# Status and Causes of Rice Loss in Vietnamese Rice Processors: A Case Study on Vietnamese Rice Processor in Mekong Delta, Vietnam

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# Abstract

**Background and Objective:** The loss of rice during processing is an important issue for Vietnam's agricultural economy, especially in the Mekong Delta region, which contributes significantly to national rice production. This study aims to analyze the situation and the primary sources of rice processing loss in Vietnam's rice processors through a comprehensive case study of CDo Company, a medium-sized rice processing facility located in the Mekong Delta with an annual processing capacity of 45,000 tons.

**Methods:** The evaluation of rice loss for this study began at the reception of raw paddy rice and ended at the final packaging of rice using direct measurement techniques. Processing data for 36 batches of the Dai Thom 8 variety, each 30,044 kg and constituting about 40% of the facility's production, were analyzed. The study involved monitoring moisture content, calculating yields, assessing quality, and evaluating economic loss. Also, a comparative analysis was carried out using the national standards of Vietnam (TCVN) and other countries (Codex, EU, and Philippines).

**Results:** The investigation uncovered total processing inefficiencies of 21.8% over industry norms. Drying processes incurred a loss of 6.0% on a dry matter basis. In milling processes, 12.7% loss was incurred. The facility's Head Rice Yield (HRY) was 46.0% and the Milled Rice Yield (MRY) was 57.3%. Regarding quality-related losses, 3,869 kg of rice was rejected on account of contamination issues, residue of pesticides, heavy metals, and mycotoxins (Aflatoxin B1, Ochratoxin A). The broken rice ratio to total milled rice reached 19.7%, indicating that the rice was subjected to severe processing damage.

**Key Findings:** The most prominent loss drivers attributed to the poor yield and quality were identified as uncontrolled moisture content, aged drying and milling equipment, contamination of raw materials, as well as poor storage environments. The longer the equipment operates without upgrades and maintenance, the more configuration errors occur, causing greater losses. The economic analysis uncovered processing losses of US $1,165,631.53 per year for just Dai Thom 8.

**Recommendations:** The research proposes a comprehensive IoT-based action plan to improve processing efficiency and reduce costs through three phases that have taken place in 6-36 months.

**Keywords:** Vietnam, rice processing, post-harvest losses, Mekong Delta, food security, agricultural technology, processing efficiency, quality control.

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# List of Abbreviations

| **Abbreviation** | **Full Form** |
|---|---|
| ACIAR | Australian Centre for International Agricultural Research |
| AI | Artificial Intelligence |
| APEC | Asia-Pacific Economic Cooperation |
| BR | Broken Rice (percentage of milled rice) |
| CAP | Controlled Atmosphere Processing |
| CEL | CEL Consulting |
| CGIAR | Consultative Group for International Agricultural Research |
| CDo | CDo Company |
| COVID-19 | Coronavirus Disease 2019 |
| DT8 | DT8 rice variety |
| EPA | Environmental Protection Agency |
| EU | European Union |
| FAO | Food and Agriculture Organization |
| FBD | Fluidized Bed Dryer |
| GDP | Gross Domestic Product |
| H0 | Null Hypothesis |
| H2 | Research Hypothesis |
| HRY | Head Rice Yield |
| ISO 22000:2018 | International Organization for Standardization food safety standard |
| IRRI | International Rice Research Institute |
| IoT | Internet of Things |
| GMP | Good Manufacturing Practice |
| JICA | Japan International Cooperation Agency |
| JIRCAS | Japan International Research Center for Agricultural Sciences |
| MC | Moisture Content |
| MRY | Milled Rice Yield |
| MT | Metric Tons |
| OM5451 | OM5451 rice variety |
| PHTI | Post-Harvest Technology Institute |

| | |
|---|---|
| PHL | Post-Harvest Loss |
| QCVN | Quy Chuẩn Việt Nam (Vietnamese National Standards) |
| RF | Radio Frequency |
| RK | Recovery of Control (benchmark recovery rate) |
| RL | Recovery of Field (actual recovery rate) |
| ROI | Return on Investment |
| SEC | Specific Energy Consumption |
| SGH | Static Grain Bed Heater |
| SRA | Static Reversible Airflow |
| SRR | Static Recirculating Rice |
| SRP | Sustainable Rice Platform |
| ST25 | ST25 rice variety |
| TCVN | Tiêu Chuẩn Việt Nam (Vietnamese Technical Standard) |
| USD | United States Dollar |
| VNA | Vietnam News Agency |
| VND | Vietnamese Dong |
| VnSAT | Vietnam Sustainable Agriculture Transformation |
| WFBR | Wageningen Food & Biobased Research |
| WHO | World Health Organization |
| $L_{general}$ | General Loss Rate |
| $L_{drying}$ | Drying Loss (Dry Matter Basis) |
| $L_{milling}$ | Milling Loss Rate |
| $L_{direct}$ | Direct Physical Loss |
| $m_{in}$ | Mass Input (before process stage) |
| $m_{out}$ | Mass Output (after process stage) |
| $m_{dry\ matter}$ | Dry Matter Mass |
| $m_{MR}$ | Milled Rice Weight |
| $m_{HR}$ | Head Rice Mass |
| $m_{BR}$ | Broken Rice Mass |

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# 1. Introduction and thesis overview

## 1.1 Introduction

### 1.1.1 Global food security objectives and resource limitations

Food security is still one of the hardest issues to solve, with approximately 733 million people facing hunger (FAO, 2024). This represents almost one in eleven individuals who is affected by chronic hunger, underscoring the alarming of the current status (FAO, 2024). The need to secure food supply is very critical as the increase in population, economic instabilities, and shifts in climatic conditions pose a threat to agricultural systems globally (Kiprutto et al., 2015; Miladinov, 2023; Mbow & Rosenzweig, 2025).

Rice is essential to world food security as it supports more than 3.5 billion people as it provides 20% of the world's dietary energy (SRP, 2025). The dependence of people on rice makes it a critical security commodity (FAO, 2014; DfGrupo, 2023). Therefore, any ineffectiveness in the production, processing, and distribution of rice is not just a concern for a nation, but the whole world (Gustafson, 2023; Gairhan, 2025).

### 1.1.2 COVID-19 Economic crisis and food system efficiency

The economic consequences of COVID-19 have escalated vulnerabilities in food security around the world while simultaneously creating an urgent need for improved efficiency and reduction in waste within the food systems (Adjognon et al., 2020; Laborde et al., 2020; Gebeyehu et al., 2022; Bilan et al., 2023). During the pandemic, the economic recession led to absolute income loss in almost all countries (International Monetary Fund, 2020; World Bank Group, 2022). Along with the rampant food supply chain disruptions, there was a huge spike in food prices (Baffes, 2024; Economist Impact, 2025; FAO, 2025). The economic downturn further worsened food accessibility, and as a result, reduction in food waste shifted from an efficiency benchmark to an economic imperative for using and balancing the cost of food (Aldaco et al., 2020; Ghafoorifard et al., 2022). In this pandemic scenario, minimizing the food loss waste has at the heart an importance of optimal utilization of food resources while curtailing economic waste (Aldaco et al., 2020; Simon et al., 2022; APEC, 2022).

### 1.1.3 Strategic challenges and position of Vietnam

Vietnam is now the world’s third largest exporter of rice (VietnamPlus, 2025). It attained export milestones of 9.18 million tons worth 5.75 billion dollars in 2024 (VietNamNet News, 2025). This marked a 12.9% growth in volume and a 23% growth in value compared to 2023 (VietNamNet News, 2025). This success is particularly significant given the economic contractions in other sectors, demonstrating rice's role in economic recovery. However, underlying this export achievement is a critical inefficiency that impacts both economic returns and food security: significant post-harvest losses along the rice processing value chain (VietNam News, 2018).

Vietnam's agricultural sector experiences post-harvest losses between 14–35%, according to United Nations statistics (Enternews, 2023). More recent field measurements by WFBR/CGIAR Can Tho University recorded rice losses at 22.3% (Kok et al., 2024). Given Vietnam's premium export prices relative to competitors, these losses translate to billions of dollars in foregone revenue annually.  This finding is reinforced by CEL Consulting (2018) report that industry estimates in Vietnam was over 3 billion USD in losses annually.

Although many studies reported the equipment improvement might help to reduce those serious losses, most Vietnamese rice processors face significant financial barriers and uncertainty to change (Le, 2023). They cannot be certain the benefits outweigh the upfront costs, leading to modernization projects in Vietnam being frequently delayed or forgone. This could be more serious when 96% of rice industrial rice mills in Vietnam are small and medium-sized enterprises (Báo Nhân Dân điện tử, 2022). In a highly competitive global market and with persistent price fluctuations, these processors might have narrow profit margins (Le, 2023). As a result, any investment in new technology or automation needs to be deeply considered for financial efficiency and food losses reduction. In this context, context-specific, data-driven evidence could be necessary for processors to make any decision on modernization.

### 1.1.4 Technological obsolescence and equipment constraints

Excessive rice processing losses in Vietnam might stem from technological obsolescence. This is supported in the literature (VietNamNet News, 2019; Le, 2023; Enternews, 2023), which identifies outdated technology as the primary driver of excessive rice processing losses in Vietnam. Most studies (VietNamNet News, 2019; Le, 2023; Enternews, 2023) agreed that age of equipment and type of technology are significantly correlated with food losses during processing. Particularly, Enternews (2023) and Ngo and his colleagues (2021) both indicated that the flat-bed batch dryers and old technology equipment without controlling temperature of the air and the moisture of the grain might lead to insufficient optimization of the processes. These findings are consistent with earlier studies by Wiset et al. (2001) and Dao and Nguyen (2017), which previously documented similar issues. Wiset and colleagues (2001) reported that many Vietnamese enterprises utilize technology that may be 3 or 4 generations behind the world's average level, with necessary integrated controls often absent. Similarly, Dao and Nguyen (2017) found that 90% of Vietnam's small and medium-capacity, established before 2010s, replied on the old version of flat-bed dryers and milling equipment, compromising operational accuracy and efficiency.

While the consensus on technology-related losses is well-established, critical limitations warrant attention. The empirical evidence by Dao and Nguyen (2017) was collected in 2017 or earlier, when equipment was estimated at 7 years old. In the meanwhile, as of now, the equipment could be more than 10-15 years old, suggesting that loss disadvantages may be significantly greater now. Furthermore, existing studies do not rigorously compare the impact of technological versus human factors (such as operator skill, training, or workflow organization). While this methodological gap is notable, this could be because rice processing is an established Vietnamese industry where operator expertise might partially mitigate equipment limitations. However, as equipment ages beyond functional lifespans, even skilled operators face diminishing capacity to maintain accuracy and efficiency, suggesting that technology remains the limiting factor.

