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Chris Jury E. Amba
College of Engineering and Geosciences, Caraga State University

Mary Grace A. Traya
College of Engineering and Geosciences, Caraga State University

Neil Caesar M. Tado
College of Engineering and Geosciences, Caraga State University

May Rose B. Osoteo
College of Engineering and Geosciences, Caraga State University

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Effect of temperature and tempering time on the sensory attributes of roasted cacao beans

Chris Jury E. Amba*, Mary Grace A. Traya, Neil Caesar M. Tado, May Rose B. Osoteo, Eldie R. Labisto
College of Engineering and Geosciences, Caraga State University, Butuan City, Philippines
* Corresponding author: chrisjury.amba@carsu.edu.ph

Abstract: *This study aimed to optimize the performance of a hybrid cacao bean roaster that integrates liquefied petroleum gas (LPG) conduction heating, near-infrared (NIR) radiation, and a feedback-controlled blower for post-roast tempering. Using Response Surface Methodology (RSM) and Central Composite Design (CCD), the effects of roasting temperature and tempering time were evaluated based on roasting efficiency, uniformity, bulk density, bean temperature, and color attributes. The optimal condition was identified at 90 °C roasting temperature and 14.2 minutes tempering time, achieving high efficiency, consistent roast quality, and desirable color development. Validation results confirmed strong alignment with model predictions, supported by the system's automatic feedback mechanism that stabilized internal bean temperature. The overlay plot and post-analysis reinforced the model's reliability and practical applicability. Overall, the hybrid roaster demonstrated consistent, high-quality performance and is recommended for small- to medium-scale cacao processing, offering an efficient and controlled approach to post-harvest bean treatment.*

Keywords: cacao roasting, hybrid heating system, response surface methodology

1. INTRODUCTION

Cacao (Theobroma cacao L.) is a high-value crop widely used in food, cosmetics, and pharmaceuticals [1]. Despite the global cacao trade reaching $9.59 billion in 2021 [2], productivity and post-harvest quality remain critical challenges, especially in regions such as the Philippines. In Caraga, which has suitable climatic conditions, cacao production remains low due to poor post-harvest practices and limited access to efficient roasting technologies [3].

Conventional roasting techniques often result in inadequate temperature control, inconsistent roasting outcomes, and reduced bean quality [4], [5]. A hybrid cocoa bean roaster was designed to overcome these limitations, utilizing liquefied petroleum gas (LPG) and near-infrared radiation (NIR) as heat sources, a blower fan for tempering, and a feedback system for precise temperature regulation. This technology seeks to improve roasting efficiency, consistency, and product quality.

The study focused on evaluating the performance of this hybrid roaster through physical parameters (roasting efficiency, uniformity, bulk density, bean temperature, and color) and sensory characteristics (flavor, aroma, and acceptability). Thirteen treatment combinations were tested, each replicated three times. The study also aimed to optimize operating parameters to improve cacao roasting performance, supporting sustainable and competitive cacao production in the Philippines.

2. Materials and Methods

2.1 Sample Preparation

Cacao beans were sourced from small-scale growers at the Langihan Public Market in Butuan City. The beans were fermented and sun-dried until they reached a moisture content of 6–8% (wet basis), in accordance with PAES 256:2018 standards. Flat and defective beans were manually removed, and the initial moisture content was determined using a digital moisture tester. A total of 20 kilograms of beans was used for the experiment, with 500 grams allocated per trial.

2.2 Hybrid Cacao Bean Roaster Machine

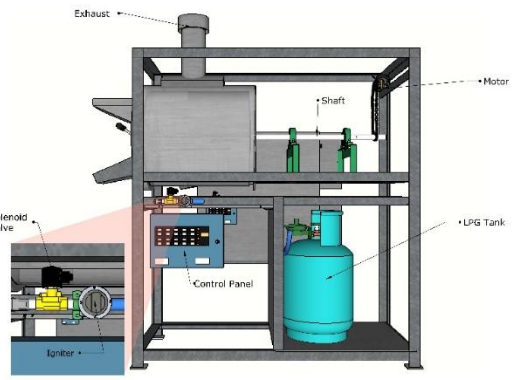


Figure 1. Hybrid Cacao Bean Roaster Machine

This study utilizes the hybrid cacao bean roaster integrating conduction and infrared as a source of heating system for roasting cacao beans.

