INTERNATIONAL JOURNAL OF AUTOMOTIVE AND MECHANICAL ENGINEERING
ISSN: 2229-8649 e-ISSN: 2180-1606
VOLUME 23, ISSUE 3, 2026, 13842 - 13850
DOI: https://doi.org/10.15282/ijame.23.3.2026.8.1044

RESEARCH ARTICLE

Optimization of mechanical convective drying parameters for fermented uf-18 cacao beans using response surface methodology

Rick Ryan G. Renegado, Harvey Bryant M. Marquez, Cresencio P. Genobiagon Jr.*

Mechanical Engineering Program, University of Mindanao, Matina Campus, Davao City, Philippines

Abstract - Mechanical drying is considered an efficient drying technique; however, continuous mechanical drying may compromise flavor and textural properties. This study aimed to create optimized drying parameters of fermented UF-18 cacao beans using a laboratory scale mechanical dryer and Response Surface Methodology (RSM). A central composite design consisting of 20 experiments was conducted within temperature ranges of 29.77 to 80.22 °C, air velocity of 0.5 to 1.5 m/s, and relative humidity of 10 to 20%. Drying time and bean quality were evaluated as response variables. The drying time was a linear function (Adjusted R^2 = 0.9854, Predicted R^2 = 0.9783), with temperature as the most significant factor ($p < 0.05$). Drying at 80.22 °C achieved the shortest drying time of 12 h but resulted in poor quality (score 5). The optimum conditions were at 57.85 °C, air velocity of 0.5 m/s and relative humidity of 10% under intermittent drying with predicted drying time of 34 h and bean quality score of 8.83 with desirability of 0.95.

Article History
Received : 31 July 2025
Revised : 28 August 2025
Accepted : 15 May 2026
Published : 25 September 2026

Keywords
Dryer
Bean
Drying time
Temperature
Air velocity

1. Introduction

Fermented cacao beans are the dried, fully fermented fatty seeds of *Theobroma cacao*, produced through a spontaneous process driven by an ordered microbial succession [1]-[2]. Among their many uses, cacao beans are an essential raw material in the chocolate, beverage, cosmetics and pharmaceutical industries [3]. The cacao industry supports the livelihoods of 50 million people, with 68% of exports going to Africa, 17% to Asia, and 15% to the Americas [4]. The Philippines has a competitive advantage in cacao production because of its strategic location and climatic conditions [5]. Cacao production increased by 7.1 percent from 2.58 thousand metric tons to 2.76 thousand metric tons in 2020 (Philippine Statistics Authority Data). The Davao Region remained the country's largest cacao-producing region, accounting for 82 percent of total cacao production during the quarter, with 2.27 thousand metric tons of output. [6]-[7]. The Philippine Cacao Industry Roadmap is anchored on the value chain approach and is aligned with the 2022 Cacao Challenge to produce 100,000 MT of dried fermented beans [4]. This vision presents an excellent opportunity to optimize the drying temperature of fermented UF-18 cacao beans to reduce mass loss, prevent spoilage, and improve production efficiency. During the primary processing of cocoa (Theobroma cacao) beans, drying fermented beans reduces the moisture content from 60% to 6-7%, enabling safe storage and transportation[8]. The extent of chemical changes and cellular structures of cocoa seeds depend on the temperature applied during processing [9]-[10]. Various drying methods and quality parameters, including open sun, solar, oven, microwave, mechanical, and freeze-drying, can improve the drying properties and final quality of cocoa beans [1],[11]. Throughout the tropics and subtropics, where solar radiation is abundant, natural sun-drying is one of the oldest, cheapest, and most popular techniques for drying crops [11]. The Auro Chocolate Industry is an internationally awarded Filipino bean-to-bar chocolate company that sustainably sources cacao beans directly from local farmers. Their products have a more natural flavor because they use open sun drying and solar tunnel drying methods, in which the beans are dried for 6–10 days inside a greenhouse-like enclosure that protects them from rainfall while allowing sufficient airflow. The manufacturers also said that it is essential not to rush the process, or only the skin or the outer layer of the beans will dry. Beans with moisture content exceeding the acceptable level after 3 – 4 months require re-evaluation. Sun-dried samples performed better than other methods at all temperatures; however, it has several disadvantages, such as uncontrollable temperature and risk of overheating the beans. In addition, sun drying is labor-intensive and requires many workers [12]-[13].

In solar dryers, fermented cacao beans are covered and protected from the wind while being exposed to solar radiation during open-air sun drying [14]. Solar dryers use solar energy to dry materials. The dryer maintains a constant air temperature and uses the heat it generates to warm the environment and dry the goods in the drying chamber [15]. Nevertheless, in other applications of this technique, the drying temperature depends entirely on natural sun-drying [16]. In contrast, mechanical dryers, which use an active heat source, improve cocoa bean quality even under unfavorable weather conditions [17]. Previous studies have shown that mechanical drying is more efficient because it offers a wide range of drying temperatures, suits heat-sensitive products, uses cheap local resources to meet energy requirements, and has a low construction cost [18]. Nonetheless, using unsuitable temperatures and air velocities to reduce the moisture content of fermented cacao seeds results in low-quality cacao beans. In cocoa production, proper moisture levels are important; over-drying or excessive dryness affects the flavor. During hulling, beans become fragile and prone to breakage. Conversely, if beans are too moist or not fully dried, they deteriorate quickly because of bacteria and fungi [17]. Although mechanical dryers provide better control than sun or solar drying, many drying operations still rely on trial and error to select the operating conditions. Recent studies have primarily focused on the effects of temperature, with less

***CORRESPONDING AUTHOR | Cresencio P. Genobiagon Jr.** | ✉ cresjohn@yahoo.com
© 2026 The Authors. Published by University Malaysia Pahang Al-Sultan Abdullah Press. This is an open access article under the CC BY-NC 4.0 license

emphasis on the effects of air velocity and relative humidity on drying performance and bean quality. Moreover, few studies have integrated a fabricated mechanical dryer with statistical multiparameter optimization and systematic quality evaluation. Although several cocoa bean drying methods have been used, a framework for optimizing the controlled convection mechanical drying of fermented cacao beans remains limited. This study promotes an understanding of how temperature, air velocity, and relative humidity interact during convective drying and affect bean quality. Simultaneously, it provides optimized drying conditions that can help farmers and processors reduce drying time, limit post-harvest losses, and achieve more consistent product quality.

