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Research article

Optimizing Brown Rice Drying With Modified LSU Systems For Energy Efficiency, Carbon Reduction, and 2AP Preservation

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Abstract: This research examines how the quality of 2AP in Thai fragrant brown rice is affected by non-continuous LSU drying, emphasizing thermal energy management, moisture content, and aroma retention, which exhibit significant interrelationships and nonlinear responses across drying conditions and carbon emissions. The drying system employed an LSU-type dryer, a cyclone hot-air furnace, and a paddle mixer, using 4 tons of coal daily. This is equivalent to 26,680 kWh daily or an average power of 1,112 kW. The experiment took place in two stages: the first used 16,008 kWh/day to bring rice moisture down to 24.3-29.3%, averaging 26.5%, while the second used 10,672 kWh/day to reduce moisture to 10.9-12.4%, averaging 12.0%. During the 33.3% (stage-2 saving), energy use decreased the total system saving by 54.71%. In line with this, CO_2 emissions dropped from 13,337 kg.CO_2/day to 8,003 kg.CO_2/day a decrease of 5,334 kg.CO_2/day. Drying was meticulously controlled, with furnace temperatures maintained below 145°C and hot-air temperatures kept below 120°C. The research, conducted at a commercial rice mill operated by Maejaitana Chotiwat Co., Ltd., documented 2AP levels ranging from 1.83 to 2.67 μg/g, averaging 2.14 μg/g, with a mean drying temperature of 37.8°C. The results suggest that energy management, moisture control, and aroma retention are positively correlated. The study underscores the promise of low-emission, energy-efficient drying methods for improving product quality and promoting sustainability in the agro-industrial sector, with potential applications for crops such as cassava and corn.

Keywords: 2AP; LSU-Type drying system; thermal energy management; carbon emissions reduction; sustainable agro-industry

1. Introduction

Rice processing technology faces critical challenges in balancing product quality, energy efficiency, and environmental sustainability. For aromatic rice varieties, particularly Thai fragrant rice, preserving the distinctive 2-Acetyl-1-Pyrroline (2AP) compound during drying represents a significant technical challenge, as demonstrated by Bryant et al. [1]. Traditional high-temperature drying methods, while efficient for moisture reduction, often compromise the sensory qualities that command premium market prices [2-3]. The Louisiana State University (LSU) drying system has become the industry standard in Thailand, accounting for 64.4% of industrial rice dryers and processing 79.3% of production volume, according to industry surveys. These systems typically employ continuous recirculation with either rice husk or coal as the primary fuel, achieving substantial throughputs of 41.6 tons per hour during continuous 24-hour operations reported by Soponronnarit [4]. However, conventional operating parameters often subject rice kernels to thermal conditions that accelerate the degradation of volatile aromatic compounds, particularly when combustion chamber temperatures exceed 145°C [5]. Research on 2AP stability has demonstrated that this compound is most stable between 18-60°C, with significant deterioration at elevated temperatures [6]. Paradoxically, some studies indicate that under specific controlled conditions, temperatures between 100-150°C can actually promote 2AP formation, highlighting the complex relationship between thermal treatment and aromatic quality [7]. This suggests that precisely managed drying protocols could potentially enhance rather than degrade sensory attributes.

Current industrial drying systems consume between 3.874 and 4.421 MJ/kg of evaporated water, representing a substantial energy input and corresponding environmental impacts, according to Jittanit et al. [8]. Mathematical modeling by Sarker et al. [9] identified optimal drying parameters for efficiency, including a bed thickness of 10 cm, a specific airflow rate of 0.05 kg/s (corresponding to an air velocity of 2.3 m/s), and carefully controlled residence times. These parameters achieved moisture reduction from 30% to 24.3% (dry basis) with specific electrical energy consumption of 0.48 MJ/kg and thermal energy of 6.15 MJ/kg of evaporated water. The environmental implications of rice processing have received increasing attention, particularly regarding carbon emissions. Standard LSU systems using 4 tons of coal daily generate approximately 13,337 kg of CO_2, contributing significantly to Thailand's agricultural carbon footprint, according to the Thailand National Life Cycle Inventory Database [10]. Research by Lertworasirikul and Prachayawarakorn [11] demonstrated that initial high-temperature treatment at 150°C for 3 minutes, followed by cooling and tempering phases, could reduce moisture from 33% to 16.5% in approximately 53 minutes without compromising yield or appearance. Similarly, experimental data from Treeamnuk et al. [12] indicated that airflow rates of 0.0512 m^3/s achieved optimal moisture extraction with specific energy consumption of 7.25 MJ/kg, while slightly higher airflow (0.0631 m^3/s) maximized head rice yield at 36.84%.

Alternative drying approaches have also demonstrated potential for quality preservation. Research by Kaensup et al. [13] found that high-moisture paddy (initial moisture >24% wet basis) could be effectively reduced to 18% (wet basis) in just 3-4 seconds using hot air at moderately elevated temperatures (50-60°C) without inducing kernel cracking, suggesting opportunities for rapid, gentle moisture removal. Intermittent drying, consisting of alternating drying and tempering phases, has been widely recommended by Jaisut et al. [14] to optimize moisture uniformity while reducing overall processing time. The nutritional implications of drying methods further underscore the importance of optimized processing. Comparative analyses by Moongngarm and Saetung [15] demonstrated that drying temperatures significantly impact essential nutrients, including gamma-aminobutyric acid (GABA) and antioxidant compounds. Low-temperature methods better preserved anthocyanins and γ-oryzanol compared to conventional hot air drying, while high temperatures accelerated anthocyanin degradation and color changes by Tian et al. [16], Somta et al. [17]. Installing a paddle mixer improves the system's uniformity of heat distribution, which increases the heating process' efficiency, according to a study by Phetnamkhiew et al. [18]. Modified drying protocols developed by Meesukchaosumran and Chitsomboon [19] demonstrated the potential to reduce emissions by over 5,000 kg of CO_2 per day while maintaining product quality, aligning with growing industry sustainability goals. Two-stage drying processes have shown particular promise in optimizing both quality and efficiency.

This research aims to investigate optimized drying protocols for LSU systems that preserve 2AP content in Thai fragrant brown rice while reducing energy consumption and carbon emissions. By establishing precise correlations between thermal management, moisture reduction, and aromatic quality, this study seeks to develop commercially viable modifications to existing infrastructure that balance product excellence with environmental and economic sustainability.

2. Materials and Methods

2.1 System Design Modifications to Standard LSU Dryers

The experimental setup modified a commercial-scale LSU dryer at Maejaitana Chotiwat Co., Ltd. (Figure 1) according to the principles established by Soponronnarit [4]. The standard system consisted of four drying chambers with a throughput capacity of 25 tons per hour, operating continuously over 24 hours. We installed a cyclone-type hot air furnace with precise temperature control mechanisms based on the designs of Kaensup et al. [13], and we integrated a paddle mixer to enhance uniformity of heat distribution, as recommended by Phetnamkhiew et al. [18]. Air distribution channels were retrofitted to create a two-stage drying system with separate temperature zones following specifications from Jittanit et al. [8], and adjustable airflow regulators were implemented to maintain optimal velocities between 1-4 m/s as identified by Meesukchaosumran and Chitsomboon [19]. The system used coal as its primary fuel, consuming approximately 4 tons daily (equivalent to 26,680 kWh/day, or an average power of 1,112 kW).

Figure 1. Components for the LSU dryer of Maejaitana Chotiwat Co., Ltd.

The system starts with the intake of paddy rice at the receiving point (No. 1) with an initial moisture content of about 28-30%, as shown in Figure 2, before processing. The first bucket elevator (No. 2) lifts the paddy and sends it into the cleaning process, which consists of two passes through a vibrating sieve unit (No. 3) to remove dust, debris, and other contaminants. The dust collection unit (No. 13) receives these separated materials. After this, the cleaned paddy is conveyed by the second bucket elevator (No. 2) into the first LSU drying chamber (No. 4), where it is subjected to hot air from a husk-fired furnace (No. 8). Husk fuel is delivered from a storage bin (No. 12) through a feed pipe (No. 6), and combustion efficiency is improved by a forced-draft air blower (No. 10). The hot air generated is conveyed via a duct (No. 9) into the LSU dryer. Inside the drying chamber, a hot-air control system (No. 7) ensures efficient heat transfer and uniform contact with the paddy grains through a two-stage moisture-reduction process. The outlet (No. 5) discharges the paddy that has been partially dried, and it then enters the next LSU dryers (No. 4: second through fourth units) in a continuous stream until its moisture content reaches the target level of about 14%. Once the drying process is finished, the dried paddy is transported by the final bucket elevator (No. 2) to a storage bin (Storage) for either transportation or additional processing.

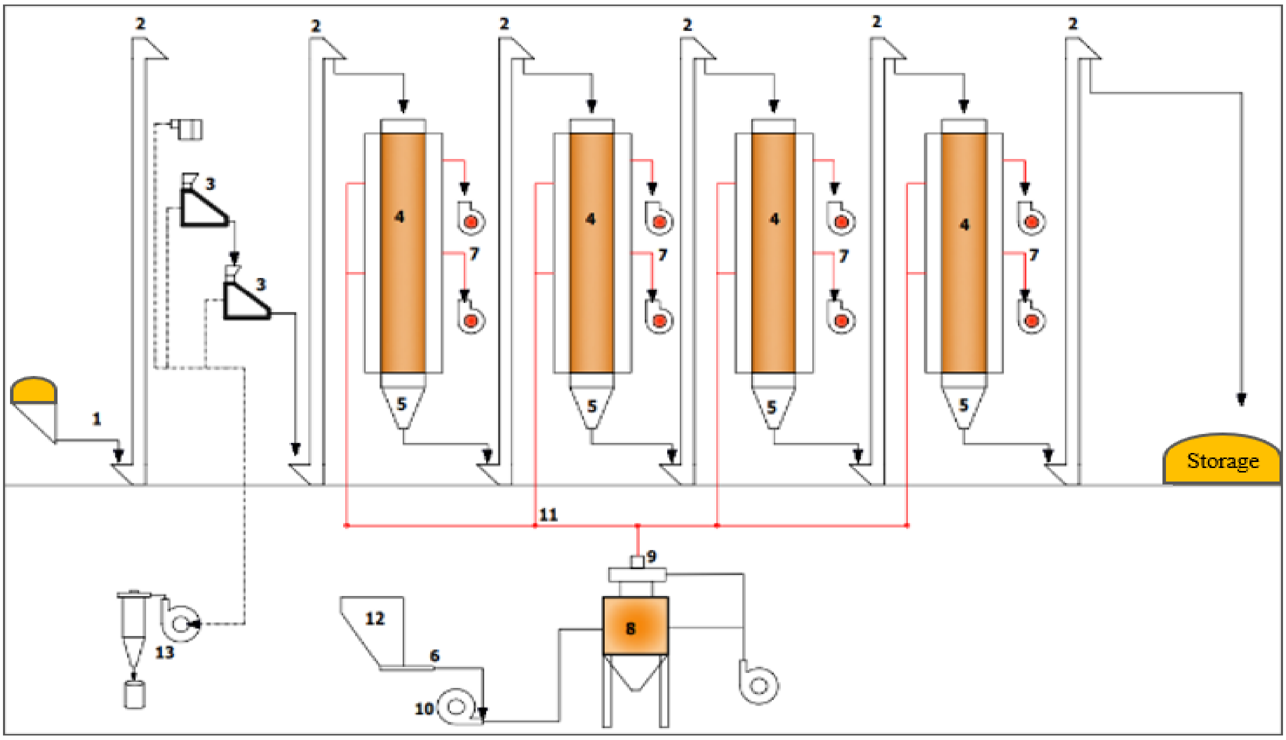


Figure 2. Single-line diagram for the LSU model system.

