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Research article

Impact of combined sun and hybrid drying technologies on cocoa drying process and quality

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A R T I C L E I N F O

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A B S T R A C T

The drying process is essential in cocoa (*Theobroma cacao* L.) production, significantly influencing product quality and energy consumption. This study compares four drying methods: sun drying (SD), solar-electric hybrid drying (HD), SD followed by HD (SD + HD), and HD followed by SD (HD + SD). The physicochemical properties (shrinkage, fermentation index, pH, total acidity, color), bioactive compounds (total phenolic content, antioxidant capacity), and drying efficiency (drying rate, effective moisture diffusivity, energy consumption) were assessed. Results show that HD and HD + SD effectively preserve cocoa's physicochemical and antioxidant properties. Starting with HD increases the drying rate by 20 %, resulting in higher moisture diffusivity coefficients (over 4.12×10^{-7} m^2/s). Combining HD with SD reduces energy consumption by 56.6 %, improving energy efficiency. SD increased cocoa bean shrinkage by up to 9 %, and HD maintained phenolic content. The HD + SD method is, therefore, a promising, energy-efficient alternative for small-scale cocoa producers, contributing to industry innovation and sustainability.

1. Introduction

Cocoa (*Theobroma cacao* L.) beans, the primary raw material for chocolate manufacturing, are derived from a crop experiencing continuous expansion in production. It is considered an economically significant activity for the primary producer countries, including Côte d'Ivoire, Ghana, Indonesia, Nigeria, Ecuador, Mexico, and Brazil [1]. Drying is a critical stage in post-harvest processing that significantly impacts the quality of cocoa beans [2]. However, the drying process for cocoa, particularly in small- and medium-scale agriculture, still relies on conventional and non-standardized methods with low energy efficiency, leading to inconsistent bean quality.

Conventional drying methods for cocoa include sun drying (SD), drying in solar greenhouse dryers, and drying with gas or diesel as an energy supply. SD is economical but has significant limitations, such as dependence on climatic conditions [2,3]. During the rainy season, there is an increase in ambient humidity, which introduces substantial complications in the drying process [4]. Using

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greenhouse dryers is an environmentally friendly method that offers higher temperatures and provides excellent protection against biotic contaminants, but it is also linked to long processing times [5]. On the other hand, using dryers with gas or diesel is faster, but it requires technical knowledge and precise control of temperature and airflow to avoid very dry or smoky beans [3].

In recent years, the search for clean, sustainable, green, and friendly technologies has increased, especially in response to the need to improve cost-effectiveness and counteract energy efficiency problems of conventional drying methods [6]. Hence, SD that works by natural or forced convection has been developed, such as solar hybrid dryers. Hybrid drying (HD) is an emerging technology combining two or more heat transfer mechanisms [7]. In these dryers, the food is dehydrated by solar energy and other secondary sources of energy that operate in off-sunshine hours, such as electric heaters, biomass furnaces, waste heat, and LPG, among others [8]. Since solar energy depends on high radiation, hybrid dryers are useful even during unfavorable weather conditions. This technology has led to energy savings of 50–70 %, reduced process times, increased effective moisture diffusivity, and improved drying [7]. HD eliminates the effect of solar radiation fluctuations and keeps the airflow temperature constant, leading to higher product quality by avoiding process interruption at night or in cloudy conditions. Consequently, the appearance of cracks, moisture reabsorption, and mold growth in the cocoa bean are mitigated [9].

Indeed, drying process deficiencies can result in cocoa beans with high moisture levels or excessively dry, leading to severe problems in the value chain [10]. Consecutively, prolonged drying promotes the development of fungi [2]. These complications adversely influence the quality, production capacity and yield of cocoa beans, leading to product losses and weakening the competitive position in the international market, which demands high standards. Adopting new drying techniques that offer greater control over the drying process, regardless of external environmental conditions, is essential. However, this is a significant challenge for small- and medium-scale farmers due to the high energy consumption inherent in the equipment, the costs associated with the implementation and utilization of electrical inputs, and the need for technical skills.

As a result, the cocoa value chain needs to establish new alternatives to improve drying time, energy consumption, and the physicochemical and bioactive quality of cocoa beans. In addition, implementing sustainable and efficient technologies is becoming increasingly relevant in today's environmental challenges and increasing energy austerity. Recently, some studies have combined different drying methods to reduce energy consumption [11] however, adopting combined drying technologies, such as SD and HD, has been little explored. Therefore, in the current study, CCN-51 cocoa samples were collected and fermented under controlled conditions, then dried using SD, HD and two combined technologies. This research evaluated the effect of combining SD and HD on cocoa drying efficiency and cocoa's bioactive and physiochemical characteristics. This study gives insight into drying technology that lowers energy consumption and increases cocoa quality, which can be applied to small and medium farms.

2. Materials and methods

2.1. Materials

Samples of cocoa variety CCN-51 were harvested in the rainy season of 2023 at a farm in the province of Guayas, in the Coastal region of Ecuador, and the pods were transported to the lab and processed immediately.

2.2. Fermentation

The farm fermentation processes are subject to high variability due to extrinsic factors such as differences in environmental microbiota, climate, substrate, and fermentation method, which they termed as confounding variables [13]. Due to research purposes, the fermentation process of the present study was carried out in a climatic chamber to eliminate variables that could interfere with the drying results. Fresh cocoa beans with mucilage (2.5 kg), with an initial moisture content of 56.45 $\pm$ 4.99 %, were separated from the pod and immediately submitted to fermentation in a climatic chamber (Memmert, TCH 750, Schwabach, Germany) at temperature-controlled (30 °C) for 5 days. The cocoa was manually turned every 24 h to promote aeration. At the end of the fermentation process, the cocoa beans reached a final moisture content of 44.14 $\pm$ 5.43 %.

2.3. Cocoa beans drying

After fermentation, the cocoa was divided into portions of 0.5 kg. Each batch of fermented cocoa was dried in a thin layer using a specific drying method described below. The drying processes applied were SD, HD, SD + HD, and HD + SD. All drying methods were conducted discontinuously over several days, with variable drying periods between 9:00 a.m. and 5:00 p.m., during which sunlight was available. The process continued until the cocoa beans reached a moisture content of approximately 6 %, a key quality parameter. Between drying sessions, the cocoa beans were stored in a desiccator to avoid the reabsorption of ambient humidity to continue with the drying process the next day.

2.3.1. Sun drying (SD)

SD was performed by spreading cocoa beans on a black plastic sheet placed on the ground and exposing them to direct sunlight for two to 8 h per day, depending on the prevailing weather conditions. The process was done over five days until the final moisture content was reached (6 %).

2.3.2. Solar-electric hybrid drying (HD)

HD was performed in a solar-electric dryer with a capacity of 12 kg (Fig. 1) [12]. The hybrid dryer has two sources of energy: solar radiation and a 2200W electrical resistance that operates mainly during periods without exposure to sunlight. The electric heater was switched on and off depending on the availability of solar radiation. The dryer is integrated with a solar collector, which preheats the air before directing it into the dryer and a 0.08 m diameter blower (energy rating by IE3) to ensure airflow circulation. The electrical resistance is controlled by a digital thermostat that maintains the temperature of the drying chamber. The drying conditions in the hybrid dryer were 50 ± 1.5 °C and an airflow rate of 2.5 m/s.