The surge in the demand for cacao beans in the Philippines has compelled farmers to expedite production using mechanical drying methods. However, using these dryers, despite knowing the correct input temperature, is likely to compromise product quality. This presents an excellent opportunity to fabricate a laboratory-scale mechanical dryer and conduct experiments to optimize the drying temperature of fermented cacao beans for producing high-quality goods. To obtain optimal drying temperature data, we will use response surface methodology and conduct various tests. The objectives of this study were as follows: 1) to optimize the drying temperature of cacao beans using Response Surface Methodology, and 2) to produce dried cacao beans with quality similar to that of sun-dried cacao beans using a fabricated mechanical dryer. This study aimed to design, fabricate, develop, test, and implement a mechanical dryer using Response Surface Methodology. The testing parameters included drying rates at different temperatures and air velocities, the interior and exterior humidity levels of the drying chamber, and the quality of the dried cacao beans, as determined by moisture content and color.

2. Materials and Methods

2.1 Materials and Resources

Fermented UF-18 cacao beans (Theobroma cacao L.) were obtained from local cacao producers in the Davao Region of the Philippines. The beans were fermented before drying. The initial moisture content was 56% (wet basis), determined using a gravimetric method. For each experimental run, 1 kg of fermented beans were loaded into the drying chamber. Drying was terminated once the moisture content reached 6–8% (wet basis), corresponding to a final mass of approximately 500–510 g per sample. The researchers will use the following materials to determine the optimal drying temperature for the fermented cacao beans. The air velocity inside the drying chamber was measured using a digital anemometer (0.0–45.0 m/s range, 0.3 m/s threshold) positioned at the drying chamber exit to monitor the airflow passing through the bean layer. Air was circulated using a rear-mounted axial fan (AC 220–240 V, 50/60 Hz, 1000 rpm, 58 CFM, 2.88 W), which forced ambient air through the heating section and into the drying chamber. A 750 W ceramic heating element (220 V) was installed upstream of the drying chamber to increase the air temperature before contact with the cacao beans. The drying chamber temperature and relative humidity were continuously monitored and regulated using a temperature controller and humidity sensor to maintain the experimental set point. The relative humidity inside the drying chamber was controlled by regulating the airflow and heating rate of the system. The relative humidity decreases as the temperature decreases, and axial fans introduce fresh air. A digital balance with an accuracy of ±0.01 g was used and placed under the drying tray to measure the weight at a specific time interval. The thermocouple had an accuracy of ±1 °C, whereas the humidity sensor had an accuracy of ±2% RH. The digital anemometer had an accuracy of ±0.1 m/s. These specifications ensured reliable measurements of the drying parameters throughout the experiments.

2.2 Experimental Setup

We designed and fabricated a mechanical dryer. Figure 1 shows a schematic of the fabricated mechanical convective dryer. The system consists of an intake fan (1) that drives the airflow through a resistor heater (2) before entering the drying chamber containing the drying trays (4). The frame (5) supports the assembly, and a temperature controller with a thermocouple (10) and hygrometer (9) measures and controls the temperature and humidity. A digital balance (3) was used to measure the mass loss during drying, and a digital anemometer (6) was used to monitor the airflow velocity. The front access door (8) with a locking mechanism (7) allows the loading and unloading of cacao beans. The dimensions of the dryer were 111 × 31 × 93 cm, with individual drying trays measuring 30 × 20 cm. The drying chamber has a drying area of 600 cm² per tray and can hold approximately 0.5 kg of fermented cacao beans per tray. Each trial used 1 kg of beans evenly distributed across two drying trays. To reduce heat loss during operation, insulation was applied to the inner walls of the chamber. An axial fan was installed to supply the required airflow. A digital balance was positioned below the drying chamber to measure the mass in real time. Type-K thermocouples and humidity sensors were set at viable locations.

The sub-experiments within the actual experiments compared continuous and intermittent drying methods. The production of marketable items can turn around more quickly during continuous drying or without breaks. Some studies suggest that rest periods during the drying cycle, also known as intermittent drying, can mitigate the drawbacks of rapid drying [19]. This study also aims to identify the differences between these two drying methods through experimentation. Each experiment used a sample size of 1 kg of UF-18 cacao beans (fermented for five days). The beans were placed on a drying tray and loaded into a mechanical dryer for drying. The experiment was configured using the specified temperature, air velocity, and relative humidity, as determined by the Design Expert software, to initiate the drying process. The gravimetric method was used to determine the drying termination point by determining the moisture content through periodic weighing of cacao beans. A moisture content of between 6% and 8%, along with a lowered acid concentration, contributes to reduced bitterness and imparts a distinct chocolate brown coloration [13]. The initial moisture content of the 5-day fermented cacao beans was 56%. The drying rate in each experimental trial was determined by recording the

bean weights at equal intervals. The cut test method was used to determine the bean quality according to the classification chart [20]. For each batch, 50 beans were sliced and visually assessed for internal color, shell appearance, structural integrity, and the presence of defects. The beans were classified according to a standardized scale ranging from poorly fermented or under-dried (levels 1–5) to well-fermented and properly dried (levels 8–9) beans. The overall quality score for each run was determined based on the dominant classification.

