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Influence of ultrasonic pretreatment on the convective drying kinetics and quality of cocoa (*Theobroma cacao L.*)

Influencia del pretratamiento ultrasónico en la cinética de secado convectivo y la calidad del cacao (*Theobroma cacao L.)*

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ABSTRACT

Background: Convective drying of cocoa (*Theobroma cacao L.*) is a critical stage in its processing, and ultrasound (US) application may represent an innovative technology to optimize this process. **Objectives**: To evaluate the effect of ultrasound pretreatment (40 kHz/130 W for 10, 20 and 30 minutes) on the convective drying of cocoa (60 °C, 2 m/s), through the description of the drying kinetics, the determination of the effective diffusion and activation energy, as well as the identification of the most appropriate mathematical model to represent the process. **Methods**: Five thin-layer mathematical models based on Fick's second law for long periods were used, employing the moisture ratio as an independent variable. Experimental data were adjusted to these models to determine drying kinetics and mass transfer coefficients. **Results**: US significantly increased ($p>0.05$) the drying speed in all treated samples, reducing drying time by an average of 52% compared to the control. The Page model was the most appropriate for predicting experimental drying curves, explaining between 98.1% and 99.2% of the variance. The US application increased both the effective diffusivity and the mass transfer coefficient, achieving a 92% weight loss compared to the initial weight. **Conclusions**: The US is a cost-effective technology for the cocoa industry, improving production times and achieving significant energy savings while maintaining product quality.

Keywords: Sonication, convective drying, drying kinetics, cocoa bean, food technology.

RESUMEN

Antecedentes: El secado convectivo del cacao (*Theobroma cacao L.)* es una etapa crucial en su procesamiento, y la aplicación de ultrasonido (US) puede representar una tecnología innovadora para optimizar este proceso. **Objetivos**: Evaluar el efecto del pretratamiento con ultrasonido (40 kHz/130 W durante 10, 20 y 30 minutos) sobre el secado convectivo del cacao (60 °C, 2 m/s), mediante la descripción de la cinética de secado, la determinación de la difusividad efectiva y la energía de activación, así como la identificación del modelo matemático más adecuado para representar el proceso. **Métodos**: Se utilizaron cinco modelos matemáticos de capa delgada basados en la ecuación integrada de la segunda ley de Fick para períodos largos, empleando la relación de humedad como variable independiente. Los datos experimentales se ajustaron a estos modelos para determinar la cinética de secado y los coeficientes de transferencia de masa. **Resultados**: El US incrementó significativamente ($p>0.05$) la velocidad de secado en todas las muestras tratadas, reduciendo en promedio un 52% el tiempo de secado con respecto al control. El modelo de Page mostró ser el más adecuado para predecir las curvas experimentales de secado, explicando entre el 98.1% y el 99.2% de la varianza. La aplicación de US aumentó tanto la difusividad efectiva como el coeficiente de transferencia de masa, logrando una pérdida de peso del 92% respecto al peso inicial. **Conclusiones**: El uso de US es una tecnología rentable para la industria del cacao, ya que mejora los tiempos de producción y genera ahorros significativos de energía, manteniendo la calidad del producto.

Palabras clave: Sonicación, secado convectivo, cinética de secado, haba de cacao, tecnología de alimentos.

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1. INTRODUCTION

The cocoa sector faces several challenges related to competitiveness and development, primarily due to the limited adoption of advanced practices among traditional farmers, which in turn decreases yields and grain quality. Furthermore, the lack of technology transfer hinders the development of new, genetically improved crops that are resistant to disease and enhance their productivity. At present, many small and medium-sized cocoa producers are unaware of standardized techniques and technologies for grain fermentation and drying, which can improve yield and quality, making them more competitive in international markets [1].

