



Factors Influencing the Incorporation of 2AP in Fluidized Bed Drying Processes

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Citation:

Khomkaew, S., Kongkhon, P., Srirugsa, T., Chuchit, T., Su-hren, W., Kaewpoung, S., factors influencing the incorporation of 2AP in fluidized bed drying processes. *ASEAN J. Sci. Tech. Report.* **2026**, 29(6), e262149. <https://doi.org/10.55164/ajstr.v29i6.262149>

Article history:

Received: October 31, 2025

Revised: April 26, 2026

Accepted: April 30, 2026

Available online: May 10, 2026

Publisher's Note:

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Abstract: Drying high-moisture paddy rice while retaining the quality of the grains and their natural aroma is one of the hardest things to perform in industrial processing. This study examines a hybrid drying system comprising drying units from Louisiana State University (LSU), a fluidized bed dryer, and a cyclone-based hot-air generator to reduce paddy moisture content from 25–30% to the safe storage level of 14% on a wet-basis. The cyclone furnace heated the air to 280°C using leftover charcoal. Before entering the fluidized bed dryer, the air was cooled to 101.7 °C. The grain's temperature was kept below 57.7 °C during this time, which helped preserve the rice's quality. After the rice had dried out a bit, it was put in six LSU (Louisiana State University) drying chambers. Each chamber could hold 37.5 tons of rubbish every hour and worked in groups for 10 hours. The procedure worked well to lower the moisture level in a single step, even when it reached 18%. By eliminating the middle resting stage, the drying process is easier and faster without affecting the final product's quality. The dried rice had 10.7% moisture, a grain temperature of 36.9°C, and 4.15 µg/g of 2-acetyl-1-pyrroline (2AP). This means that the rice still smelled good. These results show that using fluidized bed drying with LSU drying is a good approach to make large-scale commercial drying systems work better and be simpler while maintaining excellent rice quality.

Keywords: 2AP; fluidized bed; unpolished rice; rice mill; KDML 105

1. Introduction

Rice is an essential crop for Thailand's farming and cooking industries. People in both local and international markets really like fragrant rice because of its aroma, taste, and milling. But after harvest, paddy rice is often 20-30% wet (wet base). This is not a good way to store grain for a long time, as it can cause it to rot, mold, and lose its physical and chemical properties. It is vital for storage and industrial processing to reduce the moisture content of paddy rice to about 14% (wet basis) [1-2]. There are many ways to dry paddy rice, including hot-air drying, fluidized-bed drying, impinging-stream drying, and intermittent drying and tempering. There are good and bad things about each method. Intermittent drying has become very popular because it helps reduce the stress in grains caused by rapid temperature changes. This reduces the likelihood of grain shattering and improves milling quality [3]. On the other hand, fluidized bed drying offers the advantage of quick heat and mass transmission. Maintaining

the minimum air speed and grain layer height can speed up the drying process and improve its effectiveness at removing moisture [4]. The impinging-stream drying method with circulating hot air may also make the system much more energy efficient and reduce heat loss [5].

The smell is one of the most important parts of fragrant rice. The main volatile chemical responsible for Thai fragrant rice's characteristic smell is 2AP. This is especially true for Jasmine rice and Pathum Thani fragrant rice [6]. Champagne et al. [7] and Wongpornchai et al. [8] performed studies demonstrating that drying conditions, specifically the final temperature and humidity, had a direct and significant impact on the loss of 2AP and the aromatic quality of rice. The level of 2AP in rice can change depending on the type of rice, where it was grown, how it was harvested, how it was dried, and how it was stored [9]. If not done correctly, using high temperatures to speed up the drying process and reduce production time can harm grain quality. For instance, it can produce cracks, reduce head rice yield, and lower sensory quality, especially in heat-sensitive aromatic rice varieties [10-12]. Thus, tempering is used to reduce differences in moisture content within the grain, relieve thermal stress, and even out moisture distribution throughout the grain. This results in less fissuring and better milling quality [13-14].

Additionally, studies on rice quality reveal that processing technology profoundly affects the physical structure and commercial quality of rice, especially concerning grain characteristics, milling, and the preservation of aromatic compounds [15]. Soponronnarit [16] explained that managing energy throughout the grain drying process is very important for both system efficiency and production costs. This aligns with the modern approach to drying technology development, which focuses on product quality and energy efficiency. Mahatheeranont et al. [17] conclusively validated the quantification of 2AP concentration in Thai jasmine rice, while Wongpornchai et al. [18] established that the drying procedure and storage time significantly affected changes in aroma and milling quality of rice. Champagne [19] demonstrated that the aroma and flavor of rice are crucial for both market value and consumer acceptance, particularly for high-quality fragrant rice. Imran et al. [20] also noted that the Maillard reaction and temperature are particularly crucial for how 2AP accumulates and degrades in a simulated system. Buttery et al. [21] and Jesussek et al. [22] concurred that 2AP is the principal molecule responsible for the aroma of cooked and brown rice.

There have been improvements in the ways items are tempered and dried in between. These devices use AI models and data analysis to find the best way to dry things [23]. They also use advanced tools such as near-infrared spectroscopy, X-ray diffraction, and scanning electron microscopy to assess how well seeds perform in terms of their physical and structural properties [24]. Also, looking at how much energy continuous and intermittent drying uses has shown that improving the process can save significant energy and help the system run more efficiently as a whole [25]. A survey of the literature revealed that numerous studies have examined the impacts of drying temperature, grain resting, and various drying procedures on rice quality. However, there are constraints on extrapolating these findings to an industrial-scale hybrid drying system that integrates high-rate drying with a fluidized bed and an LSU drying system, particularly regarding the correlation among energy management, final moisture content, and 2AP retention in Thai fragrant rice. This study aims to assess the efficacy of a hybrid drying system comprising a cyclone furnace, a fluidized bed dryer, and an LSU drying system in examining the impact of drying conditions on moisture reduction, temperature regulation, and aroma preservation in rice. The goal was to find a way to dry things that would make the process easier, use less energy, and maintain product quality high enough for industrial use.

2. Theoretical Calculations

The Headspace Comprehensive Two-Dimensional Gas Chromatography Time-of-Flight Mass Spectrometry (HS-GCxGC-TOFMS) technique was used to analyze the fragrance components in brown rice. A TissueLyser II machine was used to grind the rice into a powder to prepare the samples. To allow the fragrance components to volatilize, 1 g of the rice powder sample was weighed and placed in a tightly sealed bottle at room temperature for at least 12 hours. The Headspace Comprehensive Two-Dimensional Gas Chromatography with Time-of-Flight Mass Spectrometer (HS-GCxGC-TOFMS, LECO) was then used to examine the samples for the composition of scent compounds [15], [37-38]. The standard moisture content on a wet basis (w.b.) is the ratio of the material's total quantity to its moisture or water content. Dry mass [16],

[31-33] and moisture content are the two main components used in its computation, as shown by equation (1). The ratio of a material's moisture content to its dry quantity, as shown in equation (2), is known as the standard moisture content on a dry basis (db.).

$$M_w = \frac{W_w}{W} = \frac{W - W_d}{W} \quad (1)$$

$$M_d = \frac{W_w}{W_d} = \frac{W - W_d}{W_d} \quad (2)$$

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)

In theoretical research, moisture content on a dry basis is frequently used. It is frequently contrasted with the constant value, W_d , which denotes the amount of heat that the heating system transfers to the air. According to equation (3), this number is equivalent to the difference in the enthalpy of the entering air [34-36].

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

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}°C)

C_v is the specific heat of steam (kJ/kg_{water}°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)

Psychrometrics is used to calculate the heat quantity of the air heating system. Equation (4) allows us to determine the amount of heat required for the material's water to evaporate while taking the drying chamber into account [26-28].

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

When Q_{evap} does water 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 quantity can be determined using equation (5) to raise the drying material's temperature from its initial temperature to its final temperature outside the drying oven [29-30].