### 1.1.5 Research gaps and methodological limitations

Current studies indicate important gaps in understanding both the loss levels and economic implications of rice processing losses in Vietnam. Most significantly, post-harvest loss estimates vary widely (Le, 2012; Nguyen et al., 2022). Particularly, the losses ranged from World Bank assessments of 10.7% (World Bank, 2020) to recent field measurements of 22.3% (Kok et al., 2024). It points to fundamental inconsistencies in how losses are defined, measured, and reported, particularly between perception-based surveys and measurement-based studies. Such methodological difference weakens the reliability of existing estimates and makes it difficult for policymakers and industry to use these figures for making technological investment decisions.

A second crucial gap concerns the limited analysis of loss levels at the factory level. Existing studies (World Bank, 2020; Kok et al., 2024) reply primarily on interviews to quantify aggregate loss rather than direct quantitative measurement. Consequently, very little is known about the relationships among the equipment age, operational parameters, the loss rates at each stage, and the effectiveness of technological interventions. This gap is especially marked regarding potential

Internet of Things (IoT) and automated processing systems to address loss hotspots in Vietnamese rice. Recent international studies (Viviane et al., 2023; Islam et al., 2024) demonstrated that systems with IoT can detect loss patterns in real-time and reduce the 14-22% grain losses typically associated with inadequate drying and storage conditions. However, there has been no systematic evaluation of the cost, operation requirements, or context-specific constraints of applying those technologies in Vietnamese rice mills. Taken together, these gaps underscore the need for rigorous, factory-level studies that link concrete loss mechanisms to both existing equipment conditions and potential digital interventions.

### 1.1.6 Industry imperatives for comprehensive factory-level analysis

The foregoing context reveals a compelling industry problem: Vietnam's rice sector simultaneously sustains strong export performance and poorly processing losses that are strongly associated with obsolete equipment (VietNamNet News, 2019; Le, 2023; Enternews, 2023). At the same time, most processors, especially small and medium-sized mills operating with tight margins and constrained capital are lack of reliable, context-specific data on losses and upgrade benefits makes modernization decisions high-risk and there by frequently postponed (Le, 2012; Enternews, 2023).

Under these circumstances, generic calls for "modernization" are not sufficient. Processors and financers might need quantitative evidence (Le, 2012; Commission for Environmental Cooperation, 2019; Nguyen & Bonn, 2024). That evidence should identify loss levels, linking specific equipment configurations and operational conditions and then, the economic performance of current/alternative upgrade options (Le, 2012; Commission for Environmental Cooperation, 2019; Nguyen & Bonn, 2024). Without this type of evidence, decisions about technology upgrades could be risked by vendor claims or engineering ideals rather than context-appropriate analytics.

Therefore, a factory-level case study is not just methodologically useful but analytically essential. Firstly, it could enable direct measurement of losses at each processing stage, generating a reliable baseline for identifying where, and to what extent, value is being destroyed (Le, 2012; Commission for Environmental Cooperation, 2019; Nguyen & Bonn, 2024). Secondly, it could allow systematic investigation of specific equipment characteristics and operational parameters such as dryer type, control capability, and operating settings. This could find out how those parameters affecting loss rates, providing insights that could be transferable to similarly configured mills (Le, 2012; Commission for Environmental Cooperation, 2019; Nguyen & Bonn, 2024). Thirdly, it could provide a framework for techno-economic analysis of alternative modernization pathways (Le, 2012;

Commission for Environmental Cooperation, 2019; Nguyen & Bonn, 2024). This framework could allow a comparison of their cost-effectiveness and payback potential under realistic operating conditions.

Critically, those analyses at factory-level help to account for non-technical constraints, including site-specific infrastructure limitations, operator capability, and management practices. Therefore, this could reflect what is feasible for actual mills rather than idealized engineering scenarios (Commission for Environmental Cooperation, 2019). In this way, comprehensive factory-level analytics directly address the twin challenges identified in the literature: loss levels at each stage and uncertain investment returns, thereby supporting more realistic and financially viable modernization decisions.

## 1.2 Research problem, aim, hypotheses, and study scope

### 1.2.1 Research problem

Although technological obsolescence driving excessive rice processing losses in Vietnam is acknowledged, there remains a lack of updated direct evidence at factory-level evidence to quantify loss levels and evaluate the actual economic impact. Existing research relies mostly on perception-based estimates rather than objective measurement, fueling ongoing uncertainty about the magnitude of technology-related losses.

### 1.2.2 Aim

This study aims to collect and analyze equipment and processing parameters at the factory level to quantify losses at each stage of rice processing. This also develops evidence-based recommendations for loss reduction and technology modernization at studied factory and similar configurated Vietnamese mills.

The objectives of this study are:

- To identify the quantitative losses at each stage of processing for Vietnamese rice processors through direct measurement and monitoring.
- To determine the equipment and processing parameters and loss rates at each stage of rice processing.
- To develop recommendations and industrial feasibility analysis for upgrading processes to improve product quality and efficiency.

### 1.2.3 Research hypotheses

To address this problem, the study tests the following hypotheses:

- H0 (Null Hypothesis): Equipment age does not significantly affect rice processing losses.
- H1 (Research Hypothesis): Older equipment is significantly associated with higher rice processing losses.

### 1.2.4 Study scope and delimitations

This investigation focuses on one medium-scale rice processor in the Mekong Delta, examining one rice variety (DT8) across one production season. While these constraints deliberately limit broad generalization, they enable rigorous factory-level analysis of equipment parameters and loss quantification. This helps directly address the methodological gap identified in prior research. While this study examines only one medium-scale processor, the findings may provide indicative insights into similarly situated mills in the Mekong Delta. Notably, this study's results cannot be automatically generalized to the entire Vietnamese rice processing sector, which encompasses diverse equipment types, scales, climates, and operational practices. Nevertheless, the methodology and analytical framework developed here may be adaptable for other facilities seeking to quantify and reduce processing losses.

## 1.3 Thesis overview

This thesis takes a comprehensive approach to the problem of rice processing losses and their technological remediation, categorizing them into components that harmoniously merge to enable industry-wide recommendations.

This introductory chapter places the Vietnamese rice sector in the context of global food security, the post-COVID economic landscape, and narrows down to the lack of up-to-date technology as the primary processing bottleneck. It articulates the research aims, research questions, scopes and boundaries.

Chapter 2 outlines key concepts, definitions, and terms in the report. It also outlines and links moisture management, milling pressure, and storage ecology to value erosion. Moreover, chapter 2 critiques existing measurement methods and catalogues advanced interventions and identify the research gaps in previous research.

Chapter 3 is material and methodology, justifying a single-case, positive structure based at CDo Company. It details data collections, formula, and calculation for key parameters.

Chapter 4 is a case study about CDo factory such as location, capacity, products, markets, human resource, processing flow chart, and its description.

Chapter 5 is results and discussions of the plant visits. Firstly, the chapter presents loss quantification including quantitative loss among stages, quality-related loss and economic loss. In the meanwhile, this chapter also discusses benchmarks CDo's performance against Thai, Indian, and Chinese mills. Secondly, the chapter includes causes analytics which cover causes among steps and its root causes. Lastly, Chapter 5 provides comprehensive recommendations and implementation roadmap to improve their practices.

Chapter 6, or the conclusions and recommendations section, the author consolidates the reasoning that the primary factor responsible for Vietnam's processing losses is the outdated machinery. The section also reflects on the single-site scope as well as precision of the instruments and highlights the empirical and practical contributions of the study. This chapter also frankly discusses scope and measurement limitations.

# 2. Literature review

## 2.1 Introduction

Overcoming rice post-harvest losses remains a significant issue for achieving global food security, particularly for Vietnam, whose rice processing systems currently suffer losses from 6.4% to 22.3%. Moreover, equipment at small and middle-capacity rice mills being 10-15 years old and even more might downgrade and be difficult to integrate with or apply new technology (Le, 2003; Enternews, 2023; Le, 2023). As a result, problem of equipment obsolescence increasingly becomes a major headache for Vietnamese rice processors (Le, 2003; Enternews, 2023; Le, 2023). Particularly, this could make loss quantification, including excessive loss weight, low head rice yield, high ratio of broken rice, spillages, discoloration, mycotoxin contamination, pesticide residues, and heavy metal non-conformities (Kok et al., 2024; Nguyen et al, 2013; Dao & Nguyen, 2017; Nguyen, 1999). Existing literature indicates a significant lack of consistency in level of losses and lack of information updated after effort of mechanization revolution in decades ago for the Vietnamese rice processing industry. This urges to have a thorough investigation through the case study approach to the Vietnamese rice processing industry.

## 2.2 Status of food loss in Vietnamese rice processing

### 2.2.1 Definition and scope of loss quantification

FAO (1990) firstly defined post-harvest loss (PHL) as "*the reduction of edible food mass within the supply chain that occurs after the harvest and before the retail sale*" (FAO, 1990, Gustafson, 2019). Post harvest loss encompasses both quantitative (physical reduction in amount) and qualitative (reduction in nutritional value, acceptability, and deteriorations worth value of being consumed) losses of rice (Ishaq Ibrahim, 2018). Since 2019, the FAO (2019) defines post-harvest loss as the "*decrease in quantity or quality of food resulting from actions of food suppliers in the chain, excluding retailers, food service providers and consumers*." This definition provides a distinguishing line between food loss and food waste, the latter of which occurs at the retail and consumer level (Gustafson, 2019). For rice specifically, Ishaq Ibrahim (2018) points out that for rice, post-harvest loss is "*any reduction in the amount of edible rice grain due to reduction of availability, edibility, wholesomeness or quality*."

However, nutritional value at factory-level is often conducted by third parties due to equipment limitations, so the report calculated the quantification of the loss by comprising excessive weight losses, quality-related losses, and economic losses. Those losses arise through several processes such as physical loss, excess moisture loss, grain breakage, and loss in quality requiring downgrading the finished product (Le, 2003). These align with avoidable losses, stemming from inefficient practices or equipment (IRRI, 2008; IRRI, 2025) without being inevitable losses (inherent to processing). For instance, moisture reduction via drying processes is an inherent to the process and expected, but excess moisture removal is avoidable losses. With that definition, Table 1 summaries PHL (%) in typical countries by loss quantification.

*Table 1: PHL % in typical countries*

| Countries | PHL % | Years of Report | Reference |
|---|---|---|---|
| Nigeria | 19.2% | 2019 | Liambee & Onu, 2022 |
| India | 3.82% | 2003-2004 | Basavaraja et al., 2007 |
| China | 3.65% | 2016 | Qu et al., 2021 |
| Indonesia | 20.51% | 2014-2018 | Falatehan et al., 2021 |
| Timor-Leste | 21% | 2017-2018 | FAO, 2018 |
| Thailand | 7.6% | 2012 | Dao & Nguyen, 2017 |
| Sub-Saharan Africa | 47.63% | 2018 | Ndindeng et al., 2021 |

| | | | |
|---|---|---|---|
| Vietnam (Mekong Delta) | 22.3% | 2024 | Kok at al., 2024 |

Research showed that global post-harvest loss quantification was between 10 and 40 percent of total production based on technology and management practices in various regions of the world (Manful, 2011; Ishaq Ibrahim, 2018). In Vietnam, post-harvest losses are 22.3% in total and quantitative post-harvest losses at the millers during the processes of threshing, drying, and milling could reach 0-16% at WFBR/CGIAR Can Tho University's study (Kok et al., 2024). The total loss rate is notably higher than comparator nations such as Thailand (7.6%), China (3.65%), and India (3.82%), though comparable to Indonesia (20.51%) and Timor-Leste (21%). This comparation underscores the rate of rice loss in Vietnam's post-harvest process is extremely high, urging to improve the process, particularly given the Mekong Delta's contributions of over 50% of the country's rice production. Moreover, the Vietnam's elevated loss rates relative to the regional competitors suggest that post-harvest losses in Vietnam should be a concern heightened by board of directors.