The post-harvest stage of cacao processing faces multiple challenges that directly affect the quality and commercial value of the bean. Improper fermentation and drying are recurring problems due to limitations in infrastructure and technical knowledge [2]. These processes, when poorly executed, generate variability in critical parameters such as humidity, pH, and phenolic content. Added to this are the effects of climate change, such as extreme temperatures and irregular rainfall, which alter harvest cycles and deteriorate the sensory quality of cacao [3]. Furthermore, conventional quality assessment methods such as cutting tests or FT-IR-ATR spectra are destructive, slow, and inaccessible to small producers [2]. At the same time, wide technological gaps persist in the processing chain, especially in Latin American and African countries, where tools such as computer vision, artificial intelligence, and digital traceability systems have not yet been widely adopted due to poor connectivity, a lack of infrastructure, and limited technological literacy [4]. Although there are promising developments in automated monitoring and remote diagnostics, their effective implementation remains a challenge due to the lack of technical training in rural areas and the lack of models adapted to the context of small producers [5].

Post-harvest processing, agricultural practices, geographic origin, and transportation conditions influence cocoa bean quality. To be marketable, it must meet specific requirements related to moisture content, acidity, microbial load, and polyphenol concentration [5, 6]. Fermentation and drying are among the most critical stages of cocoa processing, as they largely determine the chemical and sensory composition of the bean [7, 8]. During drying, if variables such as temperature, time, airflow, and process uniformity are not adequately controlled, key bioactive compounds such as flavonoids, theobromine, and phenolic acids can be lost due to oxidation, volatilization, or thermal degradation [9]. Although subsequent roasting also involves significant losses of these compounds, optimizing drying is essential because this step defines the chemical starting point of the bean before more intensive thermal processing. Poorly executed drying can exacerbate losses during roasting, while optimized drying preserves the greatest possible amount of functional compounds, thus improving the nutritional and antioxidant profile of the final product [5,9].

The chemical composition of cocoa, rich in polyphenols, reducing sugars, amino acids, and lipids, makes it especially vulnerable to poor drying. During this stage, inadequate conditions can lead to polyphenol oxidation, loss of volatile compounds formed during fermentation, and thermal degradation of lipids, which directly impacts the aroma, flavor, color, and nutritional value of the bean [2]. This chemical sensitivity reinforces the need to establish optimized drying conditions that preserve these key compounds and ensure a uniform and commercially acceptable final quality [2, 5]. For the commercialization of cocoa beans, they must have a moisture content between 5 to 8% (moist basis), the most conventional drying systems for cocoa are: open sun, solar, oven, microwave, and *freeze-drying* [6].

One of the most commonly used techniques for drying is freeze-drying, which is based on low temperatures and long processing times. Another very conventional technology is hot air drying, which requires high temperatures, based on the transfer of matter and energy by the diffusion of humidity gradients. The food sector has applied green technologies, such as US, that improve processes, such as drying, without altering the quality of the product, making the processes more efficient and profitable for the industry [10]. This technology has been applied to various foods such as fruits, vegetables, seeds, and spices to improve their quality and shelf life [5].

Recent studies have shown that applying US as a pretreatment to hot air drying reduces processing time and energy consumption of the operation, because the rate of heat and mass transfer increases in a liquid medium, and acoustic transmission and vibrations are the main reasons in a gaseous environment during drying [11]. The application of ultrasonic-assisted vacuum drying (UAVD) significantly reduced the drying time of blood orange slices compared to hot air drying (HAD) and conventional vacuum drying (VD), reaching 7.5 h at 70 °C versus 9 h for VD and 22.5 h for HAD at 50 °C. Increasing temperature accelerated drying in all methods, but the ultrasound effect resulted in higher effective diffusion coefficients (2.20×10^{-5} to 2.99×10^{-5} m^2/s) and better retention of bioactive compounds, with total phenolic content close to that of freeze-dried samples (128.77 mg GAE/100 g at 50 °C) and vitamin C levels ranging from 29.79 to 49.01 mg/100 g. Moreover, the method influenced color parameters, confirming that UAVD combines drying efficiency with the preservation of nutritional and sensory quality [11]. Ultrasound pretreatment during hot air drying of Roselle (*Hibiscus sabdariffa L*) leaves significantly improved drying efficiency and quality retention. Samples treated for 15 min (UD15) achieved about 47% shorter drying times than untreated leaves, with effective moisture diffusivity ranging from 1.21 to 3.29×10^{-1} m^2/s. The Page model best fitted the untreated samples, while the Logarithmic model suited the treated ones. UD10 showed the highest carotenoid content, and UD5 had the greatest vitamin C retention, while all treated samples exhibited lower total color change compared to controls. These results confirm that ultrasound pretreatment can reduce drying duration while preserving key nutritional and sensory attributes [12].