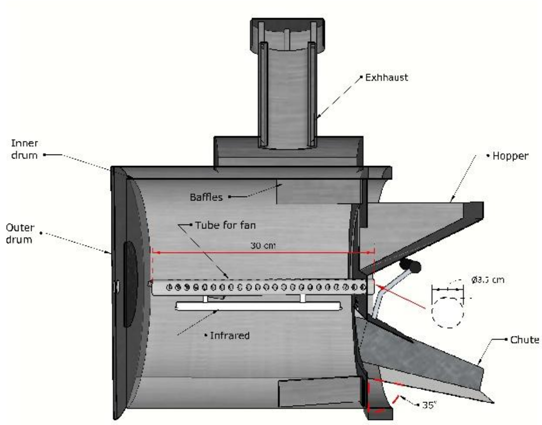


Figure 2. Cross-section of roasting drum

2.3 Experimental Design

The study employed Response Surface Methodology (RSM) using a Central Composite Design (CCD) using Design Expert version 13 to evaluate the effects of two independent variables: roasting temperature (90°C, 100°C, 110°C) and tempering time (5, 10, 15 minutes). A total of 13 treatment combinations were generated, each replicated three times. The roasting duration was fixed at 30 minutes, and the drum speed was maintained at 15 rpm.

2.4 Roasting System Description

The hybrid cacao bean roaster used in this study integrated liquefied petroleum gas (LPG) and near-infrared (NIR) heating systems. A blower fan was incorporated to temper the beans post-roast. Additionally, a feedback control system was installed to automatically regulate the fan based on internal bean temperature, ensuring consistent heat management.

2.5 Performance Evaluation

System performance was evaluated using the following parameters:

- Roasting uniformity (%)
- Roasting efficiency (%)
- Bulk density (g/cm³)
- Bean temperature (°C)
- Color properties (L*, a*, b*)

The color was assessed using the CIELAB color system, following a cut test performed on three randomly selected beans per replication. Beans were then ground and measured using a calibrated colorimeter.

2.6 Sensory Evaluation

A sensory analysis was conducted in a controlled setting at the CAA Building, located on the CSU Main Campus. Ten semi-trained panelists evaluated aroma, flavor, and overall acceptability utilizing a 10-point hedonic scale. Each panelist was provided with 13 coded samples, consisting of a row of plastic cups containing 100 g of ground beans. A blind testing setup was implemented, incorporating palate cleansers such as water and flavorless biscuits between samples to guarantee impartial results.

2.7 Validation and Post-Analysis

To verify the model's reliability, three validation runs were performed under the identified optimal conditions (90 °C roasting temperature and 14.2 minutes tempering time). The actual performance was compared with predicted values to assess accuracy and system consistency.

3. RESULTS AND DISCUSSION

3.1 Bean Count

Table 1 presents the results of the bean count method, a widely used quality assessment that measures the average number of whole cocoa beans in a 100g sample after sorting out round and flat beans. Analysis revealed an average of 0.75 beans/100g (range: 0.71–0.88; SD: 5.12), indicating moderate variability influenced by fermentation, drying conditions, and genetic factors [6]. Research also highlights an inverse relationship between bean count and size, where higher counts often correlate with smaller beans due to genetic and environmental factors [7].

Table 1. Descriptive analysis on Bean Count Data

Bean count	
Average	75.02
Standard Deviation	5.12

3.2 Bean Size

Table 2 displays the dimensional characteristics of cocoa beans, measured with a digital caliper along three axes: minor (8.9 ± 1.52 mm), intermediate (14.01 ± 1.59 mm), and major (24.87 ± 2.71 mm) dimensions. The moderate variability in these measurements, as indicated by their standard deviations, suggests inherent diversity in bean morphology. The calculated sphericity of (0.585 ±0.049) corresponds with the range (0.51–0.71) identified by Sandoval et al. [8] as indicative of well-fermented beans, highlighting satisfactory fermentation quality. The findings underscore the correlation between bean geometry and post-harvest processing, emphasizing the importance of dimensional analysis in evaluating cocoa bean quality and fermentation consistency [33].