2.3.3. Combination of sun and hybrid drying (SD + HD)

The combined drying processes were conducted in batch operations and were divided into two stages, switching from one method to another when the moisture of cocoa beans was approximately 17 %. At this moisture content, the change in moisture becomes negligible, and the drying rate decreases significantly, as observed in preliminary experiments. Therefore, in SD stage, the cocoa beans were exposed directly to the sun for 16 h discontinuously, starting from an initial moisture content of 44.14 ± 5.43 % and reducing it to 17.00 ± 0.50 %. Then, HD continued until the target moisture content was reached (from 17.00 ± 0.50 % to a final moisture content of 6.00 ± 0.50 %).

2.3.4. Combination of hybrid and sun drying (HD + SD)

This procedure also involved two batch operations, transitioning from one drying method to another when the cocoa beans reached an approximate moisture content of 17 %. For HD + SD drying, the process began with HD technology, which was conducted continuously for 8 h (from 44.14 ± 5.43 % to 17.00 ± 0.50 % of moisture content). Subsequently, SD was carried out discontinuously over multiple sessions until the final moisture content was achieved (from 17.00 ± 0.50 % to 6.00 ± 0.50 % of moisture content).

2.4. Temperature, relative humidity, and solar radiation monitoring during drying processes

The environment drying conditions of the drying area and inside the dryer chamber were monitored using a 4-channel data logging thermometer (Reed Instruments, SD947, Wilmington, USA), a thermo-hygrometer (Lascar Electronics, EL-USB-2-LCD+, Erie, USA), and a pyranometer (Campbell Scientific, CMP3, Logan, USA) for the temperature, relative humidity, and solar radiation, respectively. The airflow temperature and relative humidity at the inlet and outlet of the dryer were also recorded.

2.5. Desorption isotherm

The fermented beans were ground into a homogeneous paste for cocoa isotherm determination. The resulting paste was then dried in an oven at 50 ± 1 °C. At different times, 1 g of the sample was randomly taken from the oven to determine water activity (a_w) and moisture content. The a_w represents the amount of 'available water' in the cocoa bean for microbial growth and chemical reactions, it was determined using the AquaLab water activity meter (Decagon Devices Inc., S3TE, Pullman, Washington D.C., USA), and the moisture content measurements were performed with an infrared moisture analyzer (AS220.X2, Radwag, Radom, Polonia). This procedure was repeated until a water activity of less than 0.200 was measured. The GAB equation (Equation (1)) was fitted to the experimental data obtained using the least squares method [13].

$$m = \frac{m_o C_G K a_w}{(1 - K a_w)^*(1 - K a_w + C_G K a_w)} \tag{1}$$

where m is equilibrium moisture content, %; m_o is monolayer moisture content, %, a_w is water activity; and K and C_G are dimensionless constants related to multilayer and monolayer properties, respectively.

2.6. Drying rate curves

The experimental determination of drying rate curves for each technology was conducted in triplicate using 0.5 kg samples. The

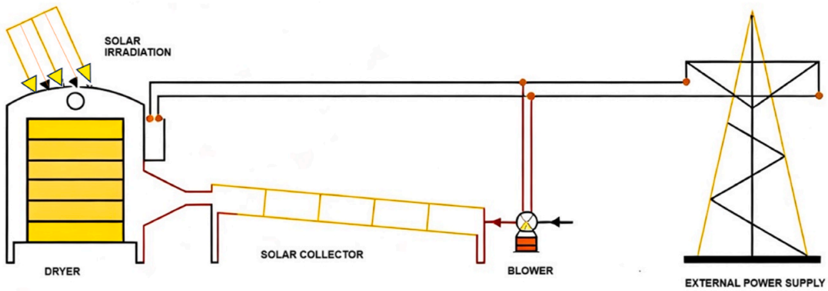

Fig. 1. Scheme of the hybrid dryer.

total weight of the wet solid at different times t (Equation (2)) was obtained by measuring the weight of the wet solid at 60-min intervals, continuing this process until no variation in the weight of the samples was observed [14]. The weighing process takes between 1 and 1.5 min.

$$X_t = (W - W_s) / W_s \ (kg\ total\ water / kg\ dry\ solid) \tag{2}$$

where X_t is the dry basis moisture content at different times t, W is the weight of the wet solid in kg total water plus dry solid, and W_s is the weight of the dry solid in kg.

The data collected during the drying experiments were expressed by plotting a graph of free moisture content X (Equation (3)) as a function of time [14].

$$X = X_t - X^* \tag{3}$$

where X is the free moisture content, X_t is the dry basis moisture content at different times t, and X^* is the equilibrium moisture content.

The drying rate curve was obtained by plotting the drying rate R (Equation (4)) as a function of free moisture [14].

$$R = -L_s\, dX / A\, dt \tag{4}$$

where R is the drying rate in kg $H_2O/h.m^2$, L_s is kg of dry solid used, and A is the surface area exposed for drying in m^2.

2.7. Mathematical modeling of drying rate curves

The experimental moisture data were fitted to three thin-layer models (Henderson and Pabis, Page, and Newton). Table 1 displays the equations of each model, where MR is moisture ratio, t is drying time (minutes), k is drying constant (minutes^{-1}), and a and N are model constants. The model constants were determined using the Microsoft Excel Solver optimization tool.

The selection of the mathematical model with the best fit to describe the drying kinetics of cocoa beans was decided based on the statistical parameters: coefficient of determination (R^2), sum of squared errors (SSE), and root mean square error (RMSE). To corroborate the fit quality, the R^2 should be high, while SSE and RMSE should tend to zero [15–17].

2.8. Estimation of effective moisture diffusivity

The effective moisture diffusivity of the cocoa bean samples was calculated using Fick's second law, assuming a spherical geometry (Equation (5)) [18].

$$MR = 6 \Big/ \pi^2 \sum_{n=1}^{\infty} \frac{1}{n^2} exp\left(-n^2\pi^2 \left(D_{eff} t / r^2\right)\right) \tag{5}$$

where MR is the moisture ratio, D_{eff} is the effective moisture diffusivity (m^2/s), r is the equivalent radius of the cocoa beans (meters), t is the drying time (seconds), and n is a positive integer. The equation can be simplified for long drying periods to Equation (6), assuming n equals one [11].

$$\ln(MR) = \ln\left(6 / \pi^2\right) - \left(\pi^2 \left(D_{eff} / r^2\right)\right)t \tag{6}$$

D_{eff} values were calculated using the negative slope k of the straight line resulting from plotting the predicted drying data relative to ln *(MR)* versus time according to Equation (7) [11]:

$$k = \pi^2 \left(D_{eff} / r^2\right) \tag{7}$$

2.9. Energy consumption

The dryer's energy consumption was evaluated by measuring electricity usage in kilowatt-hours (kWh) with power meters installed on the main power line supplying the entire system. These power meters recorded the energy consumed by the electric heater and the blower, ensuring an accurate measurement of the total energy consumption during drying. Controls were performed every hour. Total energy consumption is the sum of the energy consumed by the dryer's resistance and blower.

Table 1
Thin-layer mathematical models applied to drying kinetic data.