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

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)

Before drying, the average aroma strength and the fluctuation of 2AP concentration in paddy rice were assessed using preliminary statistical analysis. With a sample size (n) of 12, basic statistical parameters were computed. The median value was 3.35 µg/g, the range was 2.82 µg/g, the maximum was 5.49 µg/g, and the minimum was 2.67 µg/g. There was a standard deviation of almost 0.79 µg/g. Equation (6) was used to calculate the mean value.

$$\bar{x} = n \sum x_i = 123.36 + 4.69 + \dots + 5.49 \approx 3.68 \left(\frac{\mu g}{g} \right) \quad (6)$$

The levels of 2AP detectable by human perception can be divided into four categories based on the interpretation of the 2AP concentration in relation to the perceived intensity of fragrance: Very low (<0.5 µg/g; possibly non-fragrant or slightly fragrant), low (0.5–0.8 µg/g), moderate (0.8–1.2 µg/g), and high (> 1.2 µg/g). The average 2AP content, according to the results, was 3.68 µg/g, which is much greater than 1.2 µg/g. This suggests that the paddy rice samples had a very strong smell before drying. All measured values were over all established scent criteria, with a distribution ranging from 2.67 to 5.49 µg/g. The samples' smell intensity varies moderately, according to the standard deviation (~0.79 µg/g). Numerous factors, including rice type, growing conditions, environmental factors, and harvest timing, may be responsible for this variation.

2. Materials and Methods

2.1 Paddy Rice Drying and Aroma Evaluation

For the experimental study, 10 paddy rice samples were collected from a nearby rice mill. Each sample's baseline condition was established by measuring its initial moisture content before drying. A sensory sniff test was used to assess aroma intensity in advance, and analytical methods were used to quantify 2AP, the primary ingredient that gives fragrant rice its distinctive scent. The same parameters were re-evaluated after the drying process. Moisture content, 2AP concentration re-quantification, and a repeated sniff test to assess any alterations in scent quality were among the post-drying measurements. To evaluate the effect of the drying process on rice quality and aroma characteristics, all collected data were statistically analyzed, including mean values and standard deviations, and then compared between pre-drying and post-drying sample groups. The first step involved using Headspace Gas Chromatography to analyze the amount of the 2AP scent compound in the lab. Taking unhusked rice piles into account as a factor influencing loss of the 2AP fragrance compound, the link between the temperature of unhusked rice grains and the sample period was examined every hour over 10 hours. Before moisture reduction, the average temperature of the unhusked rice in the piles was 29.0 °C, with a range of 26.3 °C to 32.6 °C. The unhusked rice had an average moisture content of 23.9%, with a range of 21.9 to 26.1%. The unprocessed, unhusked rice samples' moisture content ranged from 13.81% to 15.25%, with an average of 14.76%, as determined by chemical analysis. The second phase involved adding the unhusked rice to the accelerated fluidized bed drying system by following the steps listed below: (1) pre-cleaner, (2) elevator, (3) dryer LSU, (4) discharge mechanism, (5) screw conveyor, (7) dryer blowers, (8) furnace, heat exchanger, combustion exhaust fan, chimney heat, husk hopper with conveyor, dust fan, fluidized bed, and (10) heat exchanger. After being dried to a maximum temperature of 57.7 °C, the

unhusked rice was run through the LSU drying cabinet system, which has a circulation design. The six drying cabinets that made up the system had the following characteristics: the first drying cabinet had a 40-ton capacity and a cabinet temperature of 31.24 °C. Drying Cabinet 2: Has a 35-ton capacity and maintains a temperature of 88.75°C. Drying Cabinet 3: 83.37 °C cabinet temperature and 35-ton capacity. The fourth drying cabinet has a 35-ton capacity and operates at 70.05 °C. Drying Cabinet 5: Has a 35-ton capacity and maintains a temperature of 60.86°C. The sixth drying cabinet can hold 35 tons and has a temperature of 37.71 °C. A picture of the drying cabinets can be found in (Figure 1-3).



Figure 1. Components of the LSU dryer (Ref.Tor Thaicha Roen Rice Mill Co., Ltd.).

2.2 Effect of Drying Temperature on 2AP Retention

Drying temperature had a significant effect on 2AP retention ($p < 0.05$). Increasing the drying air temperature resulted in a marked reduction in 2AP concentration. At higher temperatures, rapid moisture evaporation enhanced the volatilization and thermal degradation of 2AP. In contrast, moderate drying temperatures significantly improved 2AP retention, indicating that controlled thermal conditions are essential for preserving aroma quality. These findings are consistent with previous studies reporting increased 2AP degradation at elevated temperatures.



Figure 2. Components of the Fluidized bed (Ref.Tor Thaicha Roen Rice Mill Co., Ltd.).

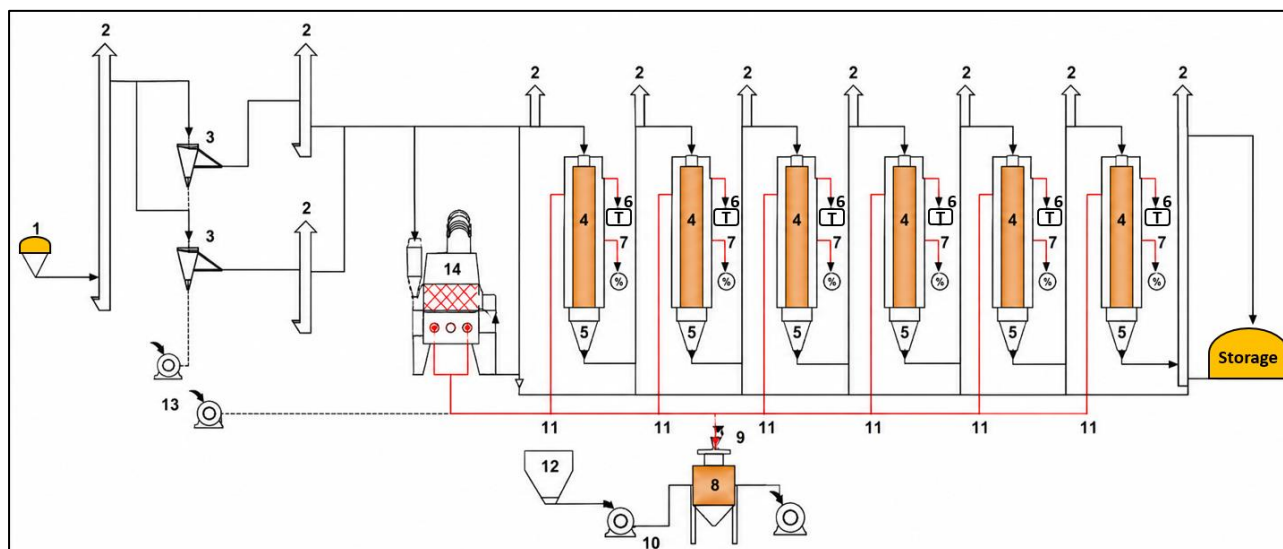


Figure 3. Model the LSU dryer in collaboration with the fluidized bed.

2.3 Effect of Air Velocity

Air velocity significantly influenced drying performance and 2AP retention ($p < 0.05$). Higher airflow rates improved heat and mass transfer, leading to faster moisture removal; however, excessive airflow increased volatile losses. An optimal air velocity range was identified, where sufficient drying efficiency was achieved without excessive loss of 2AP. This suggests that airflow control is a critical parameter in balancing drying rate and aroma preservation.

2.4 Effect of Initial Moisture Content

Initial moisture content significantly affected drying behavior and 2AP retention ($p < 0.05$). Samples with higher initial moisture content required longer drying times, increasing exposure to thermal conditions and resulting in greater aroma loss. Conversely, controlled moisture reduction during staged drying minimized thermal stress and improved 2AP retention. This highlights the importance of moisture management in multi-stage drying systems.

2.5 Performance of Integrated Drying System

The integrated fluidized bed-LSU drying system demonstrated improved performance compared to conventional drying. The system enabled rapid initial moisture reduction followed by controlled drying, resulting in enhanced 2AP retention. The final product achieved an average moisture content of 10.7% and a 2AP concentration of 4.15 $\mu\text{g/g}$. Statistical analysis confirmed that the integrated system significantly improved aroma retention compared to baseline conditions ($p < 0.05$).

