

## การเพิ่มประสิทธิภาพการเผาไหม้ด้วยชุดอุปกรณ์เผาไหม้ Improving Coconut Burning Efficiency with Coconut Burning Equipment

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### บทคัดย่อ

งานวิจัยนี้นำเสนอการพัฒนาและประเมินประสิทธิภาพของอุปกรณ์เผาไหม้ที่ปรับปรุงขึ้นมาเพื่อเปรียบเทียบกับวิธีการคั่วแบบดั้งเดิม ผลการทดลองแสดงให้เห็นว่าอุปกรณ์ที่พัฒนาขึ้นสามารถเผาไหม้ได้ 90 ผลต่อรอบการผลิต ภายใต้สภาวะที่เหมาะสมที่กำหนดโดยวิธีทางสถิติ โดยใช้ความเร็วรอบของกลองหมุน 10 รอบต่อนาที เวลาการคั่วเฉลี่ยอยู่ที่ 140.75 นาที ซึ่งลดลงจาก 151.9 นาที ของวิธีการแบบดั้งเดิม ยิ่งไปกว่านั้น อุปกรณ์ที่ปรับปรุงนี้สามารถผลิตมะพร้าวเผาที่ปราศจากข้อบกพร่องได้ถึง 99.4% ในขณะที่วิธีการแบบดั้งเดิมผลิตมะพร้าวเผาที่ได้เฉลี่ย 91% โดยรวมแล้ว วิธีการใหม่ลดเวลาการเผาโดยเฉลี่ย 11.85 นาที เพิ่มผลผลิตได้ 8.4% อย่างมีนัยสำคัญทางสถิติ ( $p$ -value = 0.000) แม้ว่ากระบวนการที่ปรับปรุงนี้จะต้องใช้ต้นทุนเชื้อเพลิงเพิ่มขึ้น 24 บาทต่อรอบการผลิต เนื่องจากการใช้พื้นที่เพิ่มขึ้น 48 กิโลกรัม แต่ก็สามารถผลิตเปลือกมะพร้าวที่นำออกจำหน่ายได้เพิ่มขึ้น 20 ผล ส่งผลให้รายได้เพิ่มขึ้น 1,051 บาทต่อรอบการผลิต ผลการวิจัยนี้ยืนยันได้ถึงอุปกรณ์เผาไหม้ที่ปรับปรุงนี้ช่วยเพิ่มประสิทธิภาพและคุณภาพของการผลิต ทั้งด้านเวลาการเผาไหม้ที่ลดลง และผลผลิตเพิ่มขึ้น ดังนั้นอุปกรณ์นี้จึงเหมาะสมสำหรับการนำไปใช้ในระดับชุมชนและมีศักยภาพในการขยายสู่เชิงพาณิชย์ งานวิจัยในอนาคตควรศึกษาการบูรณาการวัสดุที่เก็บความร้อนและการออกแบบโครงสร้างถังใหม่ เพื่อลดการสูญเสียความร้อนและลดการใช้เชื้อเพลิง โดยไม่กระทบต่อคุณภาพการเผาไหม้ นอกจากนี้ ควรเน้นไปที่การลดการปล่อย CO<sub>2</sub> ผ่านแหล่งพลังงานหมุนเวียนทางเลือก การประเมินความสามารถในการปรับตัวของระบบต่อเศษวัสดุเหลือทิ้งทางการเกษตรชนิดอื่นๆ เพื่อลดต้นทุนการผลิตโดยรวม

**คำสำคัญ:** มะพร้าวเผา, ประสิทธิภาพการเผา, วิธีการทางสถิติ, การเผาไหม้

## Abstract

This study presents the development and performance evaluation of an improved coconut roasting device, compared against the conventional roasting method. Experimental results demonstrated that the newly developed system could process 90 coconuts per batch under optimized conditions determined by the Taguchi method, with a drum rotation speed of 10 revolutions per minute. The average roasting time was 140.75 minutes, representing a reduction from 151.90 minutes observed with the traditional method. Moreover, the improved device achieved 99.4% defect-free roasted coconuts, whereas the traditional method produced an average 91% defect-free. Overall, the new method reduced burning time by an average of 11.85 minutes, increased productivity yield to 8.4%, with statistical significance ( $p$ -value = 0.000). Although the modified process required an additional fuel cost of 24 THB per batch due to higher firewood consumption (48 kilograms), it enabled the production of 20 more marketable coconuts, resulting in an increased income of 1,051 THB per batch. These findings confirm that the improved coconut roasting device enhances both efficiency and product quality in terms of decreased processing time and increased productivity. The device is therefore suitable for adoption at the community level and for potential commercial scaling. Future work should explore the integration of heat-retaining materials and redesign of the drum structure to minimize heat loss and reduce fuel consumption, without compromising roasting quality. Furthermore, focus on reducing CO<sub>2</sub> emissions through alternative renewable energy sources, as well as assessment of the system's adaptability to other agricultural residues is recommended to lower overall production costs.

**Keywords:** Coconut roasting, Combustion efficiency, Taguchi method, Process optimization

## 1. Introduction

Thailand's coconut industry represents a significant component of the national agricultural economy, positioning the country among the world's leading producers and exporters of coconut-based products. The sector generates a wide range of commodities, including coconut oil, coconut water, copra, and fiber-derived products, providing an essential and stable source of income for local farmers and small-scale enterprises (6Wresearch, 2022; BSAC, 2022; Aijen et al., 2022). The global market for these products continues to expand, driven by increasing consumer preference for plant-based and health-oriented foods as well as growing interest in distinctive local specialties (6Wresearch, 2022). Within this dynamic market, roasted coconut occupies a unique niche. It is highly valued by both Thai consumers and international visitors for its distinctive flavor profile and nutritional benefits, particularly in major cultivation areas such as Amphawa District in Samut Songkhram Province and Ratchaburi province (BSAC, 2022; Pokaisawan et al., 2024). Roasting is not only important for culinary purposes but also closely linked to energy utilization, as highlighted by Puchakawimo et al. (2005). Their research demonstrated that roasting significantly modifies coconut characteristics: the water content becomes sweeter and less acidic, while the flesh develops a more pronounced sweetness due to thermal effects.

