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Optimizing milling quality of combine-harvested paddy: The impact of pre-drying temperature and intermediate storage duration

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ABSTRACT

Combine harvesting of rice has become widespread in northern Iran, improving efficiency but creating bottlenecks in drying capacity. This often leads to delayed drying and intermediate storage of high-moisture paddy, risking quality deterioration. This study investigated the effects of pre-drying temperature and storage duration on the milling quality of Hashemi rice, a major Iranian variety. Freshly harvested paddy (~20% moisture, w.b.) was pre-dried in a recirculating dryer at 40, 50, or 60 °C to 15% moisture, then stored for 15, 30, or 45 days before undergoing final drying in a conventional batch dryer to 8.5% moisture. A factorial experiment based on a randomized complete block design (RCBD) with five replications was conducted. Results showed that both pre-drying temperature and storage duration significantly affected head rice yield (HRY) and grain fissure percentage ($p < 0.01$). Increasing the pre-drying temperature from 40 °C to 60 °C reduced HRY by approximately 2% and increased fissures by 3%. Similarly, extending storage from 15 to 45 days reduced HRY by 2.6% and increased fissures by 4.7%. Milling recovery was not significantly affected. These findings highlight that high-temperature pre-drying and prolonged intermediate storage negatively impact grain integrity. To optimize milling quality, it is recommended to use moderate pre-drying temperatures (≤40 °C) and minimize the time between pre- and final drying stages.

1. Introduction

Combine harvesting has revolutionized rice production in northern Iran, offering significant advantages in speed, labor reduction, and operational cost. However, this method generates large volumes of high-moisture paddy (>20% w.b.) that often exceed the processing capacity of local mills. As a result, paddy must be stored for extended periods before final drying, creating a critical window for quality loss.

Freshly harvested paddy is a living biological material prone to respiration, heat generation, and moisture exchange with its environment. If not dried promptly, these processes can lead to microbial growth, discoloration, and the development of mycotoxins, ultimately degrading milling quality (Molina-Hernandez et al., 2024). One of the most critical quality parameters is head rice yield (HRY)—the percentage of whole, unbroken kernels after milling—which directly determines market value and consumer acceptance.

To manage this post-harvest bottleneck, two-stage drying systems are increasingly considered. In such systems, paddy is first pre-dried to an intermediate moisture level (e.g., 14–15%) using a high-capacity dryer, then stored briefly before final drying to safe levels for milling (Nguyen-Van-Hung et al., 2018). Recirculating dryers offer potential as pre-dryers due to their ability to handle large batches efficiently.

However, excessive drying temperatures and prolonged intermediate storage may induce grain fissuring, which reduces head rice yield (HRY)—a key determinant of market value. Previous studies have shown that rapid moisture removal at high temperatures creates internal stress within kernels, leading to micro-cracks (Cnossen et al., 2003; Hashemi & Shimizu, 2008). Similarly, fluctuating humidity during storage can cause re-wetting and uneven moisture redistribution, exacerbating fissure formation (Manna et al., 2019).

International research supports the feasibility of two-stage drying. For example, researchers demonstrated that high-temperature pre-drying followed by low-temperature finishing could achieve higher throughput without compromising milling quality (Elepano et al., 2005). Scholars reported successful implementation of two-stage drying in the Philippines, emphasizing its technical viability and economic benefits (Chupungco et al., 2008). The others further validated the concept for corn, rice, and wheat, showing improved energy efficiency and grain integrity (Jittanita et al., 2010).

Recent studies have further advanced understanding of optimal drying strategies. Scientists found that multi-stage intermittent drying significantly improves HRY and reduces fissuring compared to continuous drying, particularly when temperature levels are carefully controlled (Wang et al., 2023). It was highlighted that combining pre-drying with tempering intervals

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effectively minimizes stress cracking in unparboiled paddy, preserving endosperm integrity (Keya et al., 2025). Moreover, they emphasized the critical role of tempering duration in reducing fissure formation, noting that even short rest periods between drying stages can significantly improve grain quality.

Despite these findings, most existing studies focus on fluidized bed or flash dryers as pre-dryers, while recirculating dryers—commonly available in Iranian rice mills—have received limited attention. Furthermore, there is a lack of empirical data on the interaction between pre-drying temperature and intermediate storage duration under humid subtropical conditions typical of northern Iran.