Nevertheless, the Mekong Delta rice production area of Vietnam has showed large variability in the post-harvest loss rate over time, ranging from 6.4% to 22.3% across studies conducted between 1999 and 2024 (Table 2), aligning with data in Table 1. Earlier studies by Nguyen (1999) reported loss rates of 13-16%, with losses concentrated in preservation and milling processes (7.2-8.9%). Subsequent research suggested gradual improvement: Nguyen et al. (2013) indicated losses stabilizing at 13-14%, while the IRRI/VnSAT project estimated approximately 10.7% (World Bank, 2020). These declining trends appeared to align with government-funded mechanization initiatives. However, the most recent direct measurement study by WFBR/CGIAR Can Tho University (Kok et al., 2024) reported losses reaching 22.3%, much higher than previous estimates. This finding raises critical questions: Are losses genuinely worsening over time, or do newer measurement methods reveal inefficiencies previously obscured by different methodologies?

*Table 2: A comparative analysis of study findings (1999-2024)*

| Supply chain critical stages | PHL % | | | | |
|---|---|---|---|---|---|
| | WFBR/CGIAR Can Tho University | IRRI/VnSAT project | Mekong Delta Rice Research Institute (2013) | Vietnam Technology Assessment (2012) | ACIAR/Vietnam PHTI |

| | | | | | |
|---|---|---|---|---|---|
| Harvesting | 2.0-14.8 | 7.7 | 0-4 | 2-3 | 1.3-1.7 |
| Threshing | | | 0-4.5 | - | 1.4-18 |
| Transportation | 0.4-2 | | 0-1 | 0.9 | 1.2-1.5 |
| Drying | 9 | | 0-1 | 4.2 | 1.9-2.1 |
| Storage | 0-2 | | 0-3 | 2.6 | 3.2-3.9 |
| Milling/Processing | 0-6.5 | 3 | 0-2 | 3 | 4-5 |
| **Total loss** | **6.4-22.3** | **10.7** | **0-16.5** | **13.7** | **13-16** |
| Reference | Kok et al., 2024 | World Bank, 2020 | Nguyen et al, 2013 | Dao & Nguyen, 2017 | Nguyen, 1999 |

Except for the study conducted by WFBR/CGIAR and Can Tho University in 2024, all the other studies seem to show an improvement in the total loss figures over time – from 13-16% in 1999 to 10.7% in 2022. These declining loss trends might correspond to the level of mechanization and the diffusion of technology funded by the government. Furthermore, these five studies integrated several essential insights regarding loss patterns and critical intervention areas. All studies emphasized the processing stages, especially the drying and milling stages, as major loss-risk areas. Specifically, WFBR/Can Tho study stated drying loss figures of 9.0% (Kok et al., 2024) and the World Bank study highlighted loss figures of 7.7% in transport, handling and storage (World Bank, 2020). The assessment by Dao & Nguyen, (2017) although reporting lower absolute values, similarly credited drying (4.2%) and milling (3%) as major post-harvest loss contributors. This agreement also applied to the aging and manual operation gaps as major contributors to low efficiency, with the Vietnam Technology Assessment (Dao & Nguyen, 2017) documenting gaps in mechanization in the processing stages.

Yet, there are significant differences in the estimates of loss quantification in each study. The WFBR/Can Tho study (Kok et al., 2024) reported total processing losses of 16% inclusive of drying, which greatly exceeded the evaluation estimates conducted by Nguyen et al, (2013) at Mekong Delta Rice Research Institute which found losses of around 0-6%. Further, the WFBR/Can Tho study (Kok et al., 2024) which cited loss estimates of 6.4-22.3% total processing loss, was in fact a range two to three times larger than the single study loss estimates provided in Table 2. The significant variation in reported loss rates (6.4-22.3%) does not simply reflect progress or decline over time, but also reveal deeper differences in reporting losses, equipment age, methodology, and sampling approaches that make direct comparison problematic and potentially misleading for policymakers and/or factories' financiers.

***Stage-wise reporting inconsistency could compound comparison difficulties***

These five studies presented inconsistently loss value at stage-wise inconsistently. Particularly, the World Bank (2020) aggregates loss at 7.7% across harvesting, threshing, transportation, and storage instead of disaggregating them like other earlier studies did. This aggregation makes it inherently incomparable with studies isolating drying and milling losses. Moreover, this could obscure specific operations that could drive losses and make difficulties in targeted intervention planning. In contrast, earlier studies (Nguyen, 1999; Nguyen et al., 2013; Dao & Nguyen, 2017) and the latest study (Kok et al., 2024) isolated and measured each processing stage which could highlight the drying and milling losses in the final figure.

***Equipment age and temporal gaps could render historical data obsolete for current intervention planning***

The studies span a 25-year period (1999-2024) during which technology, policy, and market structures evolved substantially. These differences in technology, policy, and market conditions likely result in significant changes following each intervention. For example, equipment that was relatively new (5–7 years old) in 2017 is now 13–15 years old and may be even more degraded. Moreover, while the findings from earlier studies like Nguyen (1999) and Nguyen et al. (2013) could be useful baselines, those now were over a decade old and might be less relevance to current processing contexts such as rapid changes in processing technology, international quality standards, and export market demands. Therefore, those findings could not reliably guide current modernization strategies. These factors create further complexity in analysis and solution suggestions.

***Methodological differences could create systematic bias***

The measurement approach fundamentally determines what losses become visible. The WFBR/Can Tho study (Kok et al., 2024) employed direct field measurement at farms combined with questionnaires specifically asking millers about quantitative losses at each processing stage (drying, milling, storage). In contrast, earlier studies relied on surveys and interviews (Nguyen et al., 2013; Dao & Nguyen, 2017) or foundational knowledge through expert synthesis (Nguyen, 1999). These methods have been replied to operator understanding and experience in collecting data. Therefore, these methods could recall bias and operator underreporting, particularly when losses occur in poorly monitored stages. The World Bank study (2020) used macro-models and secondary data across 800,000+ farmers (Table 3), achieving broad geographic scope. However, this approach could not sacrifice operational specifics essential for identifying specific loss drivers because of lack of detailed ground-level data.

The WFBR/CGIAR and Can Tho University (Kok et at., 2024) study is perhaps the most comprehensive in terms of the field work undertaken. It combines direct measurements and interviews with 48 farms, 3 traders, and 4 millers (1 miller reported) (

Table 3) in the Mekong Delta (Kok et at., 2024). This approach captures a great deal of empirical detail and contemporary insights into quantitative losses. The methodological distinction might explain why the WFBR/Can Tho study (Kok et al., 2024) found drying losses of 9.0% while the survey-based study by Dao & Nguyen (2017) reported only 4.2% for the same stage and World Bank study (2020) reported only 7.7% for even 4 stages including drying.

### ***Sampling scope could introduce representational bias***

While the apparent "improvement" from 13-16% (1999) to 10.7% (2020) may reflect mechanization, it could present sampling bias. Particularly, earlier studies (Nguyen, 1999; Nguyen et al., 2013; Dao & Nguyen, 2017) could study with newer equipment than studies conducted by World Bank (2020) and WFBR/Can Tho study (Kok et al., 2024). While WFBR/Can Tho study (Kok et al., 2024) indicated that the miller in study was a small and medium-capacity mill, the study did not report equipment age at the mill. However, given that 96% of Vietnam's rice mills are small-to-medium capacity operations (Báo Nhân Dân điện tử, 2022), and 90% use equipment over a decade old (Dao & Nguyen, 2017), the mill in WFBR/Can Tho study (Kok et al., 2024) could not be the very new establishment. Therefore, its finding of 22.3% of losses may represent the sector's proper baseline. However, the WFBR/Can Tho study (Kok et al., 2024) also noted that, because only one miller participated in the interview, the reported drying loss of 9.0% was provided solely by that miller, without verification as to whether this figure excluded losses due to expected moisture reduction. As a result, loss levels at processing stages might not be very reliable. Table 3 summarizes the methods applied in the studies reviewed.

*Table 3: A comparative analysis of study methodologies (1999-2024)*

| Report | Region | Sample size | Methods | Reference |
|---|---|---|---|---|
| WFBR/CGIAR<br>Can Tho University | Mekong Delta | 48 farms, 3 operators, 3 traders, 4 millers but just 1 miller reported | Field measurements and interview by questionnaire | Kok et at., 2024 |
| IRRI/ VnSAT project | Mekong Delta (8 provinces) | +800,000 farmers | Macro-model and secondary data | World Bank, 2020 |
| Mekong Delta Rice Research Institute (2013) | Mekong Delta (4 provinces) | 80 farmers, 10 millers, 20 exporters | Survey and interview | Nguyen et al, 2013 |
| Vietnam Technology Assessment (2012) | Mekong Delta | 11 provinces | Survey, audit and interview by questionnaire | Dao & Nguyen, 2017 |
| ACIAR / Vietnam PHTI | Mekong Delta, Red River Delta | 12 provinces | Expert review and literature | Nguyen, 1999 |

In summary, each research approach has its strengths: field-based measurement is vital for pinpointing current bottlenecks and enables targeted interventions; large-scale surveys are useful for identifying structural risks and highlighting regions that are behind; and comprehensive literature reviews help explain persistent, long-term constraints in the system. However, in today's rapidly evolving rice sector, only up-to-date, well-replicated, and operationally detailed fieldwork with rigorous, contemporary, and transparent methods can provide the solid evidence base needed for reliable modernization planning.

### 2.2.2 Definition and scope of quality-related losses

Quality-related losses in the report refer to visual defects which include discoloration, high broken rice, low head rice, fissuring which predisposes breakage, and contamination by chemical or biological hazards such as mycotoxins, pesticide residues and heavy metals (Nguyen et al., 2021; Nguyen et al., 2022). This review quantifies those quality-related losses by the quantity of rice non-conformities (mycotoxins, pesticide residues and heavy metals) without meeting the Vietnamese standard or exporting markets' requirements on grain quality (Bui et al., 2023). Table 4 shows the industry standards for main parameters in milling stage. Any results are out of these ranges implying their inefficiency and potential losses.