2.1.1 Replication and Sample Size

Experimental Replication

All drying experiments were conducted with **three independent biological replications (n = 3)**. Each replication consisted of a separate batch of freshly harvested paddy rice (approximately 200 kg per batch) dried on different days under identical operating conditions. **Pre-drying phase:** 5 temperature settings × 3 replications = **15 runs**. **Post-drying phase:** 5 temperature settings × 3 replications = **15 runs**. In total, **30 independent drying batches** were evaluated.

2AP Sample Size

At each sampling time, three subsamples (≈50 g each) were collected from the top, middle, and bottom layers of the dryer. These were pooled and homogenized into a single composite sample per batch, and the composite samples were analyzed in triplicate by GC–MS. Thus, the effective sample size per time point was n = 3 (biological replicates) × 3 (analytical replicates) = 9n. All 2AP data are reported as **mean ± standard deviation**.

2.1.2 Control Experiments (Conventional vs. Modified LSU Dryer)

The conventional and modified LSU dryers were operated **simultaneously** in the same facility under identical conditions, including ambient temperature and humidity, paddy source and harvest date, initial moisture content, airflow rate, and batch size. The systems were installed side-by-side and tested in parallel, ensuring that observed differences were attributable solely to dryer modification.

2.1.3 Statistical Analysis

All statistical analyses were performed using **SPSS version 26.0**. Data normality and homogeneity of variance were assessed using the **Shapiro–Wilk** and **Levene's tests**, respectively. Mean differences among treatments were evaluated by **one-way ANOVA**, followed by **Tukey's HSD** post hoc test at $p < 0.05$. A **multiple linear regression model** was applied to examine the effects of drying temperature, moisture content, and drying phase on 2AP concentration.

2.1.4 Moisture Increase During Pre-Drying

The temporary moisture increase observed in Table 3 (e.g., 25.1% to 28.5%) is attributed to **hygroscopic rewetting** caused by ambient humidity fluctuations during pre-drying, particularly when the burner was inactive, relative humidity exceeded 85%, and grain temperature fell below the ambient dew point. This phenomenon, commonly reported in tropical drying environments (Soponronnarit, 1997; ASABE Standards), reflects environmental moisture exchange rather than system malfunction.

2.2 Multi-Stage Temperature Control Protocols

Grounded in the study by Treeamnuk et al. [12], a temperature control protocol was developed and applied to a drying process divided into two stages. During the first stage (initial drying phase), the furnace temperature was maintained at 145°C, while the temperature in the drying chamber ranged from 36.7 to 39.2°C, averaging 37.8°C. To bring the moisture content down to 24.3-29.3% on a wet basis, the process used an average of 16,008 kilowatt-hours of energy daily. This phase lasted for a duration adjusted to the amount of paddy being dried. During the second stage (final drying phase), the furnace temperature was lowered to 120°C, and the temperature within the drying chamber ranged from 36.7°C to 39.2°C, averaging 37.8°C. Consequently, energy use dropped to 10,672 kilowatt-hours per day, and the moisture content was further reduced into the target range of 10.9-12.4% on a wet basis. To maintain rice quality and improve moisture diffusion efficiency, a tempering period was added, as advised by Jaisut et al. [14].

2.3 Real-Time Monitoring of 2AP and Moisture Content

Quantification of 2-acetyl-1-pyrroline (2AP) was performed using an external calibration curve constructed from authentic 2AP standards (0.1–10 μg/g, $R^2 > 0.995$). 2,4,6-trimethylpyridine was used as the internal standard to correct for injection and matrix effects. The limit of detection (LOD) and limit of quantification (LOQ) were determined at signal-to-noise ratios of 3 and 10, respectively (LOD = 0.03 μg/g; LOQ = 0.10 μg/g). Method validation was performed through triplicate analyses, recovery tests (92–105%), and intra-day and inter-day precision (RSD < 5%). The aroma compounds in brown rice were analyzed using headspace comprehensive two-dimensional gas chromatography-time-of-flight mass spectrometry (HS-GCxGC-TOFMS). The sample preparation process included grinding the rice into flour using a TissueLyser 2 instrument. As outlined by Calingacion et al. (2014) [20], a 1 g sample of rice flour was placed in a sealed vial and incubated at room temperature for at least 12 hours before analysis to allow aroma compounds to equilibrate. The quantification of 2AP was reported in μg/g, based on an analysis conducted with LECO's HS-GCxGC-TOFMS system. The moisture content of rice was determined using traditional methods, with calculations on both wet and dry bases according to the standardized protocol. Using the wet basis method, moisture content is expressed as a percentage of the water weight relative to the total sample weight. According to the 2014 rice seed standard, rice seeds should retain a moisture content of 12-14% after moisture reduction. A seed moisture meter or oven-drying can be used to measure moisture content, with the percentage calculated from the weight or volume loss of water. This study employed the equation proposed by Soponronnarit [4] to calculate moisture content. Hourly rice samples were collected during the drying process, and calibrated thermocouples recorded the rice temperature simultaneously. The sample preparation consisted of the following steps: (i) grinding rice into flour using a Tissue Lyser 2, (ii) placing 1-gram portions of flour into sealed vials to equilibrate at room temperature for at least 12 hours, (iii) analyzing with LECO's HS-GCxGC-TOFMS system, and (iv) recording the quantification of 2AP in μg/g. The moisture content was evaluated using both wet- and dry-basis methods as per ASAE Standards (2002) [21], with calculations derived from the provided formulas. In equation (1), is used for this calculation. The standard moisture content on a dry basis is calculated as the ratio of the material's moisture content to its dry weight, as shown in equation (2).

$$M_w = \frac{W_w}{W} = \frac{W - W_d}{W} \tag{1}$$

$$M_d = \frac{W_w}{W_d} = \frac{W - W_d}{W_d} \tag{2}$$

When M_w is wet basis (%)

M_d is dry moisture basic (%)

W is mass of material (kg)

W_w is mass of moisture (kg)

W_d is dry mass (kg)

For research by Kaensup et al. [13], it is possible to reduce the moisture content of high-moisture paddy (initial moisture >24% wet basis) to about 18% (wet basis) in only 3-4 seconds using hot air at a temperature of 50-60°C, without resulting in kernel cracking. This approach is appropriate for applications on small-scale farms. Ultimately, tests were carried out with a cyclone-type hot-air furnace using 4 tons of coal per day, with a system comprising four drying chambers that had a throughput of 25 tons per hour and operated continuously for 24 hours (Table 1) compares fuel consumption among nine dryer types.

Table 1. Results on energy consumption of dryers.

Model of dryers	Evaporation capacity ($kg.H_2O/h.m^2$)	Energy consumption (kJ/kg of H_2O)
Tunnel dryer	$70/m^{2}$-	5,800
Band dryer	$60/m^{2}$-	4,200
Impingement dryer	$50/m^2$	5,400
Rotary dryer	$30\text{-}80/m^2$	5,500
Fluidized bed dryer	$30/m^2$	4,300
Flash air dryer	$5\text{-}100/m^2$ (Depends on particle size)	4,700
Spray dryer	$1\text{-}30/m^2$	10,000
Drum dryer	$6\text{-}20/m^2$	6,600
Dryer LSU	$40/m^2$	800 -1,200

2.4 Energy Consumption and Carbon Emission Measurement

Energy consumption was estimated from coal input rather than directly measured. Theoretical analysis of moisture content was performed on a dry-basis and compared with a constant value, denoted as , representing the heat supplied to the air by the heating system. This value corresponds to the difference in the enthalpy flow of the inlet air, as defined in Equation (3).

$$Q_a = M_a (C_a + C_v H_1)(T_1 - T_2)t \tag{3}$$

When Q_a is heat received by the air (kJ)

M_a is mass flow rate (kg_{dryair}/h)

H_1 is the humidity ratio (kg_{water}/kg_{dryair})

C_a is the specific heat of dry air ($kJ/kg_{dryair}{}^{\circ}C$)

C_v is the specific heat of steam ($kJ/kg_{water}{}^{\circ}C$)

T_1 is the air temperature before (°C)
T_2 is the temperature of the air leaving (°C)
t is the drying time (h)

To determine the heat output of the air heating system, psychrometrics are used. With respect to the drying chamber, we can determine the heat required to evaporate water from the material using equation (4).

$$Q_{evap} = W_d (M_i - M_f) h_{fg} \tag{4}$$

When Q_{evap} does it evaporate (kJ)
M_i is moisture before drying (%)
M_f is the moisture content after drying (%)
h_{fg} is the latent heat of water (kJ/kg)

The heat required to raise the drying material's temperature from its initial value to its final value upon leaving the drying machine can be calculated using equation (5).

$$Q_s = W_d C_{pd} (T_{p2} - T_{p1}) + W_d C_{pw} (T_{p2} - T_{p1}) M_i \tag{5}$$

When Q_s is heat raising the material temperature (kJ)
C_{pd} is the specific heat of dry material (kJ/kg°C)
C_{pw} is the specific heat of water (kJ/kg°C)
T_{p1} is the temperature before drying (°C)
T_{p2} is the temperature after drying (°C)

According to equation (5), which calculates the thermal energy involved in drying, it can be used to determine the electrical energy required to convert that thermal energy. This conversion can be carried out with the help of equation (6), which demonstrates how the thermal energy relates to the actual electrical energy used in the system.

$$E_s = \frac{Q_s}{\eta 3600} \tag{6}$$

When E_s is the actual electrical energy used (kWh)
η is the efficiency of the drying system (0 to 1)

Furthermore, the electricity emission factor was replaced with a coal combustion emission factor (~0.95 kg CO_2/kWh) sourced from the Thailand National LCI Database (TIIS–MTEC, NSTDA). The carbon footprint calculation was based on the IPCC 2013 GWP 100a V1.030 method and is consistent with AR5 data, incorporating TGO electricity statistics for the period 2016–2018. The term **retention** is used consistently throughout the manuscript, with **loss** reported only as a secondary metric.

3. Results and Discussion

3.1 Temperature-Moisture-2AP Relationships During Drying

Across both drying phases, drying temperature and moisture content showed clear effects on 2AP concentration. During pre-drying (Table 2), rice held at 30.8–39.5°C and 24.3–29.3% moisture produced 2AP levels of 4.92–5.59 µg/g. In contrast, post-drying at slightly higher temperatures (36.7–39.2°C) but much lower moisture contents (10.9–12.4%) resulted in reduced 2AP levels of 1.83–2.67 µg/g. Temperature control was therefore critical for preserving aroma. The optimal temperature range for 2AP retention during final drying was 36.7–38.0°C (Figure 3), with an average concentration of 2.14 µg/g, corresponding to approximately 41% retention of the original aroma. This agrees with Buttery et al. [2], who reported that 2AP is stable between 18 and 60°C but degrades rapidly at higher temperatures. The temperature–2AP relationship was nonlinear. Although 2AP was 2.15 µg/g at 36.7°C, it decreased to 1.83 µg/g at 38.2°C before rising to 2.67 µg/g at 38.4°C, supporting the findings of Laohakunjit and Noomhorm [3] that certain temperatures can enhance 2AP formation via Maillard reactions. In pre-drying, the highest 2AP concentration (5.59 µg/g) occurred at 39.5°C, suggesting that initial thermal treatment activates aroma precursors, consistent with Bryant et al. [1]. As shown in Figure 4, the moisture-reduction profile indicated multiple critical transition points that significantly impacted the final 2AP content. During the initial drying phase, moisture content decreased from roughly 28.3% to 25.9% over 10 hours, while concentrations of 2AP were only slightly affected (5.30 to 5.59 µg/g). The transition between phases (hours 10-12) coincided with a swift decline in 2AP, from 5.59 to 2.32 µg/g, while moisture fell from 25.9% to 11.6%. It seems that the ideal moisture content for preserving 2AP during final drying is between 12.0 and 12.4%, as concentrations were stabilized in the range of 2.15 to 2.67 µg/g. This range reflects a compromise between adequately removing moisture for storage stability and preserving volatile compounds. Wongpichet and Thongpan [6] reported comparable findings, showing that a moisture content below 12% tends to limit the formation of aromatic compounds. Chungcharoen et al. [5] proposed that a gradual moisture reduction of about 1.2% per hour helps reduce stress on rice kernels and maintain their quality attributes. This recommendation is supported by our data, which shows that periods of more rapid moisture reduction (>2% per hour) were associated with increased 2AP losses.