Model	Equation	Reference
Henderson y Pabis	MR = a exp (-kt)	Henderson & Pabis (1962)
Page	MR = exp (-kt^N)	Page (1949)
Newton	MR = exp (-kt)	Lewis (1921)

2.10. Shrinkage

Before starting the drying process, ten fermented cocoa beans were randomly selected. Shrinkage was determined by measuring the length (a), width (b), and thickness (c) of the beans using a digital caliper with an accuracy of 0.02 mm. Measurements were made before the drying process to establish their initial dimensions. Subsequently, the dry beans were measured after the drying period to monitor the variation in these dimensions. Shrinkage parameters were expressed in terms of a_d/a (equivalent length) and R_d/R (equivalent radio), where $\underline{a}$ is the bean length before drying, a_d is the bean length of the dry bean, R is the bean radius before drying, and R_d is the bean radius of the dry bean [19]. The bean radius was calculated according to Equation (8) and Equation (9).

$$R = \sqrt{(b^*c)/6} \tag{8}$$

$$R_d = \sqrt{(b_d{}^*c_d)/6} \tag{9}$$

where b is the bean width before drying, b_d is the bean width of the dry bean, c is the bean thickness before drying, c_d is the bean thickness of the dry bean.

2.11. Fermentation index (FI)

The fermentation index or degree of fermentation was determined according to Melo et al. (2021) [20]. 20 mg of previously ground and defatted cocoa was extracted with 10 ml of methanol: HCl solution (97:3 v/v). The resulting mixtures were vortexed (Thermo Fisher Scientific, model 945405, Waltham, Massachusetts, USA.) and kept at rest at a temperature of 8 °C for 16 h. After this time interval, the extract was filtered (MN 615 Ø 125 mm, Macherey-Nagel), and then UV–Vis absorbance measurement was performed at wavelengths of 460 and 530 nm using a spectrophotometer (Biotek Instruments, Winooski, VT, USA.). The fermentation index was determined as the ratio of absorbance values measured at 460 nm and 530 nm. This analysis was performed in triplicate.

2.12. Total acidity and pH

Total acidity was established by potentiometric method with NaOH (0.1 N) until a pH of 8.3 was reached, according to AOAC 22061. For the suspension, 2.5 g of ground cocoa was shaken (Thermo Fisher Scientific, MaxQ 4450, Waltham, Massachusetts, USA.) in 22.5 ml of distilled water for 5 min. Subsequently, the suspension was centrifuged at 3200 g for 10 min at room temperature. Finally, the pH of the resulting supernatant was measured [21]. The pH of the cotyledon was determined using a pH meter (Thermo Fisher Scientific, Orion 5-Star Plus, Waltham, Massachusetts, USA.). The analyses were performed in triplicate.

2.13. Color measurement

The color parameters (L, a* and b* values) of the cotyledon from dried cocoa beans were measured with the CIE-L* a* b* uniform color space (CIE-Lab) using the NH300 Portable Digital Colorimeter Color Analyzer (Shenzhen ThreeNH Technology Co., Ltd., Shenzhen, China) [22] with slight modifications. In addition, the equipment directly provided the chroma (C^*) and the hue angle (h^*), calculated internally based on the a* and b* values, using equations (10) and (11) [23]. For each drying method, measurements were triplicated on ten cocoa beans (n = 30).

$$C^* = \left(a^{*2} + b^{*2}\right)^{\frac{1}{2}} \tag{10}$$

For a* > 0 and b* ≥ 0:

$$H = tan^{-1}\left(\frac{b^*}{a^*}\right) \tag{11}$$

For a* < 0:

$$H = 180 + tan^{-1}\left(\frac{b^*}{a^*}\right)$$

2.14. Preparation of methanolic cocoa bean extracts

Cocoa bean samples were deshelled, ground, and defatted with hexane by Soxhlet extraction. 1 g of each defatted sample was weighed into centrifuge tubes. Subsequently, 10 ml of 80:20 (v/v) solution of methanol-hydrochloric acid (1000:1 v/v) in distilled water was added and mixed using a vortex (Thermo Fisher Scientific, model 945405, Waltham, Massachusetts, USA.). The samples with the solution were stirred continuously at 200 rpm and room temperature for 16 h in an orbital shaker (Thermo Fisher Scientific, MaxQ 4450, Waltham, Massachusetts, USA.). Extracts were centrifuged (Yingtai Instrument, TGL16, Changsha, Hunan, China) at 7000 rpm at 5 °C for 10 min. Liquid extracts were stored in glass vials in a −15 °C deep freezer for further analysis.

2.15. Determination of total phenolics compounds

The content of total phenolic compounds (TPC) in cocoa beans was analyzed using the Folin-Ciocalteu colorimetric method [24]. The absorbance was read on a microplate at 739 nm using a spectrophotometer (Biotek Instruments, Winooski, VT, USA.). The TPC of the extracts was calculated from the gallic acid standard curve and expressed as milligrams of gallic acid equivalents (mg GAE) per 100 g of dry solid extract.

2.16. Determination of antioxidant capacity

The antioxidant capacity of cocoa was determined in the methanolic cocoa bean extract by the Oxygen Radical Absorbance Capacity (ORAC) method [24]. The reaction was conducted at 37 °C in 75 mM phosphate buffer (pH 7.4). 2,20-azobis(2-methylpropionamidine) dihydrochloride (AAPH) 40 mM was used as peroxyl radical generator to inhibit oxidation, Fluorescein 116.9 nM solution as an indicator, and Trolox 4 mM stock solution as standard. The absorbance was measured in black 96 well plates at 485 and 528 nm using a microplate reader (Biotek Instruments, Winooski, VT, USA.). ORAC values of the extracts were calculated from the Trolox standard calibration curve and were expressed as micromolar Trolox equivalent (μM TE) per 100 g of extract dry solid extract.

2.17. Statistical analysis

Each drying method was conducted in triplicate. For each replicate, the physicochemical characteristics were analyzed either in duplicate or triplicate. This resulted in a total of six or nine measurements (n = 6 or n = 9), depending on the type of analysis performed. Data obtained from the physicochemical analysis and antioxidant activity were analyzed in Statgraphics Centurion XVI statistical software using one-way ANOVA and the multiple range test to determine significant differences between factors at a 95 % confidence level ($p<0.05$). Results were presented as mean ± standard deviation (SD).

3. Results and discussion

3.1. Desorption isotherm

The relation between a_w and moisture content experimental data was modeled using the GAB equation to fit the experimental data until a high correlation coefficient was achieved ($R^2 = 0.9901$). As a result, the estimated parameters were 0.02 kg H_2O per kg dry solid for the monolayer moisture content (m_o), 0.96 for the k coefficient and 8.17 for C_G coefficient. The monolayer value (m_o), located between 0.2 and 0.3 water activity, suggests the optimal moisture content region to avoid spoilage reactions and ensure maximum shelf life [25]. Fig. 2 shows that the obtained desorption isotherm is typical of type III isotherms, consistent with previous studies in cocoa beans [19]. The desorption isotherm allowed the determination of the equilibrium moisture content (0.036 kg H_2O/kg dry solid) to calculate free moisture and plot the drying curves.