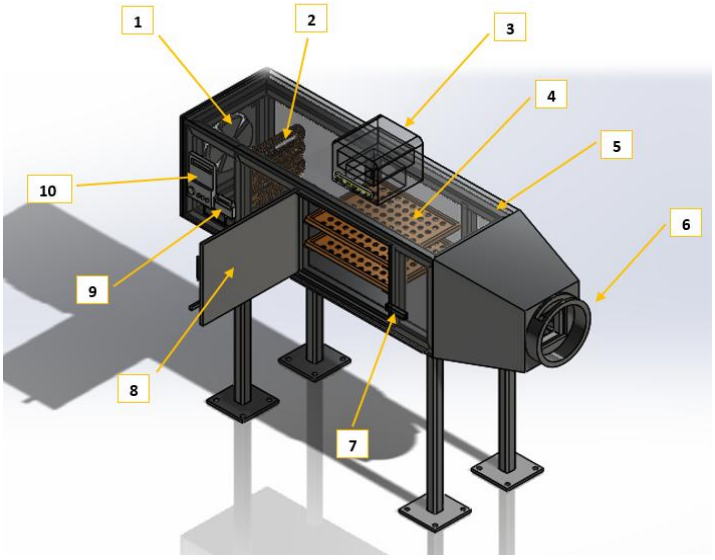


Figure 1. Schematic representation of the laboratory-scale mechanical convective dryer showing major components and measurement instruments

The statistical analysis in this study was performed using response surface methodology (RSM). RSM is a widely used mathematical and statistical method for modeling and analyzing processes. Experiments must be planned and conducted based on the number of input variables [13], [21]. Until we attain a workable model, we will examine the intricacies of the interactions between the variables. The independent variables are the parameters that affect the process, whereas the dependent variables are the responses [22]. In this case, the responses of interest were drying time and cacao bean quality, whereas the variables were the different types of drying technologies. The resulting model, which also caps the experimental run, comprises all data on the impact of the experimental conditions. Within the model's range, it can also forecast future observations [21].

2.3 Experimental Design and Optimization Procedure

To establish an experimental framework for process optimization, researchers generated operational bounds for each factor in the Design Expert Software. The temperature range was 40–70 °C, air velocity 0.5–1.5 m/s, and relative humidity 10%–20%. These parameters served as the basis for a central composite design (CCD), which generated 20 experimental runs ranging from 29.77 °C to 80.22 °C. The design included four runs at 40 °C, ten at 55 °C, and four at 70 °C, combined with variations in air velocity and relative humidity to examine the relationships between the factors. Drying was considered complete once the cacao beans reached a final weight of 500–510 g, with moisture content used as an indicator of an acceptable dried state. Under these conditions, drying time and bean quality, evaluated using a standardized cut test, were recorded as response variables.

3. Results and Discussion

Figure 2 shows the full set of experimental conditions and factor levels. At the lowest temperature of 29.77 °C, with air velocity held constant at 1.0 m/s and relative humidity at 15%, it required 64 h of intermittent drying to reduce the moisture content of 1000 g of fermented cacao beans from 56% to 6.9%. As shown in Figure 2 (a), the drying rate was highest in the first hour and gradually declined over the next 7 h, whereas the moisture content continued to decrease. The findings are in line with the scenario of internal resistance to moisture being minimal at the start of drying, when surface moisture evaporates quickly, as free moisture is readily available[3]. The cut test revealed that the beans were shiny, indicating that they were probably not dried properly. Fissures were observed, but they did not show a clear structure, and the beans gave off a vinegary smell, which is a strong indication of under-fermentation. Although pale purple beans were not labeled as defective because they turn brown during storage [23], the main features indicate insufficient drying and fermentation. Based on these points, the beans are rated 5 on the bean quality scale. Hence, the beans changed color to light gold and shrank slightly, but they still looked wet after 64 h, which resulted in a low-quality bean product. This temperature is far from the ideal temperature.