3. Results and Discussion

3.1 Instrumental/Analytical Methods for Testing Jasmine Rice KDML 105 after Drying

Once dried, Thai jasmine rice (*Oryza sativa* L. cv. Khao Dawk Mali 105) and KDML105, as well as Pathumthani rice (RD15), must be evaluated for scent using exacting and sensitive analytical techniques. This is because the concentration of 2AP, a crucial volatile component that gives aromatic rice its distinctive pandan-like scent, can be significantly affected by the post-harvest drying process. The gold standard for measuring 2AP and establishing a connection between chemical composition and sensory experience is still instrumental methods, especially gas chromatography (GC) [17–18], [20]. Hot-air drying, solar drying, LSU drying, fluidized-bed drying, hybrid drying (fluidized bed plus LSU), and low-temperature drying were among the techniques used to dry 10 samples of Khao Dawk Mali 105 paddy rice. To reduce variability, the samples were equilibrated in vacuum-sealed containers for 24 hours after drying in a controlled room environment. The main approach used for the identification and measurement of 2AP was gas

chromatography–mass spectrometry (GC–MS). Extracts from headspace solid-phase microextraction (HS-SPME) were introduced into the GC apparatus, separated using polar and non-polar columns, and then identified by mass spectrometry. Calibration curves produced from internal and synthetic 2AP standards were used for quantification (Table 1) provides a summary of the 10 Khao Dawk Mali 105 samples collected at the rice mill (sampling location). The most popular approach for identifying the primary aromatic component, 2AP, which directly contributes to rice fragrance—a crucial sensory characteristic that affects quality and consumer preference—is still GC–MS. The 2AP content of paddy rice before drying is displayed in Table 1. With an average 2AP concentration of 3.68 µg/g, the paddy rice's GC-MS analysis revealed a very high level of aroma, well over the typical threshold for fragrant rice (>0.8–1.2 µg/g). These findings provide crucial baseline data for quality assurance and post-harvest process modifications, especially for drying techniques intended to preserve fragrance quality in compliance with global standards, as shown in Figure 4.

After drying, the fragrance strength of paddy rice was analyzed by GC/MS, in conjunction with olfactory (sniff) testing, to assess changes in 2AP, the main volatile compound that gives fragrant rice its distinctive aroma. The quantity of 2AP retained in the grain can be significantly affected by the drying process, an important post-harvest phase. The data include the 2AP concentration after drying and the sniff-test results, which were used to gauge aroma strength via sensory analysis. After drying, the average 2AP content (μ) was 2.24 µg/g, which is still much higher than the criterion of 1.2 µg/g. This suggests that paddy rice retained a strong smell even after drying. All measured values ranged from 2.02 to 2.87 µg/g, which is above the threshold for fragrant rice. The standard deviation (~0.27 µg/g) indicates minimal fluctuation following drying, suggesting that the drying procedure might help samples retain their aromas more consistently. A total of ten evaluations (samples no. 1–10) were conducted in the sniff test analysis (including repeated testing). After drying, the rice retained its unique scent, as confirmed by the sensory results, which agreed with the GC/MS data. The average 2AP concentration decreased by approximately 39% from 3.68 µg/g (SD = 0.79) before drying to 2.24 µg/g (SD = 0.27) after drying, as determined by comparing pre- and post-drying data. The remaining level, however, still satisfies the requirements for rice with a noticeable fragrance. After drying, the paddy rice retained a high level of scent, as indicated by combined GC/MS and sniff test analyses (mean 2.24 µg/g). Even though 2AP decreased during the drying procedure, the decline remained within a reasonable range. The drying procedure produced consistent results, as seen by the low data variability. Additionally, sensory assessments verified that the rice's powerful scent persisted after drying. These findings suggest that current drying methods can satisfactorily preserve rice aroma; however, further adjustments to drying conditions are recommended to minimize the loss of aromatic compounds.

Table 1. The rice mill lost 2AP in Thailand.

Rice Mill	Size	Rice Varieties	Volume 2AP (µg/g)		Loss 2AP (µg/g)
			Paddy Rice before drying	Paddy Rice after drying	
RM(1)	Medium	KDML 105	3.36	1.25	62.8
RM(2)	Medium	KDML 105	4.69	2.64	43.7
RM(3)	Large	RD15	3.4	2.04	40.0
RM(4)	Small	KDML 105	3.38	2.38	29.6
RM(5)	Large	KDML 105	3.27	2.41	26.3
RM(6)	Medium	RD15	3.05	2.27	25.6
RM(7)	Medium	RD15	2.67	2.02	24.3
RM(8)	Medium	RD15	3.19	2.46	22.9
RM(9)	Large	KDML 105	4.36	3.59	17.7
RM(10)	Medium	KDML 105	3.2	2.65	17.2
RM(11)	Medium	KDML 105	3.25	2.72	16.3
RM(12)	Medium	KDML 105	5.19	4.35	16.2

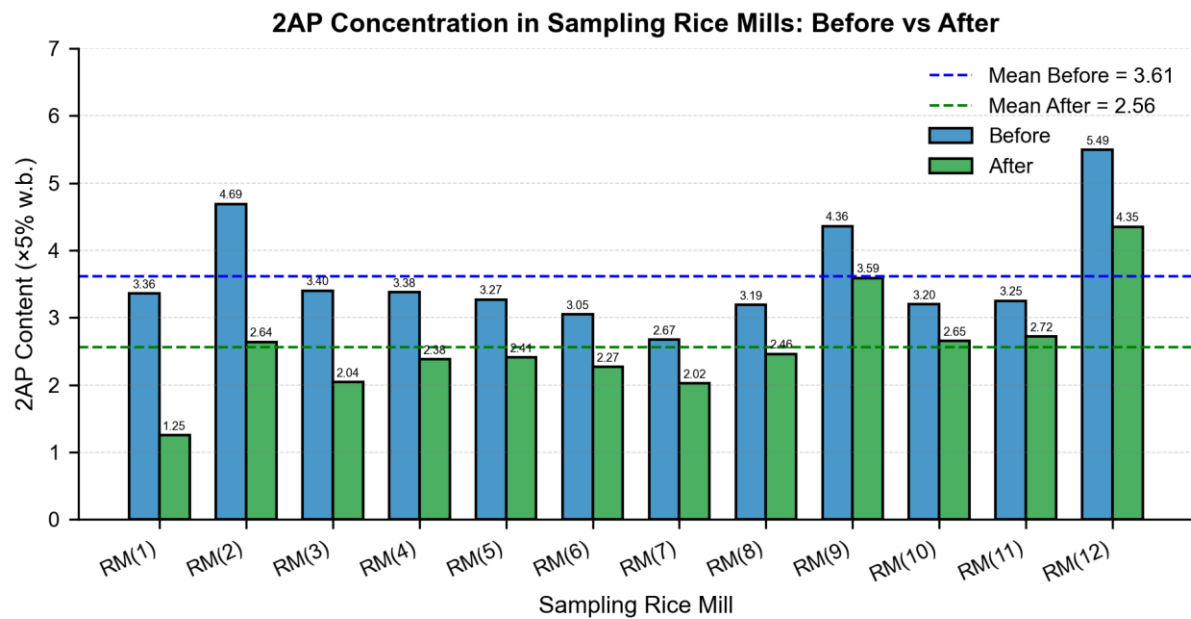


Figure 4. Sampling the rice mill with 2AP content before and after drying.