3.2. Drying curves

Three mathematical models of drying kinetics were applied to describe the drying behavior of cocoa beans. The resulting parameters of each model, coefficients of determination, RMSE values, and diffusion coefficients are presented in Table 2. It is important

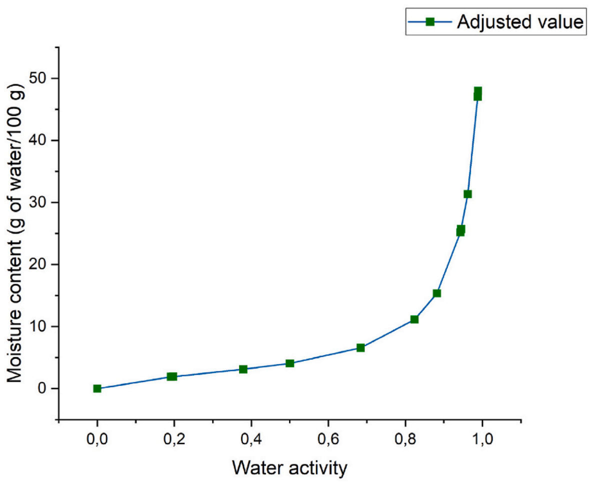

Fig. 2. Experimental moisture desorption isotherm of cocoa beans at 50 °C by applying GAB model.

to mention that RMSE ranges from 0.05 to 0.18 in all models, and coefficients of determination (R^2 values) are greater than 0.96. Indeed, the Henderson & Pabis model emerged as the most suitable for predicting the behavior of the cocoa drying process. It demonstrated the lowest average RMSE (0.07) and the highest average R^2 (0.98), consistently outperforming other models across all drying methods.

The drying coefficient k represents the moisture transfer rate. Table 2 shows that the *k* value is affected by the different drying methods ($p < 0.05$), with HD and HD + SD having the highest k values (between 55 % and 43.75 % greater than SD and SD + HD). Additionally, these methods resulted in the highest values of the effective diffusivity coefficient. Consequently, applying HD technology exhibited significantly superior drying rates, translating into a notable acceleration of the cocoa drying process. These differences in moisture transfer rate and effective diffusivity not only accelerate the drying process but can also influence important aspects of the final quality of cocoa. For instance, a higher drying rate may reduce the exposure time to heat, helping to preserve essential bioactive compounds such as polyphenols and flavonoids, which are responsible for the antioxidant properties of cocoa. However, overly rapid drying can also cause stress on the beans, increasing the risk of cracking or physical damage that may affect quality uniformity and ease of subsequent cocoa processing. Additionally, the internal structure and microbiological stability of the bean can be impacted. Fast and efficient drying can limit the growth of undesirable microorganisms, ensuring greater stability and quality of the bean during storage. On the other hand, if the drying process is not uniform, it could encourage the growth of molds or bacteria, negatively impacting the safety of the final product.

The loss of free moisture over time is shown in Fig. 3. The curves describing the reduction of free moisture for methods involving sun drying as the first stage of the process (SD and SD + HD) exhibit similar behavior, characterized by a minimal lag and an extended drying time of up to 30 h with SD. It is also noticeable that, in these two cases, the moisture content over time is higher than in methods starting with hybrid drying (HD and HD + SD). The free moisture curves of HD and HD + SD also show a similar pattern; however, they exhibit a significant lag compared to the lag observed between SD and SD + HD. In addition, after 4 h of drying process, it becomes evident that the moisture content with the application of the HD + SD technology surpasses the one observed solely with the HD, mainly as the drying process progresses beyond 8 h. This trend is attributed to the change of drying method to SD after this period, resulting in a lower decrease in moisture. Nevertheless, for all drying methods, the free moisture of cocoa beans decreases at an accelerated pace during the initial hours of drying due to the rapid removal of surface moisture, which is readily accessible to air. As the drying process progresses, the moisture loss rate slows significantly because the surface layers of the beans become harder, which creates a barrier that hinders the transfer of moisture from the internal layers to the drying medium [26].

Fig. 4 shows that the drying rate curves of the methods that start with the same drying type show analogous behaviors. The HD and HD + SD technologies register the highest drying rate throughout the process, even if the combination ends with SD. These observations suggest that the initial drying method significantly influences both the drying rate and the subsequent behavior of the process.

In the case of SD and SD + HD, they maintain a similar pattern in the direct SD stage, as was observed in Fig. 3. Concerning the curves of HD and HD + SD technologies, there is also a similarity in the drying rate behavior. As expected, HD technology demonstrated the highest drying rates. It is interesting to highlight that, from the point in the HD + SD curve where direct SD begins (free moisture of 0.24 kg of H_2O/kg of dry solid and drying rate of 0.07 kg of H_2O/h m^2), the curve adopts the same behavior observed at the end of the SD process, with a gradual reduction in the rate of moisture removal. On the other hand, it is evident that from 0.20 kg of H_2O/kg of dry solid, the drying rate decreases significantly in all methods due to the reduction of the moisture concentration difference between the product and the drying environment.

Overall, it is observed that the drying rate curves consist solely of a period of falling rate and do not exhibit a constant rate period. This drying rate behavior has been widely attributed to agricultural food products, among which have been cited moringa leaves, guava, and mango, among others [27–33]. Other authors declared that the period of constant velocity may be absent when surface moisture is rapidly removed from the food [33]. However, it can also be deduced that the free moisture in the outer layers of cocoa, which represents the easiest portion of water to remove, was removed during the fermentation stage. For this reason, the present study

Table 2
Models fitted for free moisture content versus time.

Mathematical model	Drying method	Parameter			R^2	SSE	RMSE	D_{eff} (m^2 s^{-1})
		a	k	N				
Henderson & Pabis	HD	0.84^a	0.20^{bc}	–	0.98^{ab}	0.01^a	0.05^a	$1.26x10^{-10\ bc}$
	HD + SD	0.81^a	0.16^{bcde}	–	0.98^a	0.01^a	0.05^a	$1.14x10^{-10\ cd}$
	SD	0.82^a	0.09^e	–	0.97^{cde}	0.02^{ab}	0.09^{bc}	$6.62x10^{-11g}$
	SD + HD	0.82^a	0.09^e	–	0.97^{bcd}	0.02^{ab}	0.08^b	$7.45x10^{-11\ fg}$
Page	H	–	0.35^a	0.77^a	0.97^{abcd}	0.03^{bc}	0.11^{cd}	$1.04x10^{-10\ cde}$
	HD + SD	–	0.36^a	0.69^a	0.98^{abc}	0.02^{bc}	0.10^{bc}	$8.99x10^{-11\ defg}$
	SD	–	0.22^b	0.76^a	0.97^{cde}	0.04^d	0.14^e	$6.62x10^{-11g}$
	SD + HD	–	0.19^{bcd}	0.79^a	0.97^{cde}	0.05^d	0.15^e	$6.62x10^{-11g}$
Newton	H	–	0.24^b	–	0.97^{def}	0.04^{cd}	0.13^{de}	$1.56x10^{-10a}$
	HD + SD	–	0.21^b	–	0.96^f	0.05^d	0.15^e	$1.47x10^{-10\ ab}$
	SD	–	0.12^{cde}	–	0.96^f	0.07^f	0.18^f	$9.93x10^{-11\ cdef}$
	SD + HD	–	0.12^{de}	–	0.96^{ef}	0.06^f	0.17^f	$8.28x10^{-11\ efg}$

HD: Hybrid drying; HD + SD: Combination of hybrid drying and sun drying; SD: Sun drying; SD + HD: Combination of sun drying and hybrid drying. Values followed by different letters within a column denote significant differences ($p < 0.05$). Mean ± standard deviation (n = 3).