Table 2. Major, Intermediate, Minor Size, and Sphericity of the cacao beans

Beans	Major (mm)	Intermediate (mm)	Minor (mm)	Sphericity
Avg.	24.87	14.01	8.9	0.58501
SD	2.711	1.594	1.527	0.049

3.3 Roasting Uniformity

Figure 3 illustrates how the temperature of roasting and the period of tempering affect the uniformity of the beans. Lower temperatures and shorter times result in less consistent outcomes (blue), whereas 110°C and 13 minutes yield the best results (green-red). These results align with other research that has found that roasting at higher temperatures for extended periods improves the taste and cooking uniformity of the food [9] [10] [11]. ANOVA shows that the system is stable (F = 0.91, p = 0.5256), and the fact that it does not fit (F = 0.01, p = 0.9973) validates the model's accuracy. The results demonstrate the importance of managing temperature and time precisely for even roasting and future improvements.

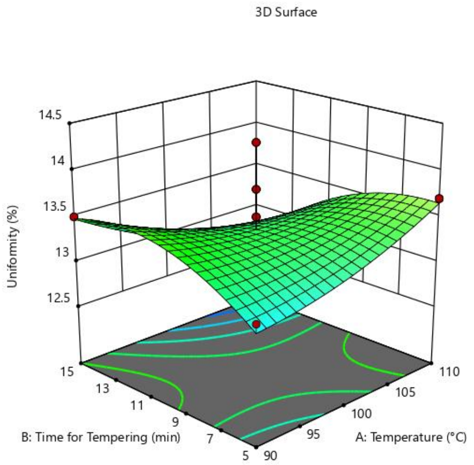


Figure 3. Roasting Uniformity

3.4 Roasting Efficiency

Figure 4 shows how temperature and duration optimize cocoa roasting. A 3D surface map revealed a possible efficiency peak at 110°C and 15 minutes of tempering [12]. This nonlinear synergy enables firms to enhance operations by utilizing color-coded data for quality control. While the model requires refinement (F = 2.63, p = 0.1198), A²'s relevance supports a crucial system link. High model accuracy (lack of fit *p* = 0.4285) confirms the method and encourages optimization. These findings suggest industry-relevant parameters and the need for additional studies, such as increased factor testing [13].

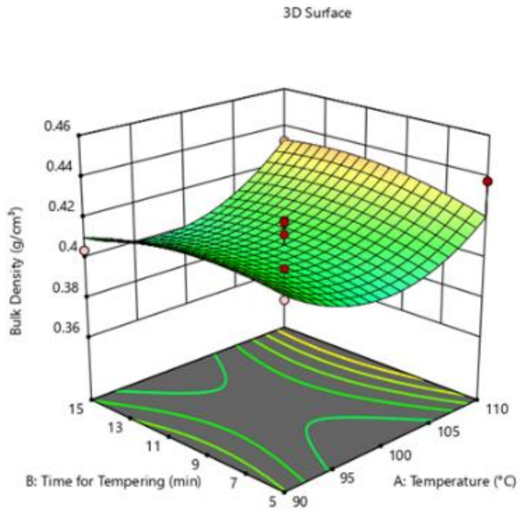


Figure 4. Roasting Efficiency

3.5 Bulk Density

In Figure 5, higher temperatures (110°C) and longer tempering times (15 minutes) (yellow/red zones) improve cellular rearrangement and particle packing, resulting in the optimal roasted cacao bulk density [14].