Traditional roasting practices predominantly use open-fire wood combustion, which poses

environmental drawbacks and energy inefficiencies (BSAC, 2022). Additionally, such methods suffer from inconsistent heat distribution and significant products loss typically about 6 defective coconuts per batch, leading to notable economic losses. Manual supervision is necessary to maintain combustion stability and fuel regulation. Despite these limitations, traditional roasting remains vital for producing diverse food products, which effect to yeast quality improvement of product through Maillard reaction and caramelization (Eliodório et al. 2023). Previous research has addressed similar challenges by introducing engineering-based solutions. For instance, Suarbawa & Mulawarman (2021) demonstrated that mechanized roasting machines could improve work productivity by over 60% while reducing labor fatigue. Saittagaroon et al. (1984) highlighted the enhancements in aroma and flavor profile through controlled thermal treatments. Studies on biomass-powered dryers further show potential gains in energy efficiency and environmental performance (Senthil et al, 2021, Muhammad et al. 2023). Nonetheless, the adoption of such technologies in local Thai communities remains limited, with many producers still relying on uncontrolled traditional methods (Suarbawa, 2022; BSAC, 2022). This reveals a research gap in developing appropriate roasting technology tailored for community-level adoption. The need for devices that optimize yield, enhance thermal efficiency, reduce raw material losses, and align with sustainable development goals is critical. Moreover, this aligns with Thailand's Bio-Circular-Green (BCG) Economy Model, advocating for sustainable agricultural processing (Maimun et al, 2023). Hence, this study aims to design and evaluate a roasting device that maximizes yield, minimizes waste, and supports sustainable coconut processing in line with modern industrial and environmental standards. In addition, research has compared traditional and modern roasting methods in terms of yield and quality. It was found that the modern method produces higher and more consistent yields and quality than the traditional method, as well as reducing product loss in each production cycle (Nwankwo et al, 2025).

Despite these opportunities, many local producers continue to depend on traditional roasting methods characterized by limited process control, low thermal efficiency, and considerable raw material losses. Typically, one batch produces approximately 70 roasted coconuts; however, variations in maturity and non-uniform heat distribution often lead to spoilage, averaging about six defective coconuts per batch, equivalent to a financial loss of around 240 THB. The process also demands continuous manual supervision to regulate fuel input and maintain stable combustion conditions. In this context, improving coconut roasting technology has become essential to enhance efficiency, reduce product loss, and strengthen the competitiveness of community-based enterprises as well as the broader coconut industry. The adoption of engineering-based solutions and modern process optimization can increase productivity, ensure consistent product quality, and create additional revenue streams for farmers. To systematically optimize the roasting process parameters, this study employs the Taguchi design of experiments methodology, which offers significant advantages for practical industrial applications. The Taguchi method enables efficient identification of optimal operating conditions with minimal experimental runs, making it particularly suitable for resource constrained small-scale producers (Antony et al. 2024). This approach systematically evaluates multiple factors including batch size and drum rotation speed to determine the combination that maximizes yield while minimizing defects and energy consumption. Importantly, this approach is consistent with

Thailand's Bio Circular Green (BCG) Economy Model, which emphasizes sustainable practices, efficient resource utilization, and value-added processing of agricultural products (Maimun et al, 2023). Consequently, the objective of this study is to develop and evaluate a roasting device using Taguchi optimization designed to maximize yield, minimize waste, and align coconut processing with sustainable industrial development goals.

## 2. Materials and methods

### 2.1 Data Collection and Problem Analysis

To obtain a comprehensive understanding of the limitations associated with conventional coconut roasting practices, a systematic study of the entire process was conducted, as illustrated in Figure 1. On-site observations were combined with detailed data collection at each stage to identify operational bottlenecks that affected both process efficiency and product quality.

The initial survey revealed a significant production constraint. Each roasting cycle was restricted to a maximum capacity of 70 coconuts, primarily due to the limited roasting chamber area and the highly labor-intensive nature of the process. Operators were required to constantly monitor the roasting chamber, manually rotate coconuts, and replenish firewood to avoid cracking or surface burning, both of which immediately resulted in product rejection.

Baseline data were compiled from 20 roasting cycles performed under traditional conditions. Results indicated that each batch consumed between 280 and 300 kilograms of firewood. The average roasting time was measured at 151.9 minutes (approximately 2.5 hours) to achieve acceptable product characteristics. More importantly, the data summarized in Table 1 showed an average of 6.26 defective or under-roasted coconuts per cycle, corresponding to a defect rate of approximately 9%. In practice, this equated to a loss of about six coconuts per batch, thereby reducing the effective yield and lowering profitability for producers.

To further investigate the root causes of these inefficiencies, a “Why-Why” analysis was applied. The results, presented in Table 2, indicated that the primary factor contributing to low efficiency was the lack of specialized roasting equipment specifically, the absence of a dedicated kiln or oven designed to provide uniform thermal distribution. In addition, limitations associated with manual handling restricted the ability of workers to rotate coconuts evenly, particularly when the coconuts were stacked or overlapped. This resulted in non-uniform roasting conditions, leading to over-roasting, under-roasting, or cracking of coconuts, as illustrated in Figure 2.



**Figure 1.** Illustrates the main steps in the roasted coconut production process, including (A) roasting and turning the coconuts, (B) peeling, and (C) polishing.

