

RESEARCH ARTICLE

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

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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.

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1. Introduction

Fermented cacao beans are the dried, fully fermented fatty seeds of *Theobroma cacao*, produced through a spontaneous process driven by ordered microbial succession [1]-[2]. Among its 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 is considered to have a competitive advantage in cacao production due to 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 largest cacao-producing region in the country, accounting for 82 percent of the country's 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 aligned with the 2022 Cacao Challenge to produce 100,000 MT of dried fermented beans [4]. With this vision, it is an excellent opportunity to optimize the drying temperature of fermented UF-18 cacao beans to reduce mass losses, prevent spoilage, and improve production.

During primary processing of cocoa (*Theobroma cacao*) beans, drying fermented beans reduces moisture content from 60% to 6-7%, enabling safe storage and transportation[8]. The extent of chemical changes and the 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, are available to improve cocoa beans' drying properties and final quality [11],[11]. Throughout the tropics and subtropics, where solar radiation is abundant, the natural sun-drying method is one of the oldest, cheapest, and most popular techniques available for drying crops[11]. According to Auro Chocolate Industry, an internationally awarded Filipino bean-to-bar chocolate company that sustainably sources cacao beans directly from local farming. 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. The results of sun-dried samples were better than those of other methods at all temperatures; however, it has several disadvantages, such as uncontrollable temperature and the risk of overheating the beans. In addition, sun drying is a labor-intensive method that involves many people [12]-[13].

In solar dryers, fermented cacao beans are covered and protected from wind while exposed to solar radiation during open-air sun drying [14]. Devices called solar dryers use the sun's 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]. On the other hand, the mechanical dryer type, which uses an active heat source, will 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, is suitable for heat-sensitive products, utilizes cheap local resources to meet energy requirements, and has a low construction cost [18]. Nonetheless, using unsuitable temperatures and air velocities to reduce the desired moisture content of fermented cacao seeds results in low-quality cacao beans. In cocoa production, proper moisture levels are important; if cocoa beans are over-dried or excessively dry, it affects flavor. During hulling, the beans become fragile and are prone to breakage. Conversely, if beans are very moist or not dried completely, they will quickly deteriorate due to

bacteria and fungi [17]. Although mechanical dryers provide better control than sun or solar drying, many drying operations still rely on trial-and-error in selecting operating conditions. Recent studies focus primarily on temperature effects, with less 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 multi-parameter optimization and systematic quality evaluation. Although several cocoa bean drying methods were used, a framework for optimizing controlled convection mechanical drying of fermented cacao beans remains limited. It promotes understanding of how temperature, air velocity, and relative humidity interact during convective drying and affect bean quality. At the same time, 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 demand for cacao beans in the Philippines has compelled farmers to expedite production by 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 to produce high-quality goods. To obtain optimal drying temperature data, we will use a surface response methodology and perform various tests. The objectives of the study are 1) to optimize the drying temperature of cacao beans utilizing Response Surface Methodology, 2) to produce dried cacao beans with quality like that of sun-dried cacao beans using a fabricated mechanical dryer. The study aims to design, fabricate, develop, test, and implement using response surface methodology. The testing parameters to consider during the experiments include drying rates at different temperatures and air velocity variations, the drying chamber's interior and exterior humidity levels, 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 made available from local cacao producers in the Davao Region, Philippines. The beans were fermented prior to drying. The initial moisture content was 56% (wet basis), determined using the gravimetric method. For each experimental run, 1 kg of fermented beans was 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.

The researchers will use the following materials to determine the optimal drying temperature for fermented cacao beans. Air velocity inside the drying chamber was measured with a digital anemometer (0.0–45.0 m/s range, 0.3 m/s threshold), positioned at the drying chamber exit to monitor airflow passing through the bean layer. Air was circulated by 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 raise 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 setpoints. Relative humidity inside the drying chamber was controlled by regulating the airflow and heating rate of the system. Relative humidity decreases as temperature decreases, and fresh air is introduced using axial fans. A digital balance with accuracy of ± 0.01 g was used and placed under the drying tray to measure the weight at a specific time. The thermocouple had an accuracy of ± 1 °C, while the humidity sensor had an accuracy of $\pm 2\%$ RH. The digital anemometer had an accuracy of ± 0.1 m/s. These specifications ensured reliable measurement of drying parameters throughout the experiments.