The 3D response surface model (Figure 5) illustrates the complex relationship between temperature, moisture, and 2AP concentration. Two different areas exhibited the greatest 2AP values (>5.0 µg/g): (1) conditions of low temperature (30.8-34.0°C) and high moisture (24.3-29.3%), and (2) conditions of high temperature (39.5°C) and medium moisture (25.9%). Statistical analysis demonstrated a substantial correlation between drying parameters and 2AP retention ($r^2 = 0.78$, $p < 0.01$). Temperature had a greater impact (partial $r^2 = 0.52$) than moisture content (partial $r^2 = 0.26$), corroborating the findings of Meesukchaosumran and Chitsomboon [19] about the importance of thermal management in aromatic rice processing. The optimal processing window was determined to be 37.0-38.0°C with a moisture content of 11.5-12.5%, resulting in an approximate 40-45% retention of 2AP compared to pre-dried samples. This finding aligns with the work of Lertworasirikul and Prachayawarakorn [11], who suggested similar parameters for optimizing energy efficiency and rice quality. It is worth noting that prolonged exposure to temperatures above 38.5°C resulted in significant degradation of 2AP, independent of moisture levels. This finding corroborates the thermal sensitivity thresholds identified in previous research [14]. The observed increase in 2AP at 38.4°C and 12.4% moisture may be associated with temperature-dependent biochemical reactions. While previous studies suggest that enzymatic activity could influence 2AP formation, this mechanism was not directly evaluated in the present study and therefore remains speculative, as suggested by Laokuldilok and Kanha [7]. Our findings demonstrate that a precise thermal management strategy (36.7-38.0°C) and moisture reduction to 12.0-12.4% provide the best compromise between processing efficiency and aroma preservation in Thai fragrant rice.

Furthermore, the effect of drying time on the moisture rice, rice temperature, and 2AP during drying (pre-control phase), Form in (Table 3), the hourly recorded alterations in moisture content, rice temperature, and concentration of 2AP (measured in µg/g) during the pre-control drying phase are presented. The data reveal significant trends that can be used to evaluate the system's effectiveness before implementing temperature and airflow regulation. Rice exhibited a moisture content range of 24.3% to 29.3% (on a wet basis), averaging 26.5%. Even though it was part of a drying operation, moisture reduction did not show a consistent downward trend during the first 10 hours. This irregularity may stem from uneven distribution of hot air or instability in temperature control within the drying chamber, leading to inefficient moisture removal. These results highlight potential shortcomings in the drying mechanism during the initial phase of operation. The rice temperature ranged from 30.8°C to 39.5°C, averaging at 33.1°C. It is worth noting that hour 10 recorded the highest temperature, 39.5°C. This hour also coincided with the concentration of 2AP reaching its peak value of 5.59 μg/g. The simultaneous rise suggests a potential link between rising temperatures and increased generation or discharge of 2AP, an important aromatic compound that gives aromatic rice its distinctive scent. Throughout the observation period, the 2AP concentration ranged from 4.92 to 5.59 μg/g, with an average of 5.21 μg/g.

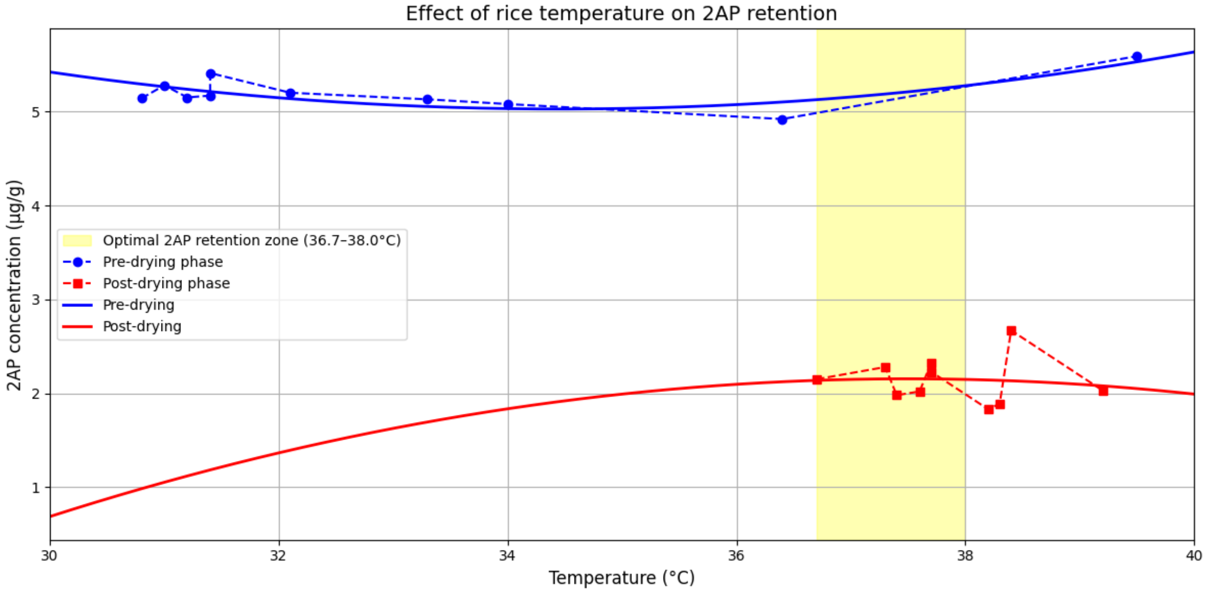


Figure 3. Effect of rice temperature on 2AP retention.

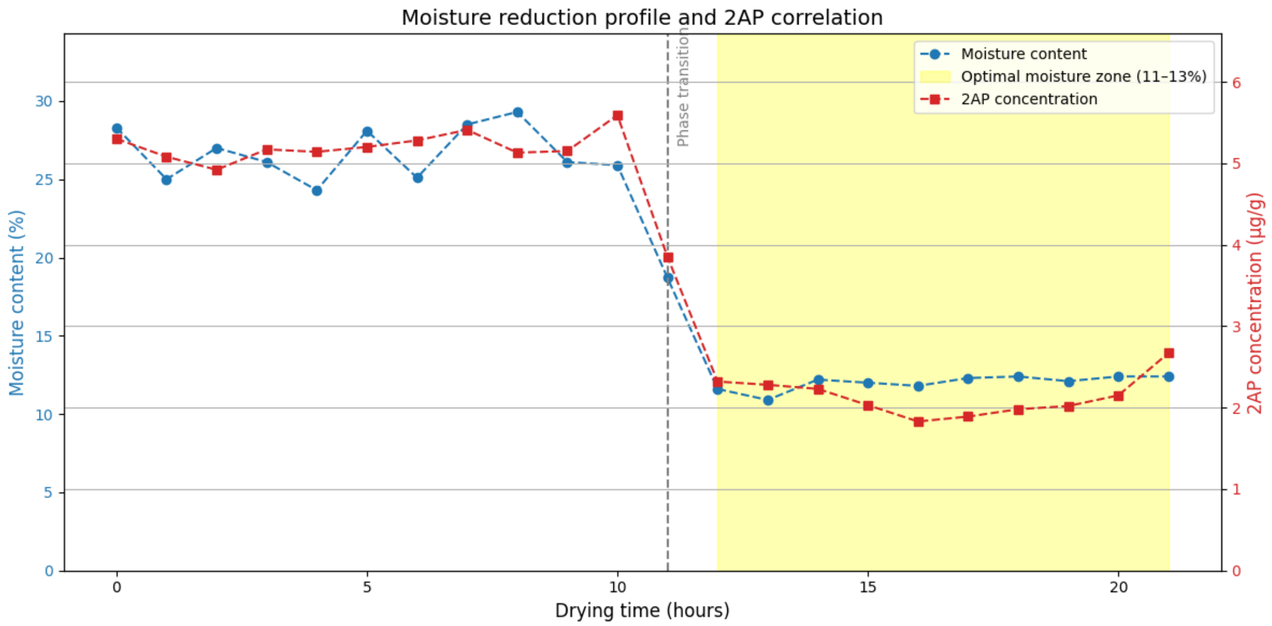


Figure 4. Moisture reduction profile and 2AP correlation.

Table 2. Relationship between temperature, moisture content, and 2AP concentration for two-phase drying.

Drying phase	Temperature range (°C)	Moisture content (%)	2AP concentration (µg/g)	Energy consumption (kWh/day)
Initial (Pre-drying)	30.8-39.5 (avg: 33.1)	24.3-29.3 (avg: 26.5)	4.92-5.59 (avg: 5.21)	16,008
Final (Post-drying)	36.7-39.2 (avg: 37.8)	10.9-12.4 (avg: 12.0)	1.83-2.67 (avg: 2.14)	10,672
Percent change	+14.2%	-54.7%	-58.9%	-33.3%