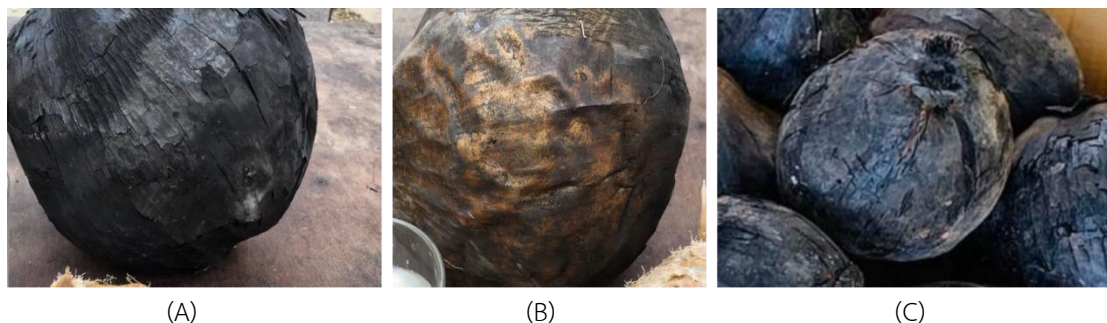


**Figure 2.** shows the characteristics of roasted coconuts using the traditional method, including (A) properly roasted coconut, (B) undercooked coconut, and (C) cracked or damaged roasted coconut.

## 2.2 Design of a Coconut Roasting Apparatus

Analysis of the baseline data presented in Table 1 indicated that the conventional roasting method produced an average yield of approximately 91% acceptable product. However, the process was highly dependent on continuous manual supervision, which required operators to rotate coconuts by hand, replenish firewood, and monitor combustion conditions. These tasks not only limited operational efficiency but also introduced potential safety hazards.

To address these shortcomings and establish a more standardized process, a coconut roasting apparatus was conceptualized and designed. The system consisted of three cylindrical roasting chambers, each fabricated from a 200-liter steel drum. These chambers were configured to operate independently and were equipped with a rotational mechanism to facilitate the turning of coconuts during roasting. This ensured uniform heat exposure across all units and minimized the risk of under-roasting, over-roasting, or surface cracking. The rotation feature was expected to reduce overall processing time while simultaneously enhancing worker safety by minimizing direct manual handling.

**Table 1.** Traditional coconut roasting method with 70 coconuts per batch.

| No.     | Roasting Time<br>(minutes) | Defective/ Unripe<br>roasted coconut (units) | Percentage of Good/Defective Coconuts (%) |                               |
|---------|----------------------------|----------------------------------------------|-------------------------------------------|-------------------------------|
|         |                            |                                              | Roasted Good<br>Coconuts                  | Roasted Defective<br>Coconuts |
| 1       | 152                        | 6                                            | 91.43                                     | 8.57                          |
| 2       | 155                        | 5                                            | 92.86                                     | 7.14                          |
| 3       | 149                        | 6                                            | 91.43                                     | 8.57                          |
| 4       | 152                        | 6                                            | 91.43                                     | 8.57                          |
| 5       | 153                        | 7                                            | 90.00                                     | 10.00                         |
| 6       | 157                        | 8                                            | 88.57                                     | 11.43                         |
| 7       | 150                        | 6                                            | 91.43                                     | 8.57                          |
| 8       | 159                        | 5                                            | 92.86                                     | 7.14                          |
| 9       | 148                        | 8                                            | 88.57                                     | 11.43                         |
| 10      | 151                        | 7                                            | 90.00                                     | 10.00                         |
| 11      | 148                        | 6                                            | 91.43                                     | 8.57                          |
| 12      | 155                        | 7                                            | 90.00                                     | 10.00                         |
| 13      | 149                        | 7                                            | 90.00                                     | 10.00                         |
| 14      | 150                        | 6                                            | 91.43                                     | 8.57                          |
| 15      | 153                        | 6                                            | 91.43                                     | 8.57                          |
| 16      | 151                        | 5                                            | 92.86                                     | 7.14                          |
| 17      | 152                        | 6                                            | 91.43                                     | 8.57                          |
| 18      | 159                        | 7                                            | 90.00                                     | 10.00                         |
| 19      | 152                        | 5                                            | 92.86                                     | 7.14                          |
| 20      | 157                        | 7                                            | 90.00                                     | 10.00                         |
| Average | 151.9                      | 6.26                                         | 91.00                                     | 9.00                          |

**Table 2.** Application of Why-Why analysis for problem identification and solution guidelines.

| Problem                                   | Why 1         | Why 2                             | Why 3                                                                                 | Consideration                                                                                                | Proposed Solution                                                            |
|-------------------------------------------|---------------|-----------------------------------|---------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------|
| Production is insufficient to meet demand | People        | Workers are fatigued              | Workers roast coconuts continuously<br>Lack of appropriate tools for turning coconuts | Workers lack rest time                                                                                       | Provide a resting area and sharp-tipped iron tools for turning coconuts      |
|                                           | Work methods  | No standardized working procedure | Visual inspection is used                                                             | Workers have over 10 years of experience                                                                     | Use photo color comparisons to identify proper roasted coconut surface       |
|                                           | Roasting kiln | Inconsistent heat                 | Results in cracked or undercooked coconuts<br>Excess firewood causes uneven heat      | Workers cannot turn coconuts in time or distribute firewood evenly<br>No method for proper heat distribution | Design a roasting device that controls heat evenly with appropriate capacity |
|                                           |               | Roasting volume is low            | Limited space                                                                         | Inadequate workspace organization                                                                            | Redesign layout to improve workspace for roasting more coconuts              |

The apparatus was specifically designed to accommodate the spatial and operational constraints of local enterprises, as illustrated in Figure 3. The system had a maximum capacity of 90 coconuts per cycle. Rotational speed could be controlled at three levels 10, 15, and 20 revolutions per minute allowing flexibility to suit varying coconut sizes and roasting conditions. By integrating these design improvements, the mechanized roasting system aimed to increase production throughput, improve product quality consistency, and reduce reliance on intensive manual labor.