2.2 Experimental Setup

A mechanical dryer was designed and fabricated. The schematic configuration of the fabricated mechanical convective dryer is shown in Figure 1. The system consists of an intake fan (1) that drives airflow through a resistor heater (2) before entering the drying chamber containing the drying trays (4). The frame (5) supports the assembly, and temperature and humidity were measured and controlled using a temperature controller with a thermocouple (10) and a hygrometer (9). A digital balance (3) is integrated to measure mass loss during drying, and airflow velocity is monitored using a digital anemometer (6). The front access door (8) with locking mechanism (7) allows loading and unloading of cacao beans. The dryer dimensions were $111 \times 31 \times 93$ 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. Each trial used 1 kg of beans, evenly distributed across two drying trays. To cut down on heat loss while running, insulation was applied to the inside walls of the chamber. To supply the required airflow, an axial fan was also put in place. A digital balance is positioned below the drying chamber to help measure the mass in real-time. Type-K thermocouples and humidity sensors were set at viable spots.

The sub-experiments within the actual experiments compare continuous and intermittent drying methods. The production of marketable items can turn around more quickly during continuous drying or without breaks. According to some studies, implementing rest periods during the drying cycle, also known as intermittent drying, can mitigate the drawbacks of rapid drying [19]. Identifying the difference between these two drying methods through experimentation is also part of this research. The series of experiments has a sample size of 1 kilogram of UF-18 cacao beans (fermented for five days) per experiment. These beans were put on the drying tray and placed inside the mechanical dryer. The experiment was configured using the specified temperature, air velocity, and relative humidity, as derived from the Design Expert software, to initiate the drying process.

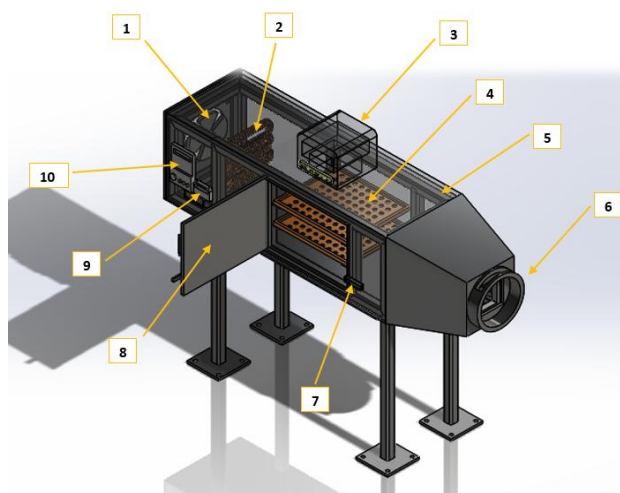


Figure 1. Schematic representation of the laboratory-scale mechanical convective dryer showing major components and measurement instruments

The gravimetric method was used to determine the drying termination point by determining the moisture content through periodic weighing of the 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 is 56%. The drying rate in each experimental trial was determined by recording the bean weight at equal intervals. The cut test method determined the bean quality according to the classification chart [20]. For each batch, 50 beans were sliced and visually assessed for internal colour, shell appearance, structural integrity, and 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). The overall quality score for each run was determined based on the dominant classification observed.

This study's statistical analysis utilizes the response surface methodology (RSM). The RSM technique is a widely used mathematical and statistical method for modeling and analyzing a process. Experiments must be planned and carried out based on the number of input variables [13], [21]. Until we attain a workable model, we will examine the intricacy of the interactions between the variables. The independent variables are the parameters that affect the process, while the dependent variables are the responses [22]. In this case, the responses of interest would be drying time and cacao bean quality, while the variables would be the different types of drying technologies. The resulting model, which also caps the experimental run, comprises all the data on the impact of the experimental conditions. Additionally, within the model's ranges, it can forecast upcoming observations [21].