*Table 4: Industrial standards for milling*

| Parameter | Industry standards | Reference |
|---|---|---|
| Milled rice recovery | 68-72% | Hardke, 2012; IRRI, 2025a |
| Head rice yield | ≥ 55% | IRRI, 2025a |
| Broken rice rate | ≤10-14% | IRRI, 2025a |

#### 2.2.2.1 Appearance- and structure-related losses

Multiple studies (Nguyen et al., 2022; Bui et al., 2023) converge on rice fragile texture, fissuring and associated breakage as the dominant appearance-based losses. Akter and colleagues (2025) stated that rice with thin pericarp characteristics increases over-milling risks because continuous stripping of bran removal, could damage outer endosperm layers (Akter et al., 2025). Besides, a varietal trial involving 140 entries in the Mekong Delta reported that with chalkiness values from 0% to 86.7% and thin pericarp, head-rice yield fell sharply once chalky area exceeded 20%, confirming the inverse relation between chalkiness, thin pericarp and milling recovery (Bui et al., 2023). Moreover, rice with yellow kernels, damaged kernels, red/red-streaked kernels impact to level of quality consistency during processing. Table 5 presents visual defect limits following TCVN (2017) for those characteristics. Physiological work on drying kinetics links these traits to rapid moisture removal: kernels dried below their critical moisture threshold fissured and later fragmented during milling, a mechanism originally quantified in Asian drying trials (Champ et al., 1995). Although such experiments provide causal insight, they are often short-term and facility-specific; nationwide incidence and economic valuation of fissuring remain poorly documented.

*Table 5: Visual defect limits (TCVN, 2017)*

| **Defect Type** | **Vietnam** TCVN 5%-broken |
|---|---|
| Chalky kernels | ≤6% |
| Yellow kernels | ≤0.5% |

| **Defect Type** | **Vietnam** TCVN 5%-broken |
|---|---|
| Damaged kernels (non-heat) | ≤1% |
| Red/red-streaked kernels | ≤0.5% |

### 2.2.2.2 Mycotoxin-related safety losses

Mycotoxin risks associated with rice from Vietnam are aflatoxins and fumonisins, with some studies suggesting these are the main mycotoxin risks for Vietnamese rice (Phan et al., 2021). In a 2017-2019 survey of the Mekong Delta, aflatoxins were detected in 24% of paddy samples and fumonisins in 22%, some of which had higher quantities than EU thresholds (Phan et al., 2021). In a follow-up market sampling study in Cần Thơ, retail rice was found to be heavily contaminated, with 78.5% of samples containing aflatoxin B1, and 15.4% of those exceeding the Vietnamese acceptable limit of 5 µg kg-1 (Nguyen et al., 2025). There were also results from a broader survey of stored paddy between 2018-2022 which showed 12 mycotoxins, some of which were new, in 47% of the samples (Phan et al., 2024). The main reason for these results was attributed to warm and humid storage conditions, and the lack of prompt drying. The reported prevalence of these conditions also varies widely, from a rough estimate of 20-80% which is attributed to differences in supply-chain nodes and analytical methods.  The company also follows to food-safety requirements at Vietnam, EU, and Philippines in Table 6.

*Table 6: Food-safety contaminant limits (QCVN, 2011; EU, 2023; Balendres et al., 2019)*

| **Contaminant** | **Vietnam** (QCVN 8-1:2011/BYT) | **EU market** (Reg. 2023/915) | **Philippines** (Balendres et al., 2019) |
|---|---|---|---|
| Aflatoxin $B_1$ | 2 µg $kg^{-1}$ | 2 µg $kg^{-1}$ | 5 -10 µg/kg |
| Ochratoxin A | 5 µg $kg^{-1}$ | 3 µg $kg^{-1}$ | 5 µg $kg^{-1}$ |

### 2.2.2.3 Heavy-metal contamination and pesticide-residue hazards

Although Vietnam is not one of the countries with the largest accumulations of heavy metals-rich soils, especially in Mekong Delta. The standard for heavy metals in Vietnam is 0.2 mg/kg as Codex guidance (Codex, 2021). Most studies found heavy metals as iron at is 0.2 mg/kg in the north of Vietnam, instead of in the south of Vietnam (Tran et al., 2020; Chu et al., 2021). This makes sense when the history of south of Vietnam did not witness heavy metals from industrial and mining activities as the north of Vietnam (Chu, 2011; Nguyen et al., 2019).

Monitoring residues is not limited to export shipments. It now includes domestic and organic supply chains. The standard for pesticide residues in Vietnam is 0.01 mg/kg as for most pesticides (Nguyen, 2023). Surveillance of "organic" farms over a five-year period across six Mekong provinces revealed 18 detectable and prohibited active ingredients. Tricyclazole was detected in 63% of the samples while chlorpyrifos-ethyl was detected in 30% of the samples (Nguyen et al., 2022). Surveys of farmer practices in Trà Vinh led to the discovery of use of class II and III pesticides far above labeled dosages, as well as container disposal practices that are harmful to food and safety. Environmental and food safety concerns have been raised (Nguyen, 2021). Another study across ten provinces revealed that residues exceeded in triple rice systems that relied heavily on fungicides (Nguyen et al., 2022). While studies agree the fact that misuse persists, violation rates in the reports range from 10% to 60% reflecting the diversity of analytical panels and ignored production systems.

### 2.2.3 Definition and scope of economic loss

In the case of Vietnamese rice processing, economic loss can be described as the total monetary loss which includes loss quantification from decreasing in physical yield and quality-related loss. This measurement goes beyond physical loss to include grade reduction due to the presence of broken, discolored, or contaminated grains, as well as the economic loss due to residues of heavy metals, pesticide contamination, and mycotoxin (of the aflatoxin and ochratoxin types) breaches. Economic loss, by definition, captures the amount of value loss there is in the rice value chain from the paddy field to the finished product, including direct value loss (revenue that could have been earned from sales) and indirect value loss (increased input, handling, and cleanup costs) (Le, 2023; VNA, 2023).

The impact of economic losses for Vietnam is emerging in more recent studies at both the national and provincial levels. Bui et al. (2023) and the World Bank (2020) use spillage, breakage, and spoilage to theoretically amplify economic losses to quantify them. They evaluate losses based on the economic value reduction which includes the pricing of defective rice, quality discounts and the loss of export eligible shipments on account of contamination (Axmann et al., 2022; Ta Bui & Nguyen, 2023). Vietnam (2018) exclaims the Mekong Delta region has experienced over 3 trillion

VND (132 million USD) in post-harvest losses which is 1 trillion more than the value of 13 to 16 percent of the harvested crops. This equates to 10-12% of the region's rice production.

Identical methods estimate losses from inadequate drying and storage which increase the number of grains classified as 5-25% broken, resulting in a decrease in rice revenue of 2.3 percent (Le, 2023). A study on the agriculture in Tien Giang province also found a loss of 10.8 percent of agricultural revenue resulting in hundreds of billions of VND in losses annually (Customs News, 2023). Thus, the national estimate for post-harvest losses in Vietnam would exceed thousands of billions of VND.

There seems to be an agreement in the literature regarding the economic loss in the processing of rice in Vietnam is significant and preventable, with the range estimated between 10–14% of the value of production available in a year (VNA, 2023; Axmann et al., 2022). Also, the weakest and most susceptible parts of the process, which are the drying and storage, are where the losses can be up to 10% due to a mixture of mechanical lack of efficiency and biological decay (Le, 2023). In addition to this, an overarching issue cited in many of the papers is the lack of clarity in how to break down economic loss into quantitative and qualitative parts. While losses of broken kernels or shrinkage losses can be measured easily by weighing them, the estimated loss due to the qualitative problems of mycotoxin, heavy metals, pesticides, and non-compliant residues is often ignored until a rejection in export does compel a crisis response. In addition to this, different methodologies to the loss quantification problem in different studies lead to diverse economic losses. Nonetheless, approaches utilizing field surveys and monitoring together with economic paradigms and market studies could produce realistic estimates of losses.

## 2.3 Likely causes of rice loss in processing in Vietnam

In Vietnam, rice loss after harvest integrates both quantitative (physical) and qualitative (value, safety, and functionality) aspects of deterioration. Continuing the literature review, the author takes into account five important works, comprising WFBR/CGIAR Can Tho University (Kok et al., 2024), IRRI/ VnSAT project (World Bank, 2020)), Mekong Delta Rice Research Institute (Nguyen et al, 2013), Vietnam Technology Assessment (2012) (Dao & Nguyen, 2017), ACIAR/Vietnam PHTI (Nguyen, 1999), that cover a 20-year period for the most convergent processing-stage evidence-based loss explanations. Likely obsolete equipment for drying and milling, as well as poor process control, are some of the identified gaps and shortcomings.

## 2.3.1 Equipment and technology issues

### 2.3.1.1 Obsolete drying equipment (High impact)

Drying is one of the typical loss hotspots where obsolete drying technology is one of the primary factors contributing to quantitative rice loss in Vietnam. Studies conducted by Kok et al., 2024; Nguyen et al, 2013; Dao & Nguyen, 2017; Nguyen, 1999 agreed this statement. In particular, those studies report that the quantitative loss in drying alone accounts for 15-40% of total quantitative loss. In addition, the loss rate has been increasing from 4.2% in 2012 (Dao & Nguyen, 2017) to 9% in 2024 (Kok, 2024). Rice drying processes have mechanized significantly over the years, starting from sun drying to SGH flat-bed, SRR low-cost, SRA reversible, recirculating column, and fluidized-bed drying. Some of which, especially SGH flat-bed, were installed at many factories before 2013 (Phan, 2013; Dao & Nguyen, 2017). The research (Kok et al., 2024; Nguyen et al, 2013; Dao & Nguyen, 2017; Nguyen, 1999) also highlights that older dryers are imprecise in measuring grain moisture content, resulting in increased breakage and loss in grain mass during every operation.

Rice drying has the most critical impact on the quality of grains by removing moisture to 14% MC as the TCVN standards mark. This drying process in rice relies on the transfer of heat and mass with the surrounding air. Effective drying occurs when the vapor pressure inside the grains exceeds that of the drying air; if not, the grains would absorb moisture instead of losing it. When both pressures reach equilibrium, the grain and surrounding environment become hygroscopic equilibrium (Silva et al., 2008).

Reducing grain moisture initiates several chemical and physical processes (Inprasit & Noomhorm, 2001). Several researchers (Champ et al., 1995, Muller, et al., 2022; Kumoro et al., 2025; Barthwal, 2025; IRRI, 2025) have agreed on the observation that thermal stress during drying causes fissuring. This mechanism involves differential rates of moisture removal from the surface and the core of the grain, leading to internal stresses (Dong et al., 2010; Kumoro et al., 2025). As moisture is removed, the outer portions of the grain shrink due to external compressive forces, and internal vapor pressure due to heating causes the inner layers to expand. A combination of these stresses can lead to fissures, cracks, or breakage due to the outer surface's inability to expand elastically. Studies on seed production have found that air temperatures above 43°C for grains or 40°C for seeds will lead to kernel cracking or discoloration (Champ et al., 1995; Dong et al., 2010; Kumoro et al., 2025; Barthwal, 2025; IRRI, 2025). On the other hand, higher moisture content can lead to mold growth on the rice grains. Therefore, the model of temperature management and drying is critical for controlling the quality of dried rice.