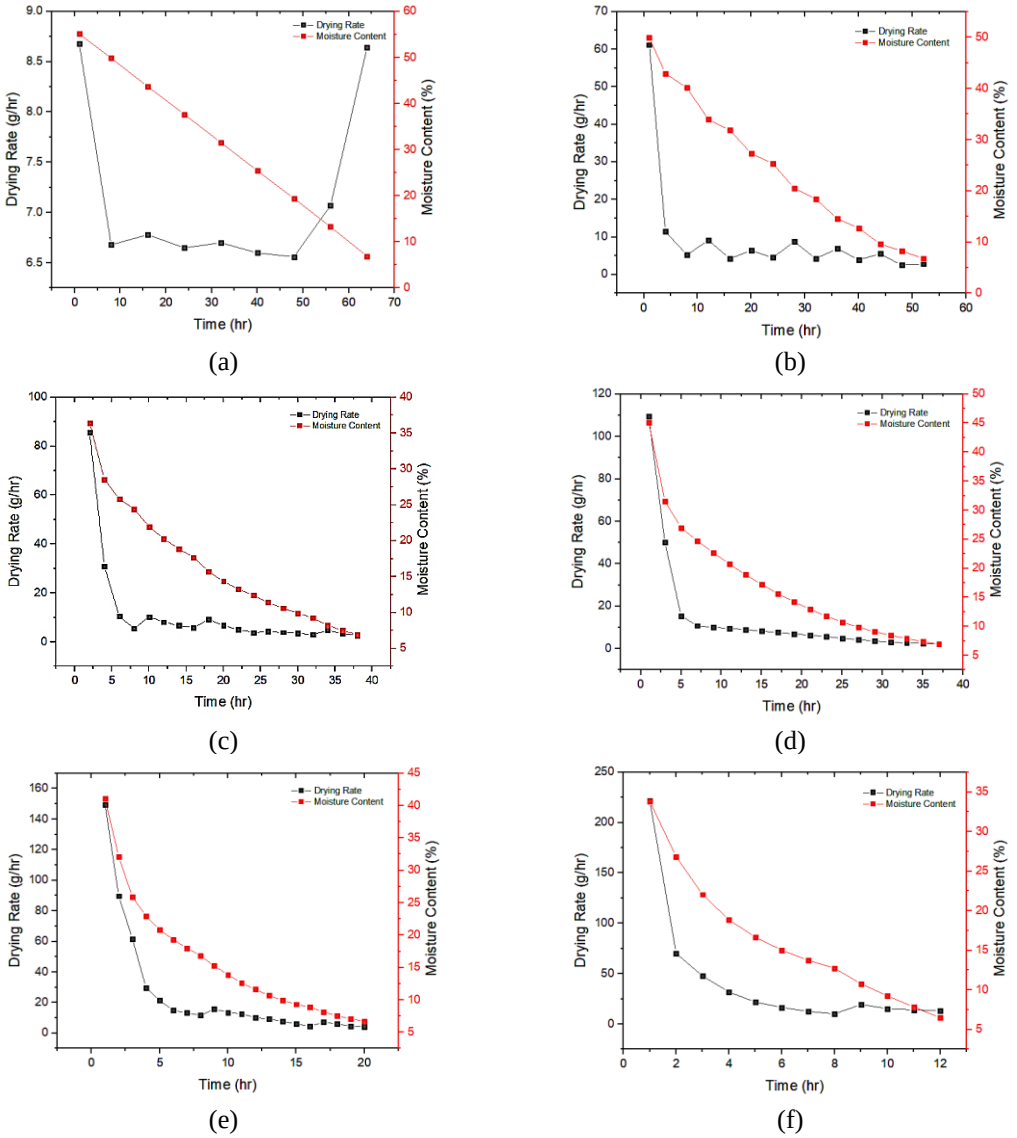


Figure 2. Moisture content and drying rate profiles under various experimental drying conditions: (a) 29.77°C, 1.0 m/s, 15% RH (64 h, intermittent); (b) 40°C, 0.5 m/s, 10% RH (52 h, intermittent); (c) 55°C, 1.0 m/s, 15% RH (38 h, intermittent); (d) 55°C, 1.0 m/s, 15% RH (37 h, continuous); (e) 70°C, 0.5–1.5 m/s, 10–20% RH (19–20 h, intermittent); (f) 80.22°C, 1.0 m/s, 15% RH (12 h, intermittent)

The drying rate dropped substantially from 61 g/h to 11 g/h during the first drying stage. This indicates that the first-stage moisture removal was significant. The drying rate between the 4th and 8th hours decreased further but at a much slower rate, with approximately one-tenth as much moisture lost. In the next phase of drying, between 8 and 12 h, the drying rate increased for a short time before decreasing again between 12 and 16 h. Figure 2(b) shows the intermittent nature of the drying process, with periodic peaks in the drying rate curve. The drying rate peaks indicate moisture uptake during the rest periods. As Oke and Omotayo [24] noted, ambient relative humidity tends to be lower during the day and more stable at night, contributing to this phenomenon. The cocoa beans were deep golden brown. This indicates that the cocoa shells had dried. The cut test showed the cores to be a deep purple, slowly turning to light brown, indicating that the beans were slightly under-fermented. The beans had a malty smell, reminiscent of the smell of traditional *Tablea*. The cut test showed that the dried beans were of quality level 6. The moisture content of the fermented cacao beans was reduced from 56% to 6.85% in approximately 50 h at 40°C with an air velocity of 1.5 m/s and in 52 h at 0.5 m/s. The variations in relative humidity did not significantly affect the drying time at this temperature. Increasing the temperature and air velocity significantly reduced the drying time. This finding is supported by Waheed and Komolafe [24], who reported that drying 0.5 kg of cacao beans at 40 °C and an air velocity of 2.7 m/s reduced the moisture content from 50.5% to 6.4% in 25 h. The same parameters were used for the six experimental runs at a drying temperature of 55 °C, air velocity of 1 m/s, and relative humidity of 15% (Figure 2(c-d)). Three of these runs were continuous drying runs, and the other three were intermittent drying runs. The continuous method took 37 h, one hour less than the intermittent method (38 h). However, because the drying was continuous, the bean quality was lower despite the shorter time.

The drying curves for the intermittent and continuous methods also exhibited distinct patterns. The intermittent drying curves showed periodic spikes in the drying rate, indicating moisture reabsorption during the rest intervals, whereas

continuous drying exhibited a steady and uninterrupted decline in both the drying rate and moisture content. These patterns align with previous studies reporting drying durations of 41 h for intermittent and 30 h for continuous drying within the 40–54 °C range using adsorbents [25], supporting the results of this study. Four additional runs at 55 °C were conducted with variations in the air velocity and relative humidity. Two of these experiments achieved the shortest drying time of 36 h: one with the highest air velocity of 1.84 m/s at 15% RH, and another with 1 m/s at the lowest RH of 6.59%, both achieving moisture content from 56% to approximately 6.95%. Longer drying times of 40 h were observed for runs with the lowest air velocity (0.16 m/s) at 15% RH and 1 m/s at the highest RH of 23.41%, with final moisture contents of 6.85% and 6.89%, respectively. This indicates that higher air velocity and temperature increase the drying rates [26], and higher relative humidity improves the overall drying efficiency [34]. Intermittent drying produces high-quality beans. Cut tests revealed brown shells and internal bean coloration, with a chocolate-like aroma corresponding to a bean quality score of 9. Moreover, continuous drying produced beans with pale brown to partially purple interiors, although they were still well dried. We classified these as bean quality level 7. Although the relative humidity (RH) is not explicitly plotted in Figures 2 and 3, its influence is embedded in each experimental condition, as defined in the central composite design. RH variations between 10% and 20% contributed to the differences in the drying rate and total drying time. The decrease in relative humidity increased the difference in moisture levels between the bean surface and the surrounding air, which accelerated the evaporation process. In contrast, higher relative humidity slightly delayed drying because it reduced the vapor pressure differences.

As shown in Figure 2(e), drying at 70 °C under intermittent conditions took 20 h at a lower air velocity of 0.5 m/s with relative humidities of 10% and 20%. Moreover, at a higher air velocity of 1.5 m/s and the same humidity levels, the drying process took 19 h. This indicates an average drying rate of 0.171 kg/h for fermented cacao beans dried at 70 °C with an air velocity of 1.3 m/s [3]. The cut test revealed a darker brown hue in the shells than in previous experiments. The internal color of the beans was deep brown, suggesting that they were well-dried and slightly over-fermented. The beans corresponded to level 8 on the bean quality chart. It should be noted that drying at temperatures higher than 60 °C may inactivate important enzymatic processes occurring during fermentation and continuing through drying[19]. Consequently, the bean quality in this experiment likely reflected the effects of fermentation more than drying alone. Drying at 70 °C under controlled air velocity and relative humidity represents a promising condition for the optimal drying of fermented cacao beans. Drying cacao beans at 70 °C or 80 °C after six days of fermentation yields a volatile compound profile comparable to sun drying, with 70 °C offering a more cost-effective option [3]. Thus, drying at 70 °C can produce high-quality cacao beans under controlled conditions.