**Figure 3.** Appearance of coconut burning equipment

### 2.3 Experiment and Data Collection

The experimental procedure employed coconuts with a maturity age of approximately 10–12 months, which was generally considered suitable for roasting applications. For each trial, 30 coconuts were placed into each roasting drum, resulting in a total batch size of 90 coconuts per cycle. A series of 20 experimental runs was conducted using the apparatus, with the rotational speed set at its maximum level of 20 revolutions per minute. The firewood was longan type that was more in this local area. The firewood was fulfilled an equal amount of about 30 kilograms per time for invariability of heat control. These trials were designed to evaluate the operational performance of the newly developed roasting system, identify potential technical issues, and refine the process parameters for optimal outcomes.

Prior to the full experimental campaign, preliminary tests were carried out to establish the optimal roasting parameters using the developed apparatus. The quality of roasted coconuts was subsequently assessed through sensory evaluation, focusing on shell coloration and the degree of surface cracking as primary indicators of roasting uniformity. The percentage of satisfactorily roasted coconuts was determined from these assessments, providing a benchmark for evaluating the efficiency and consistency of the roasting process.

The quality data obtained from sensory evaluations were systematically compared between coconuts processed using the newly developed roasting apparatus and those produced by the conventional method, as illustrated in Figure 4.



**Figure 4.** Coconut burning with equipment for burning (A) coconut filling and (B) burned coconut appearance.

This comparison was designed to evaluate the processing efficiency and quantify improvements in production capacity and cost reduction, particularly in relation to losses caused by damaged or undercooked coconuts. Prior to conducting the roasting experiments, the thermal requirements were determined in accordance with thermodynamic principles, as expressed in Equation (1). For calculation purposes, the total mass of coconuts per batch was assumed to be approximately 100 kg, with an initial temperature of 30 °C and a target final internal temperature of 140 °C (Apriyantono et al., 2002).

The effective specific heat capacity of the coconuts was estimated based on mass fraction analysis of their components: shell (10%), husk fibers (40%), flesh (30%), and coconut water (20%). According to Dirisu et al. (2020), the specific heat capacities of these constituents are approximately 1.77 kJ/kg·°C for the shell, 1.26 kJ/kg·°C for husk fibers, 3.50 kJ/kg·°C for coconut flesh, and 4.06 kJ/kg·°C for coconut water. Using these values, the overall specific heat capacity of a whole coconut was estimated at about 5.06 kJ/kg·°C.

Based on this composite value, the heat energy required to raise the temperature of a 100 kg batch of coconuts from 30 °C to 140 °C was calculated to be approximately 55.66 MJ. The corresponding firewood requirement was then estimated using Equation (2), considering the calorific value of firewood reported by the Electricity Generating Authority of Thailand (2021) as 3,820 kcal/kg (equivalent to 15,983.68 kJ/kg).

$$\text{Heat Equation} \quad Q = m \times c \times \Delta T \quad (1)$$

Where;

Q = Heat energy required (kJ)

m = Total mass of coconuts loaded into the roasting chamber (kg)

c = Specific heat capacity of coconuts (kJ/kg·°C)

$\Delta T$  = Temperature difference between the initial and final condition (°C)

$$E_{\text{input}} = m_{\text{fuel}} \times CV \quad (2)$$

Where

$E_{\text{input}}$  = Thermal energy supplied to the system (kJ)

$m_{\text{fuel}}$  = Mass of fuel consumed (kg)

CV = Calorific value of the fuel (kJ/kg)

To estimate the required quantity of firewood for the roasting process, heat balance calculations indicated that approximately 348.26 kg of firewood was necessary to uniformly roast a batch of 90 coconuts using the newly developed roasting apparatus. Following this estimation, 20 experimental roasting trials were carried out. The performance of each trial was recorded, and the mean roasting efficiency was subsequently determined.

For statistical validation, a Paired T-test was employed to compare the conventional roasting method with the equipment-assisted method. The hypotheses were defined as follows:

Null hypothesis ( $H_0$ ):  $\mu_{\text{new}} = \mu_{\text{traditional}}$  (no statistically significant difference exists between the average roasting times of the two methods).

Alternative hypothesis ( $H_1$ ):  $\mu_{\text{new}} \neq \mu_{\text{traditional}}$  (a statistically significant difference exists between the two methods in terms of the roasting parameter under consideration).

To identify the optimal roasting conditions achievable with the developed equipment, the experimental design was structured using the Taguchi method, incorporating two factors at three levels each. The considered factors were:

1. Batch size 70, 80, and 90 coconuts per roasting cycle. This range was selected based on: the traditional method's capacity of 70 coconuts, spatial constraints of the three drum system and maximum practical loading that maintains uniform heat distribution.
2. Rotational speed of the roasting drum adjusted to accommodate process conditions to 10, 15 and 20 round per minute. This range was determined through preliminary trials to identify speeds that: provide sufficient tumbling action for uniform heat exposure, maintain adequate contact time between coconuts and heated drum surface and prevent excessive mechanical stress that could damage coconuts.

These factors and level values arrangement resulted in a total of nine experimental runs, the details of which were presented in Table 3.