Aging drying systems use excessively high or poorly controlled temperatures and do not utilize staged tempering (JIRCAS, 2005). This leads to steep moisture and temperature differences between the outer pericarp and the starchy core (Cnossen et al., 2003; Chitsuthipakorn & Thanapornpoonpong, 2022; Garcia-Llobodanin & Billiris, 2023). Increased temperature leads to micro-fissures that form and propagate with later applied mechanical stress (Cnossen et al., 2003; Chitsuthipakorn & Thanapornpoonpong, 2022; Garcia-Llobodanin & Billiris, 2023). A micro-fissured state results in the kernels shattering during the milling process, drastically reducing the head-rice yield (HRY) and turning value into low-priced broken rice (Lan & Kunze, 1995; Garcia-Llobodanin & Billiris, 2023). In addition, rice dried incorrectly or excessively may result in discoloration that, alongside delayed cooling, leads to oxidative yellowing, contributing to a loss of rice quality (Liu et al., 2022).

Some studies (Dong et al., (2010); Wazed et al., (2022); Kumoro et al., (2025)) consider only one variety of rice, and amylose content and a variety's stiffness both modulate fissure sensitivity. For different varieties, however, especially the high-value fragrant and specialty varieties with low amylose content, which tend to be more sensitive to fissures, the drying process needs to be more carefully tailored.

#### 2.3.1.2 Outdated milling equipment (High impact)

Apart from drying equipment, all studies (Kok et al., 2024; Nguyen et al, 2013; Dao & Nguyen, 2017; Nguyen, 1999) agree that rice milling poses the most significant hotspot of quantitative loss in Vietnam rice rut rice defect loss and suffers the greatest loss due to outdated milling equipment. In these studies, the milling loss was found to be 12-35% of the total processing loss (Kok et al., 2024, Nguyen et al., 2013, Dao & Nguyen, 2017, Nguyen, 1999). Furthermore, Le (2023) and Nguyen et al., (2013) show that small scale mills only managed to recover 60-66% of milled rice while modern mills achieve 68-72% milled rice recovery. In addition, the proportion of broken rice in the total milled rice has stagnated at a high level of 15% instead of the optimal 5-10% (Richardson et al., 2021; Norbu, 2022)

After years of slow modernization, rice milling in Vietnam has mechanized to the level of steel hullers, rubber-roll huskers, and multi-pass machines, moving away from traditional pestle and mortar methods (Nguyen, 2013; Le 2023). However, the industry is still characterized by more than

80,000 small mills functioning at a capacity of 0.5-2 tons/hour and installed mostly before 2013. This is in stark contrast to the higher and fewer consolidated facilities in Thailand (Dang, 2017; Vichinrojjarul, 2020; and Le, 2023).

The rice milling process has the most significant linkage to the degree of refinement of a grain and the yield of whole white rice, which involves the separation of husk and bran layers from the rice grain. This is done with delicate forces (mechanical, pressure, and stage processing) to avoid damaging the kernel. Effective milling occurs when the stresses applied are below the threshold to fracture the kernel; if the forces are too much, the process will be breakage instead of clean separation (Le, 2023; IRRI 2025d).

However, obsolete milling equipment initiates a series of mechanical and structural failures that result in generous losses (Le, 2023). It is agreed in several studies (Harvie, 2001; JICA, 1997; World Bank, 2020; Nguyen et al., 2013; IRRI, 2025) that the mechanical processes of stress induced during the milling of rice with old machines are excessively contributory to the breakage of the rice kernels. This is due to several critical factors such as worn-out rubber rolls of the dehusking units that create uneven pressure, old whitening machines lack precise pressure control, and old aspiration systems do not recover valuable bran and dust fractions (Le, 2023). In these systems, kernels are subjected to impact forces of more than 20% hull and 10% bran layers which causes them to fracture and break fully.

Concentrated mechanical pressure, which is ancient milling systems, lack a consecutive step by step approach to processing. Located between the worn rubber rolls and whitening stones, these become localized known as stress concentrations. Legacy systems lack pressure control which causes compressive stress which results in micro-fractures. These systems, when left unregulated, cause the mechanical properties to be compromised and constantly replaced, forcing kernels to break and significantly decreasing head-rice yield (HRY).

Milling, much like drying technologies, has functional constraints based on a single cultivar for single stream processing (JICA, 1997; Nguyen et al., 2013; World Bank, 2020). As such, for different rice varieties, milling settings require careful recalibration. This is particularly true for high-value fragrant and specialty varieties because their distinct structural properties make them vulnerable to merciless damage from rigid, outdated machinery.

## 2.3.2 Other operations and processing conditions

### 2.3.2.1 Harvest & raw-material mismatch

Harvest and raw-material mismatch, including a suboptimal harvest window, has contributed to rice losses (Ilieva et al., 2019; Qu et al., 2021). This can be attributed to the interaction of grain hardness and amylose content. In theory, if rice is harvested too early, particularly when moisture content suggests immature fungal-laden kernels, they become more susceptible to breakage during processing (Siebenmorgen & Matsler, 2006; Silva et al., 2008; Ilieva et al., 2019). Late harvesting leads to brittle, overly dry grains which are equally vulnerable to breakdown (Siebenmorgen & Matsler, 2006; Silva et al., 2008; Ilieva et al., 2019). These drastic environmental changes during the rice life cycle prevent grains from maintaining structural quality, reducing milling recovery and head rice yield.

Also, as noted by Nguyen (2023), the mixing of rice with various degrees of maturity results in a different level of hardness, structure, and amylose content, which adds complexity to mechanical processing. The reason for this is that kernels with "mismatched" properties respond differently to the mechanical processing of milling which causes uneven dehusking and increased breakage, especially of the fragrant high-value varieties. Synchronizing studies by Nguyen (2023) and Le (2023), conducted in Vietnam and neighboring rice-growing countries, confirm improvements in milled rice yield and reduced broken kernels by synchronizing harvest with variety maturity and moisture content at 16–20% being optimal.

On the other hand, the system adopted by Vietnamese smallholders is responsible for the creation of mixed and uneven lots coming into the mill (Axmann et al., 2022). The extensive use of interviews and questionnaires is known to introduce recall bias resulting in the underestimation of these losses. However, "mismatched raw material" as a problem is persistent and vexing as climate variability and market considerations continue to shape harvest timing. Targeted intervention strategies for variety segregation, harvest timing, and best practice dissemination are needed to stem loss and improve the value chain profitability in the Vietnamese rice sector.

### 2.3.2.2 Moisture mismanagement (High impact)

Moisture mismanagement stands out as a key hotspot causing significant losses within Vietnam's rice processing industry. Particularly, moisture mismanagement causes a compound series of physicochemical and mechanical failures that greatly amplify processing losses (Kok et al., 2024; Nguyen et al, 2013; Dao & Nguyen, 2017). Studies (Kok et al., 2024; Nguyen et al, 2013; Dao & Nguyen, 2017) agree that moisture imbalances during processing amplify the degree of kernel breakage through intricate stress interactions. The degradation pathway consists of several interlinked processes: paddy with high moisture content (>15%) produces soft and friable kernels that over-compress during hulling; on the other hand, over-dried paddy (< 13%) becomes brittle and is prone to fracture under stress. As kernels with incorrect moisture content move through processing equipment, they are subjected to excessive moisture-related stress, resulting in micro-fractures and, in some cases, complete fragmentation. Cross-study evidence demonstrates a consistent trend of mills processing paddy outside the 13-14% moisture range producing broken rice ratios 50-80% higher than those of facilities maintaining optimal moisture control (Siebenmorgen & Matsler, 2006; Dong et al., 2010; Lan & Kunze, 1996). Furthermore, excessive moisture content during storage promotes mold development, oxidative yellowing, and shortens shelf life (Lantin, 1999; Borlagdan et al., 2017).

Despite the findings covering the key drivers of moisture content in rice loss, there is a clear gap in seasonal moisture management. Most studies focus on moisture content below 26% MC. However, the moisture content in rice can exceed this figure due to climatic shifts and varying regions of cultivation. Thus, it becomes essential to control losses and improve resilience with respect to input moisture levels.

#### 2.3.2.3 Storage inefficiencies

Throughout the Vietnamese rice value chain, storage conditions and management practices are significant drivers of rice losses. In Vietnam, storage management is still poorly practiced and contributes to losses throughout the rice value chain. Storage losses can include mycotoxin and aflatoxin B1 contamination, pest infestation, and discoloration, among others.

Poor storage conditions in Vietnamese rice facilities promote fungal growth. Species such as *Fusarium Proliferatum* and *Aspergillus* flavus thrive at 28–35°C and 80–94% humidity (Masood et al., 2018; Phan et al., 2024; Cao et al., 2025). When rice is stored above 14% moisture content, water activity rises to approximately 0.78, accelerating mycotoxin production, particularly aflatoxin B1, which accumulates at rates up to 4.6 μg/kg/day (Masood, 2019; Cao et al., 2025). Simultaneously, pest infestation follows predictable patterns for the rice weevil pest (*Sitophilus oryzae)* which tends to multiply during storage up to three months, resulting in an infestation rate of 25.8% at room temperature and 0% at 5°C (CABI, 2021; Gurjar, 2025). These pests consume grain mass which leads to a loss in weight during infestation periods. Studies reveal Brown rice with a moisture content of 16% sustained 29.2% weight loss for 41 weeks while rice with controlled moisture at 14% only showed 1.8% loss due to pest infestation (Gvozdenac et al., 2020). Traditional storage techniques using open warehouses and jute bags worsen the situation as moisture and peak temperature, as well as pests freely access the product.

## 2.4 Proposed technology changes to reduce rice loss in processing

Postharvest losses, especially drying and milling, are on average 9% and 0-6.5%, respectively. This represents not only merely operational inefficiencies but certain limitations in process control. The WFBR/CGIAR Can Tho University study (Kok et al., 2024) documented total processing losses of 22.3% in the Mekong Delta. This upward change raises critical questions: what technological interventions could address those losses at factory-level, and under what Vietnamese operational conditions might they prove effective? While the international literature increasingly highlights IoT, AI, and digital agriculture as transformative solutions, rigorous evidence for their efficacy in Vietnam's specific context remains sparse due to a wide range of operational conditions: capital constraints, aging equipment, processing controls.

### 2.4.1 AI-driven milling quality control: Recent scholarly evidence

AI-based quality control systems such as convolutional neural networks (CNNs), deep neural networks (DNN), and artificial neural networks (ANN) now achieve >99% accuracy in rice grain classification (Asif et al. 2025; Ilo et al., 2025). However, these systems were validated in modern facilities with integrated digital infrastructure. For Vietnamese mills operating 10–20-year-old equipment, the critical question is not whether AI works, but whether retrofitting is economically viable at their scale. Similarly, Çınarer (2024) reported that Support Vector Machine (SVM) algorithms achieved 93.53% accuracy in rice variety classification with Area Under Curve (AUC) values of 99.18%, demonstrating that morphological features can reliably distinguish rice types promising for automated quality grading.