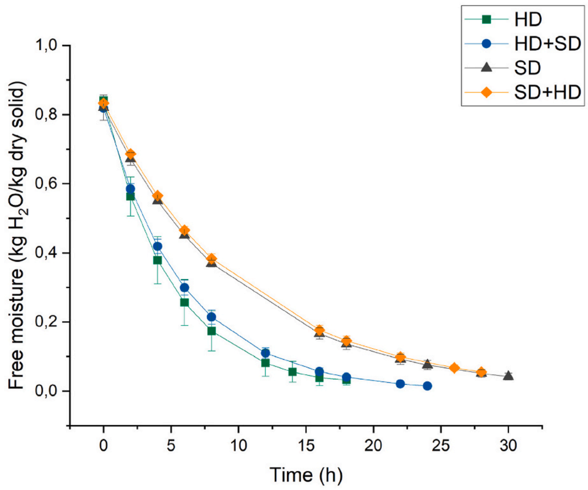

Fig. 3. Variation of predicted free moisture content by Henderson & Pabis model versus drying time for cocoa beans using different methods (HD: Hybrid drying, HD + SD: Hybrid drying followed by sun drying, SD: Sun drying, SD + HD: Sun drying followed by hybrid drying).

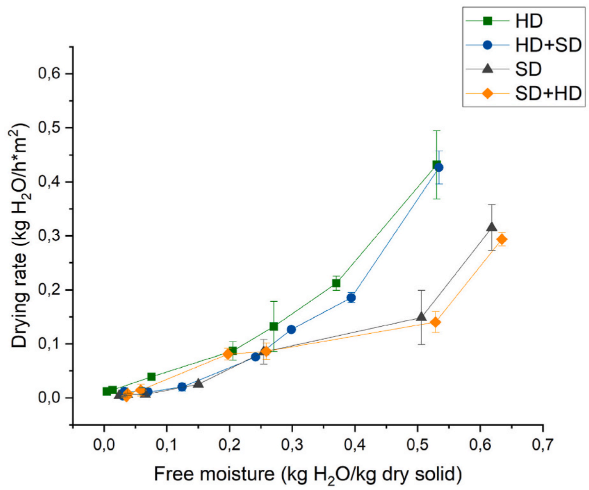

Fig. 4. Drying rate curves as a function of the free moisture content of cocoa beans using different methods (HD: Hybrid drying, HD + SD: Hybrid drying followed by sun drying, SD: Sun drying, SD + HD: Sun drying followed by hybrid drying).

does not appreciate the period of constant velocity, similar to other results obtained in previous cocoa drying studies [34].

In previous studies on cocoa drying, effective diffusivity coefficients have been reported in the range of 10^{-12} to 10^{-10} m^2/s using SD and oven methods at different temperatures (60, 70, 80 °C) [35,36]. These values coincide with those obtained in the present experiment, where effective diffusivities were recorded in the order of 10^{-10} and 10^{-11} m^2/s. Similarly, previous and current studies share the common trend that SD experiments present the lowest values of effective diffusivity to the other drying methods evaluated. This could be attributed to the relatively low range of ambient temperature observed during the SD processes (27–34 °C), which probably results in a lower driving force for moisture diffusion [36]. These results are intuitive, as higher temperatures would normally be expected to accelerate moisture diffusion, increasing effective diffusivity.

3.3. Energy consumption

Energy consumption represents a crucial aspect of the agro-industrial production chain, particularly in the drying process, which requires a substantial amount of electricity and liquefied petroleum gas (LPG) for bean dehydration, inevitably leading to increased operational costs [12]. Consequently, the selection of drying technology should be based on the profitability and commercial viability of the product. Fig. 5 shows the energy consumption associated with HD technology (using solar and electric drying) under cloudy days with humidity between 80 and 90 %, solar radiation between 160 and 500 W/m^2, and ambient temperature between 28 and 30 °C. To achieve the programmed temperature of 50 °C required for drying cocoa beans, the electric resistance supplements with 2.2 kWh, and the rest of the energy required is provided by solar radiation. This result underscores the significant contribution of solar radiation to reducing energy consumption in such dryers during days with low solar radiation. Additionally, in Fig. 5, the combination of technology usage with the SD method for cocoa (traditional method) is presented under environmental conditions similar to those described above.

For technologies involving the combination of HD and SD, the minimum energy consumption was recorded with the HD + SD method (10.10 kWh), representing a 56.62 % reduction in energy consumption compared to HD alone (23.28 kWh). It is worth mentioning that the energy consumed by the blower is always constant and directly depends on the operation time of the drying equipment, as it runs continuously to circulate air through the drying chamber. Meanwhile, the energy consumption provided by the electric resistance depends on the available solar radiation. The dryer has a control system that automatically activates the electric resistance when the energy provided by solar radiation is insufficient to maintain the target operating temperature of 50 ± 1.5 °C. As long as there is sufficient solar radiation, it will be the primary heat source for the dryer's operation, and the electric resistance will remain off. Due to this, energy consumption could vary depending on the climatic conditions during the drying process.

Regarding drying time, Fig. 6 shows that the drying time of combining SD + HD (28 h) is similar to the SD method (30 h). In contrast, a 20 % decrease in drying time was achieved with HD + SD technology (24 h) compared to the SD method, but an increase of 33.3 % if compared to the HD method (18 h). It is important to note that the presented data are under cloudy weather and low radiation conditions. The average ambient temperature was 31.36 ± 2.04 °C, and the relative humidity was 58.64 ± 6.00 %. In addition, the highest solar radiation registered was between 113,29 and 1089 W/m^2 (Supplementary Table). In addition, the drying time depends mainly on the environmental conditions (temperature and relative humidity) during the process. Energy consumption also varies widely depending on the specific conditions of each experiment and the technology used. These conditions can vary significantly from study to study, making it difficult to compare directly. Previous studies do not report in detail the environmental conditions during cocoa drying experiments or do not apply the same experimental conditions, which prevents an accurate evaluation and fair comparison with the results of the present study [35,36].

The results highlight the importance of integrating sustainable energy sources in the drying process to enhance the energy efficiency and economic feasibility of cocoa drying operations. By leveraging solar radiation, significant reductions in energy consumption can be achieved, especially under varying weather conditions, as demonstrated by the HD + SD method's lower energy demand. These findings suggest that hybrid drying systems, which rely on solar energy whenever available, can be a cost-effective alternative to fully electric drying systems. Additionally, the observed reduction in drying time with HD + SD technology emphasizes its potential to optimize operational efficiency without compromising drying effectiveness, even under low-radiation conditions. Future studies should consider standardizing experimental conditions and documenting environmental factors in detail to allow for more consistent and accurate comparisons across studies.

3.4. Shrinkage

Table 3 presents the bean contraction parameters of cocoa beans dried using different technologies. Regarding length reduction, it is observed that beans dried using SD and SD + HD technologies experienced the greatest contraction, with no statistically significant differences between them ($p < 0.05$). In contrast, applying HD and HD + SD resulted in lower shrinkage. Concerning equivalent radius, uniform contraction is evident among all samples, except for the beans subjected to the SD + HD process, which showed a significant difference ($p < 0.05$). This result suggests that applying SD + HD technology could lead to a more significant reduction in the size of cocoa beans. Thus, the initial application of SD causes cocoa bean shrinkage.

The results show that when the SD is applied at the beginning of the drying process, a significant reduction in the physical

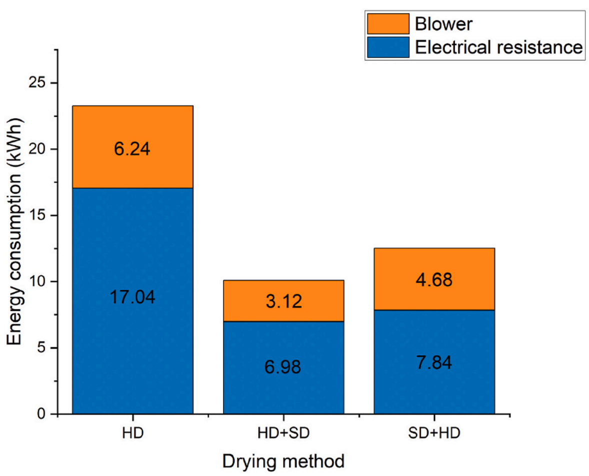

Fig. 5. Energy consumption of different drying methods for cocoa beans (HD: Hybrid drying, HD + SD: Hybrid drying followed by sun drying, SD + HD: Sun drying followed by hybrid drying).