Given the growing reliance on direct harvesting and the limited drying capacity in northern Iran, there is a clear need to evaluate locally available technologies—such as recirculating dryers—for use in two-stage drying systems. Therefore, this study aimed to investigate the effects of pre-drying temperature (40, 50, 60 °C) and intermediate storage duration (15, 30, 45 days) on the milling quality of directly harvested Hashemi paddy—a dominant local variety—using head rice yield, milling recovery, and grain fissure percentage as key indicators. The findings are intended to guide optimal drying protocols for processors facing high-volume, high-moisture paddy influx during harvest season.

2. Materials and methods

2.1. Experimental site and design

The experiment was conducted in 2024 at the Rice Research Institute of Iran (RRII), Rasht (37°12′N, 49°38′E). A factorial experiment based on a randomized complete block design (RCBD) was implemented with two main factors:

- Pre-drying air temperature: 40, 50, and 60 °C.
- Storage duration: 15, 30, and 45 days.

The experiment included five replications. An additional control treatment used conventional single-stage drying at 40 °C for comparison.

2.2. Plant material and harvesting

Paddy of the Hashemi variety was harvested directly from experimental fields using a specialized rice combine harvester. Initial moisture content averaged 20.5 ± 0.5% (wet basis), measured with a portable moisture meter (GMK RS303, Korea).

2.3. Pre-drying process using a recirculating dryer

A recirculating dryer (2 m × 1.3 m × 5 m, 2 m³ capacity) was used for pre-drying (Shalichai Co., Iran). Each batch consisted of 2 tons of paddy. The drying cycle included 105 minutes of static drying followed by 15 minutes of grain circulation, repeated until the moisture content reached 15% (w.b.). Air temperature was controlled at 40, 50, or 60 °C.

Crucially, the dryer was powered by a natural gas-fired burner system, ensuring consistent and controllable drying temperatures.

After pre-drying, paddy was sealed in plastic bags and stored under ambient warehouse conditions (average RH: 65–75%, temp: 25–30 °C) for 15, 30, or 45 days.

2.4. Final drying using a conventional batch dryer

After storage, paddy underwent final drying in a conventional fixed-bed batch dryer (2.8 m × 2 m × 0.9 m) at 40 °C until moisture reached 8.5 ± 0.5% (w.b.). This batch dryer also operated on natural gas, aligning with common industrial practices in Iranian rice mills.

2.5. Milling and quality evaluation

After final drying, samples were processed in the laboratory:

- Dehulling: 150 g of paddy was dehulled using a laboratory husker (THU35B, Satake, Japan).
- Polishing: Brown rice was polished for 45 seconds using a McGill Miller No. 2 (Baldor, USA).
- Grading: Milled rice was passed through a rotary indent cylinder sifter (TRG05B, Satake, Japan) to separate whole grains (≥75% of full length) from broken ones.

2.5.1. Quality parameters measured

- Head Rice Yield (HRY): Percentage of whole milled rice relative to initial paddy weight.
- Milling Recovery (MR): Total milled rice (whole + broken) as a percentage of initial paddy weight.
- Grain Fissure Percentage: Measured directly using a Satake TX-200 Crack Detector (Satake Corporation, Hiroshima, Japan). A sample of 100 intact head rice kernels was randomly selected. Each kernel was placed individually on the transparent glass plate of the device, illuminated from below by a high-intensity LED backlight. A trained technician visually inspected each kernel under a built-in 10× magnification monocular loupe. Any visible surface or internal crack was recorded as damaged.

$$\text{Fissure \%} = (\text{Number of fissured grains} / \text{initial sample}) \times 100$$

2.6. Statistical analysis

Data were analyzed using Minitab 20.3 (Minitab LLC, 2021). ANOVA was performed to assess significance ($\alpha = 0.05$). Tukey's HSD test was used for mean comparisons.

3. Results and discussion

The analysis of variance (ANOVA) for the effects of pre-drying temperature and intermediate storage duration on key quality parameters is presented in Table 1. Both main factors had highly significant effects ($p < 0.01$) on head rice yield (HRY) and grain fissure percentage.