Ilo et al. (2025) advanced this further by developing a hybrid YOLOv8 deep learning model for real-time rice milling morphology detection, achieving 99.5% classification accuracy for distinguishing intact, broken, and brown rice grains at processing speeds of 15 frames per second. This real-time capability is critical for industrial applications where manual inspection creates bottlenecks and inconsistencies. Asif et al. (2025) confirmed these findings, showing that CNN architectures including MobileNet (98.94% accuracy) and VGG16 (99.47% accuracy) can effectively categorize rice types, suggesting that transfer learning from pre-trained models offers cost-effective deployment pathways.

These technical capabilities establish proof-of-concept: AI-based quality control *can* replace manual inspection with superior accuracy and speed. However, the studies were conducted under controlled laboratory or modern facility conditions. To Vietnam situation, Vietnamese small and medium mills' equipment at 10-20 years old might lack the integrated digital infrastructure that enable seamless AI deployment. Therefore, the critical question now is not whether AI works, but whether retrofitting older equipment with AI systems/camera systems and processing units is economically viable at Vietnamese mill scales.

### 2.4.2 IoT-enabled monitoring and precision drying systems

IoT-based monitoring systems have demonstrated substantial improvements in drying precision and loss reduction across multiple peer-reviewed studies (Nebrida, 2024; Rodrigues et al., 2024; Hiendro et al., 2025; Latif et al., 2025; Tang et al., 2025). Rodrigues et al. (2024) showed that IoT sensors combined with machine learning models (Random Forest and Artificial Neural Networks) could accurately predict corn grain quality parameters including moisture content, germination, and dry matter loss during transportation, drying, and storage stages, with Random Forest achieving the best predictive performance.

For rice specifically, a study by Hiendro et al., (2025) developed a LoRa-IoT-based real-time paddy grain drying and monitoring system that successfully tracked heated air velocity, temperature, and relative humidity during drying from 25% to 14% moisture content, achieving moisture monitoring accuracy with RMSE of 6.17%. Similarly, Nebrida (2024) reported that an Arduino-driven rice grain dryer system demonstrated precise temperature control within 50-60°C, reducing moisture from 25.5% to 13.5% within 125 minutes for 25kg batches. This created a chance that low-cost microcontroller systems can achieve reliable drying outcomes.

Latif et al., (2025) developed an IoT-based real-time framework integrating DHT11 temperature/humidity sensors with HX711 load cells for grain drying monitoring, demonstrating that integrated sensor systems can optimize energy consumption while maintaining drying quality across seasonal variations. Tang et al., (2025) used near-infrared spectroscopy combined with CNN models to non-destructively predict brown rice rate, milled rice rate, and head rice rate, showing that spectral sensing can provide real-time quality feedback during milling operations.

While these systems demonstrate technical feasibility, their implementation assumes: (1) reliable internet connectivity for data transmission; (2) technical capacity for sensor calibration and maintenance; (3) integration infrastructure connecting sensors to existing dryer controls; and (4) operator willingness and ability to respond to real-time data. However, none of these preconditions can be assumed in Vietnam's old mill context. The one Vietnamese study on IoT agricultural applications (Eng.VNUA, 2023) noted that "applying new technologies to increase agriculture production while reducing post-harvest losses" remains largely aspirational rather than empirically validated at scale.

### 2.4.3 Hermetic and controlled atmosphere storage systems

Hermetic storage technologies have received rigorous peer-reviewed validation in recent studies. Yousuf et al., (2025) conducted comparative field trials demonstrating that hermetic bags (specifically GrainPro PHB) significantly outperformed conventional storage: moisture increase was minimal (0.33-0.50% versus 1.17-1.33% in conventional bags), grain damage was lowest (2.38-2.44% versus 4.71-5.08%), and seed germination remained highest (90.33-90.50% versus 82.67-84.33%) over six-month storage periods.

Nitrogen-controlled atmosphere (NCA) storage is now supported by mechanistic biochemical evidence (Dong et al., 2025). Research published in 2024-2025 demonstrated that NCA storage at 93%+ nitrogen concentration inhibits lipase and lipoxygenase enzymes responsible for lipid hydrolysis and oxidation, thereby preserving brown rice quality for extended periods. Shin et al., (2024)'s study confirmed that nitrogen storage effectively suppressed grain respiration rates, maintained germination capacity, and reduced both bacterial and mold counts, with mass loss decreasing up to 224.5% compared to standard atmospheric storage.

Hermetic storage represents perhaps the most cost-accessible technology for Vietnamese processors, with unit costs of $500-1,500 being within reach of medium-scale operations (CGIAR Research Program on Rice, 2019). However, adoption depends on whether markets reward extended storage life and quality preservation. If commodity rice trading continues to prioritize volume over quality differentiation, the economic incentive for hermetic investment remains weak despite proven technical benefits.

### 2.4.4 Technology integration and digital agriculture systems

Recent scholarship emphasizes that integrated technology systems yield superior results compared to single-technology implementations. Mansoor et al. (2025) provided a comprehensive review of smart sensor integration in precision agriculture, documenting how soil moisture sensors, plant stress sensors, and environmental monitors can be networked for coordinated decision-making. The global IoT grain bin monitoring system market reached USD 1.14 billion in 2024 with projected CAGR of 12.8% (Dataintelo, 2023), reflecting substantial commercial investment in integrated monitoring platforms.

Digital twin technology is emerging as a transformative approach because it could create virtual replicas of physical systems linked to real-time IoT data. Melesse (2025) reviewed digital twin applications in crop monitoring, highlighting capabilities for predictive analytics, remote monitoring, resource optimization, and automated decision support. In Vietnam specifically, Can Tho University announced development of a "National Digital Twin" concept for smart agriculture in the Mekong Delta (CTU, 2025), though implementation details and validation data remain unavailable.

Onike, 2025 conducted a comprehensive review of IoT in agriculture with 191 citations, documenting advantages including 20-25% yield improvements and 15-20% resource use reductions in optimized implementations. However, the research determined significant barriers including infrastructure limitations, cost constraints, and digital literacy gaps that constrain adoption in developing country contexts.

### 2.4.5 Proposed technology summary

The 2023-2025 peer-reviewed literature establishes clear technical capabilities:

- CNN and deep learning models achieve >99% accuracy in rice grain classification and defect detection (Azeez et al., 2024; Ilo et al., 2025; Asif et al., 2025)
- IoT sensor networks enable real-time monitoring of drying parameters with accuracy sufficient for process control (Rodrigues et al., 2024; Okonya et al., 2025)
- Hermetic and nitrogen-controlled storage demonstrably preserve grain quality over extended periods (Yousuf et al., 2025)

Despite this technical evidence, gaps on applying these technologies in Vietnam still exist, raising critical questions:

1. Retrofitting feasibility: Can AI vision systems and IoT sensors be effectively integrated with Vietnam's predominantly 10–20-year-old milling equipment, or does meaningful modernization require complete equipment replacement?

2. Economic viability at scale: What is the actual return-on-investment timeline for sensor systems, automated controls, and quality sorting equipment in Vietnamese mills?

The international scholarly literature demonstrates that IoT, AI, and digital agriculture technologies can substantially reduce post-harvest losses under favorable conditions. Although most small and medium Vietnam mills could not be in as good conditions as samples in previous literature, those companies still have a chance to access, adjust, and adapt above proposed technology. This directly motivates this thesis's empirical approach: factory-level investigation of actual operating conditions, equipment constraints, and economic realities can determine which technologies offer realistic modernization pathways for Vietnam's rice processing sector.

## 2.5 Research gaps and recommendations

### 2.5.1 Limitations of methodological approaches

The five major Vietnamese studies used different methods: expert review (Nguyen, 1999), surveys and interviews (Nguyen et al., 2013; Dao & Nguyen, 2017), macro-models (World Bank, 2020), and direct field measurement (Kok et al., 2024). Each captures certain information while missing others.

Survey-based studies consistently reported lower losses (drying: 1.9–4.2%) than direct measurement (drying: 9.0%), suggesting dependency of data accuracy to operators. Macro-models provide national-level perspective but obscure stage-specific drivers. Field measurement offers precision. However, regarding processing data, Kok et al., (2024)'s study also depended on response from one miller through questionnaire without verification, reducing reliability. As a result, there is methodology in those studies managing precision by primary data. This explains why reported losses vary threefold (6.4–22.3%), reflecting measurement approach as much as actual sectoral conditions.

### 2.5.2 Research results in inconsistencies

Loss estimates vary dramatically: total losses range 6.4–22.3%; drying losses 1.9–9.0%; milling losses 0–6.5%. Stage-wise definitions also differed in World Bank study (2020), making difficulties to compare. Thus, loss calculated at each stage might be the better way to identify loss hotpots. Moreover, equipment that were studied as "5–7 years old" in 2017 is now 13–15 years old, rendering older findings increasingly irrelevant. As a result, policy or decisions for investment could not be reliably guided by such inconsistent evidence.

Moisture management gaps are seasonal, as the majority of studies center around the 26% MC mark. Moisture content of the rice is likely to be higher due to seasonal climate shifts along the location of the cultivation. There is a lack of understanding of how different milling technologies operate under differing conditions and rice varieties, therefore, the analysis pertaining to equipment is lacking.

### 2.5.3 Research gaps requiring case study methodology

An overview from the literature shows there are significant gaps in knowledge requiring a specific focused case study on rice processing factories in Vietnam:

- It lacks validated factory-level measurement in Vietnam under actual operating conditions. Operationally centered loss mechanisms require the intricate examination of the interactions between equipment, the operators, the surroundings, and how these collectively lead to the loss of the primary data. The current studies on loss causation at the factory level are devoid of a comprehensive understanding of equipment age, maintenance, and processing efficiency.
- The existing capabilities for loss monitoring in real-time are insufficient. Many existing studies depend on scheduled evaluations or the perception of the farmers/workers instead of the monitoring of the real-time processing activities. The case study methodology can serve systematically document loss at various processing levels.
- The economic loss requires calculation from processing decisions and evaluating both quantitative output and qualitative attributes, making processing and technology improvements, or in the case of significant costs, equipment upgrades.
- Technology as IoT, AI has not really validated for Vietnam, especially for rice mills. Therefore, factories' board of directors might question whether these technologies can be retrofitted to aging equipment, whether they are economically viable at small mill scales, or whether markets reward quality improvements enough to justify investment
- The specialized contextual factors of Vietnam's processing environments which include the processing conditions, the types of rice, the quality of the product, compliance with the TCVN legal standards, the need in the market, and the constraints from the supply chain need in-depth scrutiny which can solely be achieved by focused case study research in real working environments.

This thesis addresses these gaps through factory-level direct measurement, documenting equipment-specific loss drivers and evaluating technology feasibility under real-world constraints.