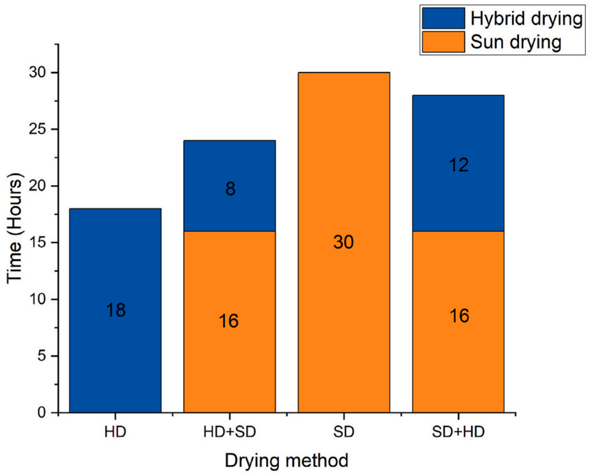

Fig. 6. Total drying time for cocoa beans under different drying methods (HD: Hybrid drying, HD + SD: Hybrid drying followed by sun drying, SD: Sun drying, SD + HD: Sun drying followed by hybrid drying).

Table 3
Physicochemical characteristics of cocoa beans.

Drying method	Shrinkage parameters[A]		Fermentation Index[B]	Total Acidity (g of acetic acid/100 g)[B]	pH[B]
	a_d/a	R_d/R			
HD	0.96 ± 0.02^a	0.93 ± 0.02^a	0.84 ± 0.02^a	1.04 ± 0.15^a	5.52 ± 0.03^b
HD + SD	0.97 ± 0.02^a	0.93 ± 0.03^a	0.84 ± 0.03^a	0.92 ± 0.05^a	5.57 ± 0.02^a
SD	0.92 ± 0.02^b	0.92 ± 0.02^a	0.83 ± 0.02^a	1.01 ± 0.08^a	5.48 ± 0.05^b
SD + HD	0.91 ± 0.02^b	0.90 ± 0.02^b	0.85 ± 0.02^a	0.96 ± 0.10^a	5.40 ± 0.04^c

HD: Hybrid drying; HD + SD: Combination of hybrid drying and sun drying; SD: Sun drying; SD + HD: Combination of sun drying and hybrid drying. Values followed by different letters within a column denote significant differences ($p < 0.05$). A: Mean ± standard deviation ($n = 10$). B: Mean ± standard deviation ($n = 9$).

dimensions of the cocoa beans was evidenced. It can be assumed that the initial drying method used in the process is likely a significant factor affecting the shrinkage parameter. In this context, the results suggest that the initial application of SD causes a significant contraction of the cocoa beans. In addition, because SD and SD + HD presented lower drying rates, it could be inferred that the lower drying rate and, therefore, longer drying time would significantly affect bean size reduction. On the other hand, the average temperature recorded during SD was 35.64 ± 3.51 °C and, since this temperature is lower than that of the HD process (50.00 ± 1.50 °C), it is dismissed from the consideration that the process temperature influenced shrinkage.

No studies compare the degree of shrinkage of cocoa beans by different drying methods. However, in a previous study on convective drying of fermented Amazonian cocoa beans [19], the authors analyzed the shrinkage of cocoa beans that were dried at 105 °C in an oven dryer for 24 h. In their research, an almost isotropic contraction was reported, with an equivalent length of 0.93 and an equivalent radius of 0.94. These results are similar to those obtained in the present study for the SD and SD + HD methods (Table 3). Although these authors conducted their experiments at a high temperature (105 °C), the observed shrinkage was notable and comparable to the shrinkage recorded with sun drying in the present study [19]. This contradicts the hypothesis that drying at a high temperature leads to surface rigidity that limits the contraction of the feed during the process [26]. However, more research is needed to understand shrinkage behavior according to drying methods.

3.5. Fermentation index (FI)

Strange and undesirable flavors characterize over-fermented cocoa beans. Poor fermentation of cocoa beans also results in a loss of quality due to the high astringency and resulting dark gray color [37]. The importance of evaluating the fermentation index (FI) in cocoa beans lies in the effect this parameter has on the quality of the final product. In practice, cocoa producers carry out the cutting test, which consists of recording the color changes that occur in the cocoa beans after fermentation and drying. However, this procedure is subjective [38]. To overcome this limitation, the FI analysis is applied, which is an indirect measure of the content of anthocyanins, one of the major components of the polyphenols of cocoa beans [40]. This analysis is based on the relationship between oxidized and polymerized polyphenols, which have a yellow color with a maximum absorbance at 460 nm (λ_{max} 460 nm), and anthocyanin monomers, which have a reddish and purple coloration with a maximum absorbance at 530 nm (λ_{max} 530 nm) [40,41].

Cocoa beans are considered well-fermented when the FI values exceed 1 [37]. In the present study, the FI results range between 0.83 and 0.85 (Table 3), reflecting a moderate anthocyanin concentration across samples. Notably, no significant differences ($p < 0.05$)

were observed between the different drying methods used, suggesting that the drying process did not markedly affect the anthocyanin levels. All samples originated from the same fermentation process, and thus, it is expected that the FI results would be relatively consistent across drying methods. The controlled temperature of 30 °C in the climate chamber may have influenced the microbial and enzymatic activity essential for anthocyanin transformation, as other studies demonstrate that fermentation processes using temperatures between 30 and 50 °C can yield varied anthocyanin profiles [21,41]. Temperature appears to be a critical parameter, as the natural cocoa mass temperature typically fluctuates during fermentation. For instance, other authors observed temperature ranges of 25–30 °C in the first 24 h, 35–45 °C between 24 and 48 h, and finally, 45–52 °C after 48 h [42]. These natural temperature increases suggest that cocoa fermentation benefits from a dynamic thermal environment rather than a constant temperature setting.

During the fermentation process, anthocyanins—pigments that exhibit a red hue under acidic conditions—undergo degradation, resulting in products such as cyanidin-3-β-D-galactoside and cyanidin-3-α-L-arabinoside. These products are then oxidized, forming distinctive brown pigments in cocoa [20]. This biochemical transformation is facilitated by polyphenol oxidase, which catalyzes the conversion of o-diphenols into o-quinones. The resulting polyphenols and quinones subsequently form complexes with peptides and proteins, contributing to the characteristic brown color observed in fermented and dried beans. According to a previous study, polyphenol oxidase operates optimally within a temperature range of 42–45 °C, typically around the third day of fermentation [37].

Several authors have noted that during the drying process, the enzymatic oxidation of polyphenols continues, leading to an intensification of chocolate's characteristic brown color [43]. Conversely, other researchers argue that when drying temperatures are elevated, the outer layer of cocoa beans hardens and adheres to the cotyledon, which restricts oxygen transport into the bean [44]. This limitation hinders the action of polyphenol oxidase, resulting in reduced oxidation of anthocyanins to quinones, and ultimately leads to the formation of violet cocoa beans with increased astringency. However, in the current study, this phenomenon did not manifest under the various drying methods used, as the fermentation index showed no significant differences.