However, neither factor significantly affected milling recovery (MR) at the 5% level. The interaction between temperature and storage duration was non-significant for all measured traits.

Table 1. ANOVA of two-stage drying effects on hashemi paddy quality traits

Source of variation	df	SS		
		HRY	MR	Fissure
Drying temperature	2	16.3568**	3.4072 ns	53.872**
Storage Duration	3	30.649**	3.682 ns	135.300**
Interaction	6	2.0648 ns	1.3289 ns	1.0124 ns
Error	44	24.121	27.821	125.324
Total	53	84.775	39.287	366.324
cv (%)		14.15	9.56	12.11

Note: ns = non-significant; ** = $p < 0.01$

Mean comparisons using Tukey's HSD test are shown in Table 2 and Fig. 1. to 4. Increasing pre-drying temperature from 40 °C to 60 °C significantly reduced HRY from 56.25% to 54.82% ($p < 0.05$) and increased grain fissure percentage from 12.38% to 15.06%. Similarly, extending storage duration from 15 to 45 days decreased HRY from 55.97% to 54.39% and increased fissures from 12.53% to 16.15%.

Table 2. Mean comparison of main effects on HRY and grain fissure percentage

Factor	**Level**	**Traits**	
		HRY	**Fissure**
Drying temperature (°C)	40	56.25^{a}	12.38^{b}
	50	55.87^{a}	13.74^{ab}
	60	54.82^{b}	15.06^{a}
Storage duration (days)	0*	56.98^{a}	11.45^{b}
	15	55.97^{a}	12.53^{b}
	30	55.24^{b}	14.81^{a}
	45	54.39^{c}	16.15^{a}

Means within columns followed by different letters differ significantly ($p < 0.05$)
* This level refers to control treatment.