3.2 Sensory Evaluation of Jasmine Rice KDML 105 after Drying

Following post-harvest drying, sensory evaluation offers crucial information about the aromatic and quality characteristics of Jasmine rice KDML 105 (Khao Dawk Mali 105). Since 2AP is primarily responsible for this variety's distinctive scent, sensory testing complements instrumental analysis by capturing consumers' perceptions of aroma intensity, flavor, and overall acceptability. The sensory quality of rice can be affected by drying conditions, including air temperature, humidity, and drying time, which can significantly influence the preservation of volatile compounds [19], [21-22]. Rice Aroma Analysis: Before and After Drying. To ascertain variations in fragrance intensity, the scent of paddy rice was analyzed both before and after drying using sensory evaluation and 2AP quantification. One important quality factor affecting rice's market value and consumer acceptability is fragrance. 2AP is the main component that gives fragrant rice its distinctive pandan-like scent. Using gas chromatography–mass spectrometry (GC/MS) to measure 2AP and olfactory testing (Sniff Test) to gauge scent intensity via sensory perception, this study sought to investigate and compare the aroma of paddy rice before and after drying. Before drying, the average 2AP content was 3.68 $\mu\text{g/g}$, with a range of 2.67 to 5.49 $\mu\text{g/g}$. This is significantly higher than the criterion for fragrant rice (>1.2 $\mu\text{g/g}$). A high level of aroma detectable by the human senses was indicated by an average sniff test score of 5.19. These findings support the results of both chemical and sensory tests, indicating that paddy rice had a very potent scent before drying. Following post-harvest drying, sensory evaluation offers crucial information about the aromatic and quality characteristics of Jasmine rice KDML 105 (Khao Dawk Mali 105). Since 2AP is primarily responsible for this variety's distinctive scent, sensory testing complements instrumental analysis by capturing consumers' perceptions of aroma intensity, flavor, and overall acceptability. The sensory quality of rice can be affected by drying conditions, including air temperature, humidity, and drying time, which can significantly influence the preservation of volatile compounds [19].

The 2AP concentration ranged from 2.02 to 2.87 $\mu\text{g/g}$, with the mean concentration dropping to 2.24 $\mu\text{g/g}$ after drying. Retained 2AP levels were significantly over the threshold for fragrant rice, and the sniff test still identified a discernible strength of aroma. According to the results, paddy rice has very good aroma quality, both chemically and perceptually, before drying. The drying process results in a moderate drop in 2AP, but the aroma remains potent and suitable for commercial use. It seems that current drying techniques improve fragrance consistency, which is advantageous for product standardization and quality control. Nevertheless, more research is advised to identify the ideal drying parameters, such as temperature, relative humidity, and time, to reduce the deterioration of aromatic compounds and maintain the highest level of fragrance quality in Figure 5.

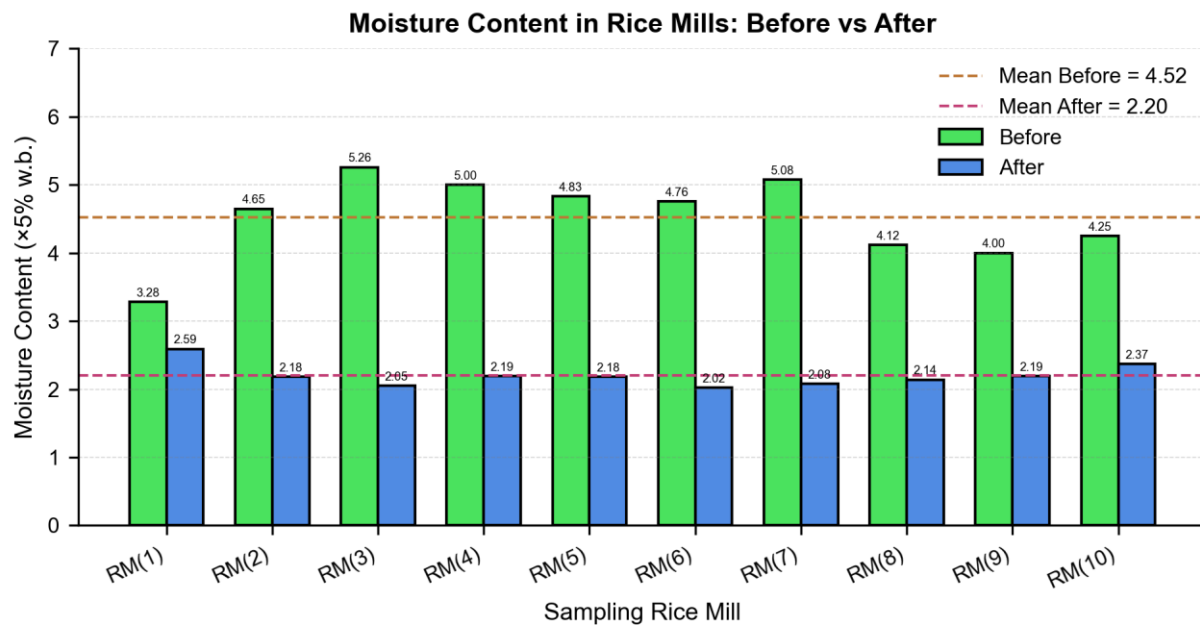


Figure 5. Sniff-test the moisture in the rice before and after drying.

3.3 Drying Via a Fluidized Bed Dryer

Evaluation of the initial physicochemical characteristics of paddy grains is crucial before the drying process begins, as these parameters are important markers of raw material conditions that directly impact drying effectiveness and the aromatic quality of fragrant rice products (Table 2). The relationship between the moisture content and grain temperature of the paddy before drying in various rice mills is depicted in Figure 6. The mills' varying environmental conditions were reflected in average temperatures of 28.97 °C and average moisture contents of 23.90% w.b. While Mills Nos. 2 and 9 displayed moisture levels above 28% w.b., Mill No. 3 had the greatest temperature (32.6 °C) and a slightly lower-than-average moisture content. These changes could lead to higher drying energy consumption and a greater chance of volatile chemical loss, especially 2AP, in later stages. The data's disarray points to irregularities in the timing of harvesting and in the processing of raw materials before drying, two crucial elements that affect the fragrant rice's ultimate scent quality.

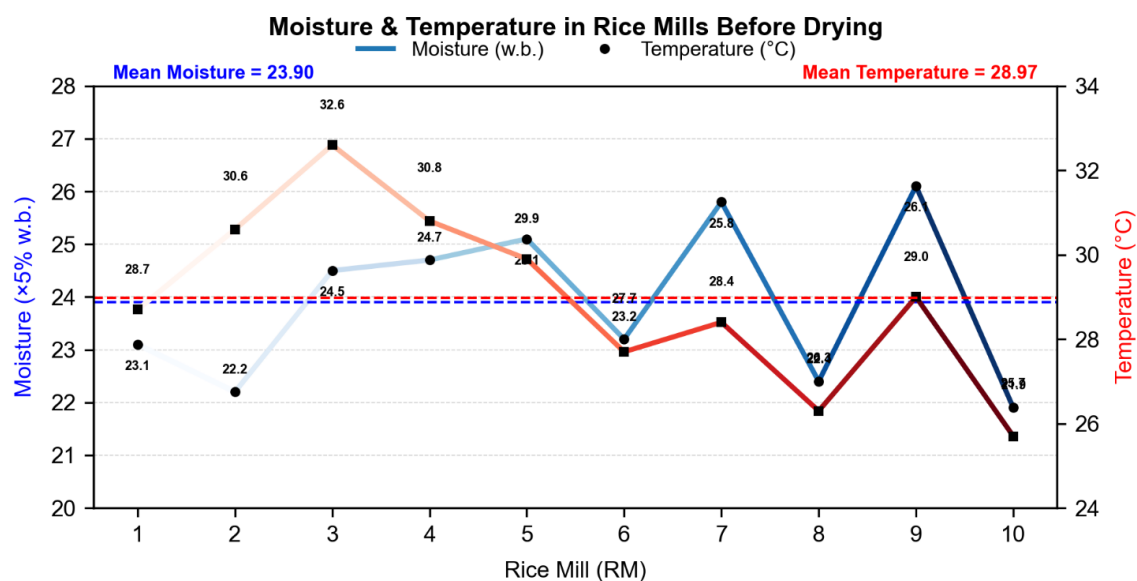
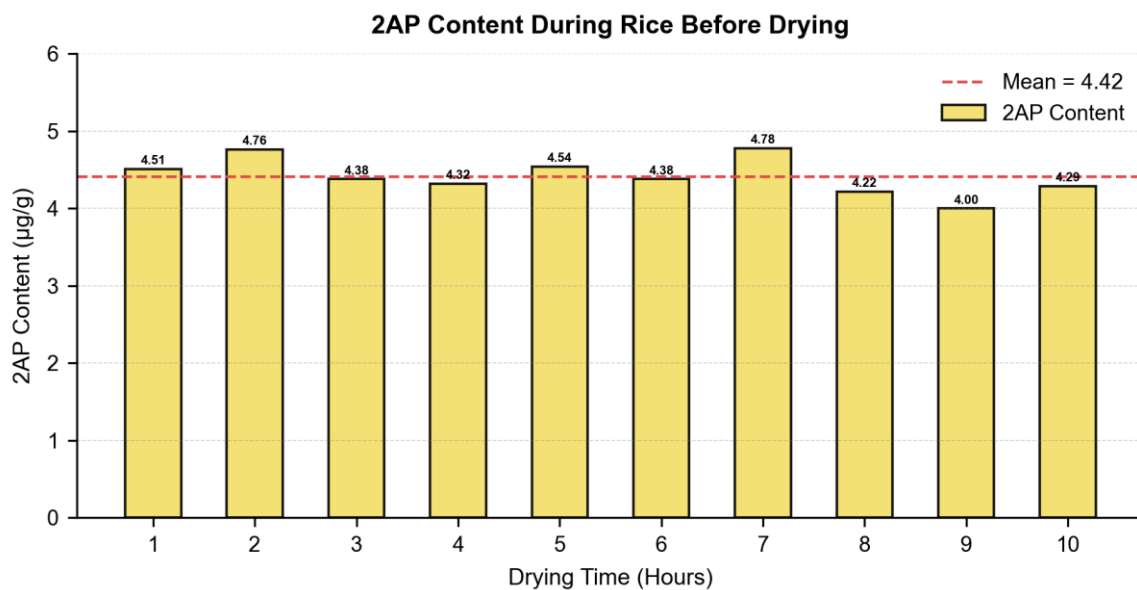