# 3. Material and Methodology

## 3.1 Research design and methods

The focal point for this mid-level rice processing workshop within the Mekong Delta Region of Vietnam is the CDo Company, chosen through the single-case study approach. This strategy is deemed most suitable due to providing critical understanding of the interventions employed and their measurable effects on loss reduction (Commission for Environmental Cooperation, 2019). Single-case design is flexible and permits the investigation of a bounded context (Commission for Environmental Cooperation, 2019; Kazdin, 2019).

This study relies primarily on a quantitative approach integrating measurements of technology used as processing losses and reviewing the technology and operations. This insight provides an actionable analysis relative to the related industry which could be beneficial for the stakeholders in the industry (Commission for Environmental Cooperation, 2019).

## 3.2 Study area selection

Below is brief information about why CDo to be selected for the project:

- Strategic positioning: CDo is in the Co Do district of Can Tho province which is the center of Mekong Delta rice production.
- Scale representativeness: CDo is positioned as a mid-level processor as its annual capacity is 45,000 MT, which is representative of the middle-range integrated processor category.
- Old equipment: CDo's equipment was installed in 2011 and was a mix of domestic (Bui Van Ngo) and imported (Satake, Buhler) equipment.
- Market diversity: The company serves a mix of market segments with 30% premium, 55% mid-range, and 15% domestic indicating a representative of Vietnamese export-oriented mills.
- Operational accessibility: The processor had openness to control access towards the processing and quality control processes, and the financial documentation for analysis.

## 3.3 Data collection methods

### 3.3.1 Primary data collection

The direct measurement approach was utilized for the quantitative assessment of rice post-harvest losses as per international standards. The methodologies outlined for data collection include the following.

- Record keeping: Input and output recording through weight measurement at every processing stage using digital scales with an accuracy of ±0.1g.
- Moisture content assessment: Measurements from the Wile 55 moisture tester (3 replicates per measurement) every 2 hours during the drying process, increasing the frequency to every 30-60 minutes as moisture content neared the target.
- Observation of the processes: Equipment settings, timers, and their respective durations for each processing stage

### 3.3.2 Observation and documentation

Integrated systematic observation for processing operations documented over multiple production cycles to account for the variability in season and the operational practices. The most important include:

- Procedures for operating the equipment.
- Control practices for quality.
- Conditions related to the handling and storage of the materials.

### 3.3.3 Secondary data analysis

Analyzing company records which include:

- Quality control logs and rice sample rejection records documenting internal assessment for physical defects, contamination levels, and adherence to international benchmarks (TCVN, and Philippines and Indonesia import regulations).
- Market and pricing data

## 3.4 Sampling methods

Observations and assessments focused on the DT8 variety (40% of production) subsampling. To quantify loss, the primary data collection period spans three separate days (December 12, 2024, December 17, 2024, and December 25, 2024) during the company's processing of 36 batches of DT8 rice. Each batch is approximately 30 tons. The data collection period is documented in section 3.5. Data collection methods. To describe qualitative loss, under confidentiality constraints, data provided by the factory concerning the rates of non-conformity of batches processed for DT8 and the total of finished goods which were deemed substandard over the 12-month period (1st January 2024 – 1st January 2025) were utilized.

## 3.5 Data analysis methods

### 3.5.1 Loss quantification and descriptive statistics

All measured parameters were subjected to both descriptive and inferential statistical analysis.

Descriptive statistics include calculations of means, standard deviations (SD), 95% confidence intervals (CI), ranges, and coefficient of variation (CV) for all loss parameters across the 36 batches. These parameters characterize the central tendency, dispersion, and stability of processing losses at each stage.

The coefficient of variation (CV) was calculated to assess process stability:

$$CV = \frac{SD}{Mean} \times 100\%$$

CV interpretation thresholds:

- CV < 10%: Highly stable process (systematic factors dominate)
- CV 10-20%: Moderate variability (mixed factors)
- CV > 20%: High variability (random/upstream factors dominate)

Additionally, the calculation of descriptive parameters is done as follows Table 7 and Table 8:

*Table 7: Primary loss calculation formulas (Suismono & JICA, 2012)*

| Loss Category | Formula | Application |
|---|---|---|
| General Loss Rate | $L_{general}\% = \frac{m_{in} - m_{out}}{m_{in}} \times 100$ | Used for receiving, cleaning, storage, color sorting, packaging |
| Drying Loss (Dry | $m_{dry\ matter} = m_{\ in} \times \frac{1 - MC}{100}$<br>$L_{drying}\% = \frac{m_{dry\ matter\ in} - m_{dry\ mater\ out}}{m_{dry\ mater\ in}} \times 100$ | Specifically for drying stage to exclude water evaporation |

| | | |
|---|---|---|
| Matter Basis) | | |
| Milling Loss Rate | $L_{milling}\% = RK - RL$ | Comparing actual recovery with controlled milling process, in which Recovery of Control applied at 70% around 68-72% |
| Direct physical Loss | $L_{direct}\% = m_{in} - m_{out}$<br>$L_{direct}\% = \frac{m_{in} - m_{out}}{m_{in}} \times 100$ | Physical quantity loss including all by-products, applying at milling stages. |

*Table 8: Yield and recovery indicators during milling (Bao, 2019)*

| **Indicator** | **Formula** |
|---|---|
| Milled Rice Weight | $m_{MR} = m_{HR} + m_{BR}$ |
| Milled Rice Yield (MRY) | $MRY\ (\%) = \frac{m_{MR\ out}}{m_{in}} \times 100$ |
| Head Rice Yield (HRY) | $HRY\ (\%) = \frac{m_{HR}}{m_{in}} \times 100$ |
| Broken Rice (of milled rice) | $BR\ (\%) = \frac{m_{BR}}{m_{MR\ out}} \times 100$ |
| Husk Percentage | $Husk\ (\%) = \frac{m_{Husk}}{m_{in}} \times 100$ |

### 3.5.2 Inferential statistics for root cause analytics

#### 3.5.2.1 ANOVA and Post-hoc analysis

One-way Analysis of Variance (ANOVA) was conducted to determine whether there is a statistically significant batch-to-batch variation (Andriani et al., 2024; Garcia-Llobodanin & Billiris, 2023). Moreover, ANOVA tests whether mean values differ significantly across categorical groups. In this study, ANOVA was conducted to answer the following research questions:

1. Do processing losses differ systematically by collection date, or are they consistent across the observation period?
2. Does input moisture content significantly affect losses at different processing stages?

**Hypotheses**

- $H_0$: $\mu_1 = \mu_2 = \mu_3$ (Mean losses are equal across groups)
- $H_1$: At least one mean differs significantly

**Grouping Variables**

Two grouping variables were examined:

1. Collection date (three levels): December 12, December 17, and December 25, 2024. The grouping variable is used to assess temporal variability in losses and validate measurement consistency
2. Input moisture content (four levels): 27%, 28%, 29%, 30%. The grouping variable is used to identify moisture-driven loss patterns and quantify upstream factor effects.

ANOVA applications by drying stage and milling stage where losses might happen significantly and ANOVA application for total loss presenting in Table 9**.**

*Table 9: ANOVA Application (Andriani et al., 2024; Garcia-Llobodanin & Billiris, 2023)*

| Processing stage | Outcome variables tested | Purpose |
|---|---|---|
| Drying stage | Drying loss ~ Collection date | Assess temporal consistency |
| | Drying loss ~ Input MC | Test upstream factor effect |
| Milling stage | Milling loss ~ Collection date | Assess temporal consistency |
| | Milling loss ~ Input MC | Test equipment vs. upstream factors |
| | HRY ~ Collection date | Assess HRY temporal consistency |
| | HRY ~ Input MC | Test equipment vs. upstream factors |
| Overall | Total loss ~ Collection date | Validate measurement reliability |

Statistical significance was set at $\alpha = 0.05$ for all tests. This significance level was chosen to maintain adequate statistical power given the sample size ($n = 36$ batches) while remaining consistent with standard practice in rice post-harvest loss research (Andriani et al., 2024; Garcia-Llobodanin & Billiris, 2023)

### 3.5.2.2 Post-hoc analysis

Where ANOVA indicated significant differences ($p < 0.05$), Tukey's Honestly Significant Difference (HSD) post-hoc tests were performed to identify which specific pairs differed significantly (Andriani et al., 2024; Garcia-Llobodanin & Billiris, 2023).

**Effect size reporting**

Effect size was reported using eta-squared ($\eta^2$), calculated as below and its interpretation in Table 10:

$$\eta^2 = \frac{SS_{between}}{SS_{total}}$$

*Table 10: Effect size interpretation followed Richardson (2011) guidelines*

| $\eta^2$ Value | Effect Size |
|---|---|
| $\eta^2 < 0.06$ | Small |
| $0.06 \leq \eta^2 < 0.14$ | Medium |
| $\eta^2 \geq 0.14$ | Large |

#### 3.5.2.3 Regression analysis

Linear regression analysis was conducted to model predictive relationships between input moisture content / equipment and processing losses, following established methodology in rice post-harvest research (Liambee et al., 2022; Garcia-Llobodanin & Billiris, 2023). Moreover, this analysis aimed to identify which operational factors most strongly predict processing losses and quantify effect sizes for intervention prioritization.

Three primary regression models were constructed in Table 11:

*Table 11: Regression models*

| Model | Dependent variable | Independent variable | Purpose |
|---|---|---|---|
| Model 1 | Drying loss (%) | Input moisture content (%) | Quantify moisture–drying loss relationship |
| Model 2 | Total loss (%) | Input moisture content (%) | Estimate overall upstream contribution |
| Model 3 | Head rice yield (%) | Input moisture content (%) | Test equipment vs. upstream causation |

For each model, the coefficient of determination ($R^2$) was used to quantify the proportion of variance explained by the predictor variable, enabling variance decomposition into upstream contribution ($R^2 \times 100\%$) and equipment/residual contribution ($100\% - R^2$). This approach aligns with standard practice where $R^2$ values indicate model adequacy and the relative importance of different loss factors (Ogunbiyi, 2018; Mahfeli et al., 2022). Model significance was assessed using F-statistics and p-values at $\alpha = 0.05$, with slope coefficients ($\beta$) representing effect sizes for intervention prioritization (Ogunbiyi, 2018).

### 3.5.3 Economic loss assessment

Economic loss is evaluated by two main pathways:

- Quantity/value degradation inside the milling line (low Head Rice Yield and high broken-rice output).
- Complete rejection of finished rice due to contamination or quality non-conformities.

All calculations adopt 2024 price data for Vietnamese 5%-broken DT8 rice (US$520/ton) and assume broken kernels earn 60% of the head-rice price (World Bank, 2019), equivalence with US$312/ton of broken rice. Assuming that the main revenue of factory comes from selling head rice and broken rice.

***Batch Revenue***

$$Batch\ Revenue = m_{HR} \times P_{HR} + m_{BR} \times P_{BR}$$

***Economic loss per batch from low HRY***

$$L_{economic/batch} = R_{theoretical} - R_{empirical}$$

In which, assuming that theoretical batch revenue ($R_{theoretical}$) has HRY accounting for 55% of milled rice and broken rice percentage of the total original rough rice is 10% (IRRI, 2025a).