2.3 Experimental Design and Optimization Procedure

To establish the experimental framework for process optimization, the researchers generate the operational bounds for each factor in the Design Expert Software. The temperature range was 40 °C to 70 °C, air velocity 0.5 m/s to 1.5 m/s, and relative humidity 10% to 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 among the factors. Drying was considered complete once the cacao beans reached a final weight of 500 to 510 grams, 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

The entire set of experimental conditions generated along with their factor levels is shown in Figure 2. At the lowest temperature of 29.77 °C, keeping the air velocity constant at 1.0 m/s and 15% relative humidity, it required 64 hours of intermittent drying to decrease the moisture content of 1000 g of fermented cacao beans from 56% to 6.9%. As seen in Figure 2 (a), the drying rate was highest in the first hour and gradually declined over the next 7 hours, whereas the moisture content continuously went down. 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 there is free moisture readily available [3]. The cut test reveals that beans are shiny and indicates that they were probably not dried properly. Fissures were seen 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 since they turn brown during storage [23], the main features point out insufficient drying and fermentation. From these points, the beans are at level 5 on the bean quality scale. Hence, the beans changed their color to light gold and shrank a bit, but they still looked wet after 64 hours, which gave a low-quality bean product. This temperature is far from ideal.

The drying rate dropped substantially from 61g/h to 11g/h at the first drying stage. This indicates that the first stage moisture removal was significant. The drying rate between the 4th and the 8th hour decreases further but much slower -

about one tenth as much moisture is lost. In the next phase of drying, between hours 8 and 12, the drying rate increased for a short time before decreasing again between hours 12 and 16. Fig. These changes 2b show the intermittent nature of the drying process, having periodic peaks in the curve of drying rate. The drying rate peaks show moisture uptake again during the rest periods. As supported by Oke and Omotayo[24], ambient relative humidity tends to be lower during the day and more stable at night, contributing to this behavior. The cocoa beans were a deep golden-brown color. This showed that the cocoa shells had been dried. The cut test showed the cores to be a deep purple, slowly turning to light brown, indicating the beans were slightly underfermented. The beans had a malty smell, reminding me of the smell of the traditional *Tablea*. The cut test showed the dried beans were of quality level 6.