Ultrasonic cavitation-induced heating results in a localized increase in temperature and accelerated mass transfer within the material. This effect enhances internal water diffusion, generating changes in the material's microstructure and physical properties, as well as dynamic interactions that promote its drying process [11, 12]. The objective of this study is to evaluate the effect of pretreatment with US (40 kHz/200W/10, 20, and 30 min) on convective drying at 60°C/2m/s of cocoa beans (*Theobroma cacao L.).*

2. MATERIALS AND METHODS

2.1 Location and raw material

This research work was developed in the facilities of the Foundation Alcaraván, specifically in the Cocoa School, located in the municipality of Arauca situated in the Department of Arauca, Colombia. For the study, samples of cacao beans fermented for seven days were used, from crops established at the Foundation Alcaraván. Beans were randomly selected with a diameter between 2 and 3 cm. It should be noted that the moisture content (MR) was considered a dependent variable, as its value varies depending on the time and conditions applied during the drying process.

2.2 Ultrasound treatment

The 500g samples, previously vacuum-packed in polyethylene bags, were subjected to treatment in Branson 1510 ultrasonic baths (40kHz/ 110W), using deionized water as the transmission medium. The temperature was digitally controlled at 30°C, and treatments were applied for 10, 20, and 30 min, generating three experimental conditions. Grains that did not receive ultrasonic treatment were used as a control group. Each treatment was replicated three times for subsequent statistical analysis.

2.3 Convective drying

The determination of the drying kinetics was carried out in a convection dryer with small-scale trays Model PS-SE-001/PE, Brand Generatoris. The samples were placed on waxed paper to avoid overlapping, and speed variables were controlled. air constant 2m/s at 60°C. Initially, measurements were taken every five minutes for the first 30 min, then weight and moisture data were recorded every ten minutes until the sample weight stabilized. The experiments were carried out at least in triplicate and were extended until the samples lost 90 to 92% of their initial weight [13].

2.4 Calculation of the effective diffusivity coefficient and activation energy

In the present experiment, the moisture ratio (MR) was used as an independent variable in Equation "(1)", which relates the moisture gradient of the sample in real time with the equilibrium moisture content. To describe mathematically the kinetics of drying the integrated equation of Fick second law was used for long periods "(2)" [14].

$$MR = \frac{Xwt - Xwe}{Xwo} - Xwe \quad (1)$$

$$MR = \frac{6}{\pi^2} \sum_{j=1}^{\infty} \frac{1}{j^2} exp\left[\frac{-j^2 D_{eff\,\pi^2 t}}{r^2} \right] \quad (2)$$

Where: Xwt: moisture content in real time (kg w / kg m.s); Xwo: initial moisture content (kg w / kg m.s); Xwe: equilibrium moisture content (kg w / kg m.s); J: number of terms; T: time (min); R is the radius of the sample (m); Deff: effective water diffusivity (m^2 / s).

2.5 Mathematical Modeling

Five thin-layer mathematical models, among the most commonly used in literature, were employed to represent the experimental drying kinetics. Table 1 shows the expression of selected models. In these models, the dependent variable is MR, which represents the moisture ratio (MR = M / M0). Where: M is the product moisture at a given time, M0 is the moisture at the initial time, t is the drying time, and k, n, a, b, c, g, and h are parameters or constants in the models.

Table 1. Mathematical models used by different authors in the study of drying behavior.