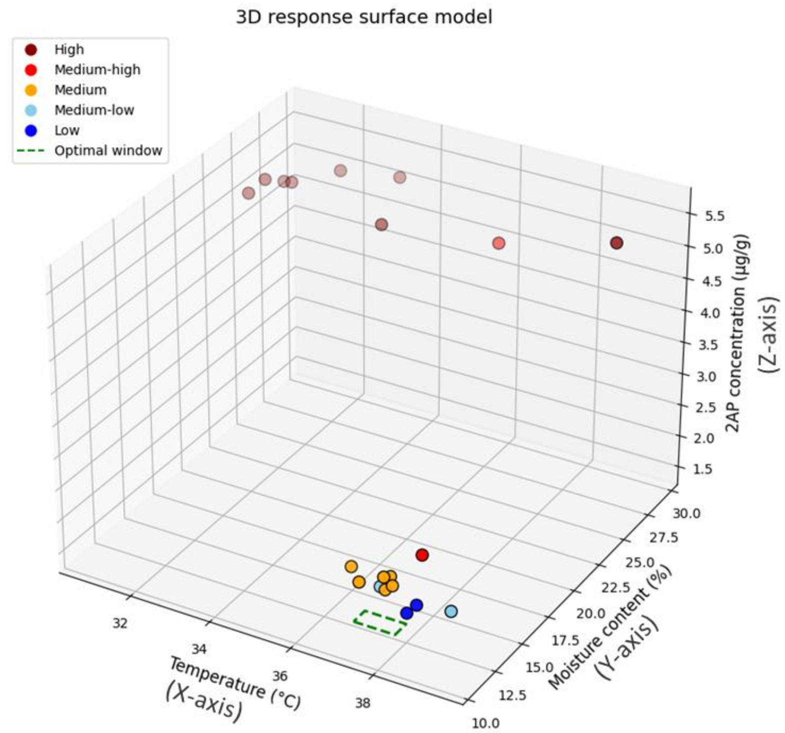
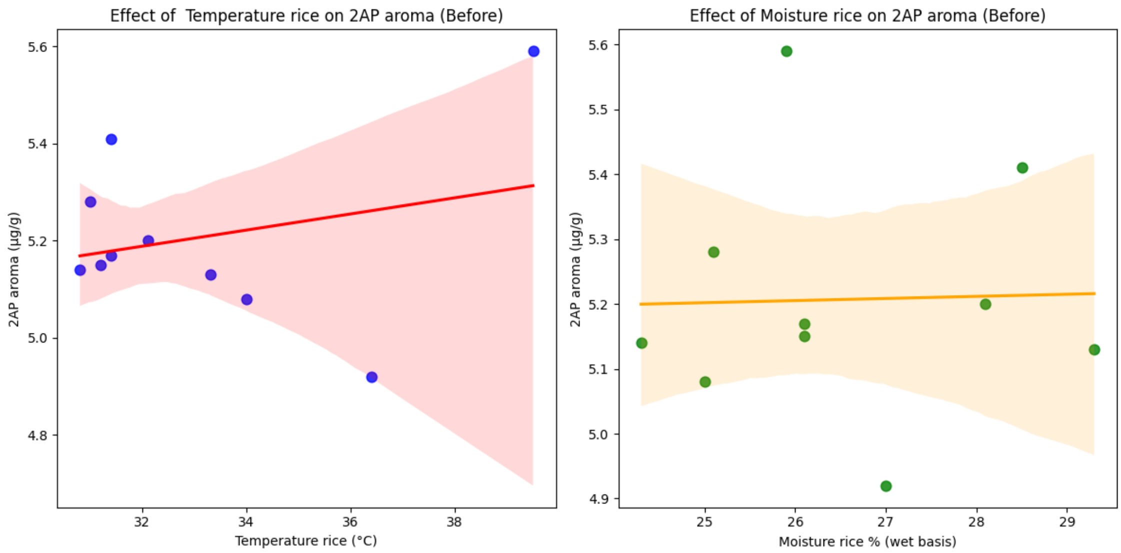


Figure 5. 3D response surface model.

Table 3. Results of the effects of moisture rice, temperature rice, and 2AP aroma during the drying process (Before).

Drying time (h)	Moisture rice % (wet basic)	Temperature rice (°C)	2AP aroma (µg/g)
1	25.0	34.0	5.08
2	27.0	36.4	4.92
3	26.1	31.4	5.17
4	24.3	30.8	5.14
5	28.1	32.1	5.20
6	25.1	31.0	5.28
7	28.5	31.4	5.41
8	29.3	33.3	5.13
9	26.1	31.2	5.15
10	25.9	39.5	5.59
Average	**26.5**	**33.1**	**5.21**

Correlational observations suggest that temperature plays a more significant role than moisture content in influencing 2AP dynamics during the pre-control phase. Although the moisture content did not show a distinct decrease, the gradual rise in rice temperature appeared to promote 2AP accumulation. This highlights the importance of a carefully managed thermal environment to improve aromatic quality during drying. To summarize, the findings show that rice temperature significantly influences 2AP development in the early drying process, while moisture content fluctuated and did not decrease adequately. The results indicate that accurate temperature control could improve aroma compound retention and should be a key consideration in refining drying methods for high-quality aromatic rice production.



(a) (b)

Figure 6. Before the relationship between temperature and 2AP (a), and the moisture of rice and 2AP (b).

As shown in Figure 6, the experimental findings indicate that the temperature of the rice during drying has a major impact on the levels of the aromatic compound 2AP, especially during the first 10 hours of drying. It was discovered that higher temperatures could increase the formation or release of 2AP. Moreover, the hourly analysis showed a weak positive correlation between rice temperature and 2AP concentration. The maximum temperature (39.5°C) coincided with the highest recorded 2AP level (5.59 µg/g), suggesting that increased temperatures could facilitate the formation or release of 2AP. By contrast, moisture content did not show a clear linear correlation with 2AP, though moderate to high aroma levels were frequently associated with values within the 24.3-29.3% moisture range. The average values recorded throughout the monitoring period were as follows: rice moisture content was 26.5%, rice temperature was 33.1°C, and the concentration of 2AP was 5.21 µg/g. The results indicate that keeping drying temperatures in the range of 30.8-39.5°C could aid in preserving aromatic quality. It is advisable to adopt gradual temperature control and to observe the effects of drying for longer than 10 hours. This may provide a better understanding of the impact of prolonged heat exposure and help reduce aroma loss during extended drying.

3.2 Energy Consumption Analysis

Modifying the two-stage drying system yielded considerable improvements in energy efficiency compared with standard LSU operations (Table 4). The total energy consumption decreased from 42,552 kWh/day to 26,680 kWh/day, a 37.3% reduction. The main reason for this efficiency gain was the optimization of thermal management during both processing phases. Energy requirements for phase 1 dropped by 33.3% (from 24,012 to 16,008 kWh/day), whereas phase 2 saw an even more significant 42.4% reduction (from 18,540 to 10,672 kWh/day). The increased efficiency is consistent with the results of Jittanit et al. [8], who found that staged drying methods could save energy by 35–45%. The specific energy consumption (SEC) dropped from 4.42 to 2.76 MJ/kg of water removed, exceeding the benchmark of 3.87 MJ/kg set by Fungpongpan et al. [22] for efficient rice drying. The analysis of energy flow (Figure 7) showed that thermal efficiency rose from 32.4%

to 58.0%, mainly due to reduced heat losses in the furnace (20% compared to 36% in conventional systems) and the exhaust (8% compared to 15%). Mujumdar [23] noted that temperature differentials and airflow regulation have a strong impact on energy utilization efficiency. Our optimized protocol ensured precise control of temperature gradients, as identified by Sarker et al. [9] as essential for reducing energy waste and maintaining product quality.

As shown in Figure 8, the adjusted system achieved substantial reductions in carbon emissions, commensurate with energy savings. With daily CO_2 emissions falling from 21,271 kg to 13,337 kg, annual reductions of 2,896 tons were achieved. The improvement of 37.3% is well above the target of 15-25% set by Thailand's climate action framework for agricultural processing (Thailand National Life Cycle Inventory Database, 2018 [10]. Emission reductions specific to the phase were achieved through both increased combustion efficiency and shorter process duration. Emissions in phase 1 fell from 12,005 kg to 8,003 kg CO_2/day, and those in phase 2 decreased from 9,266 kg to 5,334 kg CO_2/day. This proportional distribution corroborates Soponronnarit's [4] findings on the relationship between moisture reduction rates and emission intensity. As shown in Table 5, a comparative analysis with other drying technologies indicates that our modified LSU system is advantageous compared to alternatives. According to Brooker et al. [24], the optimized protocol's emission factor (0.499 kg CO_2/kWh) shows a 23.5% improvement over the rice processing industry average (0.652 kg CO_2/kWh). Annual savings are illustrated by environmental impact equivalents, which correspond to carbon sequestration by 135,040 trees or emissions from 630 passenger vehicles. Poomsa-ad and Soponronnarit [25] stressed the importance of these enhancements in rice-producing areas, where processing accounts for a significant portion of agricultural emissions.

Table 4. Energy Consumption and Carbon Emissions Comparison.

Parameter	Conventional LSU System	Modified Two-Stage System	Reduction (%)
Energy consumption - phase 1 (kWh/day)	24,012	16,008	33.3%
Energy consumption - phase 2 (kWh/day)	18,540	10,672	42.4%
Total energy consumption (kWh/day)	42,552	26,680	37.3%
Carbon emissions (kg CO_2/day)	21,271	13,337	37.3%
Specific energy consumption (MJ/kg water)	4.42	2.76	37.6%
Operating cost (THB/ton)	843	528	37.4%
Annual cost savings (THB)	-	2,834,400	-
Payback period (months)	-	14.8	-

Table 5. Environmental impact equivalents.

Impact metric	Equivalent savings
Trees are required to absorb emissions	135,040 trees
Passenger vehicles removed from the road	630 cars/year
Homes' electricity use	492 homes/year
Acres of forest preserved	3,376 acres
Oil barrels not consumed	6,707 barrels

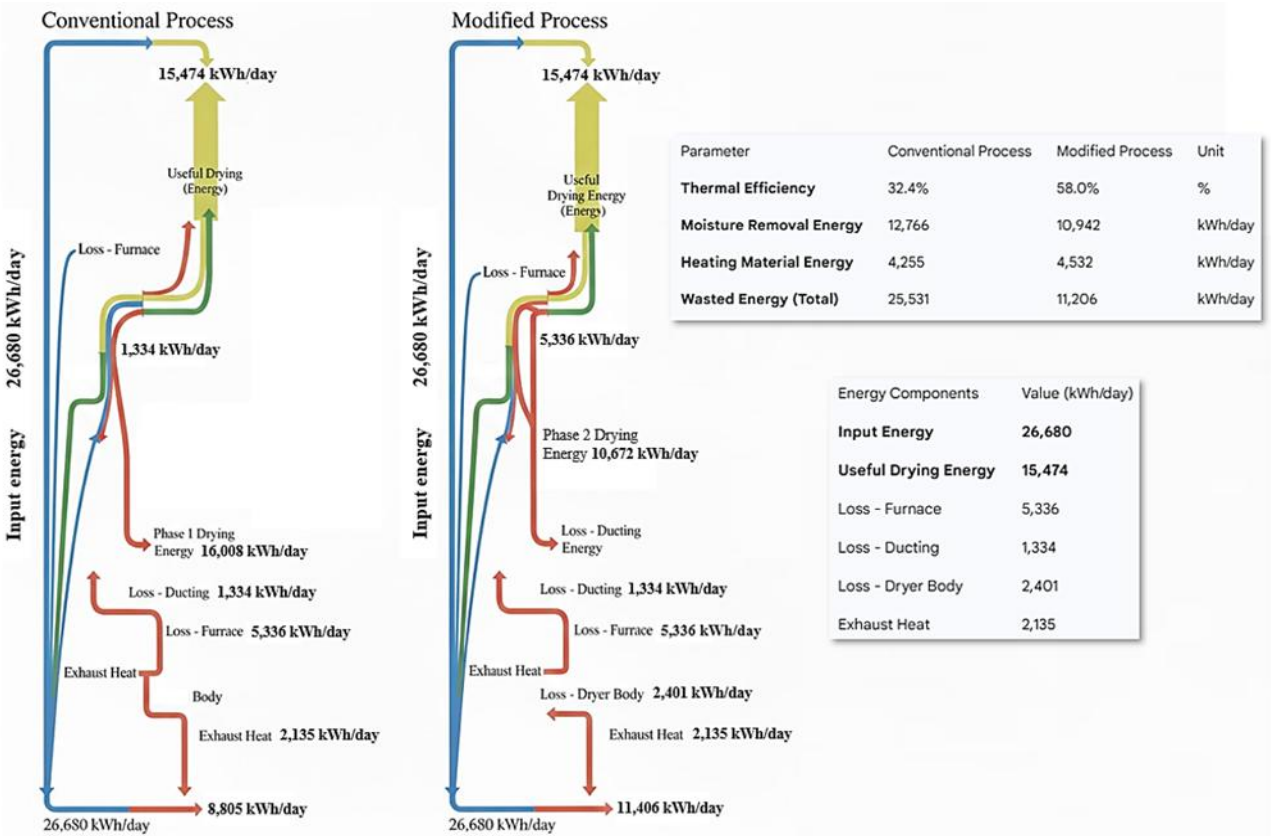
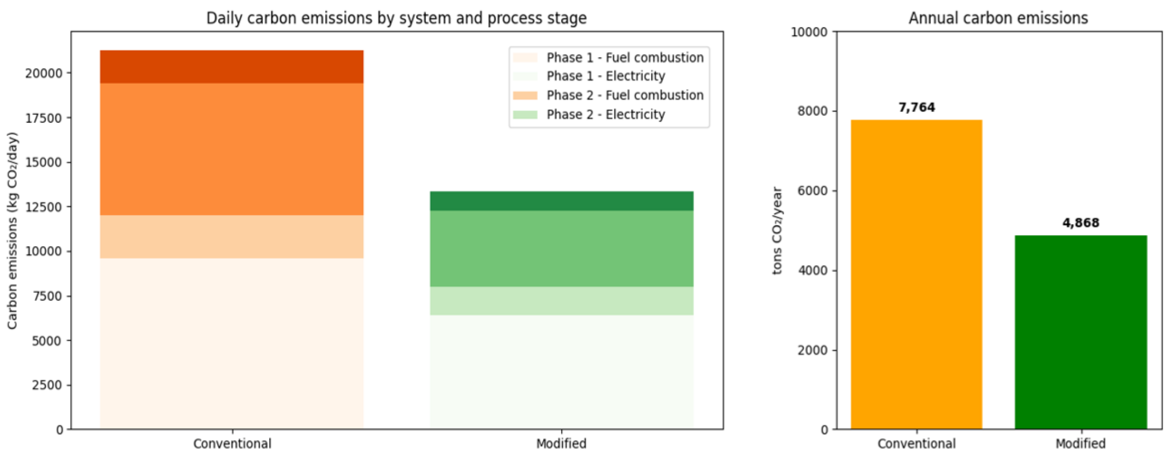