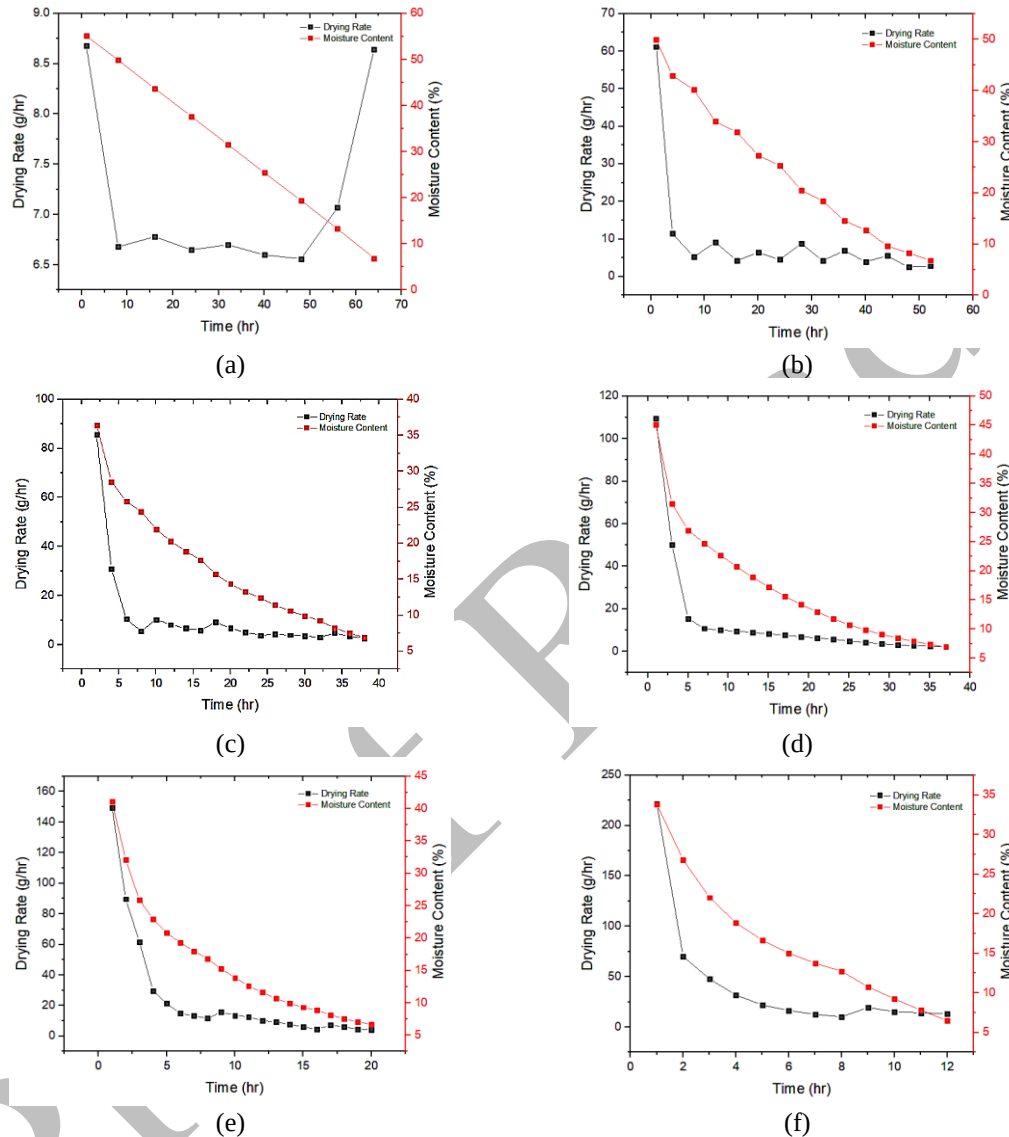


Figure 2. Moisture content and drying rate profiles under various experimental drying conditions: (a) 29.77°C, 1.0 m/s, 15% RH (64 h, intermittent); (b) 40°C, 0.5 m/s, 10% RH (52 h, intermittent); (c) 55°C, 1.0 m/s, 15% RH (38 h, intermittent); (d) 55°C, 1.0 m/s, 15% RH (37 h, continuous); (e) 70°C, 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 moisture content of the fermented cacao beans was reduced from 56% to 6.85% in around 50 hours at 40°C with an air velocity of 1.5 m/sec and in 52 hours at 0.5 m/sec. The variations of relative humidity did not significantly affect the drying time at this temperature. The increasing 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 hours. The same parameters were used for six experimental runs at drying temperature 55 °C, air velocity 1 m/s, and relative humidity 15% (Figure 2c and Figure 2d). Three of these runs were continuous drying runs, and three were intermittent drying runs. Drying time of the continuous method is 37 hours, and it was an hour less than intermittent drying (38 hours). But the drying was continuous, and the quality of beans was lower, despite the shorter time. The drying curves for intermittent and continuous methods also show distinctive patterns. The intermittent drying curves showed periodic spikes in the drying rate, indicating moisture reabsorption during the rest of the intervals, whereas continuous drying exhibited a steady, uninterrupted decline in both the drying rate and moisture content. These patterns align with previous studies indicating drying durations of 41

hours for intermittent and 30 hours for continuous drying within the 40–54 °C range using adsorbents [25], lending support to this study's results.

Four additional runs at 55 °C were conducted with variations in air velocity and relative humidity. Two of these experiments achieved the shortest drying time of 36 hours: 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%. While longer drying times of 40 hours were observed for runs with the lowest air velocity (0.16 m/s) at 15% RH and with 1 m/s at the highest RH of 23.41%, and final moisture contents of 6.85% and 6.89%, respectively. This indicates that increases in air velocity and temperature enhance drying rates [26], and the relative humidity improves overall drying efficiency [34]. Intermittent drying produced good-quality beans. Cut tests show brown shells and internal bean coloration, with a chocolate-like aroma that corresponds to a bean quality score of 9. Moreover, continuous drying resulted in beans with pale brown to partially purple interiors, though still well-dried. These were classified as bean quality level 7. Although 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. Variations in RH between 10% and 20% contributed to differences in drying rate and total drying time. The decrease in relative humidity helped to increase the difference in moisture levels between the bean surface and the surrounding air, which sped up the evaporation process. On the other hand, the increase in relative humidity slightly delayed the drying process because of smaller vapor pressure differences.