Equation	Nombre	Ecuación modelo	Referencias
"(4)"	Newton	*MR = exp(-kt)*	Vega et al. [14]
"(5)"	Henderson and Pabi	*MR = a * exp(-kt)*	Doymaz [15]
"(6)"	Page	*MR = exp(-ktn)*	Senadeera et al. [16]
"(7)"	Page Modificada	*MR = exp(-kt)n*	Toğrul and Pehlivan [17]
"(8)"	Exponential	*MR =exp (-k • t)*	Khampakool et al. [18]

The mathematical models selected to describe drying kinetics, Newton, Henderson and Pabis, Page, Modified Page, and Exponential, were chosen for their broad application in the study of agricultural products with hygroscopic characteristics similar to cocoa beans. These empirical and semi-empirical models allow for precise adjustment of the evolution of the moisture content over time and have demonstrated good performance in previous studies on fruits, seeds, and beans with high initial moisture content [19]. Furthermore, their relatively simple mathematical structure facilitates parameter adjustment and statistical comparison between treatments. While more complex models exist, such as those based on neural networks, finite elements, or multiscale approaches, these require more controlled experimental conditions, greater computational power, and more extensive data sets, which go beyond the objectives of this research. Therefore, models that balance reliability, ease of implementation, and validity for the type of material studied were chosen [13].

2.6 Fitting of the model

In the modeling of the kinetics of drying, the effective diffusivity was identified by adjusting diffusive models to experimental data. The identification was carried out by the method of optimization of Generalized Reduced Gradient. (GRG). The fitting was determined from the percentage of explained variance (% VAR, "(9)") [13].

$$\%VAR = 1 - \frac{S_{xy}^2}{S_y^2} * 100 \quad (9)$$

Where: Sxy and Sy are the standard deviation of the estimate and the sample, respectively.

To evaluate the fitting of the mathematical models with experimental data, the following statistical coefficients were used: the coefficient of determination (R^2), CHI-square (X2) "(10)"and squared sum of errors (SSE) "(11)". The best fittings were those models that had the lowest values of X2 and SSE and the highest values of R^2 (Campo et al., 2020a).

$$X^2 = \frac{\sum_{i=1} N\left(MR_{\exp,i} - MR_{pre,i}\right)^2}{N - z} \quad (10)$$

$$SSE = \frac{1}{N} * \sum_{i=1} N\left(MR_{exp,i} - MR_{pre,i}\right)^2 \quad (11)$$

where MRexp.i represents the moisture ratio obtained experimentally, MRpre.i are the predictions made by the mathematical models, N is the number of data z the number of constants. Fitting and calculations of these statistical analyses were performed using the Microsoft Excel software.

2.7 Statistical analysis

The results obtained were treated statistically through standard analysis of variance (ANOVA). To better discern the results of the ANOVA, the post hoc test of Minimum Significant Differences (MSD) was used. The experiments were carried out in triplicate using the statistical software package SPSS version 26.0.

3. RESULTS

3.1 Convective drying.

Figure 1 shows the behavior of the experimental drying curves of cocoa pretreated with US and the control sample, with an average initial moisture content of 5.22 ± 0.02 kg w/kg m.s., observing a rapid decrease in grain moisture (critical phase) during the first 300 min to subsequently decrease as the process time increases, because the water is bound to the monolayer of the solid phase of the fruit [13]. The samples treated with US showed significant differences (p<0.05) by presenting greater moisture loss in the three exposure times compared to the control sample.