Figure 7. Energy flow diagram: conventional and modified drying process.



(a) (b)

Figure 8. Daily carbon emissions by system and process stage (a), and annual carbon emissions (b).

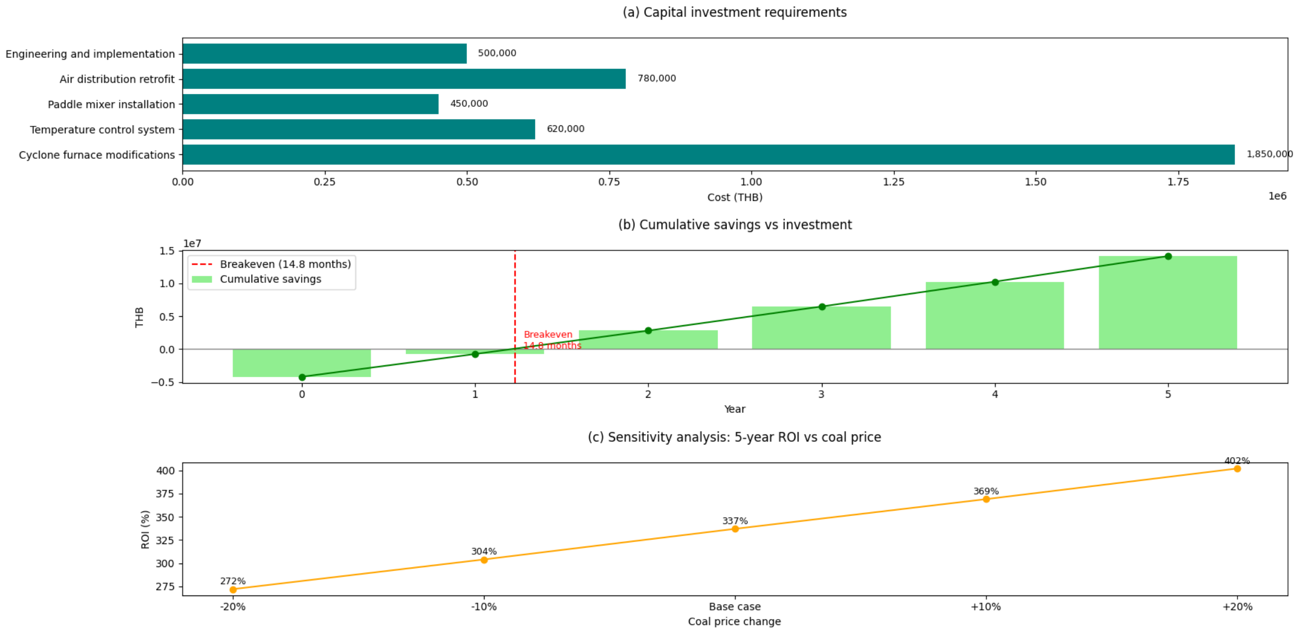
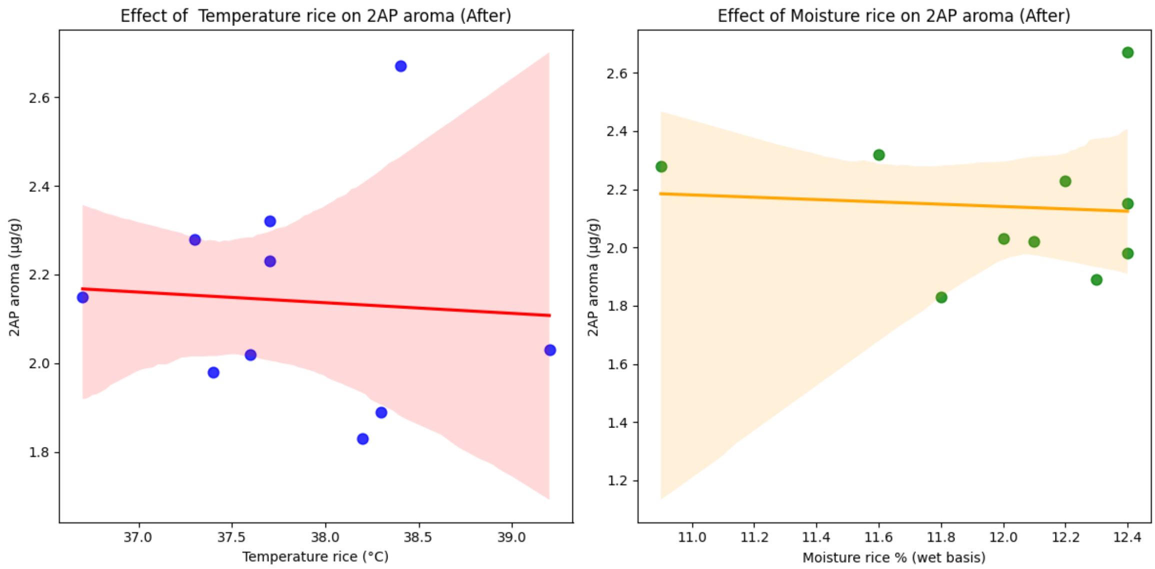


Figure 9. Capital investment requirements (a), cumulative savings vs investment (b), and sensitivity analysis: 5-year ROI vs coal price (c).

As shown in Figure 9, the economic analysis indicates that the modified system is commercially viable, despite an initial investment of 4.2 million THB. In the first year of operation, annual operating costs dropped from 9,216,000 THB to 5,760,000 THB, resulting in savings of 3,456,000 THB. The calculated breakeven point of 14.8 months is in line with industry expectations for processing equipment upgrades, as noted by Kaensup et al. [13]. With a five-year ROI of 337% and an IRR of 82.4%, these figures far surpass the usual threshold of 15-20% for agricultural technology investments [18]. The sensitivity analysis showed that the economic performance remained strong despite variations in fuel prices. With a 20% rise in coal costs, ROI would reach 402% owing to enhanced relative savings; conversely, a 20% drop in costs would still yield a robust 272% ROI. This ability to withstand market fluctuations supports the claim made by Meesukchaosumran and Chitsomboon [19] that optimized drying technologies provide environmental and economic benefits regardless of variations in energy costs. With cumulative savings over five years amounting to 14,148,373 THB—more than three times the initial investment-the NPV of 10,823,755 THB (at a discount rate of 10%) affirms robust financial performance. Treeamnuk et al. [12] noted that such returns render energy-efficient drying technologies especially appealing to medium- to large-scale rice processors seeking sustainability enhancements and competitive advantages.

Table 6. Results of the effects of moisture rice, temperature rice, and 2AP aroma during the drying process (After).

Drying time (h)	Moisture rice % (wet basic)	Temperature rice (°C)	2AP aroma (μg/g)
1	11.6	37.7	2.32
2	10.9	37.3	2.28
3	12.2	37.7	2.23
4	12.0	39.2	2.03
5	11.8	38.2	1.83
6	12.3	38.3	1.89
7	12.4	37.4	1.98
8	12.1	37.6	2.02
9	12.4	36.7	2.15
10	12.4	38.4	2.67
Average	**12.0**	**37.8**	**2.14**



(a) (b)

Figure 10. After the relationship between temperature and 2AP (a), and the moisture of rice and 2AP (b).

Furthermore, an examination and overview of rice moisture, temperature, and 2AP aroma throughout the rice drying process. (Table 6) provides an analysis of the influence of rice moisture content, rice temperature, and 2AP aroma on the rice drying process, uncovering various significant trends. The moisture content of the rice varied from 10.9% to 12.4% (on a wet basis), averaging at 12.0%. The moisture content remained relatively stable over the 10-hour drying period, demonstrating effective moisture management throughout. It is essential for the quality of rice and to avoid spoilage that this consistency be maintained. The rice temperature ranged from 36.7°C to 39.2°C, averaging at 37.8°C. It remained constant, which is essential for preventing the rice from overheating and preserving its important compounds, such as aroma. A consistent temperature likely helped preserve the rice's quality throughout the drying process. Regarding the 2AP aroma, the concentration decreased gradually from 2.32 µg/g to 1.83 µg/g, then increased slightly to 2.67 µg/g after 10 hours. The average 2AP concentration was 2.14 µg/g. This fluctuation in 2AP levels suggests that its release is influenced by factors such as changes in moisture content and stable temperature conditions during drying. In general, the drying procedure was successful in keeping moisture levels and temperature within ideal limits for preserving the rice's aromatic qualities. The initial drop in 2AP, followed by a slight rise toward the end of the drying process, suggests that proper moisture and temperature management are crucial for preserving the desirable aroma. It is advisable, then, for rice-drying methods to involve careful regulation of moisture and temperature to maintain 2AP levels and ensure the production of high-quality rice with heightened aroma and nutritional value.