3.6. Total acidity and pH

Total acidity and pH are critical physicochemical properties of cocoa quality, as they indicate the level of acidity production during fermentation and are also determining factors in the flavor of the beans [45]. During drying, cocoa beans may experience the loss of volatile organic acids such as acetic acid, especially when the moisture removal process has been slow [44]. Table 3 shows that the drying technologies did not have a statistically significant effect on total acidity. This finding would suggest that the dissipation of volatile acids, mainly acetic acid in this study, occurred uniformly in all samples, regardless of the specific drying technology implemented.

In contrast, slight differences in pH are reported between drying technologies ($p < 0.05$). The highest pH value corresponds to the cocoa sample dried by the HD + SD process, followed by single drying, which did not show significant differences between them (Table 3). The minimum pH value was measured in cocoa subjected to SD + HD technology. These results show that HD technology does not significantly affect pH compared to SD. However, combining both drying methods influences this parameter, with HD + SD resulting in cocoa with the highest pH. These findings contrast with those reported by other researchers, who noted that the pH of sun-dried cocoa does not show significant differences compared to cocoa dried using artificial techniques [44]. Additionally, the results regarding total acidity and pH obtained in this research diverge from previous studies, which indicated that cocoa beans dried artificially in ovens exhibited higher acidity and lower pH levels than those dried in the sun [34]. This discrepancy is attributed to the higher dissipation rate of acetic acid during slower drying processes [34]. Conversely, the rapid drying associated with artificial methods tends to harden the surface of the food, creating an impermeable barrier that inhibits the diffusion of acids.

In agreement with a previous study, the standard pH of dried cocoa is 3.8–5.5 [4]. However, it has been found that pH values between 4.0 and 4.5 are associated with excessive acidity, considerably reducing the sensory quality of cocoa due to an excess of lactic and citric acid in the bean matrix, which is undesirable [45]. Conversely, a pH range between 5.0 and 5.5 in cocoa beans is associated with a high potential for an adequate chocolate flavor. Other authors [44] also point out that cocoa with high flavor potential is obtained from fermentations with moderate acidification (pH between 5.0 and 5.5), which allows the selective degradation of proteins. This results in cocoa with high levels of hydrophobic amino acids and hydrophilic peptides compared to acidic fermentations. This information agrees with another study that states that the final pH of dried cocoa beans is crucial because this physicochemical parameter changes the type of products that result from enzymatic proteolysis [40]. These products (peptides and amino acids) are precursors from which the flavor and aroma of cocoa will develop during the roasting process, and the minimum suggested pH value for the efficient activity of carboxypeptidase during fermentation is 5.2 [40]. It has been reported that, during fermentation, the final

Table 4
Color parameters of fermented and dried cocoa cotyledon.

Sample	L*	a*	b*	C*	h°
Fermented beans before drying	53.34 ± 2.06^{a}	11.36 ± 1.12^{a}	4.07 ± 1.14^{d}	12.59 ± 1.21^{ab}	9.87 ± 1.52^{d}
HD	35.45 ± 2.45^{b}	10.99 ± 1.22^{a}	11.21 ± 2.31^{a}	15.76 ± 3.28^{a}	45.80 ± 5.00^{ab}
HD + SD	33.80 ± 1.90^{c}	10.16 ± 2.83^{a}	11.02 ± 2.42^{a}	14.95 ± 3.42^{a}	47.77 ± 3.88^{a}
SD	31.21 ± 2.78^{d}	9.57 ± 2.93^{a}	7.71 ± 2.25^{c}	12.36 ± 3.45^{b}	39.00 ± 6.31^{c}
SD + HD	32.14 ± 2.16^{d}	9.66 ± 2.81^{a}	9.66 ± 2.81^{b}	14.27 ± 3.62^{a}	43.07 ± 8.21^{b}

HD: Hybrid drying; HD + SD: Combination of hybrid drying and sun drying; SD: Sun drying; SD + HD: Combination of sun drying and hybrid drying. Values followed by different letters within a column denote significant differences ($p < 0.05$). Mean ± standard deviation ($n = 30$).

pH of cocoa must be 5.0–5.5 for fermented and dried beans to result in a high level of aroma compounds [22]. Therefore, the pH values obtained in this study (5.40–5.57) can be considered appropriate, except for the dried cocoa from HD + SD technology, which slightly exceeds the standard pH.

3.7. Color

The L* (luminosity), a* (range from red and green), b* (range from yellow and blue), C* (saturation, intensity, and purity of color), and h° (hue) color coordinates of cocoa bean samples subjected to the different drying technologies are consigned to Table 4. Regarding the cocoa beans' cotyledon, luminosity (L*) data reveal a drastic decrease during drying, dropping from 53.18 to values between 31.09 and 35.39. However, no statistically significant differences were identified among the different drying technologies, indicating that the drying method does not appreciably affect the cotyledon's luminosity ($p < 0.05$). Similarly, the applied drying technology does not affect the coordinate a*, which indicates red hues. However, there is also no statistically significant difference between the measured values in fermented cocoa beans and the dried beans obtained through different methods.

Regarding the b* coordinate, it is notable that SD + HD did not have a significant effect on this value. On the contrary, the HD and HD + SD methods resulted in the most significant increase in this parameter related to yellowish colorations. These observations could suggest that integrating HD, whether entirely or in the first phase of the process, leads to cocoa beans with reduced bluish cotyledon tones and more yellowish cotyledon hues compared to fermented cocoa beans and the beans subjected to conventional SD (direct exposure to the sun). Concerning Chroma (C*) and hue angle value (h°), Table 4 shows that saturation and hue were affected by different drying technologies, with HD and HD + SD methods preserving intensity and purity in the husk to a greater extent. Similarly, with these technologies, the saturation and hue of the cotyledon were higher. This indicates the predominance of yellow tones [22].

The color of fermented and dried cocoa beans is the most important quality parameter for the chocolate industry, as poor fermentation of cocoa can result in chocolate with a different and unpleasant flavor and aroma profile. Cocoa beans that have successfully completed the fermentation process should have brown or reddish-brown cotyledons. On the other hand, beans whose fermentation is not complete have a violet or violet-brown color and a higher degree of bitterness and astringency, which is the reason why they are rejected [46]. This phenomenon is attributed to the significant degradation of anthocyanin content during fermentation, manifesting a loss of approximately 93 % after 4 days of processing [47]. Anthocyanins are responsible for providing blue, purple, and red pigments to food matrices, and their reduction during cocoa processing is considered an indicator of the degree of fermentation of cocoa beans[47,48]. Research has shown that the content of anthocyanins is lower in well-fermented cocoa beans than in those that have not completed fermentation [49]. Conversely, proanthocyanidins are brown or invisible pigments [50]. It has been explained that diffusion of polyphenols occurs during fermentation, followed by oxidation and reduction with other cellular compounds, resulting in the characteristic brown pigments of fermented dried cocoa beans [37].

As a quality requirement, it is typically acceptable to have up to 25 % of violet beans or up to 30–40 %, including partially brown (brown-violet) beans because, during storage, these can transform into brown [20]. For this reason, it is expected that in the CIE-L* a* b* color space, cocoa beans exhibit intense red hues (positive values of a*) and yellow hues (positive values of b*), which would give the expected brown color [51].