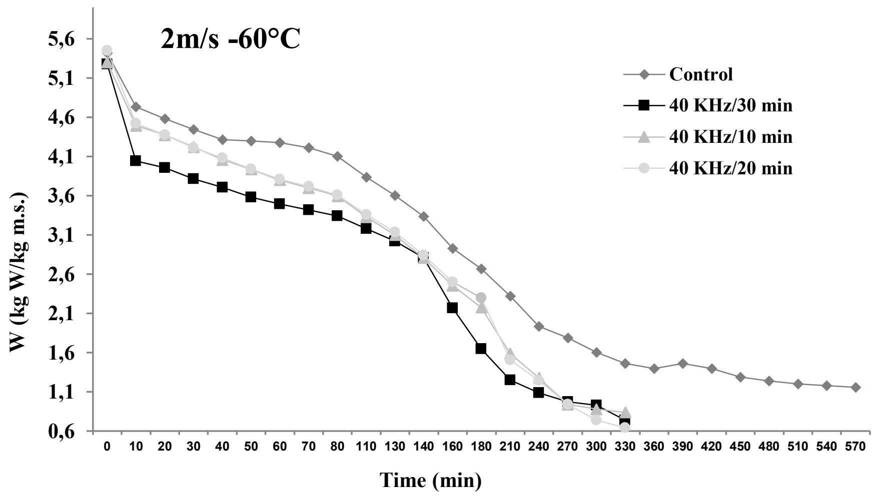

Figure 1. Moisture content curves of cocoa pretreated with US (40kHz) during hot air drying (60°C and 2m/s). ± SD: n: 3. The different letters represent statistical differences among the groups (p <0.05).

The control samples needed 10 h to reach an average moisture content of 1.2 ± 0.1 kg w/gm.s., similar results were reported by Bardales et al. [20] when evaluating the drying time of cocoa (*Theobroma cacao L*) using forced convection solar dryers based with an initial humidity of 55%; the total drying time was 22 h, with an average temperature range of the drying chamber of 42.7 °C. Likewise, studies carried out by Atiaga and Tarco [9] when evaluating the behavior of the drying kinetics of national cocoa and CCN-51 from Ecuador at a variable drying temperature scale from 35 °C to 70 °C based on the second law of Fick at an air speed of 2m/s at 60°C with an initial humidity of 50%, it was found that the national cocoa reached a minimum drying time of 7 h and in the CCN-51 of Ecuador a drying time of 6.5 h with a moisture content of 5.4 %, for temperatures of 70 °C.

Chica [21] evaluated the drying conditions for cocoa beans (variety TCS01) under controlled operating conditions with two types of drying (stationary and transitory) at 50°C, 60°C, 70°C with an air flow constant of 1 L/min with an initial humidity of 48%, where I report a drying time of 30, 20 and 11 h respectively for each temperature until reaching an average final humidity of 7% in the cocoa bean.

US treatment for 30 min showed the best drying performance, reaching a final moisture content of approximately 0.61 kg H_2O/kg m^2/s in 270 min. This was followed by treatments lasting 10 and 20 min, which reached their minimum moisture content in 330 min, while the control sample reached its minimum moisture content in 600 min. Compared to the control, the US treatments achieved a reduction in drying time of 55% and 45%, respectively.

Similar results were presented by Azoubel et al. [19] when evaluating the pretreatment with US (25 kHz/30°C/ 10, 20 and 30 min) on the kinetics of banana drying based on the diffusional model (Fick second law) at an air velocity of 3.0 m/s, finding that the US increased the diffusivity with increasing temperature and the process time was significantly reduced, where the Page Model was the one that best fit the experimental drying kinetics with an error mean relative calculated between 1.89% and 12.76% and R^2 values greater than 0.99. Likewise, La Fuente et al. [22] applied a pretreatment with US (154 W/25 kHz) for 20 and 25 min at 50 and 60 °C before drying the banana with hot air, finding a reduction in the drying time of the banana. 28% and 18% respectively, due to cell rupture that generates microscopic channels facilitating the movement of water, accelerating the drying process.

Nadery & Taghian, [23] studied carboxymethylcellulose (CMC) coatings (1:2, 1:3 and 1:4) and pretreatments with US (20 kHz/ 0, 500 and 1000 W) at an air speed of 3 m/s in the convection drying of banana slices, observing that the increase in ultrasonic power of 1000 W decreased the drying time. A ratio of sample to coating solution of 1:4 improved the porosity of the slices of dried banana. Similar results were reported by Campo et al. (2020a) when performing the drying kinetics (60°C/2ms^{-1}) of banana slices treated with US (40kH/130W/30min), observing an average reduction of 50% in the drying time and achieving a weight loss of 77% of the initial weight; this may be due to the formation of microchannels that is caused by cavitation, facilitating the escape of water from the matrix in the form of vapor by sublimation, which causes an increase in drying rates.

