days) exhibited the highest mean emergence time, suggesting an early adverse physiological effect associated with the higher intensity applied.

At 5 minutes of exposure, the treatments of 1 MHz–1.0 W/cm² (37.55±1.07 days) and 3 MHz–2.0 W/cm² (38.72±0.93 days) showed the lowest mean emergence times, both statistically lower than the other treatments. These results suggested that this time exposure promoted faster seedling emergence.

At 7 minutes, the treatment of 3 MHz–1.0 W/cm² (38.26±0.39 days) exhibited the shortest mean emergence time, with statistically significant differences, maintaining the favorable performance observed at shorter durations. Similarly, 1 MHz–1.0 W/cm² (38.51±0.67 days) and 1 MHz–2.0 W/cm² (39.59±0.53 days) also maintained reduced values, indicating consistency in their positive responses. On the other hand, 1 MHz–0.5

ISSN: 1696-8352

W/cm² (48.71±0.65 days) and 1 MHz–1.5 W/cm² (49.94±0.67 days) showed increased mean times, suggesting a loss of efficiency at prolonged time (> 7 minutes).

At 9 minutes of exposure, a clear trend of adverse effects was observed in certain treatments. The treatment of 3 MHz–1.5 W/cm² (56.19±0.42 days) recorded the highest mean emergence time, statistically superior to the others, reflecting a negative physiological response likely associated with stress induced by prolonged ultrasound exposure. Conversely, treatments of 1 MHz–2.0 W/cm² (37.91±1.41 days), 3 MHz–1.0 W/cm² (39.24±0.27 days), and 3 MHz–2.0 W/cm² (36.85±0.49 days) exhibited the lowest mean values at this exposure duration, indicating that, even under extended exposure, specific combinations of frequency and intensity can still elicit beneficial effects.

Table 6. Mean ± standard error of the Mean Emergence Time (days) of *Euterpe precatoria* Mart. seeds as a function of the time of exposure to ultrasound, considering different combinations of frequency and intensity.

Frequency and intensity		Ultrasound exposure time			
		3 min	5 min	7 min	9 min
Control (No ultrasound)		46.01 ± 1.52^{bcd}	46.01 ± 1.52^{abc}	46.01 ± 1.52^{ab}	46.01 ± 1.52^{bc}
1MHz	0.5W/cm^2	38.97 ± 0.49^{e}	41.49 ± 1.34^{cde}	48.71 ± 0.65^{ab}	41.28 ± 0.87^{cd}
	1.0W/cm^2	48.81 ± 3.39^{b}	37.55 ± 1.07^{e}	38.51 ± 0.67^{c}	39.82 ± 1.02^{d}
	1.5W/cm^2	46.48 ± 1.64^{bc}	47.53 ± 0.99^{ab}	49.94 ± 0.67^{a}	48.24 ± 0.54^{b}
	2.0W/cm^2	40.63 ± 0.82^{de}	39.54 ± 0.82^{de}	39.59 ± 0.53^{c}	37.91 ± 1.41^{d}
3MHz	0.5W/cm^2	40.69 ± 3.46^{cde}	44.70 ± 2.68^{bcd}	46.45 ± 0.35^{ab}	46.21 ± 0.69^{bc}
	1.0W/cm^2	49.80 ± 1.38^{b}	45.84 ± 1.03^{abc}	38.26 ± 0.39^{c}	39.24 ± 0.27^{d}
	1.5W/cm^2	58.35 ± 0.52^{a}	50.66 ± 1.01^{a}	49.37 ± 0.54^{ab}	56.19 ± 0.42^{a}
	2.0W/cm^2	47.17 ± 0.59^{b}	38.72 ± 0.93^{e}	43.96 ± 0.66^{bc}	36.85 ± 0.49^{d}
F test:			8.15		
Coefficient of variation:			5.86%		

Lowercase letters next to the mean values (± standard error) indicate statistical differences between ultrasound exposure times by Tukey's test at 5% probability (p<0.05). Values followed by the same letter do not differ statistically from each other and different letters indicate a significant difference.

Source: Authors

The 1 MHz-1.0 W/cm^2 treatment was the most effective in reducing the mean emergence time, standing out especially at 5 minutes (37.55±1.07 days), a reduction of 8 days compared to the control group. Furthermore, it was the most consistent across the different exposure times to ultrasound waves, with a high coefficient of determination (R^2=0.91) and high statistical significance (p<0.001). In comparison with other studies, Firmino (2013) reported emergence of *Euterpe precatoria* at 39 days, a time longer than that observed in the present study, while Butzke (2019) recorded emergence of *E.*

precatória seedlings between 35 and 40 days, in pulped seeds sown in trays with sawdust, resulting in some non-uniformity in the process.

4 CONCLUSIONS

The *Euterpe precatoria* Mart. seeds analyzed exhibited physical characteristics such as a rounded shape, with average length and width of 15.09±0.24 mm and 12.45±0.83 mm, respectively. The mean area was 144.34±4.02 mm², with a perimeter of 48.32±1.78 mm. Circularity (0.79 ± 0.03) and roundness (0.84±0.08) values revealed slight irregularities in seed shape. From a physiological standpoint, the seed lot demonstrated high viability (97.00%), with a moisture content of 16.05%, and a thousand-seed weight of 923.55 g, classifying them as large seeds.

The results indicated that ultrasound application can significantly influence the emergence of *Euterpe precatoria* Mart., depending on the specific combination of frequency, intensity, and exposure duration.

Among the treatments evaluated, 1 MHz at 1.0 W/cm² for 7 minutes was the most effective, achieving the highest emergence percentage (93.00 ± 1.00%) and Emergence Speed Index (0.61 ± 0.01 seeds/day). This treatment also yielded the shortest Mean Emergence Time at 5 and 7 minutes (37.55 ± 1.07 and 38.51 ± 0.67 days, respectively). Furthermore, it exhibited statistical significance in regression analyses, confirming its effectiveness in promoting the emergence of *Euterpe precatoria* Mart. seedlings.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the support of the Brazilian Federal Agency for Support and Evaluation of Graduate Education (CAPES) and the National Council for Scientific and Technological Development (CNPq) for the scholarship and MDAS tranks the Natural Sciences and Engineering Research Council of Canada (NSERC #05151-2025) for funding her research program on Emerging processing technologies at University of Alberta.

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