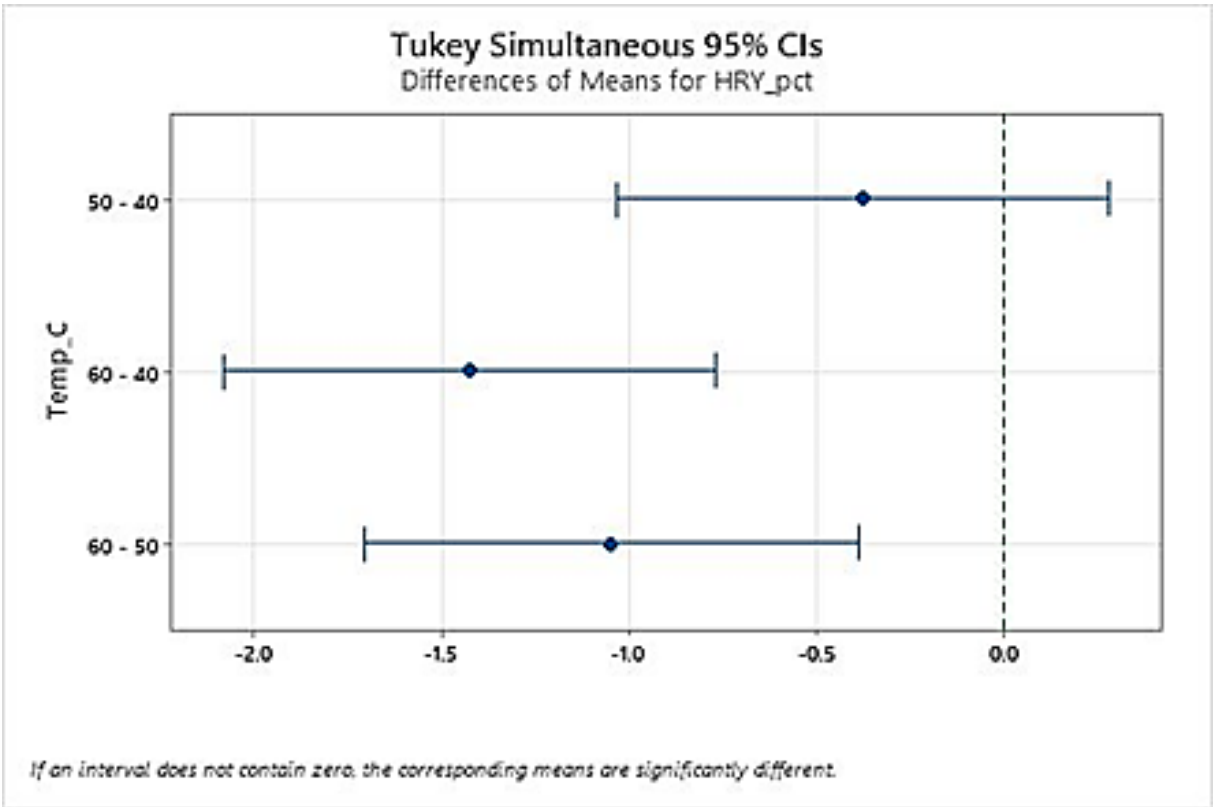

Fig. 1. Pairwise comparison for HRY on drying temperature

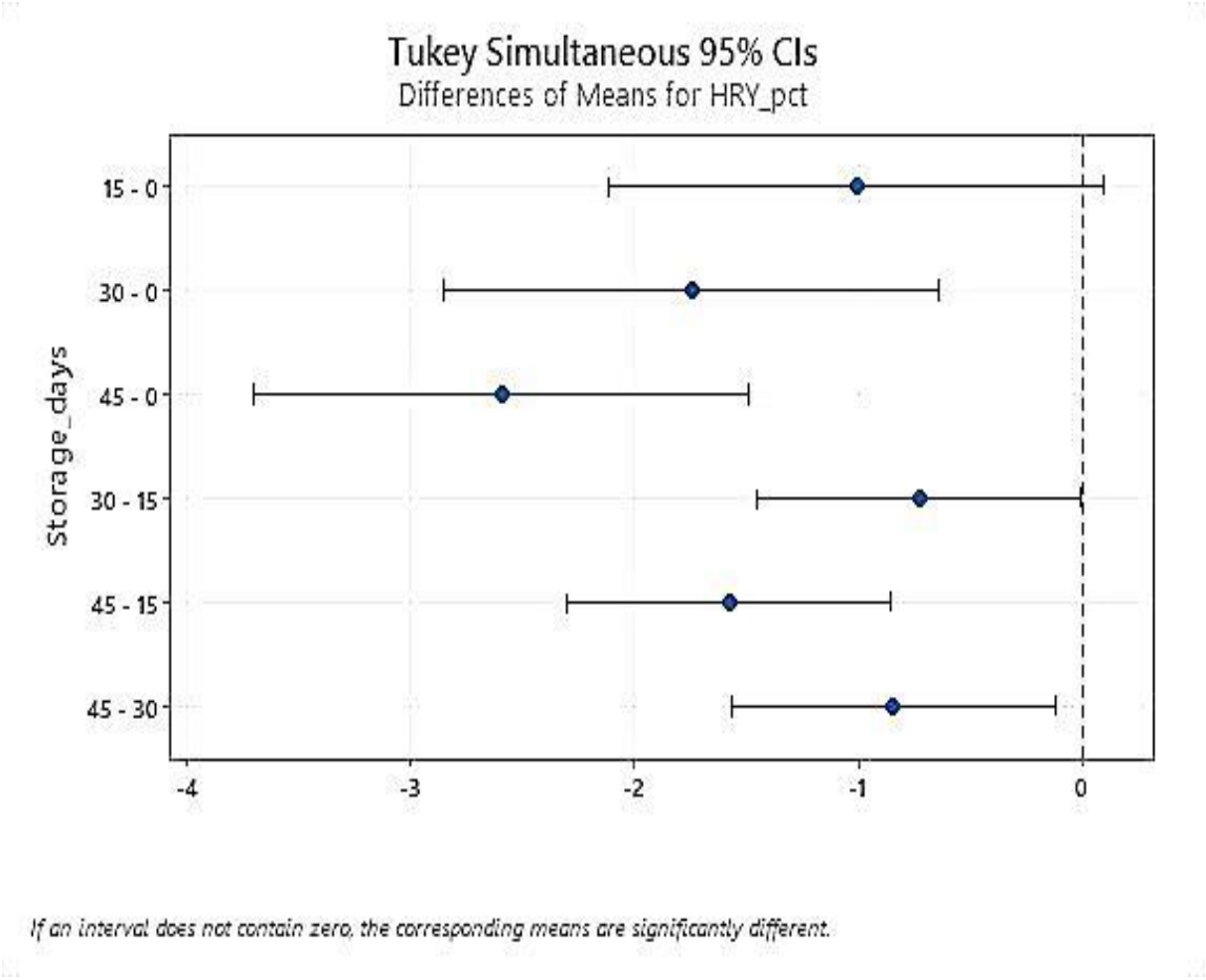

Fig. 2. pairwise comparison for HRY on storage duration

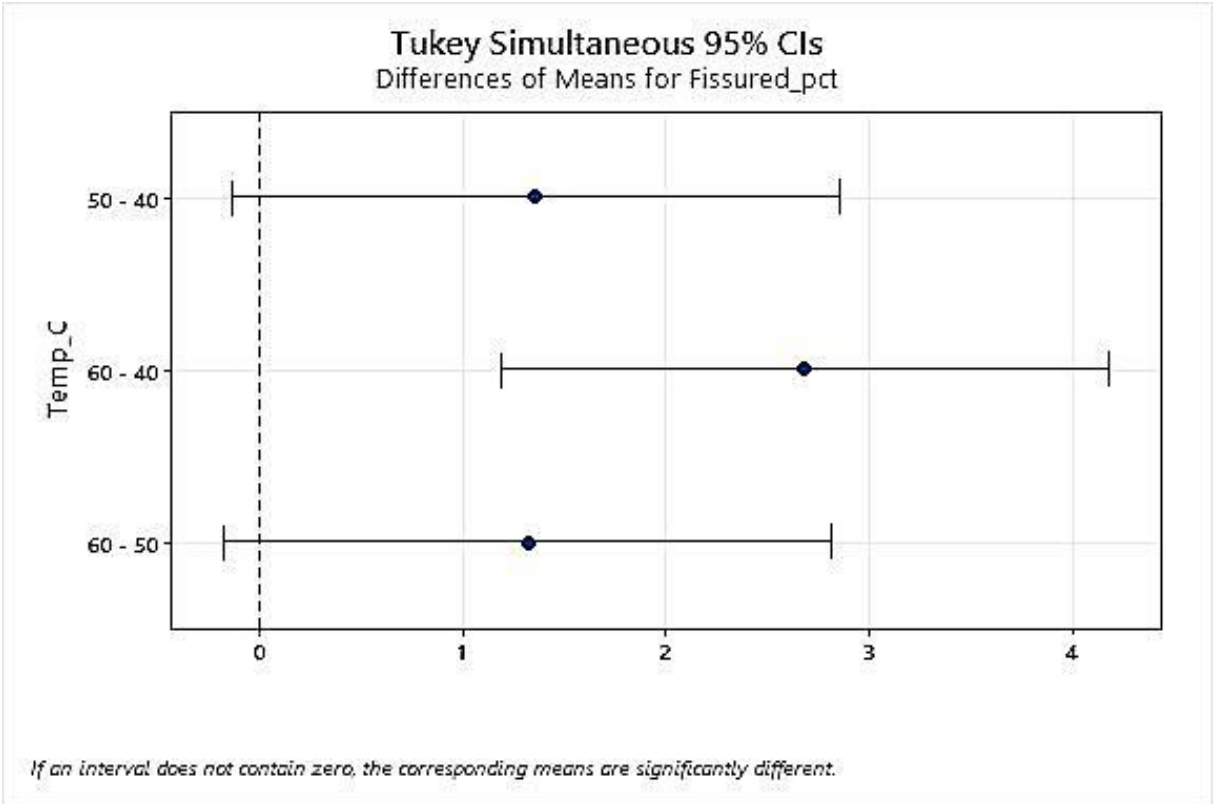

Fig. 3. pairwise comparison for Fissure on drying temperature

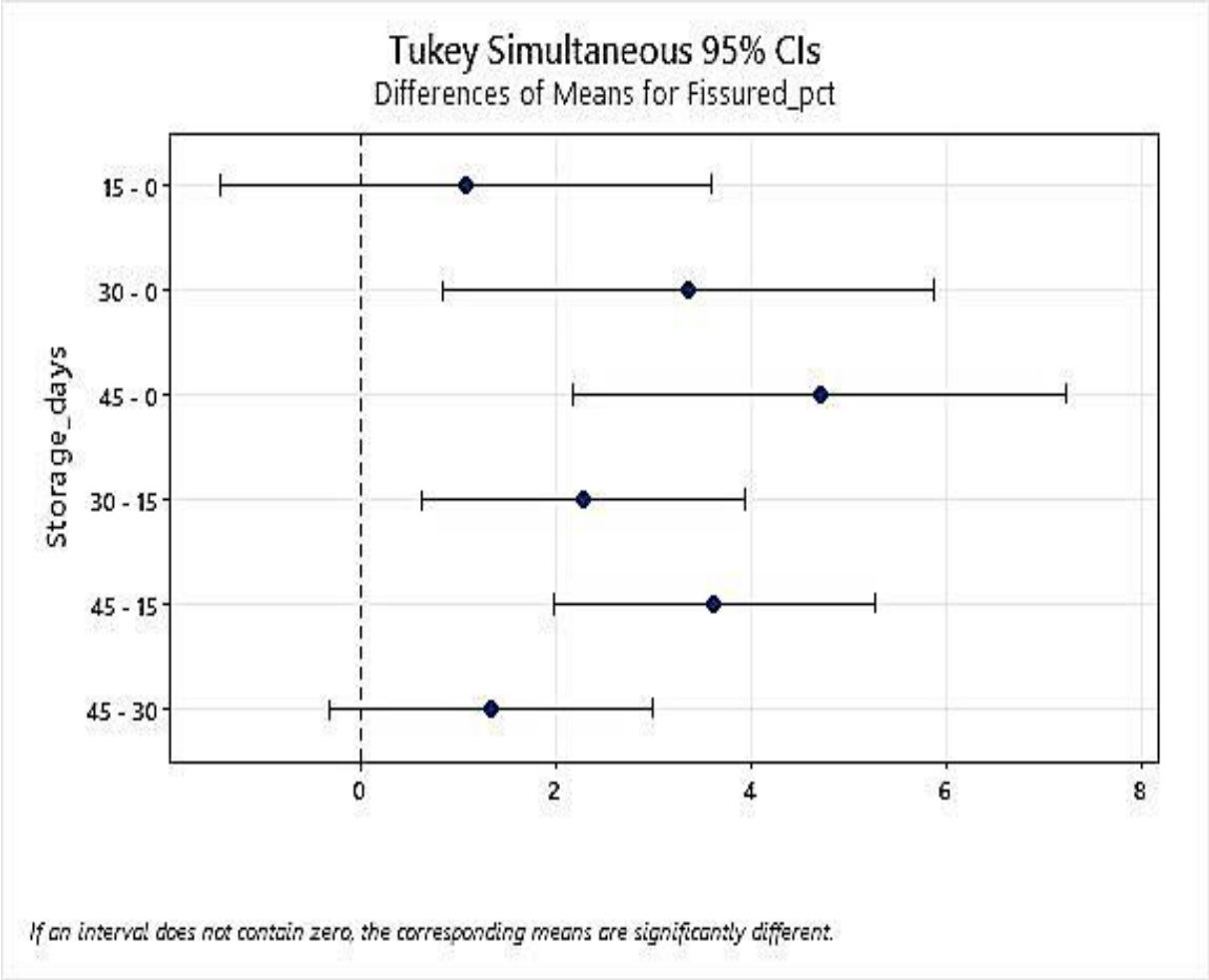

Fig. 4. pairwise comparison for Fissure on storage duration

This study demonstrates that both pre-drying temperature and intermediate storage duration significantly affect the post-harvest quality of Hashemi paddy, particularly head rice yield and grain fissuring. These findings have direct implications for processors facing high-volume, high-moisture paddy influx during harvest season.

3.1. Effect of pre-drying temperature

The significant reduction in HRY with increasing drying temperature is consistent with established principles of grain physics. High-temperature drying creates steep moisture gradients between the kernel's surface and core, generating internal tensile stresses that lead to micro-cracks (Cnossen et al., 2003; Dong et al., 2010). Our finding that a 20°C increase in temperature resulted in a ~3% increase in fissures aligns with the results reported in (Sarkar et al., 2022; Barthwal, 2025).