Likewise, Wang et al. [24] obtained a weight loss of 35% in the okra when exposing it to 25 kHz/25°C for 15 min, and Allahdad et al. [25] a weight loss of 45 and 50 % in the grenade at 40 kHz/100 W at 30°C for 60 and 80 min respectively. Similarly, studies carried out by Bozkir et al. [26] evaluated the effect of US at 35 kHz for 10, 20 and 30 min on osmotic dehydration (30 °C, 45 °Brix) before convective drying (60 °C/ 1.5 m/s) of the persimmon fruit, finding increased water loss and sugar gain; with an increase of 21% in the effective diffusivity of the water at 30 min; because US waves increase the mass transfer from the liquid medium to the fruit, they accelerate the mass (sugar) transfer. Zhang & Abatzoglou [27] and Kewlani et al. [28] describe that the US causes a 'Sponge Effect' that is mainly responsible for mass transfer as a result of a series of rapid compression and expansion movements that lead to improve the rate of internal diffusion, facilitating the release of intracellular components.

Studies Rojas et al. [29] reported a 70% reduction in conventional drying time by applying US (21.77 kHz for 30 min) to apple slices previously immersed in ethanol for the same time. This effect is attributed to the fact that ultrasonic frequencies below 40 kHz significantly increase extraction efficiency, due to the natural resonance frequency of the bubbles in the solution, which generates a greater oscillation amplitude and intensifies cavitation [30, 31].

Liu et al. [32] evaluated the effect of US (28 kHz/0, 18, 36, and 54 W/40 °C) on the drying kinetics of kiwi slices, observing a decrease in drying times of 360, 300, and 240 min at ultrasonic powers of 18. 36 and 54 W with a reduction of 20%, 33% and 46% respectively, with values of the effective diffusivity coefficient (Deff) of water increased from 2.304×10−9 to 4.026 10 −9 m^2/s; Scanning electron microscopy (SEM) analysis showed that US could produce a more porous and spacious microstructure, improving migration or complete removal of free water and to a lesser extent bound water based on the results of nuclear magnetic resonance analysis (RNM). According to Liu et al. [33], US penetrating food matrices causes microbubbles that, when bursting, produce vibration and turbulence, reducing the adsorption capacity of water, improving fluidity, diffusion, and mass transfer, and decreasing drying time.

3.2 Determination of the diffusivity coefficient.

Table 2 shows the values of the effective diffusivity coefficient (Deff) of the water with and without the application of US, where the adjustment of the model to the experimental values was better in the samples treated with US, with percentage values of 98.1 to 99.2% variance, while the control showed 88.5%.

Table 2. Values of the effective diffusion coefficient in cocoa drying with and without US application.

Estimated parameters	Control	Treatments (40KHz/130W/30°C)		
		10 min	20 min	30 min
***Deff*(10^{-10} m^2/s)**	3.22±0.81^a	6.65±0.3^b	7.45±0.2^b	8.87±0.7^c
%VAR	88.5	98.1	98.7	99.2

± SD: n: 3. The different letters (a, b) show statistical differences among the groups (p <0.05).

It is observed that the Deff value increases significantly ($p<0.05$) as the exposure time to US increases from 6.65 to 8.87 x 10-10 m^2/s; possibly because the US increases this parameter by expanding the heat energy and the increase in temperature by generating the cavitation phenomenon; facilitating drying by accelerating the loss of water due to the formation of microchannels in the matrix that facilitate the escape of water. Similar results in Deff values were reported in previous studies of vegetables dried with US pretreatment, such as carrots [34], parsley leaves [35], banana [13], and cape orange [11].