Figure 6. The relationship between the before-drying time and the moisture content and temperature of paddy.

Table 2. The impacts of rice's before moisture content, temperature, and 2AP scent before drying.

Drying Time (Hours)	Moisture (x5% w.b.)	Temperature (°C)	2AP content (µg/g)
1	23.1	28.7	4.51
2	22.2	30.6	4.76
3	24.5	32.6	4.38
4	24.7	30.8	4.32
5	25.1	29.9	4.54
6	23.2	27.7	4.38
7	25.8	28.4	4.78
8	22.4	26.3	4.22
9	26.1	29.0	4.00
10	21.9	25.7	4.29
Mean	23.90	28.97	4.42

The content of 2AP, an aromatic volatile chemical, in paddy before drying is shown in Figure 7, with an average value of 4.42 µg/g. Mill No. 9 had the lowest 2AP concentration at 4.00 µg/g, whereas Mills No. 2 and 7 had the highest contents at 4.76 and 4.78 µg/g, respectively. Some samples may contain less than 2AP due to suboptimal storage conditions or delayed harvesting, which can hasten 2AP decay. The study suggests a possible relationship between the original moisture and temperature of the grains and the pre-drying 2AP levels: paddy with higher moisture and lower temperature tended to retain a greater amount of aromatic compounds. These results are essential for determining the best drying conditions to successfully maintain the distinctive flavor and aroma of Thai fragrant rice.

**Figure 7.** The relationship between pre-drying time and 2AP aroma value.

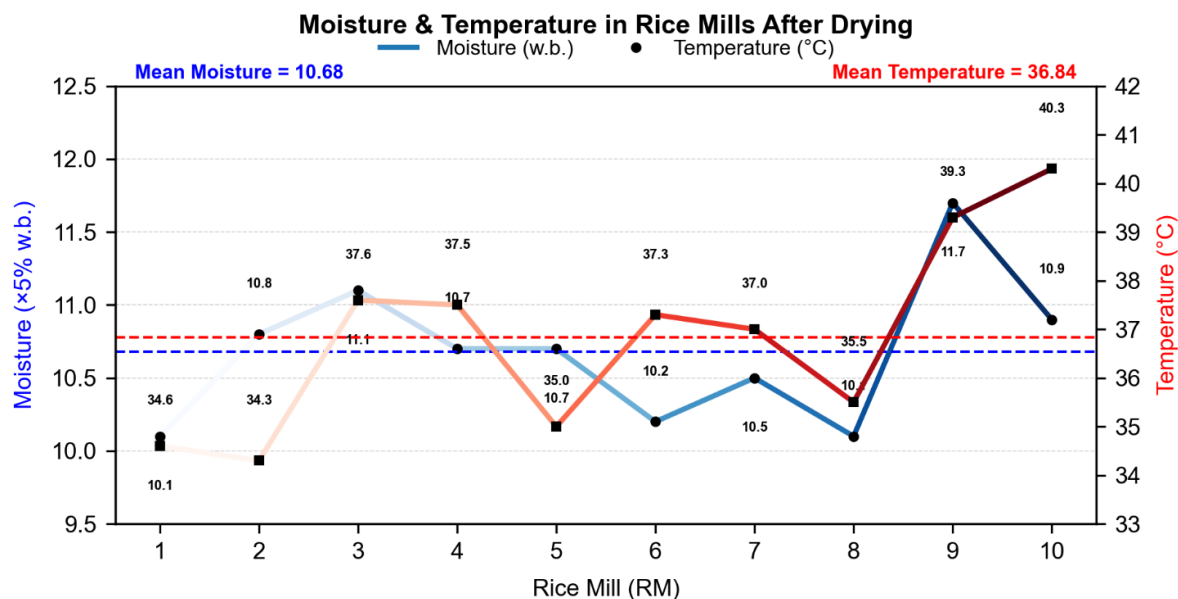


Figure 8. The relationship between after-drying time, moisture content, and paddy temperature.

Analyzing the physicochemical characteristics of paddy rice after drying is crucial for assessing drying effectiveness and its impact on the aromatic quality of Thai fragrant rice in the post-production stage. (Figure 8) shows how the paddy temperature after drying in various rice mills relates to its moisture content. The substantial heat transfer during drying was reflected in the mean temperature of 36.84 °C, which was significantly higher than the pre-drying condition, and the average post-drying moisture content of 10.68% w.b. With the maximum temperatures of 39.3 °C and 40.3 °C, respectively, as well as lower moisture levels below 11% w.b., rice mills No. 9 and No. 10 demonstrated effective water evaporation. Excessively high temperatures, however, may increase the risk of volatilization and the breakdown of important aroma components, especially 2AP, which gives aromatic rice its distinctive scent (Table 3).

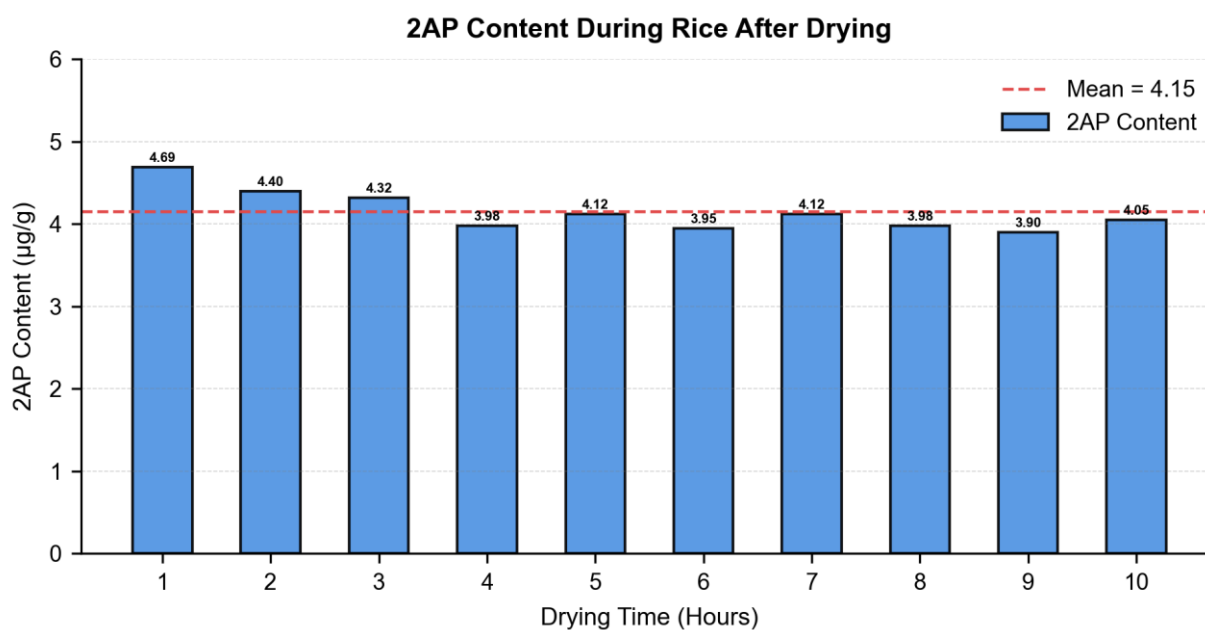


Figure 9. The relationship between after-drying time and 2AP aroma value.