The lowest drying time of 12 h was achieved at a drying temperature of 80.22 °C, relative humidity of 15%, and air velocity of 1 m/s, as shown in Figure 2f. This trial had the steepest drying curve among all 20 experimental runs. However, the high drying temperature reduced the bean quality. The cut test showed that the shells were overdried and the interiors were under dried. The bean quality rating was level 5 on the quality chart. This condition resulted in uneven drying. Earlier studies on temperature-dependent drying kinetics have shown that rapid drying restricts the oxidation processes in beans required for a homogeneous brown color. [3]. Therefore, this study confirmed that higher temperatures and shorter drying durations do not necessarily yield superior bean quality. These results emphasize the need to achieve optimum drying parameters. The drying rate of cocoa beans decreases progressively, making it a critical factor in the design of post-harvest drying systems [26]. Engineers and practitioners can use these findings to select drying conditions that ensure both efficiency and quality in cocoa processing.

3.1 Response Surface

Design-Expert uses ANOVA, fit statistics, and coefficient analysis to validate the model. The equation, with factor levels set at +1 and -1, enabled the comparison of factor effects and indicated their relative importance. Conversely, the actual-factor equation, expressed in the original units, is useful for prediction but not for assessing factor significance because of coefficient scaling and a non-central intercept. For Response 1, as shown in Figure 3, we evaluated multiple models based on their statistical validity, model hierarchy, and predictive accuracy. The cubic model showed the least significant lack of fit; however, its aliased status rendered it invalid. The quadratic model showed an insignificant lack of fit, with high Adjusted R^2 and Predicted R^2 values, but it did not provide the optimal fit. Therefore, the linear model was considered the most appropriate for modeling the drying time. The Model F-value of 427.38 implies that the model is significant. There is only a 0.01% chance that an F-value this large could occur because of noise. P-values less than 0.0500 indicated that the model terms were significant. The Lack-of-Fit F-value of 12.33 indicated a moderately significant lack of fit, which was attributed to noise in only 0.61% of the cases; thus, the overall model fit remained acceptable. The adjusted R^2 (0.9854) and predicted R^2 (0.9783) were correlated, with a difference of less than 0.2, indicating a strong predictive performance. The Adequate Precision value of 72.720, far exceeding the minimum threshold of 4, confirms a strong signal-to-noise ratio and validates the model's utility for navigating the design space.

The mathematical model shows how temperature, air velocity, and moisture content influence the drying time. The linear equation for response 1 had a drying time constant of +36.70. This indicates that this is the lowest possible drying time for beans to achieve maximum quality. This is followed by the term -15.70A, which is the temperature factor. The negative sign indicates an inverse relationship between temperature and drying time; as the temperature decreases, the drying time increases, and vice versa. Likewise, the coefficient -0.86B shows that the relationship between air velocity and drying time is inversely proportional. The coefficient of +0.56 °C shows a direct relationship with relative humidity, where an increase in humidity slightly prolongs drying. The results showed that drying temperature and air velocity affect cocoa bean drying through two measures: the drying constant, which is highly correlated with temperature (R^2 = 84.8%),

whereas R^2 decreases to 80.9% when air velocity is considered. The conclusion is that temperature is the dominant factor over air velocity in determining the drying behavior of cocoa beans. After fixing the temperature, the drying rate increased with both increasing temperature and increasing air velocity; however, as expected, the drying rate declined over time [3].

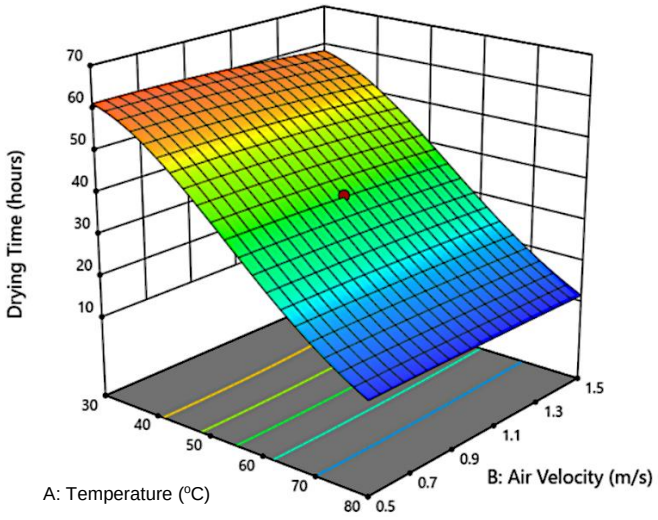


Figure 3. 3D graphical representation of drying time response

The linear model for Response 1: Drying Time, generated by Design-Expert, was used to create response surface plots to investigate the effects of temperature, relative humidity, and air velocity on the drying time. As shown in Figure 3, the region of interest appeared between 30 and 40 h on the drying time axis. The predicted optimal drying time corresponded to a temperature range of 30–60 °C at an air velocity of approximately 1 m/s. The model for Response 2 is illustrated in Figure 4. The aliased status indicated that the cubic model was invalid, and the linear model yielded negative Adjusted R^2 and Predicted R^2 values, thus invalid as well. Therefore, the quadratic model was identified as the most appropriate model for bean quality. The Model F-value of 9.77 suggested that the model was significant, with only a 0.07% probability that such a high F-value occurred because of noise. Model terms with P-values less than 0.0500 were considered significant; in this case, A (temperature) and A^2 (temperature2) were the significant terms. Model terms with P-values greater than 0.1000 were considered insignificant. With many insignificant terms, excluding those required to maintain the model hierarchy can improve the model. The Predicted R^2 of 0.2258 is not as close to the Adjusted R^2 of 0.8061 as one might normally expect; that is, the difference is more than 0.2. This indicates a large block effect or a possible problem with the model and/or data. Consider model reduction, response transformation, and outliers. All empirical models should be tested by performing confirmation runs. Adeq Precision measures the signal-to-noise ratio (SNR). A ratio greater than 4 is desirable for the study.