According to Lin et al. [36], SEM analysis revealed that ultrasonic pretreatment induced pronounced microstructural disruption in orange peel, characterized by the formation of pores, cracks, and partial epidermal detachment compared to the smooth, intact surface of fresh samples. The severity of damage increased with ultrasonic power and exposure time, indicating that mechanical vibrations and localized pressure fluctuations facilitated cell wall rupture and membrane collapse, consistent with the mechanisms described by Gao et al. [37] and García et al. [38]. These findings are in agreement with Lai et al. [39] and Tamer et al. [40], confirming that combined physical effects intensify tissue breakdown, accelerating water removal but potentially compromising structural integrity.

3.3 Modeling of drying kinetics

The results of the 5 models (Newton, Henderson and Pabis, Page, modified Page and exponential) used to determine the estimated values of the drying parameters can be seen in table 3, which includes the quality criteria (R^2, SSE and x2), with standard deviation of 3 replicates showing that different letters (a, b) show statistical differences between the groups ($p<0.05$). The model that best represented the experimental drying curves for the three conditions studied was the Page model; closer to 1.0 and SSE and x2 closer to zero, with an increase in the values of the constant k for all the treatments applied to US, which means that the drying model is dependent on the exposure time; other studies carried out for banana drying such as Atiaga and Tarco, [9] report the same model.

Table 3. Values of the adjustment parameters of the selected drying models.

Models	Statistical tests	Control	TREATMENTS (40KHz/130W/30°C)		
			US/10min	US/20min	US/30min
Newton	k ($x10^{-3}$)	$3.18±0.05^a$	$6.19±0.23^b$	$8.78±0.72^c$	$12.12±0.13^d$
Henderson and Pabi	k($x10^{-3}$)	$4.08±0.14^a$	$6.35±0.12^b$	$8.21±0.86^b$	$12.12±0.51^c$
Page	k($x10^{-4}$)	$0.11±0.01^a$	$0.53±0.02^b$	$0.79±0.02^c$	$1.01±0.02^d$
	n	$1.48±0.05^a$	$1.11±0.02^b$	$1.23±0.02^b$	$1.05±0.01^c$
Page Modificada	k($x10^{-3}$)	$2.74±0.22^a$	$5.67±0.32^b$	$8.43±0.65^c$	$11.67±0.24^d$
	n	$1.23±0.01^d$	$1.45±0.01^b$	$1.47±0.03^c$	$1.47±0.07^c$
Exponencial	k($x10^{-2}$)	$8.21±0.16^a$	$9.54±0.73^a$	$11.12±0.99^a$	$26.09±0.87^b$
	n	$1.22±0.01^a$	$1.76±0.02^b$	$1.56±0.05^a$	$1.47±0.09^b$
	a	$-0.49±0.03^a$	$-0.34±0.02^b$	$-0.15±0.02^c$	$-0.04±0.01^d$

± SD: n: 3. The different letters (a, b) show statistical differences among the groups ($p<0.05$).

DISCUSSION

The results of this study highlight the significant impact of US pretreatment on the convective drying process of cocoa. Figure 1 demonstrates that US-treated samples experienced a substantial reduction in drying time compared to the control, reaching final moisture content levels much faster. Specifically, samples subjected to 30 min of US exposure achieved their target moisture content in just 270 min, representing a 55% reduction in drying time compared to the control. This finding aligns with previous studies on other fruits, such as bananas, which reported accelerated drying rates and reduced drying times with US application [19, 22].

The increase in drying efficiency can be attributed to the cavitation phenomenon induced by US, which creates microchannels in the cocoa matrix. These microchannels facilitate water escape and enhance mass transfer, as observed in similar studies on fruits like kiwi [32] and persimmons [26]. The effective diffusivity coefficient (Deff) values further corroborate these findings, showing a significant increase ($p<0.05$) from 3.22×10^{-10} m²/s in the control to 8.87×10^{-10} m²/s in the samples treated with US for 30 min.