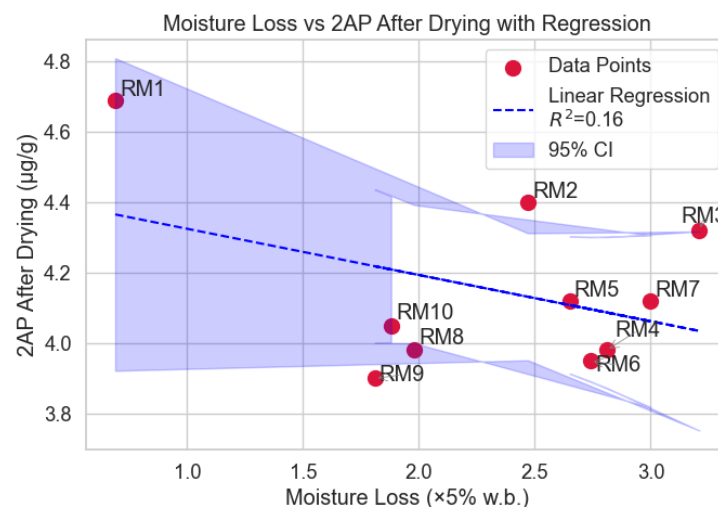
Table 3. The impacts of rice after moisture content, temperature, and 2AP scent before drying.

Drying Time (Hours)	Moisture (x5% w.b.)	Temperature (°C)	2AP content (µg/g)
1	10.1	34.6	4.69
2	10.8	34.3	4.40
3	11.1	37.6	4.32
4	10.7	37.5	3.98
5	10.7	35.0	4.12
6	10.2	37.3	3.95
7	10.5	37.0	4.12
8	10.1	35.5	3.98
9	11.7	39.3	3.90
10	10.9	40.3	4.05
Mean	10.68	36.84	4.15

The concentration of 2AP in paddy after drying is shown in Figure 9, where the average value is 4.15 µg/g, marginally lower than the pre-drying mean of 4.42 µg/g, indicating a loss of aroma compounds during the process. At 4.69 and 4.60 µg/g, respectively, rice mills No. 1 and No. 2 had the highest 2AP values, whereas mill No. 9 had the lowest value at 3.96 µg/g. According to these findings, drying temperature and moisture reduction rate are both essential factors in preserving 2AP content. Paddy that was dried at moderate temperatures and had its moisture removed gradually tended to retain more of its scent. Overall, the results highlight the importance of optimizing drying conditions to reduce the loss of volatile compounds and improve the consistency and quality of Thai fragrant rice aroma during post-harvest processing.

3.4 Effects of Drying Parameters and Economic Assessment on Rice Quality and Sustainability

The amount of 2AP during drying shows a minor negative correlation with rice moisture loss, as illustrated in Figure 10 (moisture loss vs. 2AP after drying, with regression). The linear regression line shows a weak correlation between these two variables, with 2AP content after drying tending to decrease slightly as moisture loss increases ($R^2 = 0.16$). Variations in moisture loss and 2AP retention are shown by data points from individual mills (RM1–RM10). While RM6 and RM9 show the lowest 2AP levels despite not having the maximum moisture loss, RM1 shows the highest 2AP content despite little moisture loss. Furthermore, the 95% confidence interval (95% CI), represented by the shaded blue region surrounding the regression line, emphasizes the diversity of the data and the prediction uncertainty. Moisture loss generally has little effect on 2AP reduction after drying, and maintaining the aromatic quality of jasmine rice requires careful temperature control and drying management to achieve the best possible results in both quality and drying efficiency.

**Figure 10.** Effect of moisture loss on 2AP retention after drying.

A Pareto chart of moisture loss from 10 rice mills is shown in Figure 11. The red dotted line shows the cumulative percentage, while the blue bars show the amount of moisture loss (Moisture Loss $\times 5\%$ w.b.). All samples had a total moisture loss of about 23.24 units. Approximately 13.8%, 12.9%, 12.1%, 11.8%, 11.4%, 10.6%, 8.5%, 8.1%, 7.8%, and 3.0% of the total was lost in mills No. 3 (3.21), 7 (3.00), 4 (2.81), 6 (2.74), 5 (2.65), 2 (2.47), 8 (1.98), 10 (1.88), 9 (1.81), and 1 (0.69), which had the biggest losses. The combined loss from the top five mills (Nos. 3, 7, 4, 6, and 5) was around 62%; adding mill No. 2 increased this to 72.6%; and the top nine mills made up nearly 97% of the total. The Pareto principle is reflected in this pattern, which shows that a small number of mills cause the majority of system losses. To identify underlying causes such as excessive starting grain moisture, incorrect dryer design or settings, uneven feed rates, inadequate equipment maintenance, dryer overloading, or sensor calibration issues, mills experiencing high moisture loss should undergo a thorough root-cause analysis. If temperature and drying time are not properly controlled, excessive moisture loss can also have a detrimental effect on grain quality, leading to cracking, discoloration, or a decrease in the aromatic compound 2AP. Since the top six mills (Nos. 3, 7, 4, 6, 5, and 2) together account for more than 70% of the overall loss, the Pareto principle should be used to prioritize process improvement. Along with ongoing fan and heating system performance checks, systematic monitoring of the moisture content before and after drying, drying temperature, duration, feed rate, and airflow is advised. Technical countermeasures include integrating energy recovery systems to improve energy efficiency, applying PID-based automatic temperature control, adopting staged drying or tempering procedures to prevent rapid moisture loss, and adjusting the input rate to match the dryer's capacity. Maintaining long-term gains also requires operator training on the principles of process control.

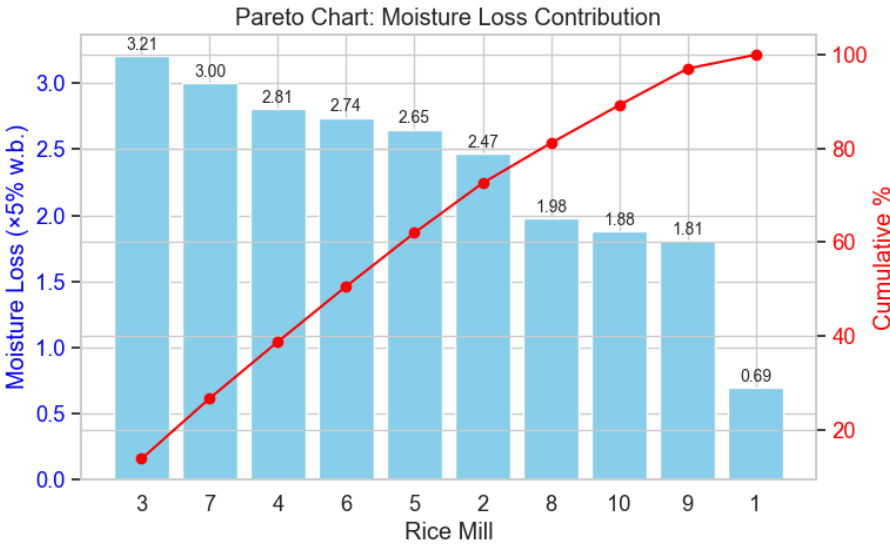


Figure 11. Pareto analysis of rice mills' contribution to moisture loss.