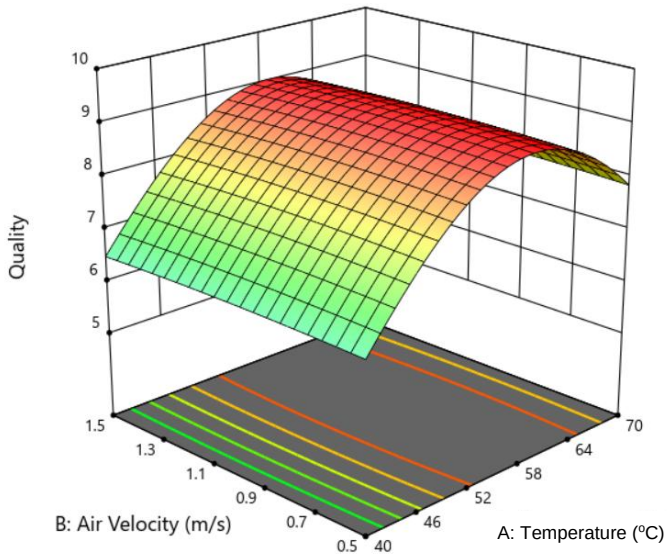


Figure 4. 3D graphical representation of the bean quality response to temperature, relative humidity, and air velocity

The quadratic model for Response 3: Bean Quality, generated by Design-Expert, was used to construct response surface plots to examine the effects of temperature, relative humidity, and air velocity on bean quality. As shown in Figure 3, the region of interest was centered on a bean quality value of approximately 9. The predicted optimal bean quality corresponded to a temperature range of 52–64 °C. Bean quality was evaluated based on the researcher's sensory

assessment and was therefore subjective. Bean quality is sensitive to temperature. Under-dried beans with lower quality scores were produced at temperatures of 29.77-40°C with slow moisture removal. Rapid surface drying at 80.22 °C caused non-uniform drying and poor quality by hindering the diffusion of internal moisture. The best quality was obtained in the middle temperature range of 52-64 °C, confirming a nonlinear relationship between drying temperature and bean quality. This agrees with the findings of Gopaulchan et al. [27], who stated that elevated drying temperatures may alter volatile compound development and affect flavor formation. Similarly, Castillo-Orozco et al. Al. [28] noted that temperature influences drying kinetics and final bean characteristics, reinforcing the dominant role of temperature over air velocity.

3.2 Optimization

Using predictions from validated mathematical models for drying time and bean quality, Design Expert generated optimization solutions that satisfied the design constraints. The drying temperature was set to 30-60 °C, as the graphical model indicated that the region of interest was within range. The air velocity was set to 0.5 m/s to minimize the power consumption. Similarly, the relative humidity was set to 10%, recognizing that cacao beans dry more slowly in high-humidity environments. To optimize both quality and efficiency, the design constraints were aimed at minimizing the drying time while maximizing the bean quality. Each solution found using these criteria has a desirability value, and the solution closest to 1.0 is likely to yield the most favorable drying conditions. The report showed that of the 26 solutions, one optimal solution was selected with a desirability value of 0.95 (Figure 5), a predicted drying time of 34 h, and a quality of 8.83 (Figure 6). The optimization process identified the optimal drying conditions for cacao beans at 57.85°C, 0.5 m/s air velocity, and 10% relative humidity. These results confirm the correlation between moderate drying temperatures and bean quality. While higher temperatures reduce drying time, excessive thermal exposure compromises the internal structural and biochemical stability.

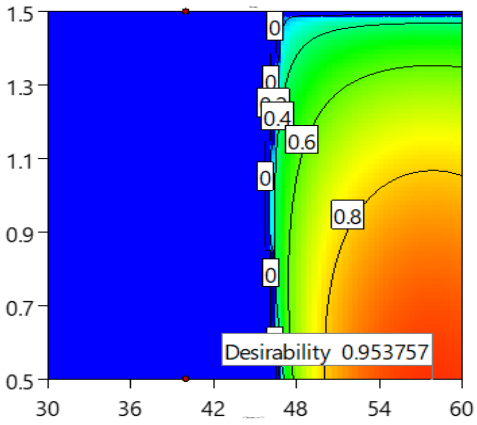
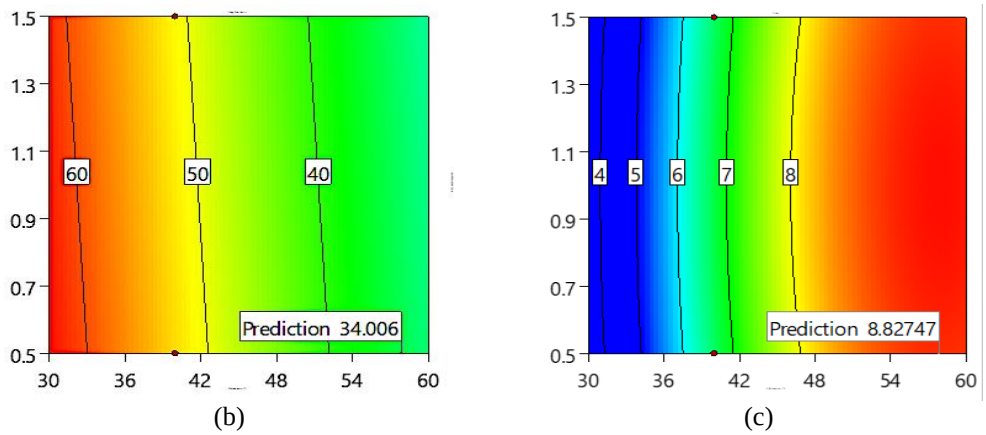