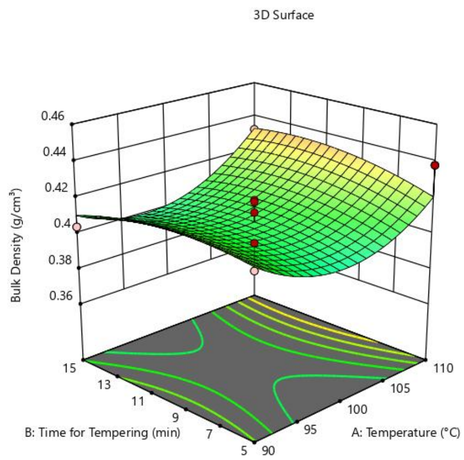


Figure 5. Bulk Density

The low noise probability (1.24%) suggests the patterns are fundamental despite the non-significant ANOVA results (F = 2.58). This high-efficiency zone and avoiding low-temperature/short-time circumstances (90°C/5min, blue zones) that occur during unfinished development can help manufacturers standardize and simplify [15]. Bulk density is an effective quality control measure since it shows structure change and process efficiency [10].

3.6 Bean Temperature

Figure 6 indicates that there is a significant linear relationship between the final bean temperature and the roasting parameters (temperature and tempering time) [16]. The model is statistically significant ($F = 5.63$, $p < 0.05$), and tempering time (Factor B) is a critical variable. There is a 42.08% chance that the lack of fit is noise, which means that the model fits well.

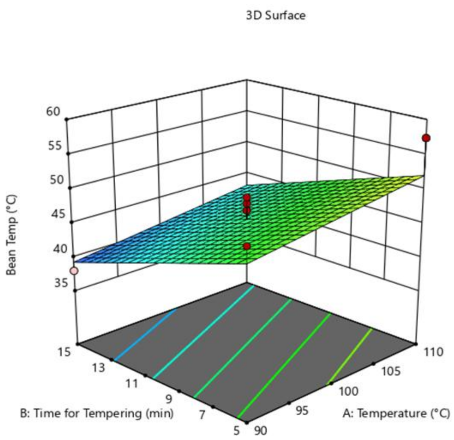


Figure 6. Response Surface Plot Showing the Effect of Temperature and Tempering Time on Temperature

These results enable real-world uses: precise temperature control (38–57 °C) improves flavor without causing degradation [17], guarantees batch consistency [18], and finds the best industrial setting (110 °C, 15-minute tempering) for feedback control.

3.7 Sensory Analysis

3.7.1 Aroma

The grading scale for the sensory analysis for aroma is shown in Table 3.

Table 3. Quality grade scale of cacao sensory analysis. Adapted from: Equal Exchange [20]

0	1	2	3	4	5	6	7	8	9	10
Terrible		Bad		Ordinary		Good		Excellent		

The results in Figure 7 shows that T6 and T8 scored 8 points, and T3, T4, and T7 scored 6. The majority of treatments scored 7 points on the quality grade scale. Such ratings imply excellent fermentation and roasting conditions for chocolate taste precursors, according to Afoakwa et al. [4]. According to Rocha et al. [19], good-quality cacao should have balanced sensory ratings in this moderate range after being roasted at 90-110°C. Most treatments scored similarly, indicating that they maintained a lasting fragrance under the examined processing conditions.

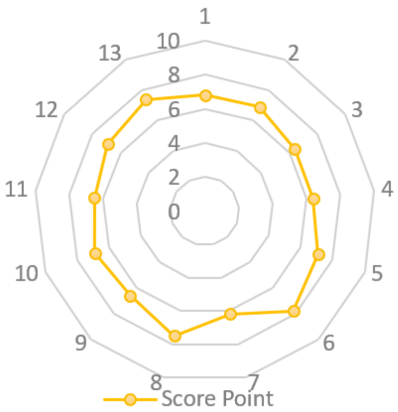


Figure 7. Sensory Analysis of Aroma

Figure 7 reveals that T6 and T8 scored 8 points, and T3, T4, and T7 scored 6. The majority of treatments scored 7. The ratings imply excellent fermentation and roasting conditions for chocolate taste precursors, according to Afoakwa et al. [4]. According to Rocha et al. [19], good-quality cacao should have balanced sensory ratings in this moderate range after being roasted at 90-110°C. Most treatments scored similarly, indicating that they maintained a lasting fragrance under the examined processing conditions.