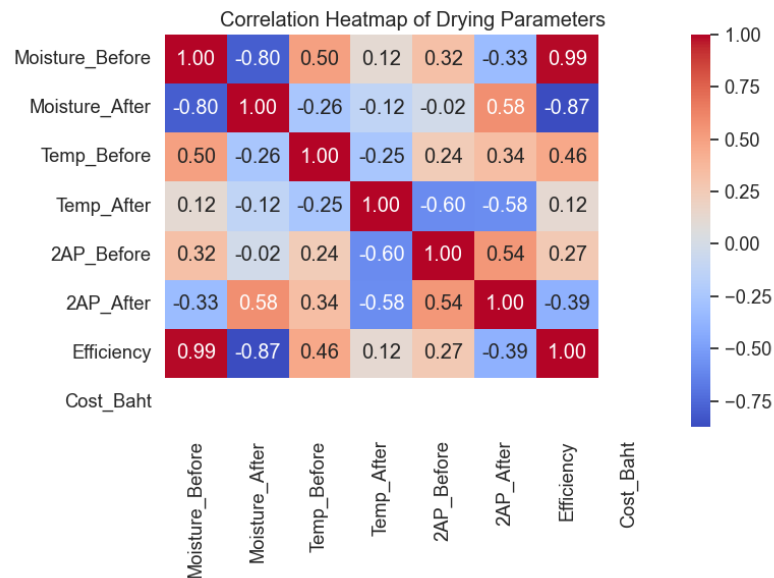


Figure 12. Analysis of the correlation among rice drying parameters.

Economically speaking, a mere 10–20% reduction in losses in the mills with the largest losses could yield substantial energy savings and productivity gains. The percentage of batches within the target moisture range, specific energy consumption (kWh/ton), moisture loss per batch, and 2AP retention are key performance indicators (KPIs) that should be used to assess continuous performance. To find the optimal balance between drying effectiveness and sensory quality preservation, future research should examine the relationship between moisture loss and rice quality traits, such as color, grain breaking, and 2AP stability. To create technically and financially optimal drying procedures, comparative studies on drying parameters, including temperature, airflow, and drying stages, are also advised. To sum up, the Pareto graphic clearly shows that a small number of mills account for the majority of overall moisture losses. The best way to reduce moisture loss, boost energy efficiency, and sustainably preserve rice quality and fragrance compounds in industrial-scale drying operations is to concentrate on these high-loss mills and allocate resources accordingly. According to the Correlation Heatmap of Drying Parameters, the analysis of correlations among rice drying parameters revealed distinct linear relationships among key drying process factors. Rice with a higher initial moisture content may be better utilized by the drying system, according to the substantial positive association found between pre-drying moisture content (moisture before) and drying efficiency (Efficiency, $r = 0.99$) in Figure 12. On the other hand, there was a significant negative connection between efficiency and post-drying moisture (moisture after) ($r = -0.87$), suggesting that increased drying efficiency is a result of greater moisture reduction.

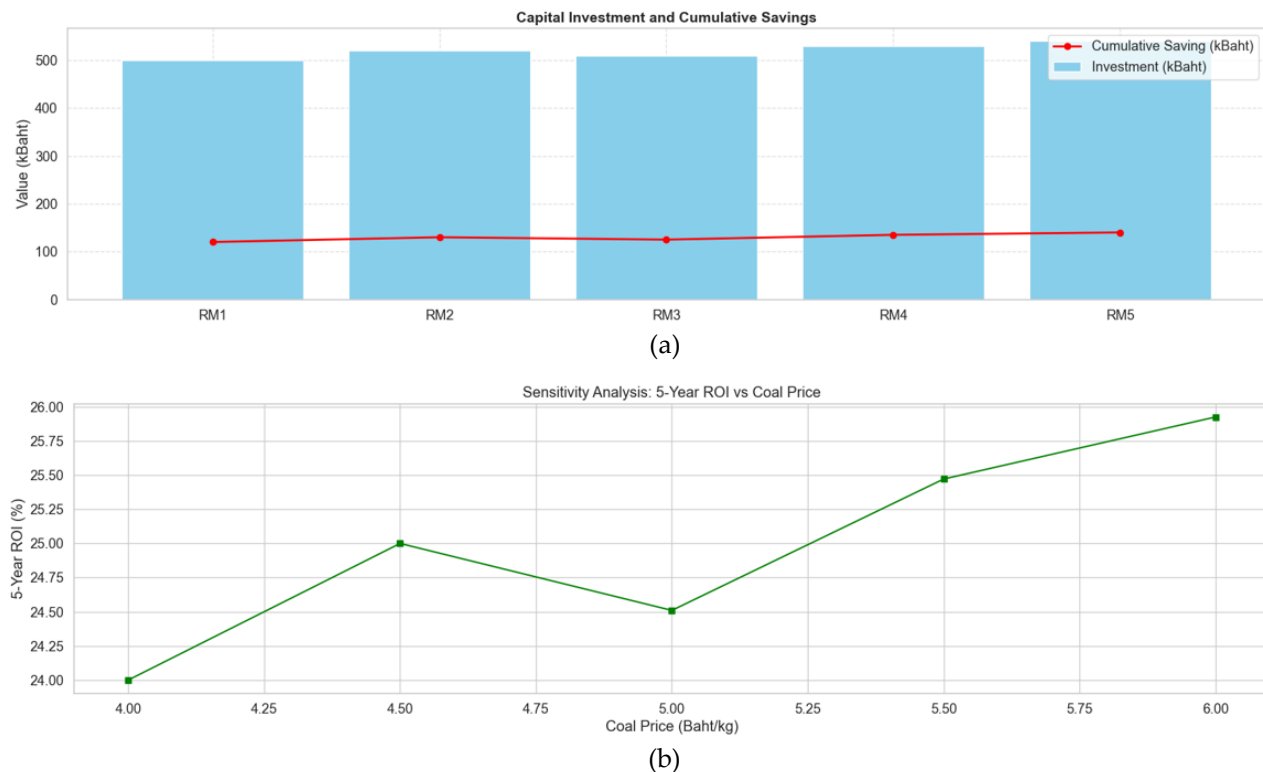


Figure 13. (a) Capital investment and cumulative savings for rice mills. (b) Sensitivity analysis: 5-year ROI vs coal price.

The initial investment and total savings for each rice mill (RM1-RM5) are shown in Figure 13. The monetary values in thousand Baht (kBaht) are displayed on the Y-axis. Even though the initial investment, shown by the blue bars, is practically the same across all mills, the cumulative savings over time, shown by the red line, exhibit a modest upward trend from RM1 to RM5. Additionally, a sensitivity analysis of the ROI over five years to coal prices is provided. The ROI tends to rise in tandem with growing coal costs, as the green line illustrates. In particular, the 5-year ROI fluctuates between 24.0% and 25.9% when coal prices range from 4.00 to 5.75 baht/kg, suggesting a favorable relationship between coal prices and investment returns. A radar chart showing the sensory assessment of the product under study in five dimensions—aroma, taste, appearance, texture, and overall—is shown in Figure 14. Taste scored about 7, while Appearance received the highest score of 9. Overall, Texture and Aroma both received about 8 points. These findings demonstrate that although the product's visual quality is excellent, its taste could use some improvement to increase overall customer satisfaction. When taken together, the two numbers provide a clear quantitative and qualitative picture of financial performance and product quality, which is helpful for investment decisions in the industrial sector and for product development.