Figure 5. Contour graph representation of 0.95 desirability



(b) (c)

Figure 6. Contour graphical representation of the (a)predicted drying time (in hours), (b) predicted bean quality

4. Conclusions

In conclusion, this study successfully conducted the necessary experiments using a fabricated mechanical dryer and employed response surface methodology to optimize the drying temperature of fermented cacao beans. Based on the results, the optimal drying temperature for fermented UF-18 cacao beans is 57.85°C, with an air velocity of 0.5 m/s and 10% relative humidity; these conditions will produce the best quality when applied intermittently for a total of 34 h of drying time. This study also showed that fermentation is the most significant factor affecting bean quality, regardless of the drying method, whether natural or artificial, intermittent, or continuous. This study successfully optimized the mechanical convective drying parameters of fermented UF-18 cacao beans using Response Surface Methodology.

Temperature was identified as the most significant factor influencing both the drying time and bean quality. While higher temperatures reduced the drying time, excessive heat negatively affected the internal structure and quality of the beans. The optimum drying temperature was 57.85°C, air velocity of 0.5 m/s, and relative humidity of 10% under intermittent drying, achieving a predicted drying time of 34 h and a quality score of 8.83. These results show that controlled moderate drying conditions balance the efficiency and quality of mechanical cacao drying systems.

Acknowledgements
The authors thank the Mechanical Engineering Program, University of Mindanao, Matina Campus, Philippines, for providing the infrastructure needed to carry out this research.

Funding
This study was not supported by any grants from funding bodies in the public, private, or non-profit sectors.

Declaration of Competing Interests
The authors declare no conflicts of interest

CRediT Author Contribution Statement
Rick Ryan G. Renegado: Conceptualization; Methodology; Analysis; Resources; Writing – original draft
Harvey Bryant M. Marquez: Methodology; Analysis; Resources; Data Curation; Writing – review & revise
Cresencio P. Genobiagon Jr.: Conceptualization; Methodology; Analysis Supervision; Writing – review & revise; Project administration

Availability of Data and Materials
The data supporting the findings of this study are available upon request from the corresponding author.

Ethics Statement
This study did not involve human participants or animal subjects. Therefore, ethical approval was not required.

Generative Artificial Intelligence Disclosure
The authors claim that artificial intelligence-assisted technologies, such as generative AI, were not used to generate content, ideas, or theories. We have used AI to enhance readability and refine the language. This was used with extreme human control and oversight. The authors take full responsibility for reviewing and approving the content.

References

[1] M. V. A. Gonzales and A. A. Janaban, "Cacao industry: Its status, opportunities and challenges," *International Journal of Science and Management Studies (IJSMS)*, vol. 7, no. 6, pp. 178–196, 2024. https://doi.org/10.51386/25815946/ijsms-v7i6p120.

[2] F. Ramírez, G. Adolfo, P. A. Polanía-Hincapié, L. J. López, and J. C. Suárez, "Fermentation and its effect on the physicochemical and sensory attributes of cocoa beans in the Colombian Amazon," *PLOS ONE*, vol. 19, no. 10, Art. no. e0306680, 2024. https://doi.org/10.1371/journal.pone.0306680.

[3] M. Santander, V. Chica, H. A. M. Correa, *et al.*, "Unravelling cocoa drying technology: A comprehensive review of the influence on flavor formation and quality," *Foods*, vol. 14, no. 5, Art. no. 721, 2025. https://doi.org/10.3390/foods14050721.

[4] J. Pita-Garcia, J. Reinoso-Tigre, S. Palacios-Ponce, *et al.*, "Impact of combined sun and hybrid drying technologies on cocoa drying process and quality," *Heliyon*, vol. 11, no. 4, Art. no. e42884, 2025. https://doi.org/10.1016/j.heliyon.2025.e42884.

[5] S. G. P. Placencia, A. K. E. Carbonel, L. N. Digal, and C. Q. Balgos, "Factors influencing the technical efficiency of smallholder cacao farmers in Davao de Oro, Philippines," *Asian Journal of Agriculture and Development*, vol. 22, no. 1, pp. 75–97, 2025. https://doi.org/10.37801/ajad2025.22.1.5.

[6] A. G. D. Barros and R. P. Octavio, "Profitability of cacao (Theobroma cacao L.) production in the selected areas of Misamis Oriental," *International Journal of Agricultural Technology*, vol. 22, no. 2, pp. 593–612, 2026. https://doi.org/10.63369/ijat.2026.22.2.593-612.

[7] M. Marabulas, S. Jayme, H. Colita, *et al.*, "An AHP-based GIS method to detect biotic and abiotic stress factors of a cacao farm in Cebu, Philippines," in *Proc. 2023 IEEE Asia-Pacific Conf. Geoscience, Electronics and Remote Sensing Technology (AGERS)*, 2023, pp. 63–70. https://doi.org/10.1109/AGERS61027.2023.10490613.

[8] S. Tepthanee, J. Taweekun, and P. Vessakosol, "Application of passive technique to cocoa beans batch dryer and assessment of thin layer models," *International Journal of Automotive and Mechanical Engineering*, vol. 21, no. 2, pp. 11398–11414, 2024. https://doi.org/10.15282/ijame.21.2.2024.17.0880.

[9] J. E. Kongor, M. Owusu, and C. Oduro-Yeboah, "Cocoa production in the 2020s: Challenges and solutions," *CABI Agriculture and Bioscience*, vol. 5, no. 1, Art. no. 102, 2024. https://doi.org/10.1186/s43170-024-00310-6.

[10] H. de Barros Kobi, R. B. A. Fernandes, D. S. de Senna, *et al.*, "Metabolic profile of fatty acids, phenolic compounds, and methylxanthines of cocoa kernels (Theobroma cacao L.) from different cultivars produced in cabruca and full

sun farming systems," *Food Research International*, vol. 197, Art. no. 115198, 2024. https://doi.org/10.1016/j.foodres.2024.115198.