3.7.2 Flavor

The sensory evaluation results, as depicted in Figure 8, demonstrate that the average scores provided by panelists varied between 12 and 16 points, with the majority of treatments concentrated around 15, suggesting a consistent level of high quality.

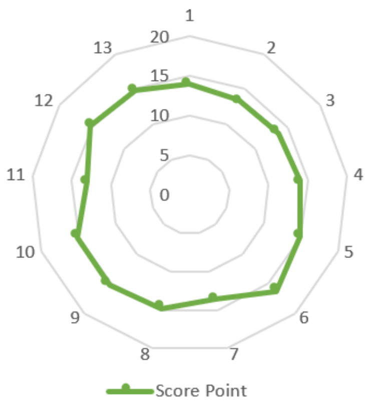


Figure 8. Sensory Analysis of Flavor

Treatment 6 achieved the highest score of 16, whereas Treatment 2 received the lowest at 13. These findings are consistent with prior research indicating that sensory scores within this range are indicative of desirable flavor development in roasted cacao beans.

The variation observed across treatments may be explained by differing roasting temperatures and tempering durations, factors known to affect the formation of flavor compounds through thermal degradation and Maillard reactions [24], [25]. Additionally, the implementation of a feedback mechanism likely enhanced uniformity among treatments by facilitating real-time modifications to maintain optimal processing parameters [26].

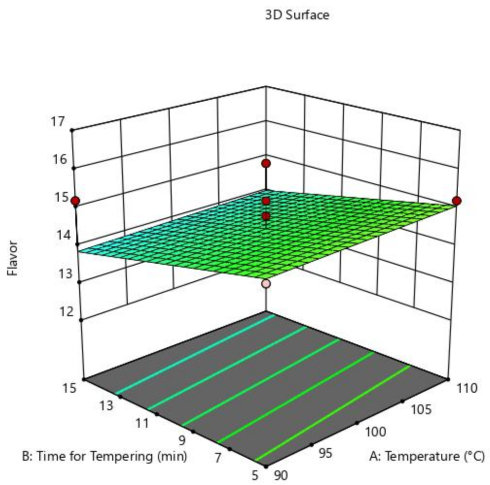


Figure 9. Response Surface Plot Showing the Effect of Temperature and Tempering Time on Flavor

Figure 9 showed that the taste ANOVA had an F-value of 1.33, indicating that the model was not statistically significant (*p* = 0.3079). The discrepancy in flavor scores may have been caused to random fluctuations rather than roasting circumstances [22], [27]. No significant model variables were found at *p* < 0.05, indicating that experimental factors had little impact on flavor results [28]. The lack-of-fit F-value of 1.15 was not statistically significant (*p* = 0.4680), showing that experimental variability rather than model deficiency caused differences between anticipated and actual values [23]. These findings indicate that the current paradigm fails to explain how processing characteristics affect flavor perception. This requires improving input variables or conducting additional experiments [21].

3.7.3 General Acceptability

Figure 10 illustrates the relative score points, which range from 7 to 8, as shown in Figure 7. This figure represents the measurement scale and indicates a good quality assessment of the comprehensive treatment comprised of 13 sessions distributed across the specified points. Januszewska et al. [29] pointed out that cultural and personal tastes can change how scores are given, but a score above seven usually means there is market potential. This is in line with industry norms, which say that items with scores of 7 or higher are feasible for business [30].