The experiment of coconut burning in each condition was repeated three times for fine burned coconut. The roasting experiments were conducted in accordance with the predefined experimental plan. The results obtained from the most effective roasting batches were selected for further analysis using the Taguchi method. The evaluation emphasized the Signal-to-Noise (S/N) ratio, applying the larger-is-better criterion as expressed in Equation (3). This analytical approach was adopted to identify the optimal operating conditions for coconut roasting when employing the developed apparatus.

**Table 3.** Taguchi design for experiment.

| Numbers | Coconut Numbers (Coconuts) | Rotation Speeds (Rpm) |
|---------|----------------------------|-----------------------|
| 1       | 70                         | 10                    |
| 2       | 70                         | 15                    |
| 3       | 70                         | 20                    |
| 4       | 80                         | 10                    |
| 5       | 80                         | 15                    |
| 6       | 80                         | 20                    |
| 7       | 90                         | 10                    |
| 8       | 90                         | 15                    |
| 9       | 90                         | 20                    |

$$S/N \text{ ration} = -10 \log \left( \frac{1}{n} \sum_{i=1}^n 1/y_i^2 \right) \quad (3)$$

When

$y_i$  = The measured response obtained from the  $i^{\text{th}}$  trial in the set of  $n$  experimental runs.

$n$  = number of replications ( $n = 3$ )

### 3. Results

The coconut roasting trials carried out using the newly developed apparatus, with a batch size of 90 coconuts, demonstrated an average roasting time of 140.75 minutes ( $\approx$  2.34 hours). The average number of defective coconuts per batch was 0.6 units, corresponding to a defect rate of 0.67%. In comparison, the conventional open-fire method required an average roasting time of 151.9 minutes (Table 4). This reflected a reduction of approximately 11.85 minutes per batch when using the improved system.

In terms of product quality, the new method yielded a substantially lower number of defective coconuts, averaging 0.6 per batch, compared with the higher defect count observed in the traditional method. Consequently, the overall success rate of the new process was 99.33%, an improvement of 8.33% over the 91% success rate achieved by the conventional method. This clearly highlights the superior performance and consistency of the newly designed equipment in minimizing product loss. The improvement in yield can be attributed to enhanced heat retention within the roasting drum, which reduces thermal losses commonly encountered in open-air roasting. The rotating drum mechanism facilitates uniform heat distribution, preventing localized overheating that typically causes surface cracking. As a result, coconuts roasted using the improved device exhibited more consistent cooking quality. Additionally, the capability to estimate and regulate fuel consumption contributed to more precise heat control, thereby improving process accuracy and repeatability.

**Table 4.** Comparison of results of new coconut burning methods and the old method.

| No.  | Burning    |            | Time<br>difference<br>(minutes) | Waste      |            | Difference<br>between<br>damaged<br>coconuts<br>(units) | Good       |            | %<br>difference<br>of good |
|------|------------|------------|---------------------------------|------------|------------|---------------------------------------------------------|------------|------------|----------------------------|
|      | Time       |            |                                 | coconut    |            |                                                         | efficiency |            |                            |
|      | (minutes)  |            |                                 | (units)    |            |                                                         | percentage |            |                            |
|      | New<br>way | Old<br>way |                                 | New<br>way | Old<br>way |                                                         | New<br>way | Old<br>way |                            |
| 1    | 140        | 152        | -12                             | 1          | 6          | -5                                                      | 98.89      | 91.43      | 7.46                       |
| 2    | 141        | 155        | -14                             | 0          | 5          | -5                                                      | 100        | 92.86      | 7.14                       |
| 3    | 140        | 149        | -9                              | 2          | 6          | -4                                                      | 97.78      | 91.43      | 6.35                       |
| 4    | 140        | 152        | -12                             | 1          | 6          | -5                                                      | 98.89      | 91.43      | 7.46                       |
| 5    | 142        | 153        | -11                             | 1          | 7          | -6                                                      | 98.89      | 90.00      | 8.89                       |
| 6    | 140        | 157        | -17                             | 0          | 8          | -8                                                      | 100        | 88.57      | 11.43                      |
| 7    | 141        | 150        | -9                              | 0          | 6          | -6                                                      | 100        | 91.43      | 8.57                       |
| 8    | 140        | 159        | -19                             | 2          | 5          | -3                                                      | 97.78      | 92.86      | 4.92                       |
| 9    | 143        | 148        | -5                              | 0          | 8          | -8                                                      | 100        | 88.57      | 11.43                      |
| 10   | 140        | 151        | -11                             | 1          | 7          | -6                                                      | 98.89      | 90.00      | 8.89                       |
| 11   | 140        | 148        | -8                              | 1          | 6          | -5                                                      | 98.89      | 91.43      | 7.46                       |
| 12   | 141        | 155        | -14                             | 0          | 7          | -7                                                      | 100        | 90.00      | 10.00                      |
| 13   | 141        | 149        | -8                              | 0          | 7          | -7                                                      | 100        | 90.00      | 10.00                      |
| 14   | 140        | 150        | -10                             | 1          | 6          | -5                                                      | 98.89      | 91.43      | 7.46                       |
| 15   | 140        | 153        | -13                             | 1          | 6          | -5                                                      | 98.89      | 91.43      | 7.46                       |
| 16   | 141        | 151        | -10                             | 0          | 5          | -5                                                      | 100        | 92.86      | 7.14                       |
| 17   | 142        | 152        | -10                             | 0          | 6          | -6                                                      | 100        | 91.43      | 8.57                       |
| 18   | 142        | 159        | -17                             | 0          | 7          | -7                                                      | 100        | 90.00      | 10.00                      |
| 19   | 141        | 152        | -11                             | 0          | 5          | -5                                                      | 100        | 92.86      | 7.14                       |
| 20   | 140        | 157        | -17                             | 1          | 7          | -6                                                      | 98.89      | 90.00      | 8.89                       |
| Avg. | 140.7      | 151.9      | -11.85                          | 0.6        | 6.26       | -5.7                                                    | 99.33      | 91.00      | 8.33                       |