[11] A. N. Mbakouop, H. Tchakounté, A. I. Ankungha, and C. B. Nzoundja Fapi, "Experimental performance analysis of a mixed forced convection solar dryer: Application to cocoa bean drying," *Solar Energy*, vol. 257, pp. 110–124, 2023. https://doi.org/10.1016/j.solener.2023.04.010.

[12] C. P. Genobiagon, Jr., "Performance of solar cabinet dryer utilizing thermosyphon water heater," in *Technological Advancement in Instrumentation & Human Engineering*, M. H. A. Hassan et al., Eds. Singapore: Springer Nature Singapore, vol. 882, 2023, pp. 243–252. https://doi.org/10.1007/978-981-19-1577-2_18.

[13] R. Niikoi Kotey, D. A. Odoom, P. Kumah, *et al.*, "Effects of fermentation periods and drying methods on post-harvest quality of cocoa (Theobroma cacao) beans in Ghana," *Journal of Food Quality*, vol. 2022, Art. no. 7871543, 2022. https://doi.org/10.1155/2022/7871543.

[14] T. R. F. Sinuhaji, S. Suherman, and H. Hadiyanto, "A systematic literature review of the drying of cocoa in 2003–2023," *Food and Humanity*, vol. 3, Art. no. 100347, 2024. https://doi.org/10.1016/j.foohum.2024.100347.

[15] G. There and R. Sharma, "A comprehensive review of design and technological advancements across various types of solar dryers," *Energy Engineering*, vol. 121, no. 10, pp. 2851–2892, 2024. https://doi.org/10.32604/ee.2024.049506.

[16] N. Konar, I. Palabiyik, A. Karimidastjerd, O. S. Toker, and A. Gorgulu, "Recent advances in cocoa chemistry and roasting," *Trends in Food Science & Technology*, vol. 162, Art. no. 105036, 2025. https://doi.org/10.1016/j.tifs.2025.105036.

[17] K. Y. B. Diez, J. P. A. Yap, and C. P. Genobiagon, Jr., "Temperature profile of mixed mode solar cabinet coconut dryer," in *Technological Advancement in Instrumentation & Human Engineering*, M. H. A. Hassan et al., Eds. Singapore: Springer Nature Singapore, vol. 882, 2023, pp. 231–241. https://doi.org/10.1007/978-981-19-1577-2_17.

[18] I. A. Dharma, M. G. Z. Haikal, M. Ridlwan, S. A. Dewanto, and M. A. Rahman, "Heat transfer simulation for re-design of tray dryer to reduce the energy consumption in the cocoa bean drying process," *IOP Conference Series: Earth and Environmental Science*, vol. 1372, no. 1, Art. no. 012095, 2024. https://doi.org/10.1088/1755-1315/1372/1/012095.

[19] M. P. López, B. L. Botina, M. C. Garcia, *et al.*, "Reducing dead time and improving flavour profile by pulp conditioning of cacao beans," *Chemical Engineering and Processing — Process Intensification*, vol. 176, Art. no. 108979, 2022. https://doi.org/10.1016/j.cep.2022.108979.

[20] J. Suarez, J. Espinosa, K. Contreras, and J. Bacca, "Automated classification of cocoa bean fermentation levels using computer vision," in *Proc. 2025 XXV Symp. Image, Signal Processing, and Artificial Vision (STSIVA)*, 2025, pp. 1–5. https://doi.org/10.1109/STSIVA66383.2025.11156348.

[21] A. Boublia, S. E. I. Lebouachera, N. Haddaoui, *et al.*, "State-of-the-art review on recent advances in polymer engineering: Modeling and optimization through response surface methodology approach," *Polymer Bulletin*, vol. 80, no. 6, pp. 5999–6031, 2023. https://doi.org/10.1007/s00289-022-04398-6.

[22] M. Reji and R. Kumar, "Response surface methodology (RSM): An overview to analyze multivariate data," *Indian Journal of Microbiology Research*, vol. 9, no. 4, pp. 241–248, 2022. https://doi.org/10.18231/j.ijmr.2022.042.

[23] P. R. do N. Costa, M. da S. Silveira, J. C. DoVale, and P. H. M. de Sousa, "Bean-to-bar chocolate: An integrative framework linking terroir, biochemistry, processing, and sensory expression," *Comprehensive Reviews in Food Science and Food Safety*, vol. 25, no. 3, Art. no. e70515, 2026. https://doi.org/10.1111/1541-4337.70515.

[24] D. O. Oke and K. F. Omotayo, "Effect of forced-air artificial intermittent drying on cocoa beans in South-Western Nigeria," *Journal of Cereals and Oilseeds*, vol. 3, no. 1, pp. 1–5, 2012. https://doi.org/10.5897/JCO11.037.

[25] G. V. S. Lima, C. G. e Gonçalves, A. S. O. Pinto, E. M. da Silva, J. N. S. de Souza, and H. Rogez, "Impact of post-harvest processing and roasting conditions on the physicochemical properties, phenolic compounds, and antioxidant capacity of cocoa beans from the Brazilian Amazon," *LWT*, vol. 210, Art. no. 116825, 2024. https://doi.org/10.1016/j.lwt.2024.116825.

[26] I. K. E. H. Wiryanta and I. M. A. Adiaksa, "The effect of fluid flow variation on clove dryer machine with control of air temperature and relative humidity," *Journal of Physics: Conference Series*, vol. 1450, no. 1, Art. no. 012102, 2020. https://doi.org/10.1088/1742-6596/1450/1/012102.

[27] D. Gopaulchan, C. Moore, N. Ali *et al.*, "A defined microbial community reproduces attributes of fine flavour chocolate fermentation," *Nature Microbiology*, vol. 10, no. 9, 2025. https://doi.org/10.1038/s41564-025-02077-6.

[28] E. Castillo-Orozco, O. Garavitto, O. Saavedra, and D. Mantilla, "The drying kinetics and CFD multidomain model of cocoa bean variety CCN51," *Foods*, vol. 12, no. 5, Art. no. 1082, 2023. https://doi.org/10.3390/foods12051082.