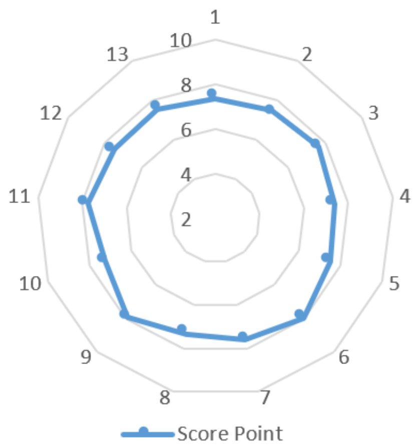


Figure 10. Sensory Analysis of General Acceptability

The ANOVA for general acceptance had an F-value of 1.92 (p = 0.1965), indicating no statistical significance. It shows that random noise rather than process variable effects may explain acceptability score fluctuation [22], [27]. The study found no significant model terms at $p < 0.05$, indicating that experimental effects had no impact on consumer impression [23]. The lack of fit F-value of 1.14 was not significant (p = 0.4616), suggesting that experimental variability rather than model structure caused the discrepancy [23]. The results suggest that the existing model doesn't accurately link processing features to overall acceptability. This requires re-evaluating the model through more trials or input variable refinement [21].

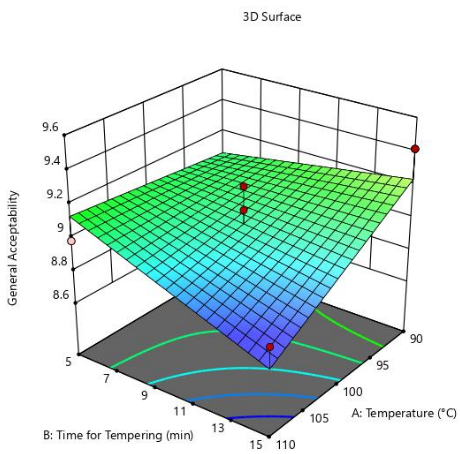
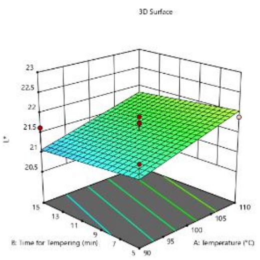


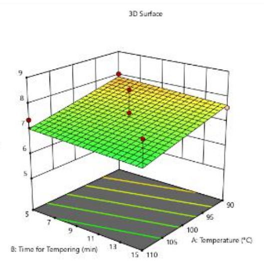
Figure 11. Response Surface Plot Showing the Effect of Temperature and Tempering Time on General Acceptability

3.8 Color Properties

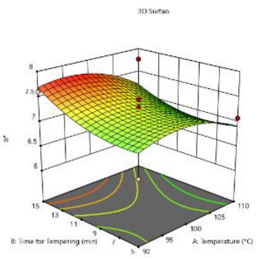
Figure 12 presents the ANOVA results for the color parameters L*, a*, and b*. For L*, the model shows marginal significance ($p = 0.0742$), indicating that temperature has a detectable influence on lightness, consistent with previous findings showing that higher roasting temperatures decrease L* values through Maillard reactions and caramelization [25]. The lack of fit p-value of 0.3373 further supports the model's acceptability, suggesting discrepancies between predictions and observations are likely due to random variation [23].



Lightness (L*)



Redness to greenness (a*)



Yellowness to Blueness (b*)

Figure 12. Response Surface Plot Showing the Effect of Temperature and Tempering Time on Color Profile

The non-significant a* model ($p = 0.2115$) found no important factors. According to study, chromatic components may be more affected by unmeasured parameters like bean composition or moisture than controlled process variables [4]. Inadequate model performance is indicated by the b* model's high noise probability ($p = 0.2486$) and low lack of fit p-value (0.0038). These data suggest that moisture content or roast profile must be added to present variables to capture yellowness determinants [31]. Roasting temperature controls lightness (L*), however a* and b* need more research to improve model predictability [32].

3.9 Optimization of Parameters

Figure 13 shows the expected experimental data for optimizing responses, focusing on temperature (90°C) and tempering duration (14.2 minutes). The processing results are moderate yet constant, with 74.2% roasting efficiency and 13.5% uniformity. It suggests thermal performance is stable. Physical metrics, such as bulk density (0.41 g/cm³) and bean temperature (40°C), indicate stable structure and controlled heating.