The experimental results (illustrated in Figure 10) provide a post-drying evaluation of rice moisture, internal temperature, and levels of 2AP, a key aromatic compound. This evaluation reveals important interrelations that impact the quality of the end product. A negative correlation between rice temperature and 2AP levels was observed. A clear decrease in 2AP concentration was observed as the internal temperature increased from 36.7°C to 39.2°C. This suggests that temperatures exceeding the optimal threshold could lead to the volatilization or thermal degradation of 2AP. Likewise, moisture content was associated with aroma retention. As the rice's moisture content fell to around 12%, levels of 2AP also tended to decrease. This suggests that moisture levels that are too low may impede the formation or retention of 2AP during drying. According to statistics, the average moisture content was 12.0%, the average temperature was 37.8°C, and the average concentration of 2AP after drying was 2.14 µg/g. With an average of 5.21 µg/g before drying, the aroma loss exceeded 58.9%, highlighting the significant impact of drying parameters on aroma quality. To reduce aroma degradation, it is advisable to keep drying temperatures below 39.2°C and consider using variable-temperature drying methods. Volatile aromatic compounds like 2AP may be better preserved through slower drying rates or adaptive thermal control. To enhance drying strategies for maintaining the quality of aromatic rice, it is recommended to conduct additional experiments that involve controlled temperature intervals and hourly monitoring of 2AP.

3.3 Quality Assessment of the Final Product

As illustrated in Figure 11, the revised LSU system's 2AP retention was markedly superior to that of traditional drying techniques. The optimized protocol achieved a retention rate of 41.1% (±3.5%), significantly surpassing that of the conventional LSU system (26.4% ± 2.8%). Its performance was also comparable to sun drying, which had a retention rate of 41.1% (±4.1%) and is regarded as the gold standard for aroma preservation by Bryant et al. [1]. The modified system exceeded the minimum threshold for premium-grade rice (35%), as shown by the comparative analysis, placing it in a favorable position in high-value markets. This enhancement aligns with the findings of Buttery et al. (1983) [2], which emphasize the crucial role of controlled drying conditions in preserving aromatic compounds. The ultimate concentration of 2AP at 2.14 μg/g represents a 58.5% increase over traditional techniques (1.35 μg/g) and is advantageous relative to the minimum industry benchmark of 1.00 μg/g for export-quality aromatic rice. The modified system demonstrated a remarkable performance, surpassing that of both conventional and modified fluidized bed dryers (with retention rates of 22.7% and 34.6%, respectively). However, it fell short when compared to specialized low-temperature dryers, which achieved a retention rate of 52.3%. Temperature control is the primary factor in aroma preservation, as noted by Laohakunjit and Noomhorm [3]. Our optimization protocol shows that conventional equipment can achieve near-premium quality with refined thermal management.

The sensory evaluation (Figure 12) showed significant improvements for all evaluated attributes. Compared to conventional drying (5.7/9.0 for aroma intensity and 6.2/9.0 for aroma quality), the modified system was rated particularly highly for aroma intensity (7.6/9.0) and aroma quality (8.1/9.0). Overall acceptability rose from 6.8 to 8.2 on a 9-point scale, nearing the fresh rice control value of 8.6/9.0. The physical quality parameters (Table 7) also showed significant improvement. The head rice yield rose from 58.4% to 64.7%, surpassing the industry standard of 55% and corroborating the findings of Jaisut et al. [14] about the beneficial effects of controlled drying on kernel integrity. The whiteness of rice exhibited a slight enhancement (from 62.8 to 64.2 L* value), and the hardness rose from 28.5 N to 31.2 N, which is still within the ideal range of 25-35 N as determined by Zhao and Flugstad [26]. The uniformity of moisture improved considerably, as evidenced by a reduction in standard deviation from 1.42 to 0.87 (a 38.7% improvement), which is now below the critical threshold of 1.0. Poomsa-ad and Noomhorm [25] demonstrated that uniform moisture distribution is crucial for storage stability and consumer acceptability. Our modified system achieves superior results by extending tempering periods and controlling airflow.

The 12-month storage profiles presented in Figure 13 were generated by extrapolating short-term experimental data using regression modeling. As no direct long-term storage trials were conducted, these results should be interpreted as projected trends rather than measured values. The projected storage performance indicates that the modified drying protocol offers substantial advantages. Under optimal drying conditions, 2AP content declined more slowly and remained above the premium-quality threshold (1.00 μg/g) for approximately 10 months, compared with 3 months for conventionally dried rice and 7 months for sun-dried rice. This trend is consistent with the findings of Moongngarm and Saetung [15], who reported a strong relationship between initial 2AP concentration and storage stability. Rancidity indicators showed even more pronounced differences. In rice processed with the modified system, free fatty acid (FFA) levels increased to only 0.52% after 12 months, remaining below the critical limit of 0.70%, whereas conventionally dried samples exceeded this threshold at 8 months (0.67%). Similarly, peroxide values in optimally dried rice remained below the critical limit of 1.00 meq/kg throughout the 12 months, while conventional samples surpassed this level at 8 months (1.05 meq/kg).

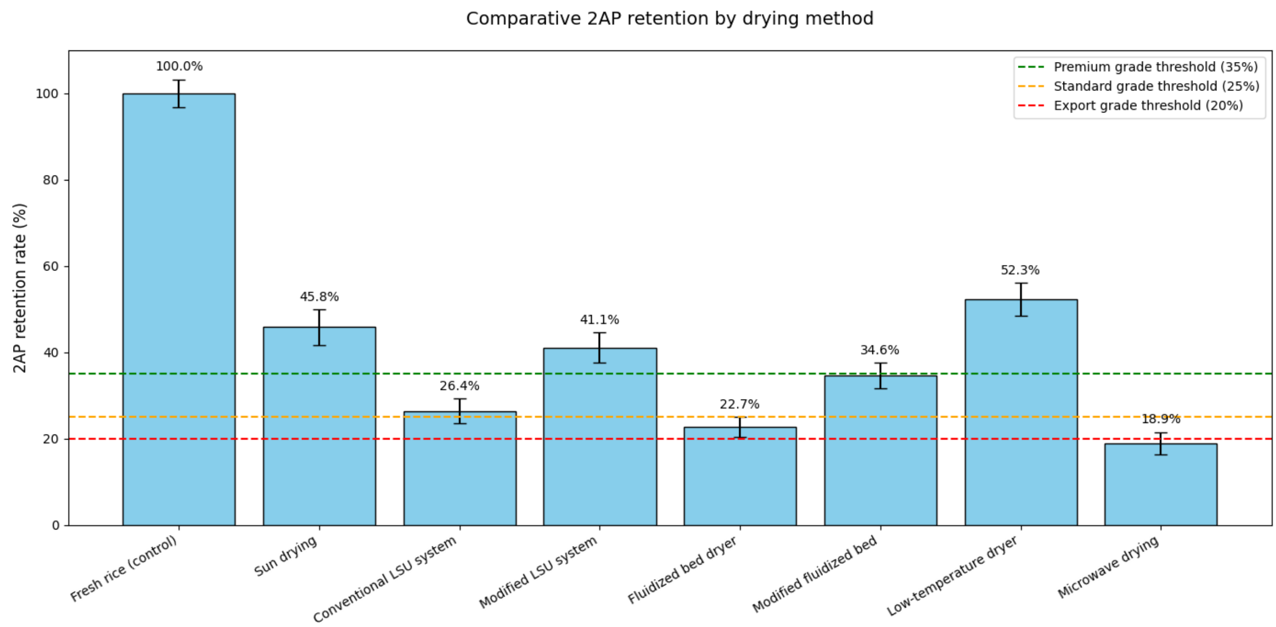


Figure 11. Comparative 2AP retention by drying method.

These improvements can be attributed to the precise moisture-reduction pattern and the uniform final moisture content achieved by the modified drying protocol. As reported by Tian et al. [16], controlled drying conditions help preserve aromatic compounds and reduce lipid degradation by limiting enzymatic activity. The substantial extension of shelf life projected in this study represents a significant commercial advantage, with the potential to reduce postharvest losses and expand market opportunities for Thai aromatic rice.

Table 7. Quality assessment of rice after drying.

Quality parameter	Conventional system	Modified system	Industry standard	Improvement (%)
2AP content (μg/g)	1.35	2.14	≥1.00	58.5%
2AP retention rate (%)	26.4%	41.1%	≥25%	55.7%
Head rice yield (%)	58.4%	64.7%	≥55%	10.8%
Whiteness (L* value)	62.8	64.2	≥60	2.2%
Hardness (N)	28.5	31.2	25-35	9.5%
Moisture uniformity (SD)	1.42	0.87	≤1.0	38.7%
Overall sensory score (0-9)	6.8	8.2	≥7.0	20.6%

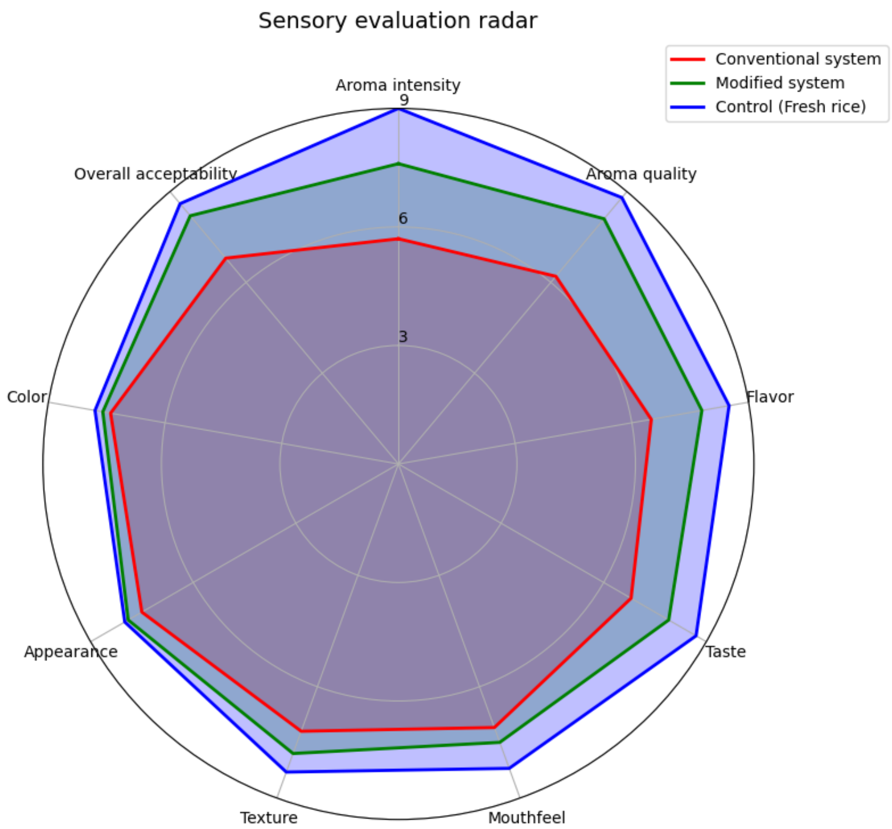


Figure 12. Sensory evaluation radar.