The Page model was determined to be the best fit for describing the drying kinetics, with R^2 values nearing 1.0 and minimal SSE and χ^2 values, indicating high accuracy. The model's reliability aligns with findings from similar research on cocoa and other agricultural products, as reported by Atiaga and Tarco [9] and Azoubel et al. [19]. The observed dependence of the drying rate constant (k) on ultrasound (US) exposure time highlights the significant influence of this technology in enhancing drying efficiency, reinforcing its potential as a viable method for improving both process performance and product quality [26].

Duan et al. [41] evaluated US pretreatment in Carrot samples at different power levels before EHD drying to determine optimal conditions. Compared to the CK group, US reduced drying time by 17.4%–39.1% and increased the drying rate by 21.0%–54.4%. The best results were observed at 180 W, improving rehydration, maintaining color, and optimizing volatile compounds. Overall, 180 W was the most effective pretreatment condition for enhancing drying efficiency and quality.

Llavata et al. [42] investigated the effects of freeze-thaw and pulsed electric field (PEF) pretreatments on the drying kinetics and microstructural integrity of orange peels using conventional and US-assisted methods. The study found that fast freezing generated small ice crystals that hindered water diffusion, whereas slow freezing produced larger crystals that facilitated moisture transport. While PEF pretreatment enhanced moisture diffusivity, it also risked collapsing the food matrix. Notably, US-assisted drying significantly reduced drying time and preserved microstructure, with LiPEF-US achieving the greatest reduction (40%) and the highest effective diffusivity and drying rate. These findings underscore the potential of integrating pretreatments with US to optimize drying efficiency while maintaining the structural integrity of orange peels, contributing to sustainable waste management in the juice industry.

According to Zhou et al. [43], US technology has emerged as an effective non-thermal method for enhancing drying efficiency and quality in fruits and vegetables. Traditional drying techniques, such as hot air and vacuum drying, often result in slow drying rates and nutrient loss. US accelerates the drying process by facilitating moisture migration through mechanisms like cavitation, the sponge effect, and mechanical impact. The review highlights that the US not only reduces drying time but also preserves key quality attributes, including color, texture, microstructure, and bioactive compounds. Additionally, it improves antioxidant capacity and microbial quality, making it a promising solution for the food industry. Despite its advantages, further research is needed to optimize US-assisted drying for large-scale applications.

However, it is essential to note some limitations of the present study. The experiments were conducted under controlled laboratory conditions, which may not fully represent industrial-scale applications. Additionally, while the focus was on drying efficiency and diffusivity, other quality parameters such as flavor, texture, and nutritional content were not evaluated. Future research should address these aspects to provide a more comprehensive understanding of the implications of US technology in cocoa drying.

4. CONCLUSIONS

This study demonstrated that ultrasound pretreatment significantly improves the convective drying of cocoa, reducing drying time by up to 55% compared to untreated samples. The treatment enhanced water removal efficiency, increased effective diffusivity, and elevated the mass transfer coefficient, confirming its potential as an intensification technology for cocoa postharvest processing. Among the evaluated mathematical models, the Page model provided the best fit, accurately describing the drying behavior and enabling precise prediction of process performance. The originality of this work lies in applying ultrasound pretreatment to cocoa, a crop of high economic and social relevance, under controlled convective drying conditions and comparing different exposure times. The results provide novel evidence that ultrasound can act as a cost-effective, energy-saving, and quality-preserving alternative for optimizing cocoa drying. These findings not only contribute to advancing food engineering applications but also open practical opportunities for more sustainable and competitive cocoa production.

Conflicts of interest: The authors declare that there are no conflicts of interest regarding the publication of this research.

Authors' contributions: YCV contributed to the conception and design of the study, as well as the collection, analysis, and interpretation of data. She was also responsible for drafting the manuscript and ensuring its scientific rigor. **MAD** participated in the development of the methodology, supervised the data analysis, and provided critical revisions to the manuscript. Both authors engaged in discussions throughout the research process, reviewed and approved the final version of the manuscript, and agree with the responsibilities attributed to them. Their collaborative efforts reflect a significant contribution to the successful completion of this work.

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