The observed 2% drop in HRY when temperature rose from 40 °C to 60 °C confirms that thermal stress directly compromises grain integrity. This effect is particularly critical in humid climates like northern Iran, where rapid drying may be tempting but comes at a cost to premium-quality grain. The results support International Rice Research Institute (IRRI's) recommendation to limit drying air temperature to ≤43 °C to preserve seed viability and minimize fissuring (IRRI, 2022).

Interestingly, milling recovery remained stable across treatments, suggesting that while fissures increase breakage, total milled output is not compromised. This observation agrees with the studies who noted that fissured grains contribute to broken rice yield without necessarily reducing overall mass (Velupillai & Pandey, 1990). Thus, the economic loss lies not in total volume but in the reduction of market value due to lower proportions of whole kernels.

3.2. Effect of intermediate storage duration

Prolonged intermediate storage also exacerbated fissuring, likely due to moisture re-absorption from the humid environment and subsequent uneven redistribution within the grain. As shown in Table 2, extending storage from 15 to 45 days led to a 4.7% increase in fissures and a 2.6% decrease in HRY—findings that underscore the importance of minimizing delays between drying stages.

Scholars reported similar outcomes, noting that extended storage after partial drying increases the risk of moisture cycling, which induces expansion and contraction in different layers of the grain, promoting crack formation (Manna et al., 2019). Furthermore, some others emphasized that even small fluctuations in ambient

humidity can trigger re-wetting, especially when paddy is stored in non-sealed containers (Srzednicki & Driscoll, 2008).

Our use of natural gas-powered dryers reflects real-world conditions in Iranian rice mills, enhancing the applicability of these findings. In practice, processors often face unavoidable delays due to limited capacity. However, this study clearly shows that each additional week of storage carries a measurable quality penalty.

3.3. Lack of interaction effect

The absence of a significant interaction effect suggests that the impacts of temperature and storage are additive rather than synergistic. Nevertheless, their combined influence—up to a 4.7% increase in fissures and 2.6% drop in HRY—can translate into substantial economic losses at commercial scale, where premium prices are paid for whole grains.

3.4. Practical implications and alignment with literature

These findings are in line with those who found that two-stage drying systems can improve throughput without compromising quality—provided that high temperatures are used only in the initial phase and low-temperature finishing follows (Elepano et al., 2005). Studies further validated this concept in tropical conditions, highlighting its technical feasibility (Chupungco et al., 2008).

Recent studies reinforce our conclusions. Scientists demonstrated that multi-stage intermittent drying improves HRY and reduces fissuring compared to continuous drying (Wang et al., 2023). Some others also highlighted the effectiveness of tempering intervals in minimizing stress cracking in unparboiled paddy (Keya et al., 2025). Moreover, scientists emphasized that even short rest periods between drying stages can significantly reduce fissure formation (Siebenmorgen et al., 2005; Chayjan et al., 2019).

However, most existing research focuses on fluidized bed or flash dryers as pre-dryers. This study fills a gap by evaluating the recirculating dryer, a common yet understudied technology in Iranian rice processing facilities. Our results show that while it is effective for rapid moisture removal, its benefits must be balanced against the risk of quality degradation if operated at excessive temperatures or paired with prolonged storage.

Finally, scholars have identified multiple sources of fissuring throughout the supply chain—from field to mill (Bunna et al., 2018; Iguaz et al., 2006). Our data confirm that pre-drying temperature and post-drying storage are two critical control points where targeted interventions can yield significant improvements in final product quality.

4. Conclusions

The findings of this study indicate that milling quality can be effectively optimized by controlling key parameters in the two-stage drying process. In particular, the use of moderate pre-drying temperatures (≤40 °C) and the minimization of intermediate storage duration play a crucial role in preserving grain integrity and improving head rice yield. Additionally, storing pre-dried paddy in sealed, moisture-proof containers is recommended to limit moisture reabsorption and reduce the development of grain fissures during the storage period. The results also suggest that the application of variable-temperature drying regimes combined with appropriate tempering intervals may further enhance milling performance by promoting more uniform moisture distribution within the kernel. Future research should focus on evaluating different tempering strategies, investigating intra-kernel moisture dynamics under two-stage drying conditions, assessing varietal sensitivity to drying and storage parameters and conducting cost–benefit analyses of optimized drying systems to support their practical adoption in rice processing facilities.

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