Statistical evaluation of roasting performance between the two methods confirmed a significant difference, with a p-value of 0.000 as shown in Table 5. Accordingly, the null hypothesis was rejected, and the alternative hypothesis ( $H_1$ ) was accepted, verifying the superior efficiency of the new method. To further refine the roasting process, experiments were designed using the Taguchi method. The results, summarized in Table 6, showed that nearly all trials produced high-quality roasted coconuts. Analysis of the “larger-is-better” Signal-to-Noise (S/N) ratio, as illustrated in Figure 5, identified 90 coconuts per batch as the most effective operating condition for the developed apparatus. Analysis of the S/N ratios in Table 7 reveals distinct patterns in factor influence. Batch size demonstrates a clear upward trend, with S/N values increasing from 36.90 at 70 coconuts to 39.04 at 90 coconuts a delta of 2.14. This progression indicates that

larger batches yield more consistent outcomes, likely due to enhanced thermal mass stabilizing temperature fluctuations within the drum. Conversely, rotation speed shows minimal variation across the tested range to 10–20 RPM, with S/N ratios remaining essentially constant at approximately 38 at  $\Delta = 0.01$ . Such negligible differences suggest that heat distribution remains uniform regardless of minor speed adjustments within this operational window.

Mean response data corroborate these trends. Success rates remained exceptionally high across all batch sizes: 100% for 70 coconuts, 99.58% for 80 coconuts, and 99.51% for 90 coconuts. The  $\Delta$  of 19.56 coconuts between minimum and maximum batch levels underscores the substantial effect of capacity on absolute output. In contrast, rotation speed produced nearly identical mean values at 79.67–79.78 good coconuts, with a  $\Delta$  of merely 0.11 units. This consistency confirms that tumbling action within 10–20 RPM sufficiently exposes all coconuts to heating conditions. Main effects plots illustrate these relationships visually. Coconut number exhibits steep positive slopes for both mean and S/N responses, rising linearly from 70 to 89 and 37 to 39, respectively. Meanwhile, rotation speed profiles remain flat at approximately 80 of mean and 38 of S/N ratio, confirming its limited influence. Factor ranking assigns batch size as Rank 1, while rotation speed occupies Rank 2. These rankings highlight that maximizing batch capacity drives performance gains, whereas rotation speed functions as a non-critical variable adjustable for operational convenience.

Based on this analysis, optimal conditions were established at 90 coconuts per batch and 10 RPM. This configuration maximizes throughput while maintaining process stability  $S/N = 39.04$  and product quality 99.51% success rate. Selecting the lowest effective rotation speed additionally reduces energy consumption and mechanical wear. Confirmation trials (Table 7) validated these parameters, consistently achieving 89–90 properly roasted coconuts per batch. The Taguchi methodology thus provided a systematic framework for process optimization, identifying batch capacity as the primary control lever while demonstrating rotation speed's flexibility within the tested range.

**Table 5.** Statistical results of coconut burning efficiency test using paired T-test.

| Paired T-Test and CI: new method effectiveness, old method effectiveness    |    |         |        |         |
|-----------------------------------------------------------------------------|----|---------|--------|---------|
| Paired T for new method effectiveness - old method effectiveness            |    |         |        |         |
|                                                                             | N  | Mean    | StDev  | SE Mean |
| New method                                                                  | 20 | 99.3340 | 0.7554 | 0.1689  |
| Old method                                                                  | 20 | 83.6425 | 3.4511 | 0.7717  |
| Difference                                                                  | 20 | 15.6915 | 3.5422 | 0.7921  |
| 95% CI for mean difference: (14.0337, 17.3493)                              |    |         |        |         |
| T-Test of mean difference = 0 (vs not = 0): T-Value = 19.81 P-Value = 0.000 |    |         |        |         |

**Table 6.** Result of Taguchi design experiment.

| Numbers | Factors         |                 | Good burned coconut |           |           |       | S/N   |
|---------|-----------------|-----------------|---------------------|-----------|-----------|-------|-------|
|         | Coconut numbers | rotation speeds | Replicate           | Replicate | Replicate | Avg   | Ratio |
|         |                 |                 | 1                   | 2         | 3         |       |       |
| 1       | 70              | 10              | 70                  | 70        | 70        | 70    | 36.90 |
| 2       | 70              | 15              | 70                  | 70        | 70        | 70    | 36.90 |
| 3       | 70              | 20              | 70                  | 70        | 70        | 70    | 36.90 |
| 4       | 80              | 10              | 80                  | 80        | 80        | 80    | 38.06 |
| 5       | 80              | 15              | 80                  | 79        | 80        | 79.66 | 38.02 |
| 6       | 80              | 20              | 79                  | 79        | 80        | 79.33 | 37.98 |
| 7       | 90              | 10              | 89                  | 90        | 90        | 89.66 | 38.98 |
| 8       | 90              | 15              | 89                  | 90        | 90        | 89.66 | 39.05 |
| 9       | 90              | 20              | 90                  | 90        | 90        | 90    | 39.08 |