As shown in Figure 2 (e), the drying conducted at 70 °C under intermittent drying conditions took 20 hours to complete 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 time was 19 hours. 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 shell than in previous experiments. The internal color of the beans was a deep brown, suggesting that they were well-dried and slightly over-fermented. The beans correspond 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 resulting bean quality in this experiment likely reflects the effects of fermentation more than those of drying alone.

Drying at 70 °C under controlled air velocity and relative humidity represents a promising condition for 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 with a relative humidity of 15% and an air velocity of 1 m/s, as shown in Figure 2f. This trial had the steepest drying curve of all 20 experimental runs. The high drying temperature, however, reduced the quality of the beans. The cut test showed shells that were overdried and interiors that were under dried. The bean quality rating was level 5 on the quality chart. This condition shows uneven drying. Earlier studies on the temperature-dependent drying kinetics demonstrated that quick drying restricts the complete oxidation processes in beans needed for a homogeneous brown color. [3]. Therefore, this experiment confirms that higher temperature and shorter drying duration do not necessarily yield superior bean quality. Results emphasized that optimum drying parameters should be achieved. The drying rate of cocoa beans decreases progressively, making it a critical factor in designing post-harvest drying systems [26]. The findings can be adopted by engineers and practitioners in selecting drying conditions that ensure both efficiency and quality in cocoa processing.

A. Response Surface

Design Expert used ANOVA, fit statistics, and coefficient analysis to validate the model. The equation, with factor levels set at +1 and -1, enabled comparison of factor effects, indicating their relative importance. Conversely, the actual-factor equation, expressed in original units, is useful for prediction but not for assessing factor significance due to coefficient scaling and a non-central intercept. For Response 1, as shown in Figure 3, multiple models were evaluated through statistical validity, model hierarchy, and predictive accuracy. The cubic model exhibited the least significant lack-of-fit; its aliased status rendered it invalid. The quadratic model shows an insignificant lack of fit with high Adjusted R² and Predicted R² values and did not provide the optimal fit. Therefore, the linear model was considered the most appropriate for modeling drying time. The Model F-value of 427.38 implies the model is significant. There is only a 0.01% chance that an F-value this large could occur due to noise. P-values less than 0.0500 indicate that the model terms are 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 cases thus, overall model fit remained acceptable. The adjusted R² (0.9854) and predicted R² (0.9783) correlate, with a difference of less than 0.2, indicating strong predictive performance. The Adequate Precision value of 72.720, far exceeding the minimum threshold of 4, confirmed a strong signal-to-noise ratio, validating the model's utility for navigating the design space.

The mathematical model shows the influence of temperature, air velocity, and moisture content on drying time. The linear equation for response 1 has a drying time constant of +36.70. This means that it is the lowest possible drying time for the beans to achieve the maximum quality. It is followed by the term -15.70A, which is the temperature factor. The negative sign indicates that there is an inverse relation between temperature and drying time, which means that as temperature decreases, drying time increases, and vice versa. Likewise, the coefficient -0.86B shows that the relationship between air velocity and drying time is inversely weaker. The coefficient of +0.56 °C shows a direct relation to relative humidity, where an increase in humidity slightly prolongs drying.

The results of the study showed that drying temperature and air velocity affect the drying of cocoa beans through two measures; the drying constant which is highly correlated with temperature has an R^2 of 84.8%, while the R^2 decreases to 80.9% when considering air velocity. 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 rate of drying increased with both increasing temperature and increasing air velocity, but, as expected, the rate of drying declined over time [3]. The validity of the linear model for Response 1: Drying Time, as generated by Design Expert, was applied to the response surface plots to investigate the effects of temperature, relative humidity, and air velocity on drying time. As shown in Figure 3, the region of interest appeared between 30 and 40 hours on the drying time axis. The predicted optimal drying time corresponded to a temperature range of 30–60 °C, at approximately 1 m/s air velocity.

The model for Response 2 is shown 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 for modeling 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 due to noise. Model terms with P-values less than 0.0500 were considered significant; in this case, A (temperature) and A^2 (temperature squared) were significant terms. Model terms with P-values greater than 0.1000 were considered insignificant. In the presence of many insignificant terms, excluding those required to maintain the model hierarchy, model reduction could improve the model. to Temperature, Relative Humidity, and Air Velocity. The Predicted R^2 of 0.2258 is not as close to the Adjusted R^2 of 0.8061 as one might normally expect, i.e., the difference is more than 0.2. This indicates a large block effect or a possible problem with your model and/or data. Things to consider are model reduction, response transformation, outliers, etc. All empirical models should be tested by doing confirmation runs. Adeq Precision measures the signal-to-noise ratio. A ratio greater than 4 is desirable.