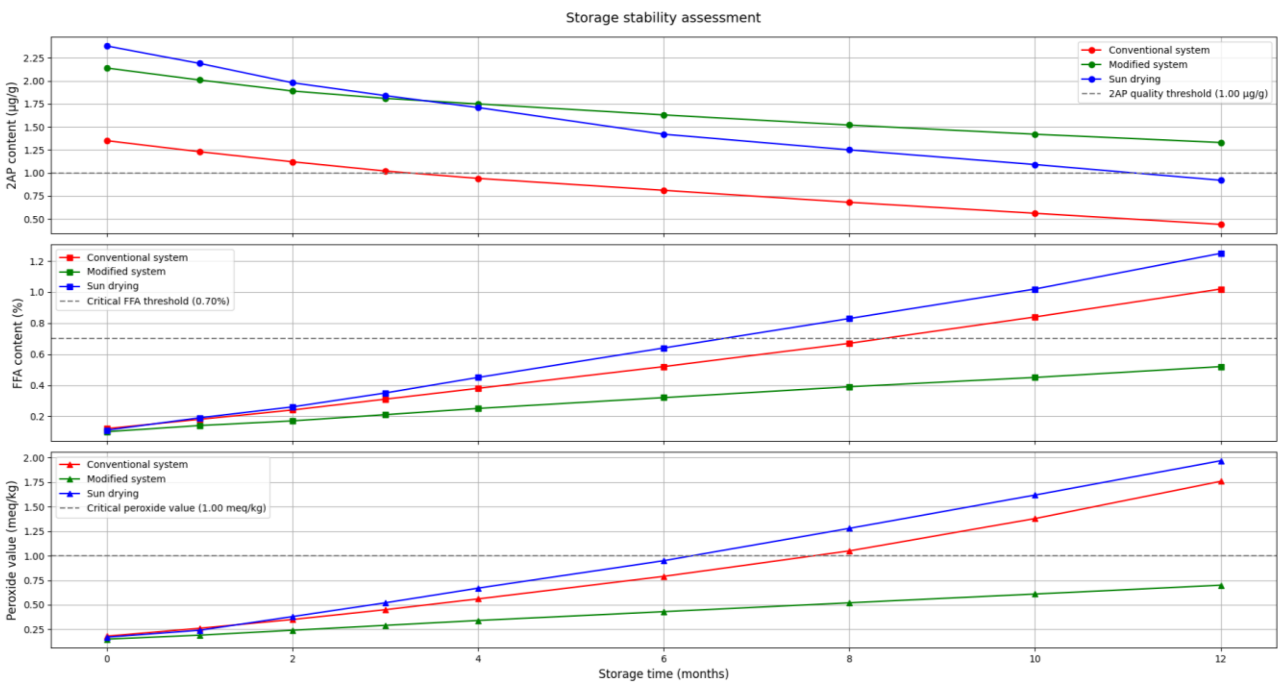


Figure 13. Storage stability assessment.

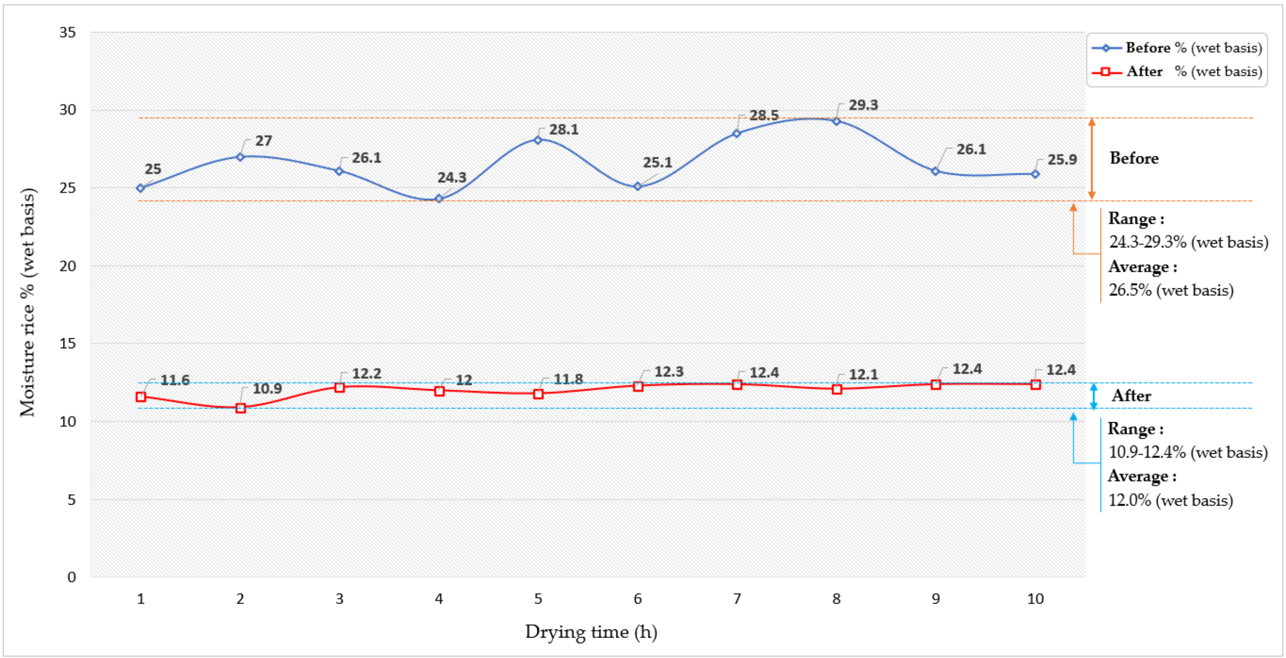


Figure 14. The relationship between the moisture of rice and drying time.

Regarding the impact of rice moisture content during drying, it was noted that before drying, moisture levels ranged from about 24.3% to 29.3%, averaging 26.5%. During certain intervals, variations were observed, for example, the moisture content rose from 25.1% at hour 6 to 28.5% at hour 7, signifying inconsistent water absorption dynamics. The drying process led to a significant reduction in moisture content, ranging from 10.8% to 12.4% with an average of 12.0%. These results demonstrate how effective the drying method was in reducing rice moisture content over 10 hours. (Figure 14) depicts the comparative moisture trends throughout the drying period.

3.4 Commercial Implementation Considerations

The analysis of 2AP concentrations revealed a clear link between the drying process and the compound's behavior. Before drying, the levels of 2AP ranged from 4.92 µg/g to 5.59 µg/g, with a mean of 5.21 µg/g. The relatively high values suggest that freshly harvested rice possesses a considerable aromatic potential. After drying, the 2AP concentration ranged from 1.83 µg/g to 2.67 µg/g, averaging 2.14 µg/g. The noted decrease in 2AP suggests that the drying process may contribute to the compound's partial loss or transformation. It is worth noting that the highest 2AP value after drying, 2.67 µg/g, was observed at a final moisture content of 12.4%. This suggests that certain drying conditions may help preserve more of the aroma. Overall, the data show that drying significantly affects 2AP levels, and it is crucial to optimize drying conditions to maintain rice's aromatic quality. 2AP concentration trends during the 10-hour drying period are depicted in Figure 15.

Table 8. Scalability and economic analysis of modified LSU systems.

Parameter	Small-scale (<10 tons/day)	Medium-scale (10-50 tons/day)	Large-scale (>50 tons/day)
Initial investment (THB)	850,000-1,200,000	2,800,000-4,500,000	6,500,000-9,800,000
Installation timeframe (days)	15-25	30-45	60-90
Energy savings (%)	28-32%	35-39%	40-45%
Operating cost reduction (THB/year)	420,000-680,000	2,100,000-3,800,000	5,200,000-12,400,000
Payback period (months)	18-22	14-16	12-15
5-year ROI (%)	210-260%	290-350%	380-450%
Quality premium potential (%)	8-12%	12-18%	15-22%

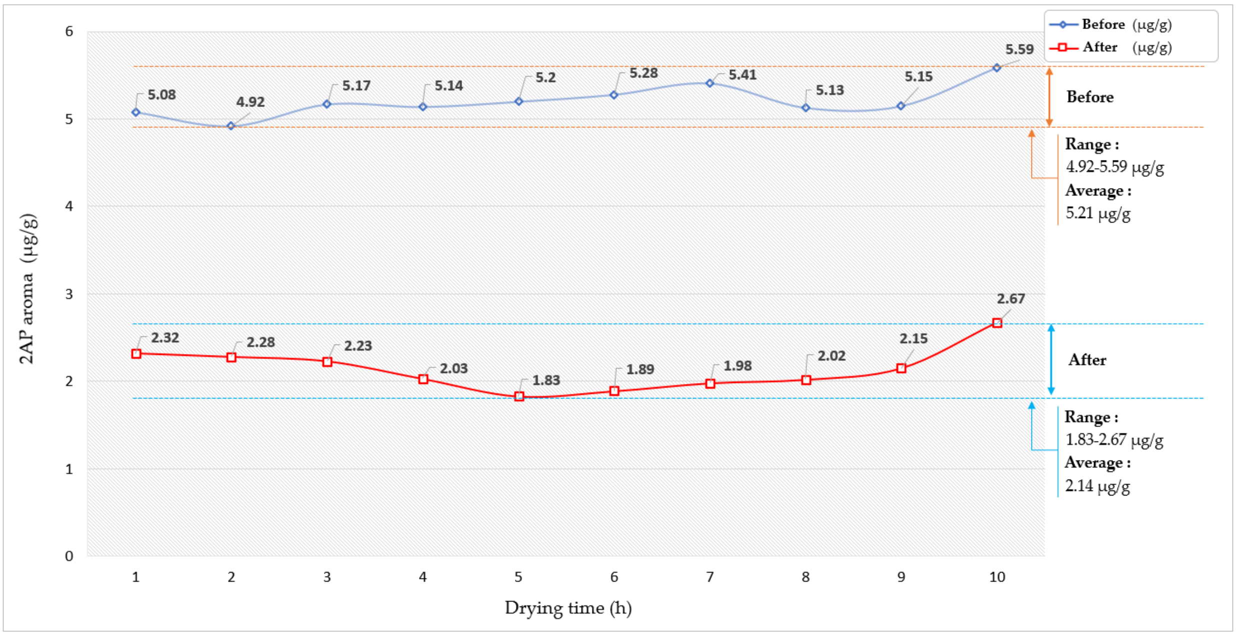


Figure 15. The relationship between 2AP aroma and drying time.

Regarding the effect of rice temperature on 2AP aroma, it was observed that before drying, a slight positive correlation existed between rice temperature and 2AP concentration. Higher temperatures were associated with a slight increase in aroma levels. The highest 2AP concentration, recorded at 39.5°C, was 5.59 µg/g. This suggests that rice temperature may affect the release of 2AP. This effect, however, seemed rather mild during the pre-drying phase. Throughout this timeframe, temperatures fluctuated between about 30.8°C and 39.5°C, averaging at 33.1°C. After drying, the effect of temperature on the 2AP aroma was accentuated. The release of 2AP was significantly enhanced by drying, with the highest concentration measured post-drying being 2.67 µg/g at 38.4°C. This indicates that drying is crucial for promoting the release of 2AP at high temperatures. Rice temperatures in the post-drying phase varied from 36.7°C to 39.2°C, averaging at 37.8°C. (Figure 16) illustrates the detailed variation in rice temperature during the 10-hour drying period.