**Table 7** Taguchi Analysis of Good burned coco versus Coconut Numbers, Rotation Speeds.

| Response Table for Signal to Noise Ratios<br>“Larger is better” |                               |                          | Response Table for Means |                               |                          |
|-----------------------------------------------------------------|-------------------------------|--------------------------|--------------------------|-------------------------------|--------------------------|
| Level                                                           | Coconut Numbers<br>(Coconuts) | Rotation Speeds<br>(Rpm) | Level                    | Coconut Numbers<br>(Coconuts) | Rotation Speeds<br>(Rpm) |
| 1                                                               | 36.90                         | 37.98                    | 1                        | 70.00                         | 79.67                    |
| 2                                                               | 38.03                         | 37.99                    | 2                        | 79.67                         | 79.78                    |
| 3                                                               | 39.04                         | 37.99                    | 3                        | 89.56                         | 79.78                    |
| Delta                                                           | 2.14                          | 0.01                     | Delta                    | 19.56                         | 0.11                     |
| Rank                                                            | 1                             | 2                        | Rank                     | 1                             | 2                        |

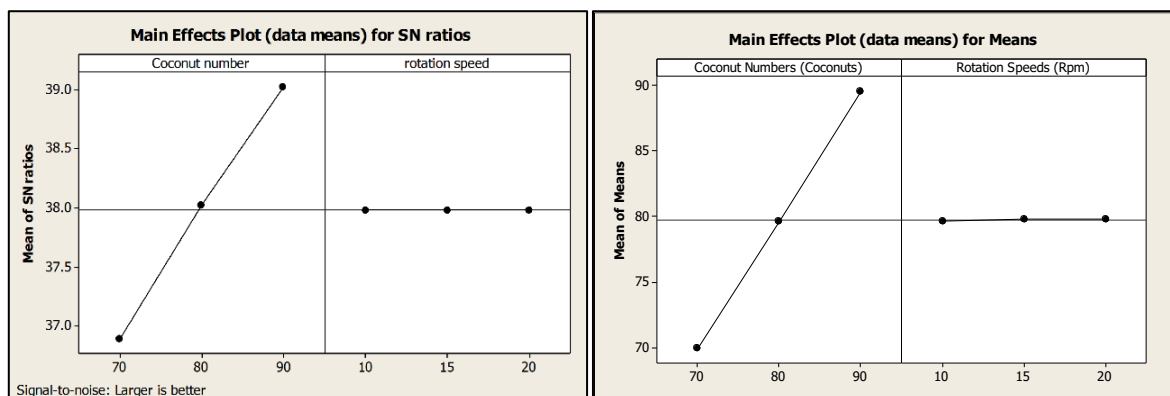


**Figure 5.** Main effect for S/N ratios and means analysis.

With respect to drum rotation speed, the experimental results demonstrated comparable roasting outcomes across the tested range of 10–20 revolutions per minute (RPM). This finding suggests that any speed within this interval is technically feasible. Accordingly, the optimal operating condition was determined to be 90 coconuts per batch at a drum speed of 10 RPM. Under these settings, heat distribution was effectively maintained, resulting in uniform roasting across all coconuts. When this configuration was retested (Table 8), all 90 coconuts were evenly and properly roasted, confirming the consistency of the process.

**Table 8.** Comparison of fuel costs of coconut burning methods.

| Burn<br>Coconut<br>Method | Quantity<br>of<br>Coconut<br>(Unit) | Firewood<br>(Kg) | Price<br>Per<br>Unit<br>(Bath) | Firewood<br>Cost<br>(Bath) | Good<br>Average<br>Yield<br>(Unit) | Price of<br>Roasted<br>Coconut<br>Per Unit | Opportunity<br>to Sell Roasted<br>Coconut<br>(Bath) |
|---------------------------|-------------------------------------|------------------|--------------------------------|----------------------------|------------------------------------|--------------------------------------------|-----------------------------------------------------|
| New way                   | 90                                  | 348              | 0.5                            | 174                        | 90                                 | 40                                         | 3,600                                               |
| Old way                   | 70                                  | 300              |                                | 150                        | 63.74                              |                                            | 2,549                                               |
| difference                | 20                                  | 48               | -                              | 24                         | 25.66                              | -                                          | 1,051                                               |

In terms of fuel consumption, the improved method required approximately 348 kg of firewood per batch, which was 48 kg more than that consumed in the conventional process. This additional usage increased the fuel cost by about 24 THB per roasting cycle. However, despite the marginal rise in fuel cost, the newly developed apparatus significantly enhanced productivity by increasing the batch capacity from 70 coconuts (traditional method) to 90 coconuts.

The additional capacity of 20 coconuts per batch contributed to a substantial reduction in overall product loss. At an average market price of 40 THB per roasted coconut, this increase in yield corresponds to an additional revenue of approximately 1,051 THB per cycle. This added economic value effectively offsets the relatively small increase in fuel expenditure, thereby confirming that the newly developed roasting method represents a more efficient and economically viable improvement over conventional practices.

#### 4. Discussion

Based on the experimental evaluation of the newly developed coconut roasting apparatus, the proposed method demonstrated superior performance compared with the conventional open-fire approach in terms of roasting time, product quality, and overall process efficiency. The average roasting duration was 140.75 minutes per batch, representing a time saving of approximately 11.85 minutes when compared with the 151.90 minutes required by the traditional method. Under the optimal conditions identified through the Taguchi method namely, roasting 90 coconuts per batch at a drum rotation speed of 10 RPM all coconuts were evenly roasted. The performance gains observed stem from fundamental improvements in heat transfer within the enclosed drum configuration. Traditional open-fire roasting relies

heavily on radiation and convection, with substantial thermal losses to ambient air. By contrast, the drum system functions as a semi-enclosed chamber that retains heat more effectively while promoting better distribution throughout the roasting volume. Hot combustion gases naturally rise and circulate along the curved interior walls due to buoyancy-driven flow, establishing organized convective patterns. Simultaneously, drum rotation ensures each coconut repeatedly cycles through different thermal zones, receiving balanced exposure to heated surfaces and gas streams. Optimization trials identified 10 RPM as the preferred rotation speed, representing an equilibrium between two competing requirements. Adequate tumbling frequency prevents coconuts from remaining stationary long enough to develop localized hot spots or charring. At the same time, sufficient contact duration with the heated drum wall allows progressive moisture removal and promotes Maillard browning reactions essential for desired color and flavor development. Preliminary tests at lower speeds resulted in scorched areas where coconuts stayed in prolonged contact with heat sources. Conversely, higher rotation rates shortened individual exposure intervals, reducing thermal energy transfer per cycle and compromising roasting uniformity. The 10 RPM setting thus emerged as a practical compromise that maintains product quality while minimizing mechanical stress and energy consumption.