According to other authors, fermented cocoa beans exhibit a higher yellow hue due to the oxidation of polyphenols during fermentation [22]. The results indicated elevated values of the chromatic parameters a* and b* in the fermented beans, attributed to the reduction of anthocyanins responsible for purple and violet colorations. In contrast, the beans with insufficient fermentation presented low values of a* and b*, indicating a higher content of purple pigments. In this context, the HD and HD + SD methods achieved the best results in terms of color, as they presented a higher yellow hue (higher values of b*), suggesting a lower anthocyanin content and, therefore, fewer violet pigments. It has been reported values of colorimetric parameters L* between 23.63 and 35.56, a* between 8.91 and 13.23, b* between 6.2 and 10.99, C* between 11.52 and 15.67, and h° between 29.30 and 44.56 for CCN-51 cocoa variety [52]. Within the context of the combined drying technologies evaluated in this study, these results are consistent with those obtained using all drying methods except SD + HD.

3.8. Phenolic content and antioxidant capacity

Table 5 summarizes the total phenolic content (TPC) and antioxidant capacity from different drying processes. A significant reduction of TPC is observed with the application of processes that include SD (HD + SD, SD and SD + HD) compared to the cocoa

Table 5
Bio-active characterization of cocoa beans.

Sample	Total Phenolic Content (mg GAE/100 g)	Antioxidant Capacity (mM TE/100 g)
Fermented beans before drying	21160.90 ± 296.54^{a}	104673.86 ± 1323.06^{a}
HD	21164.40 ± 896.11^{a}	98930.50 ± 515.85^{b}
HD + SD	12527.8 ± 188.34^{b}	98480.50 ± 6304.09^{b}
SD	12963.6 ± 924.27^{b}	87003.10 ± 7777.99^{c}
SD + HD	14024.8 ± 434.80^{b}	91452.10 ± 767.03^{c}

HD: Hybrid drying; HD + SD: Combination of hybrid drying and sun drying; SD: Sun drying; SD + HD: Combination of sun drying and hybrid drying. Values followed by different letters within a column denote significant differences ($p < 0.05$). Mean ± standard deviation ($n = 6$).

beans before drying. In contrast, the TPC remains constant with HD. These results suggest that the exposure of cocoa beans to sunlight would be a critical factor in the content of phenolic compounds. On the other hand, the antioxidant capacity of cocoa decreased significantly with all drying processes; however, with HD and HD + SD, the reduction is lower (5.92 % and 5.49 %, respectively) than with SD and SD + HD methods (16.88 % and 12.63 %, respectively). These observations would indicate that the application of HD technology contributes to reducing the loss of the antioxidant properties of cocoa, retaining up to 13.20 % more antioxidant capacity compared to SD, whose application caused a more significant reduction. Additionally, it could be inferred that the application of SD in the first stage of the process would have a more drastic effect on the degradation of antioxidant compounds. The results contradict a previous study that reported a reduction of the antioxidant capacity and TPC with different drying methods, except for SD, in which the TPC was preserved in fermented cocoa [53]. They argued that the lower temperatures in which the fermented cocoa is exposed to sun drying reduce the loss of TPC compared to temperatures of 60 °C with heated air circulation. Despite the apparent discrepancy, the temperatures (50 ± 1.5 °C) and airflow (2.5 m/s) applied in our study with HD are low enough (compared to 60 °C) that could potentially contribute to maintaining the TPC and antioxidant capacity of fermented cocoa. Indeed, our results are aligned with those observed in a recent study which found much higher TPC values in hybrid cocoa variety subjected to a 5-day fermentation process and subsequently dried with a solar biomass hybrid dryer at temperatures ranging from 35.28 °C to 47.17 °C [54].

Cocoa is an important source of polyphenols, secondary metabolites that are part of the group of natural antioxidants and are stored in the pigments of cotyledon. These compounds are responsible for the strong astringency of fresh cocoa, which is undesirable [55]. It has also been reported that phenolic compounds may react with sugars, interfering with the Maillard reaction and, thus, the formation of flavor compounds. However, polyphenols provide an important antioxidant activity that is of interest to preserve if the goal is to produce cocoa products with health benefits [43].

The group of total phenols is made up of flavonoids (flavones, isoflavones, flavanones, flavanols, and anthocyanins) and non-flavonoid polyphenols (derivatives of hydroxybenzoic and hydroxycinnamic acids). The importance of these biologically active compounds lies in the presence of hydroxyl groups in their structure, which gives them the ability to bind to free radicals and reactive oxygen species that act by destroying cells and tissues. This aspect is particularly relevant because abnormalities in cells induced by free radicals represent the foundation of the aging process and the onset of cancer [55]. Additionally, phenolic compounds have been attributed with anti-inflammatory, antithrombotic, antiviral properties, cardiovascular effects, and increased HDL cholesterol [56,57].

According to previous findings, the degradation process of bioactive compounds continues during drying because of the enzyme polyphenol oxidase, which is activated under oxygen availability and intermediate acidity levels [56]. Polyphenol oxidase transforms polyphenols into quinones and remains active at this stage. These quinones undergo subsequent condensation with amine and sulfhydryl groups, resulting in brown polymers that contribute to the typical brown color of cocoa [47]. However, the degradation of phenolic compounds during drying does not occur solely due to the action of polyphenol oxidase but is also associated with the migration of polyphenols that occurs together with water evaporation [55,58]. Likewise, it has been reported that these bioactive compounds are sensitive to high temperatures and extended drying times, leading to their reduction during the process [59–61].

4. Conclusions

The results suggest that combining drying processes improves cocoa's (*Theobroma cacao* L.) physicochemical and biological quality. Indeed, the order in which the drying technology is applied influences the cocoa quality. When HD is applied at the beginning, better results are obtained, and the drying rate is positively impacted. Therefore, the technology that combines HD + SD results in lower energy consumption. On the other hand, when SD is applied first, the cocoa bean shrinkage is increased. Moreover, when SD is applied at any stage, it significantly reduces TPC and antioxidant capacity. Evaluating combined drying technologies on cocoa's physicochemical quality and bioactive compounds is at the forefront of research efforts to improve the efficiency and sustainability of cocoa processing methods in small and medium farms.

Although HD is identified as a potential alternative to enhance the physicochemical and antioxidant properties of cocoa, it is important to consider the factor of energy consumption, which is why the HD-SD methodology emerges as a promising option to be implemented in small and medium-sized cocoa farms, to improve the quality of the final product. Applying HD in combination with SD represents a paradigm shift in cocoa processing, leveraging conventional and innovative approaches to optimize drying efficiency while minimizing energy consumption and loss of quality. Further studies are required to apply other innovative technologies with less energy consumption.

CRediT authorship contribution statement

Johanna Pita-Garcia: Writing – original draft, Validation, Methodology, Investigation, Formal analysis, Data curation. **José Reinoso-Tigre:** Writing – review & editing, Methodology, Investigation, Formal analysis. **Sócrates Palacios-Ponce:** Writing – review & editing, Validation, Formal analysis, Conceptualization. **Emerita Delgado-Plaza:** Writing – review & editing, Resources, Methodology. **Diana Coello-Montoya:** Writing – review & editing, Validation, Methodology. **Rómulo Salazar:** Writing – review & editing, Methodology. **Jonathan Coronel-León:** Writing – review & editing, Methodology. **Juan Peralta:** Writing – review & editing, Methodology. **Fabiola Cornejo:** Writing – review & editing, Supervision, Resources, Project administration, Conceptualization.

Data available statement

The data that support the findings of this study are available on request from the corresponding author, FC.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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