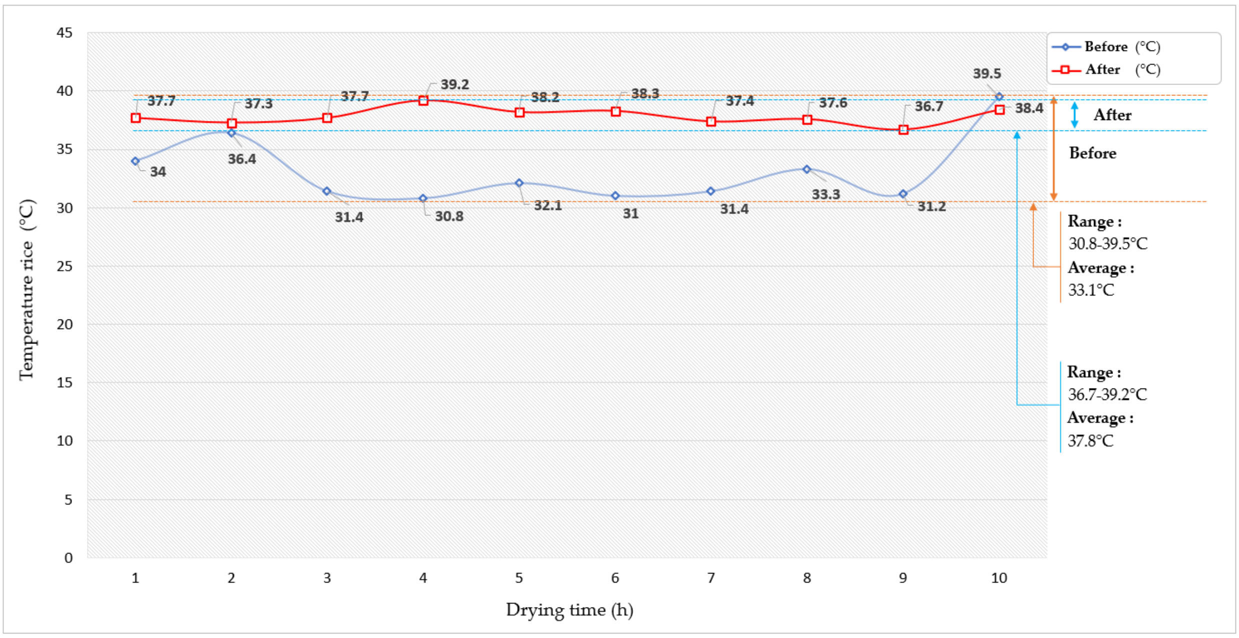


Figure 16. The relationship between temperature and rice drying time.

The performance of the modified LSU drying system was scalable across various production capacities (Table 8). The analysis of implementation uncovered the need for adaptations tailored to individual facilities, with the complexity of these adaptations growing in direct relation to scale. According to Nimmol [27], large-scale operations (>50 tons/day) achieved the greatest efficiency gains (40-45%), but compared with small-scale facilities, they required more significant alterations. Scaling factors specific to components showed that complexity varied across facility configurations (Figure 17). Airflow regulation systems faced the greatest scaling challenges during continuous operations, whereas temperature control systems showed relatively stable implementation parameters across different scales. This is consistent with the findings of Fungpongpan et al. [22] concerning the dimensional scaling of thermal management systems. Meesukchaosumran and Chitsomboon [19] observed that the duration of implementation varies significantly depending on the facility configuration, with timelines ranging from 2-3 months for small-scale operations to 5-8 months for large-scale continuous systems. This study's modular approach enables a phased implementation that minimizes operational disruption and realizes 60-75% of the efficiency benefits during transitional periods.

The economic analysis showed that investment parameters are favorable across all production scales, with larger operations benefiting from economies of scale that yield increased returns. Small-scale facilities (less than 10 tons/day) necessitated initial investments ranging from 850,000 to 1,200,000 THB and had payback periods of 18-22 months. In contrast, large-scale operations achieved payback in 12-15 months despite their higher initial investments (6,500,000-9,800,000 THB). Calculations of ROI indicated considerable variation based on scale, with percentages ranging from 210-260% for small facilities and 380-450% for large operations over five years. These results are consistent with the economic forecasts of Jittanit et al. [8], who observed that investments in process optimization usually yield scale-dependent returns in agricultural processing. Quality premiums provide a significant extra advantage, especially for medium- and large-scale producers, with possible price hikes of 12-22% for optimally dried aromatic rice. As noted by Laohakunjit and Noomhorm [3], the market premiums for high-quality aromatic rice often surpass the cost difference associated with enhanced processing techniques, thereby bolstering the economic justification for altering the system.

As illustrated in Table 9, the intricacy of integration varied significantly by facility type; continuous systems posed greater implementation challenges than batch operations. The most intricate integration aspects involved upgrading cyclone furnaces and modifying ducting, especially in expansive, continuous facilities, where Treeamnuk et al. [12] noted possible synchronization difficulties. The implementation pathway decision tree (Figure 17) provided structured guidance for facility-specific modifications, including critical assessment checkpoints to verify performance at each implementation stage. This method is in accordance with the advice of Phetnamkhiew et al. [18] regarding the gradual implementation of process changes in commercial rice mills. For facilities with particular limitations, alternative implementation pathways were devised. The phased implementation over 12 to 18 months has been shown to be feasible for operations with budget constraints, whereas installation on weekends and holidays meets the needs of facilities that must operate continuously. Kaensup et al. [13] noted that flexible implementation methods are crucial for the commercial adoption of enhanced drying technologies in areas with limited processing capacity.

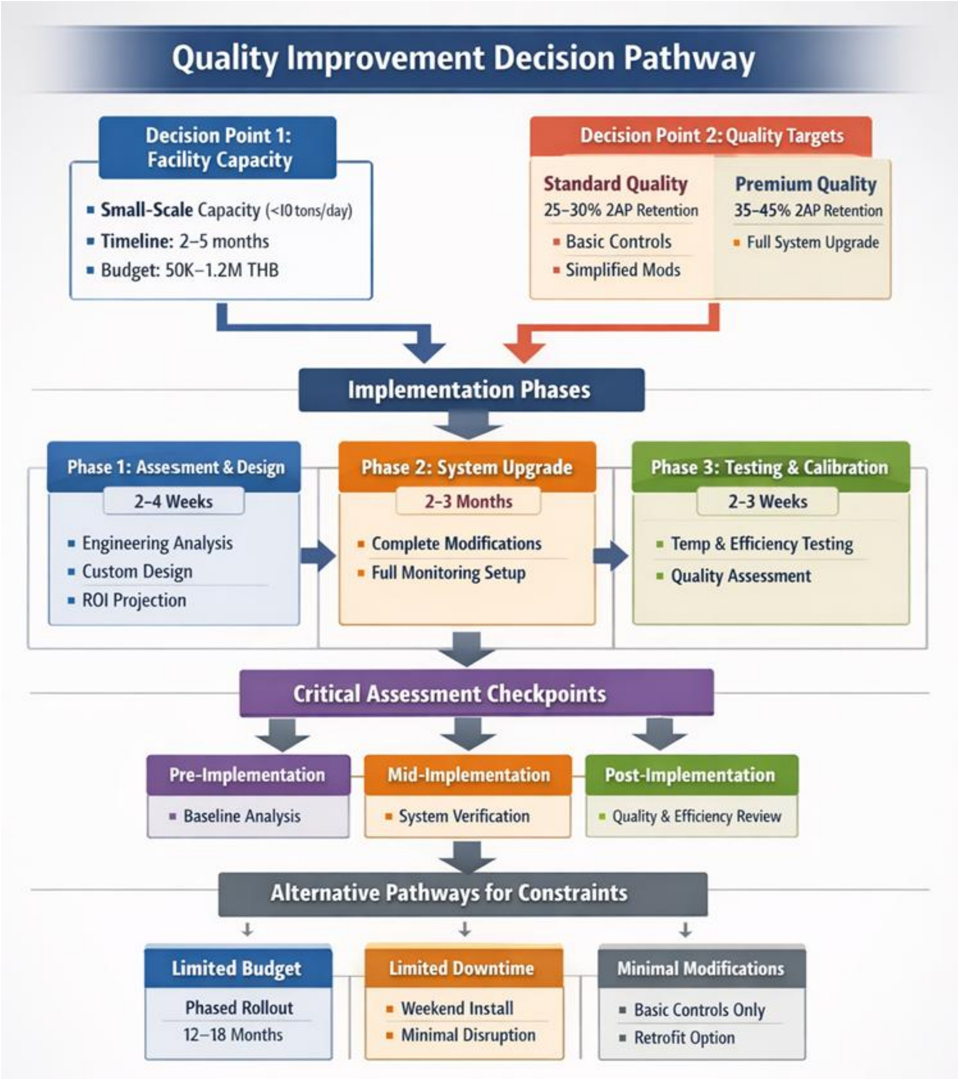


Figure 17. Implementation pathway decision tree.

The integration requirements are linked to different kinds of thermal processing facilities, categorized by operational mode (batch vs. continuous) and capacity scale (small, medium, or large). The matrix evaluates six essential elements of system modification-cyclone furnace upgrades, temperature sensors, airflow regulators, paddle mixers, control systems, and ducting modifications- across various types of facilities. Every integration scenario is assessed for complexity using a four-tier scale: low, medium, high, and very high. These ratings take into account the difficulty of installation, anticipated operational disruption, and necessary downtime, which can vary from minimal (1-3 days) to extensive (over 14 days). Generally, small- to medium-batch facilities are of lower to moderate complexity, whereas large-batch and continuous systems, especially at higher capacities, encounter greater difficulties due to their scale and interdependence. Upgrading cyclone furnaces and control systems in large continuous operations is generally deemed "very high" in complexity due to the necessity for significant reconfigurations and extended shutdowns.

On the other hand, less complex upgrades, such as adding temperature sensors or making duct modifications, are classified as "low" complexity in small-batch facilities. Additionally, the figure highlights major integration challenges specific to each facility type. Facilities that operate on small batches often face space and cost constraints. It is necessary to carefully balance throughput and product quality in medium-batch systems, whereas large-batch setups must address complexities in heat distribution and material handling. In continuous systems, small facilities are susceptible to disruptions in the control system; medium-sized operations face challenges in maintaining airflow and throughput; and large continuous facilities have trouble synchronizing complex systems during retrofits. This matrix framework serves as a clear reference for evaluating upgrade feasibility and anticipating integration challenges across various thermal processing environments.

Table 9. Matrix of facility types and modification components.

Modification component	Small batch	Medium batch	Large batch	Small continuous	Medium continuous	Large continuous
Cyclone furnace upgrade	Medium	Medium	High	Medium	High	Very high
Temperature sensors	Low	Medium	Medium	Low	Medium	High
Airflow regulators	Low	Medium	Medium	Medium	High	Very high
Paddle mixer	Medium	High	High	Low	Medium	High
Control systems	Medium	Medium	High	High	Very high	Very high
Ducting modifications	Low	Medium	High	Medium	High	Very high

4. Conclusions

This research demonstrated that optimized two-stage drying protocols in modified LSU systems can significantly enhance aromatic rice quality while reducing energy consumption. The optimal parameters identified include a temperature range of 36.7-38.0°C, gradual moisture reduction to 12.0-12.4%, and extended tempering periods. These parameters achieved 41.1% 2AP retention compared to 26.4% in conventional systems, while reducing energy consumption by 37.3% and carbon emissions by 5,334 kg CO_2 per day. Clear trade-offs emerged between processing parameters. Higher temperatures accelerated drying but degraded aroma compounds, while longer tempering periods improved quality but reduced daily throughput. The optimal balance was achieved through a two-phase approach: initial gentle drying followed by precisely controlled final moisture reduction. For industry adoption, we recommend: (1) phased implementation starting with temperature control systems; (2) staff training emphasizing the critical relationship between thermal management and product quality; (3) regular calibration of monitoring systems to maintain optimal conditions; and (4) quality-based pricing structures to capture premium market opportunities. Future research should focus on: (1) developing real-time 2AP monitoring technologies for dynamic process control; (2) investigating non-thermal drying alternatives such as low-pressure systems; (3) optimizing protocols for different rice varieties with varying aromatic profiles; and (4) exploring the potential of renewable energy integration to reduce carbon footprint further. This study establishes that economic and environmental benefits can be achieved simultaneously with quality improvements, offering a compelling case for industry-wide adoption of optimized drying protocols in aromatic rice processing.

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Conflicts of Interest: The authors declare that there are no conflicts of interest.

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