3.5 Discussion

An LSU-type paddy dryer with a recirculating system was selected to reduce energy consumption and improve drying efficiency, given the high initial moisture content of paddy rice (about 30%). This setup was intended to boost throughput and reduce drying time. The dryer had six drying chambers, the first of which served as a forced-air, high-temperature preheating stage. Until the final moisture content reached 14%, drying was carried out with hot air entering at 101.7 °C and leaving at 57.7 °C. For almost ten hours, the average drying temperature was kept at 61.9 °C. The paddy produced met the quality requirements for Thai fragrant rice thanks to this preheating step. Particularly under high-temperature air conditions, the LSU drying system efficiently reduced the paddy's moisture content from 30% to 14% (w.b.) with exceptional uniformity and rapid drying rates by incorporating resting (tempering) times between drying cycles. A homogeneous surface moisture profile was established during each resting phase as internal moisture moved

toward the grain surface, facilitating effective, reliable removal in subsequent cycles. The drying rate was greatly accelerated by higher drying air temperatures and velocities, with temperature acting as the primary determinant. The rate of surface moisture transfer was limited at lower temperatures due to a decrease in the internal moisture diffusion coefficient, but air velocity had a greater impact at higher temperatures. As a result, at low temperatures, the drying rate was not significantly affected by excessively high air velocities.

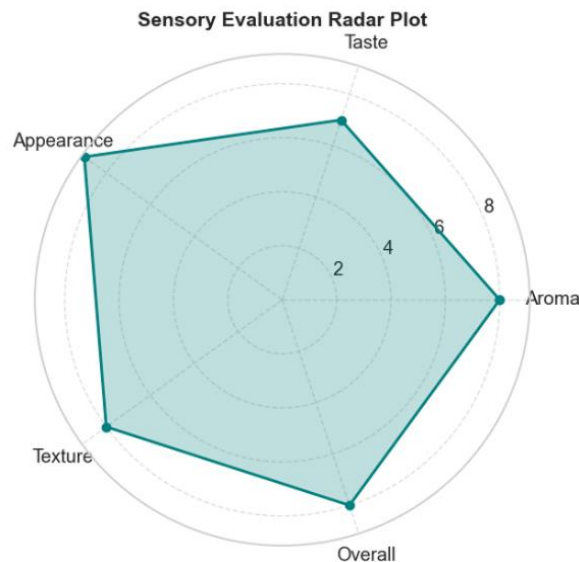


Figure 14. Sensory evaluation radar chart of the product.

Under all drying conditions, head rice yield was maintained with tempering times of more than one hour per cycle. Grain residual stress decreased following brief exposure to hot air, which reduced internal moisture gradients that quickly evaporated after repose. Compared with ambient air drying, this method produced a high head rice recovery of 55% to 60% at a final moisture content of 14% (w.b.). On the other hand, the yield of head rice was significantly reduced by continued drying. Following drying, the whiteness of the rice kernels was similar to that of the control samples. According to a sensory investigation, the main aroma constituent in jasmine rice, 2AP, had an average aroma level of 2.30 $\mu\text{g/g}$ before drying, which is considered to be fairly fragrant. After drying, 2AP concentrations averaged 4.15 $\mu\text{g/g}$, with a range of 3.90 to 4.69 $\mu\text{g/g}$. Longer rest intervals between drying cycles enhanced drying performance, but careful grain temperature control was required during these times. The internal moisture diffusion coefficient increased with higher resting temperatures, thereby affecting grain microstructure and 2AP retention.

The internal structure changed from glassy to rubbery as the grain temperature exceeded the glass transition temperature, loosening starch granules and increasing molecular mobility. Grain temperatures kept just above the transition temperature when at rest maximized diffusion, enhancing drying effectiveness and preserving scent. After drying, a sensory assessment of Jasmine rice KDML 105 provided important insights into consumer acceptance, aroma retention, and the overall effects of post-harvest drying techniques. Sensory testing, when combined with instrumental methods, provided a thorough assessment of rice quality, which is essential for breeding initiatives and post-harvest process optimization. Analytical techniques such as gas chromatography–mass spectrometry (GC–MS) in conjunction with headspace solid-phase microextraction (HS–SPME) or gas chromatography–nitrogen–phosphorus detection (GC–NPD) provided reliable, accurate quantification of aroma compounds across a range of drying conditions. A comprehensive understanding of quality variations during post-harvest processing was made possible by these instrumental data, which corroborated sensory observations. The average 2AP content decreased by approximately 39% from 3.68 $\mu\text{g/g}$ (SD = 0.79) prior to drying to 2.24 $\mu\text{g/g}$ (SD = 0.27) following drying, as indicated by a comparison of pre- and post-drying data. The main cause of this decline was the drying process's evaporation or thermal breakdown

of volatile aromatic chemicals. The residual 2AP concentration (2.24 $\mu\text{g/g}$), which is almost twice the minimum criteria for fragrant rice classification, remained noticeably aromatic despite this decrease. Additionally, the lower standard deviation (from 0.79 to 0.27) indicated that the drying procedure increased sample fragrance homogeneity, thereby enhancing product consistency. Although some aroma loss occurred, the post-drying rice retained a strong, commercially acceptable level of fragrance, as evidenced by the positive association between 2AP content and sensory fragrance intensity.

The study found that, although there are differences between mills, moisture loss during rice drying had a minor detrimental impact on the retention of the aromatic component 2AP. To maintain the rice's quality and aroma, the drying temperature and time must be carefully regulated. The majority of moisture losses are caused by a limited number of mills, according to Pareto analysis. Rice quality can be preserved, losses minimized, and energy efficiency increased through process innovations such as automated temperature control, feed rate adjustments, fan and heater performance monitoring, and operator training. Furthermore, a correlation analysis of drying parameters indicates that the initial moisture content has a positive effect on drying efficiency, whereas post-drying moisture content has a negative effect. A financial examination of mill investments demonstrated that return on investment (ROI) increases with rising coal prices, despite a sensory review of taste, aroma, sight, texture, and overall impression revealing good visual quality but inferior flavor. The initial moisture content has a beneficial effect on drying efficiency, whereas post-drying moisture has a negative effect, according to a correlation analysis of drying parameters. Although a sensory assessment of taste, fragrance, sight, texture, and overall impression revealed good visual quality but poor flavor, a financial examination of mill investments demonstrated that ROI rose as coal prices rose. These findings provide a comprehensive understanding of the relationships among process management, energy loss, investment returns, and product quality in the rice industry.

5. Conclusions

The fluidized bed–LSU hybrid drying method successfully decreased paddy moisture content while maintaining a high degree of fragrance quality. Combining short-duration, high-temperature drying with tempering (resting) phases reduced thermal stress, enhanced drying homogeneity, and restricted 2AP loss. The resulting rice exceeded international quality standards for its commercially acceptable scent level, despite a small drop in aroma components. The study concludes that intermittent tempering and controlled high-temperature drying provide the best possible balance between energy efficiency and scent preservation in Thai fragrant rice. To reduce 2AP degradation, more research should focus on fine-tuning key parameters such as temperature, humidity, and resting time. Enhancing these characteristics would promote the industrial scalability of energy-efficient drying methods and expand scientific knowledge of the mechanisms behind scent preservation. In the end, this work offers a framework for reference that may be used to improve the quality of Thailand's premium aromatic rice exports and encourage sustainable post-harvest innovations across the ASEAN region.

6. Acknowledgments

The authors would like to thank the Ministry of Agriculture and Cooperatives' Rice Department and the Agricultural Research Development Agency (Public Organization) for their significant assistance in sponsoring this study. Additionally, special thanks are given to Tor Thaicha Roen Rice Mill Co., Ltd. for providing vital information and materials that were crucial to the successful completion of this experimental investigation.

Author Contributions: At the outset, S.K., P.K., T.S., T.C., and W.S. envisioned the simulation strategy and methodology. S.K. and S.K. conducted the simulation, collected the data, analyzed the results, and came to the conclusion. The content was drafted and adjusted, generally with assistance from the authors S.K., P.K., T.S., T.C., and W.S.

Funding: Under the direction of the National Research Council of Thailand (NRCT) under the Ministry of Higher Education, Science, Research, and Innovation, the Researcher and Research for Industry Development Program (RRID) provided funding for this work.

Conflicts of Interest: The study's authors report none.

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