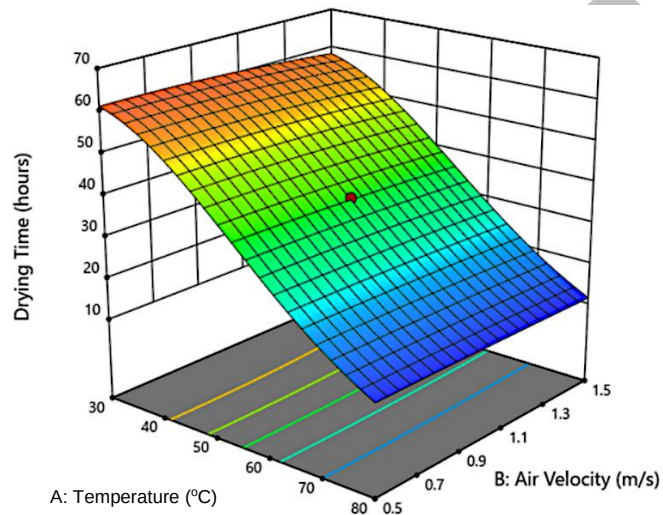


Figure 3. 3D graphical representation of drying time response

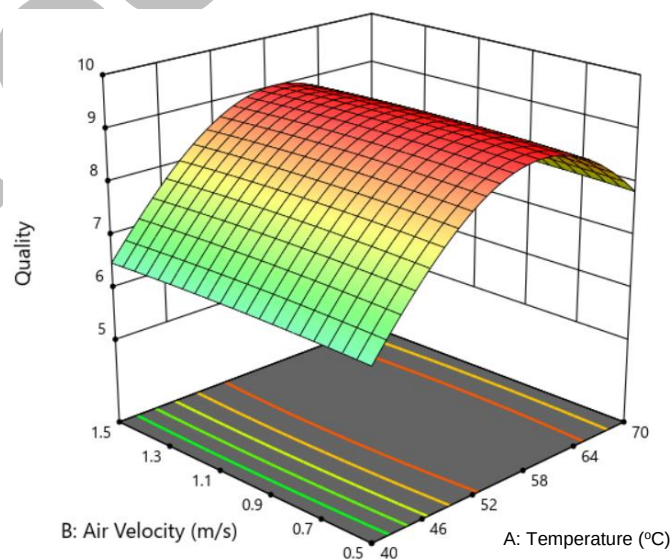


Figure 4. 3D graphical representation of the bean quality response to temperature, relative humidity, and air velocity

The quadratic model for Response 3: Bean Quality, generated by Design-Expert, was used to construct response surface plots examining the effects of temperature, relative humidity, and air velocity on bean quality. As shown in Figure

3, the region of interest was centered around a bean quality value of approximately 9. The predicted optimal bean quality corresponded to a temperature range of 52–64 °C. Evaluation of bean quality was based on the researcher's sensory assessment and was therefore subjective. Bean quality was sensitive to temperature. Under-dried beans of lower quality scores were produced at temperatures of 29.77–40°C with slow moisture removal. Non-uniform drying and poor quality were due to rapid drying of the surface at 80.22 °C, which hindered the diffusion of internal moisture. The best quality was obtained in the middle temperature range of 52–64°C, which confirmed that there was a nonlinear relationship between drying temperature and quality of beans. This agrees with Gopaulchan et al. [27], who state that elevated drying temperatures may alter volatile compound development, affecting flavor formation. Similarly, Castillo-Orozco et. Al. [28] noted that temperature influences drying kinetics and final bean characteristics, reinforcing the dominant role of temperature over air velocity.