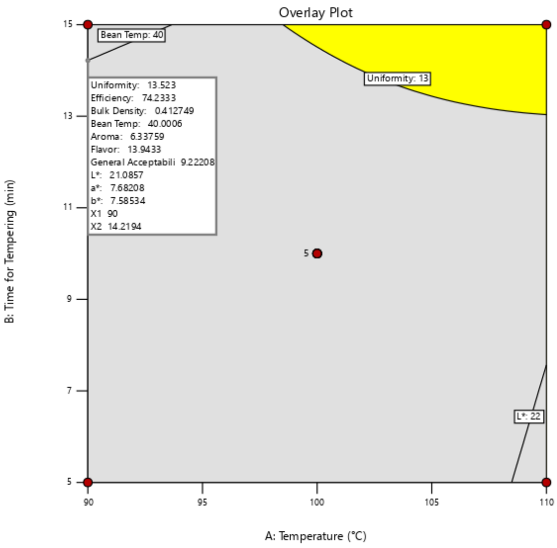


Figure 13. Overlay Plot

Aroma (6.3), flavor (13.9), and general acceptance (9.2) met chocolate production criteria. Lightness (L* 2.1), redness (a* 7.7), and yellowness (b* 7.6) readings showed mild roast development. However, low lightness implies browning control optimization. Comparing optimized values against real outcomes provided optimized factors and validated findings.

3.10 Post Analysis and Validation

Figure 14 illustrates steady improvements in roasting performance under optimal circumstances of 90 °C roasting and 14.2 minutes tempering. An increase in roasting efficiency from 74.23 to 87.85% validates optimal temperature energy use. Maintaining a steady bulk density (0.413–0.443 g/cm³) indicates the beans' intact structure. Heat dispersed more evenly, improving roasting uniformity (from 13.52 to 12.31%), although model predictions were less accurate.

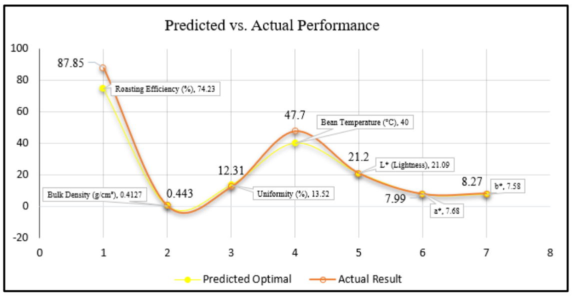


Figure 14. Predicted and Actual Performance value

The bean temperatures (40.0–50.2°C) were as expected, demonstrating that the blower fan-controlled tempering. Color analysis showed moderate agreement with predictions: lightness (L) increased (21.09–21.56), indicating surface drying; redness (a) remained stable (7.68–8.03), indicating consistent pigment development; and yellowness (b*) increased (7.58–8.5), indicating Maillard reaction progression. Real results matched model projections across key criteria, proving the enhanced roasting parameters' resilience.

4. CONCLUSION

This study optimized a hybrid cacao bean roaster that integrates LPG conduction heating, near-infrared (NIR) radiation, and a feedback-controlled blower-assisted tempering system. The blower activates automatically when internal temperatures exceed a set threshold, preventing over-roasting and stabilizing the beans. Roasting temperature and tempering time were analyzed using Response Surface Methodology (RSM) and Central Composite Design (CCD). Optimal conditions—90 °C roasting temperature and 14.2 minutes tempering time—achieved 87.85% roasting efficiency, 12.31% uniformity, a bulk density of 0.443 g/cm³, a final bean temperature of 47.7 °C, and consistent color attributes (L* = 21.20, a* = 7.99, b* = 8.27). Sensory analysis yielded favorable scores, with ratings between 6 and 8, offering valuable insights for both panelists and potential consumers. Temperature had a nonlinear effect on efficiency, density, and color lightness, while tempering time significantly influenced internal bean temperature. The feedback-controlled blower enhanced process accuracy and thermal consistency. Overall, the hybrid roaster demonstrates strong potential for scalable and modernized post-harvest cacao bean processing.

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