Combustion characteristics also differ markedly between the two systems. Controlled airflow entering through the drum base facilitates more complete fuel oxidation, improving stoichiometric efficiency and reducing smoke emissions. Temperature stability throughout the roasting cycle benefits from this regulated combustion environment, minimizing the fluctuations typical of open-fire arrangements. Energy analysis using Equation (2) revealed an apparent paradox: while absolute firewood consumption rose by 48 kg per batch, effective energy utilization improved by approximately 28%. This efficiency gain reflects reduced thermal losses through better containment and more uniform heat distribution within the semi-enclosed chamber. Product quality metrics demonstrate the practical impact of these thermal improvements. The new system achieved 99.6% defect-free output, compared to 91% for traditional roasting. This enhancement stems from maintaining coconut surface temperatures within the 105–120°C range optimal for Maillard reactions that develop desirable browning and flavor compounds (Apriyantono et al., 2002). Simultaneously, the uniform thermal field prevents localized temperature excursions above 140°C that would cause charring and product rejection. The controlled heating environment thus ensures both chemical transformation necessary for quality and avoidance of thermal degradation that creates waste. Although the new process required an additional 48 kg of firewood per batch, corresponding to an increased fuel cost of approximately 24 THB per roasting cycle, the benefits substantially outweighed the additional expense. By increasing the roasting capacity from 70 to 90 coconuts per cycle and reducing the number of defective products, the method enabled the sale of approximately 25.66 additional coconuts per batch. At a market price of 40 THB per coconut, this translated into an average revenue gain of about 1,051 THB per roasting cycle, which clearly offset the minor increase in fuel cost.

The findings align with Suarbawa & Mulawarman (2021), who demonstrated that ergonomically designed roasting equipment improves production efficiency while reducing operator workload. Their mechanized system reduced musculoskeletal complaints by 42.21% and decreased working pulse elevation

from 54.48% to 39.00%. Similarly, the rotating drum mechanism in this study eliminates continuous manual stirring, reducing operator fatigue and heat exposure. The consistent 10 RPM rotation ensures uniform heat distribution without physical intervention, improving both product quality and worker safety, particularly important for small-scale producers working long hours. The 62.07% productivity increase reported by Suarbawa & Mulawarman (2021) supports the economic viability demonstrated in this study, where increased capacity (70 to 90 coconuts per batch) and 99.6% success rate reflect similar gains. The drum's heat-retaining properties and mechanical rotation mechanism ensure consistent quality, aligning with Sucahyo & Mustaqimah (2021), who reported that a vertically partitioned drum kiln enhances heat confinement and distribution via radiation and convection, achieving controlled carbonization temperatures (~295 °C) and improved charcoal yield.

In conclusion, the improved coconut roasting method effectively reduces roasting time, minimizes product loss, and enhances energy utilization while simultaneously generating additional economic value. These results suggest that the method is highly suitable for implementation at the community level and for small-scale industrial applications, providing both technical and economic advantages over traditional practices.

## 5. Conclusion and Suggestion

This study developed and evaluated the performance of a newly designed coconut roasting apparatus, benchmarked against the conventional open-fire method. Experimental results confirmed that the improved system could operate effectively under the optimal conditions identified using the Taguchi method with the larger-is-better criterion. With a batch size of 90 coconuts and a drum rotation speed of 10 RPM, the device consistently produced properly roasted coconuts in an average roasting time of 140.75 minutes. In comparison, the traditional method required 151.90 minutes and resulted in an average of 6.26 defective coconuts per batch, equivalent to a 9.00% defect rate. Thus, the new method reduced roasting time by approximately 11.85 minutes per cycle, minimized product defects, and increased the yield of quality products from 91% to 99.6%. This improvement was statistically significant ( $P\text{-value} = 0.000$ ). Although the new process required an additional 48 kg of firewood per batch, corresponding to a fuel cost increase of about 24 THB per cycle, it enabled the roasting of 20 additional coconuts per batch while reducing waste. As a result, the potential revenue increased by approximately 1,051 THB per cycle, representing a substantial return relative to the marginal rise in fuel expense.

Overall, the findings demonstrate that the newly developed coconut roasting device significantly improves the efficiency, quality, and economic viability of the roasting process. The apparatus is therefore well-suited for adoption in community-based enterprises and holds strong potential for small-scale commercial expansion. Nevertheless, the issue of higher fuel consumption requires attention within a broader sustainability framework. Future studies should investigate strategies to reduce the environmental footprint of the roasting process, including the incorporation of thermal insulation materials or structural modifications to minimize heat loss and enhance biomass utilization efficiency. More importantly, research should focus on reducing CO<sub>2</sub> emissions through alternative renewable energy sources, such as biogas from

agricultural waste or solar-assisted heating systems, which would align with Thailand's Bio-Circular-Green Economy Model. Additionally, exploring the potential for utilizing coconut shell charcoal or other agricultural residues as fuel sources could simultaneously reduce operating costs, decrease dependence on firewood, and contribute to circular economic principles by converting waste into valuable energy. Life cycle assessment (LCA) studies would provide valuable insights into the overall environmental impact and guide the development of more sustainable roasting technologies that balance productivity, quality, and ecological responsibility.

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