B. Optimization

Using predictions from validated mathematical models for drying time and bean quality, Design Expert generated optimization solutions that met 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 power consumption. Similarly, 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 aimed to minimize drying time while maximizing bean quality. Each solution found by these criteria has a desirability value, and the solution with the closest desirability to 1.0 is likely to yield the most favorable drying condition. The report shows that, out of 26 solutions, one optimal solution was selected with a desirability value of 0.95 (Figure 5), with a predicted drying time of 34 hours and a quality of 8.83 (Figure 6). The optimization process produced the optimal drying conditions for cacao beans at a temperature of 57.85°C, 0.5m/s air velocity, and 10% relative humidity. These results confirm a correlation between moderate drying temperature and bean quality. While increasing temperature reduces drying time, excessive thermal exposure compromises internal structural and biochemical stability.

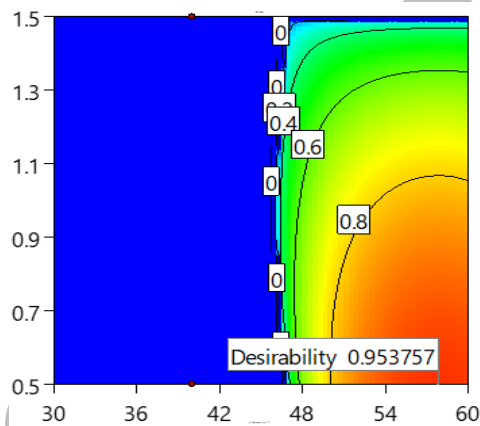


Figure 5. Contour graph representation of 0.95 desirability

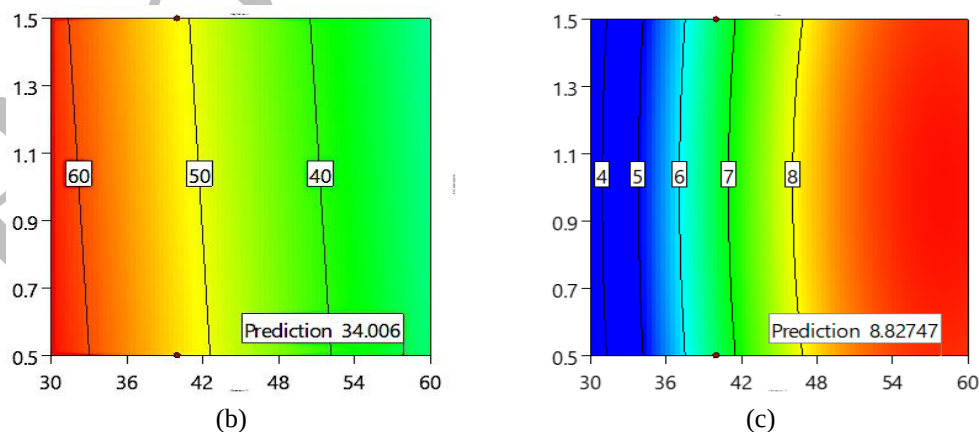


Figure 6. Contour graphical representation of the (a) predicted drying time (in hours), (b) predicted bean quality

4. Conclusions

In conclusion, this study successfully conducted the necessary experiments using a fabricated mechanical dryer and used 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 hours of drying time. This study also shows that the fermentation process is the most significant factor affecting the beans' quality, regardless

of the drying method, be it 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 drying time and bean quality. While higher temperatures reduced drying duration, excessive thermal exposure negatively affected internal bean structure and quality. 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 hours and a quality score of 8.83. These demonstrate that controlled moderate drying conditions provide a balance between efficiency and quality in mechanical cacao drying systems.

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Declaration of Competing Interests

The authors declare no conflicts of interest

CRediT Author Contribution Statement

Rick Ryan G. Renegado: (Conceptualization; Methodology; Formal Analysis; Resources; Writing – Original Draft)
Harvey Bryant M. Marquez: (Formal Analysis; Resources; Data Curation; Writing – Review and Editing)
Cresencio P. Genobiagon Jr.: (Supervision; Writing – Review & Editing; Project Administration)

Ethics Statement

This study did not involve human participants or animal subjects. Ethical approval was therefore not required for this research.

Generative Artificial Intelligence Disclosure

The authors report that generative artificial intelligence (AI) techniques were not used to create the scientific content, concepts, analysis, or findings in this study. Any AI-assisted technologies used were for language improvement and readability enhancement under stringent human oversight and control. The authors are responsible for the integrity, accuracy and final content of the paper.

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