***Economic Loss per year for DT8, accounting for 40% HRY of total productivity (45000MT).***

$$L_{economic/year} = \frac{L_{economic/batch} \times 0.4 \times 45000}{HRY\ (\%)}$$

***Economic loss per batch from DT8 rejected quality***

$$Economic\ Loss\ from\ rejected\ quality = Quantity\ of\ Head\ Rice\ Rejected\ x\ Head\ Rice\ Price$$

$$L_{quality} = m_{HR} \times P_{HR}$$

***Total economic loss for DT8***

$$L_{total\ economic} = L_{economic/year} - L_{quality}$$

## 3.6 Measurement of reliability and potential bias

The design of the study identified and addressed several potential sources of measurement error and bias:

- Instrument calibration: Digital scales (±0.1g accuracy) were verified against certified reference weights before each collection day. The Wile 55 moisture tester was calibrated per manufacturer specifications, with three replicate readings taken by measurement to account for instrument variability; the means of triplicates was used for analysis.
- Operator variability: Processing operations at CDo involve multiple operators across shifts. To minimize operator-related variability, data collection was conducted during consistent shift periods, and the researcher directly observed and recorded measurements rather than relying solely on operator-reported data. However, some operator-to-operator variations in equipment handling (e.g., paddy loading rates, tempering decisions) may have influenced batch outcomes. This variability was partially captured through batch-level analysis but could not be fully isolated without a controlled experimental design.
- Measurement timing: Weight measurements were taken at standardized points in the processing sequence (post-receiving, post-drying, post-husking, post-whitening, post-grading). Minor timing variations (±5 minutes) are unlikely to materially affect weight-based loss calculations but are acknowledged as a source of minor measurement noise.

Potential biases:

- Selection bias: The three collection days were selected based on operational scheduling and researcher access, not random sampling from the production calendar. Results may not capture atypical operating conditions.
- Hawthorne effect: Operator awareness of data collection may have influenced behavior toward more careful processing. Therefore, measured losses may underestimate typical operational losses.
- Single-source data for quality losses: Quality non-conformity data were provided by factory records rather than independently verified, introducing potential reporting bias.

Mitigation: multiple data sources (direct measurement, factory records, visual observation) were triangulated to validate findings when it is possible. In the meanwhile, limitations that could not be fully mitigated are acknowledged explicitly in the interpretation of results (Chapter 5).

## 3.7 Scope limitations and generalizability

This study employs a single-case design with inherent boundaries that must be explicitly acknowledged:

- Single facility: Data was collected from one mid-capacity mill (CDo Company, 45,000 MT/year). While CDo was selected for representativeness of Vietnamese small-to-medium mills, the findings may not fully generalize to mills with different equipment configurations, management practices, or regional conditions.
- Single variety: Analysis focused on DT8 rice, which represents 40% of CDo's production. DT8 is a common medium-grain variety, but loss rates may differ for long-grain export varieties, fragrant/specialty varieties with different amylose content, or glutinous rice that responds differently to drying and milling stresses (Kumoro et al., 2025).
- Single season: Data collection occurred in December 2024 (Autumn-Winter season). Seasonal factors may affect processing losses and differ loss levels. This is because seasonal factors such as ambient temperature, humidity, and incoming paddy moisture vary throughout the year and months. For example, the Mekong Delta's main harvest seasons (winter-spring, summer-autumn, autumn-winter) present different operational challenges not captured in this single-season study.

Generalizability considerations: Despite these limitations, the single-case design was deliberately chosen because: (1) No Vietnamese study has previously documented factory-level losses with this level of operational detail; (2) The methodology can be replicated at other facilities to build comparative evidence; and (3) CDo's equipment profile reflects the modal Vietnamese mill, suggesting findings have indicative value for similar operations.

Results should be interpreted as representative of conditions at one mid-capacity mill during one processing period, providing a detailed baseline that future multi-site studies can extend and validate.

# 4. Selected study company

## 4.1 Introduction

This chapter presents CDo company’s context and baseline information. CDo Company employs a comprehensive rice processing sequence that transforms freshly harvested paddy into market-ready milled rice products. The facility's processing operations encompass eleven sequential stages, from initial material reception through final shipment preparation. The processing sequence follows standardized procedures established for integrated rice milling operations, utilizing a combination of domestic and imported equipment installed across different phases of the facility's development. Each processing stage employs specific quality control protocols and operational parameters calibrated for the diverse rice varieties processed at the facility, including fragrant, white, and Japanese rice categories.

## 4.2 Case study company profile

### 4.2.1 Company overview and industry context

CDo Company is an integrated rice processing plant set up in 2010 and started rice operations in 2011, located in the Co Do district, Can Tho province in the Mekong Delta region of Vietnam. The plant runs a processing line of 45,000 metric tons per year, classifying the firm as a middle-tier operator in the national rice sector. Báo Nhân Dân điện tử cites a 2022 report noting that Vietnam has 582 industrial rice milling plants, of which 61.5% have capacities above 10,000 metric tons per year, and only 3% operate beyond 100,000 metric tons per year. CDo fits into the substantial band that links smaller, traditional milling shops and upscale industrial complexes, thereby supporting Vietnam's achieving a record exported volume of 9 million metric tons and associated turnover of $5.7 billion in 2024 (Vietnam Export Data, 2025).

### 4.2.2 Geographic location and infrastructure

The factory occupies 220,000 square meters in the Mekong Delta, accounting for 50% of the country's overall rice production and 90% of national rice exports (MARD, 2025). Within Mekong Delta, Can Tho province develop 78,000 hectares of rice cultivation, generating 1.3 million tons annual output, predominantly high-quality and specialty aromatic varieties (Kontgis et al., 2019; Vov, 2025). Moreover, the CDo location takes advantage of multimodal transportation access through Cai Son River for barge delivery up to 100 tons, National Highway 922 apart 30 km from Can Tho International Port), and Provincial Road 367 for domestic distribution.

### 4.2.3 Operational structure and workforce

CDo employs 70 permanent staff across nine departments and approximately 70 seasonal workers during peak periods (October-December, February-April) when processing volumes increase 2-3 times. Table 12 presents the workforce distribution.

*Table 12: CDo workforce structure*

| Department | Employees | Female (%) | Primary Functions |
|---|---|---|---|
| Production | 25 | 12% | Rice processing operations |
| Quality Control & Assurance | 10 | 70% | Quality testing, compliance |
| Maintenance | 10 | 0% | Equipment maintenance |
| Human Resources | 5 | 100% | Personnel management |
| Finance & Accounting | 5 | 60% | Financial operations |
| Planning & Materials | 5 | 20% | Supply chain management |
| General Management | 4 | 25% | Overall coordination |
| Sales | 4 | 75% | Marketing, customer relations |
| IT | 2 | 0% | Technology support |
| **Total Permanent** | **70** | **33%** | **All operations** |

**Data collected from CDo company*

### 4.2.4 Technology and equipment configuration

CDo's processing infrastructure reflects phased technological development combining domestic and imported machinery. The facility began with domestic equipment (2011) and upgraded precision end-line units with imported technology (2015), boosting whole-grain retention. Table 13 summarizes the company's machinery specifications.

*Table 13: CDo company machinery specifications*

| **Processing stage** | **Equipment** | **Year** | **Manufacturer** | **Purpose** |
|---|---|---|---|---|
| Cleaning | Impurities screening system | 2011 | Bui Van Ngo (Vietnam) | Remove foreign materials |
| Drying | Flatbed dryers | 2011 | Bui Van Ngo (Vietnam) | Moisture control |
| Husking | Rubber roller huskers | 2011 | Bui Van Ngo (Vietnam) | Remove rice husk |
| Whitening | Vertical rice mill | 2011 | Bui Van Ngo (Vietnam) | Remove bran layer |
| Polishing | Water mist polishers | 2015 | Bühler (Switzerland) | Surface finishing |
| Sorting | Digital camera sorters | 2015 | Satake (Japan) | Quality grading |

**Data collected from CDo company*

### 4.2.5 Product portfolio and market distribution

CDo processes a wide range of rice varieties and utilizes all paddy components to maximize integrated value. However, due to the shift of market demands, the company has strategically prioritized fragrant types since 2020. Among those fragrant rice, Dai Thom 8 represents the largest produced single variety and contributes 60% of CDo's revenue in 2024. Dai Thom 8 has gained preference in the Philippines and Indonesia, increasing high demands recent years (Son, 2024). Table 14 present the rice varieties, product portfolio, market distribution, and revenue structure.

*Table 14: Rice varieties and product portfolio (2024)*

| Rice Type | Variety | % Volume | Market Focus |
|---|---|---|---|
| Fragrant rice | DT8 | 40% | Mid-range export markets |
| Fragrant rice | ST25 | 15% | Premium export markets |
| Fragrant rice | Jasmine | 5% | Premium export markets |
| White rice (high yield) | OM5451 | 20% | Mid-range/domestic markets |
| White rice (high yield) | OM18 | 15% | Mid-range/domestic markets |
| Japanese rice | Jumbo | 5% | Premium export markets |

**Data collected from CDo company*

*Table 15: Market distribution and revenue structure (2024)*

| Market Tier | Destinations | Quality Standards | Revenue (%) |
|---|---|---|---|
| Premium | Australia, South Korea | ≤5% broken grains | 30% |
| Mid-range | China, Philippines, Indonesia, Ghana, Ivory Coast | ≤10% broken grains | 55% |
| Domestic | Vietnam | ≤15% broken grains | 15% |

**Data collected from CDo company*

### 4.2.6 By-product utilization and circular practices

CDo implements circular economic practices through by-product utilization. Particularly, while rice bran could serve animal feed markets, broken rice often supplies brewing and processed food industries. Moreover, one of notable circular economic practices is that rice husks are converted to charcoal for on-site drying operations, eliminating external fuel requirements. Those best practices allow the company to maximize value extraction from raw materials while reducing environmental impact.

### 4.2.7 CDo's financial profile and investment capacity

Table 16 shows CDo financial capacity information.

*Table 16: CDo financial capacity assessment*

| **Financial Indicator** | **CDo Estimate** | **Assessment** |
|---|---|---|
| Annual Revenue | ~$23.5 million | Medium-scale processor |
| Annual Revenue (DT8) | ~$9.4 million | Medium-scale processor |
| Annual Net Margin (est.) | 5-8% | ~$470,000-$750,000 |
| Cash Reserve (est.) | $200,000-$400,000 | Limited buffer |
| Debt Capacity | Limited | Constrained |
| Annual CapEx Budget (est.) | $125,000-$250,000 | Modest |

**Data collected from CDo factory*

CDo as other SMEs has limited cash reserves, most of cash can be used for working capitals and paying materials, especially concentrating in harvest period. Therefore, any large investment will be considered to mitigate the financial risk and ensure project quality. However, the company can consider accessing credits for upgrading equipment with preferential rates.

## 4.3 CDo's rice processing flow chart and its description

### 4.3.1 CDo's rice processing flow chart

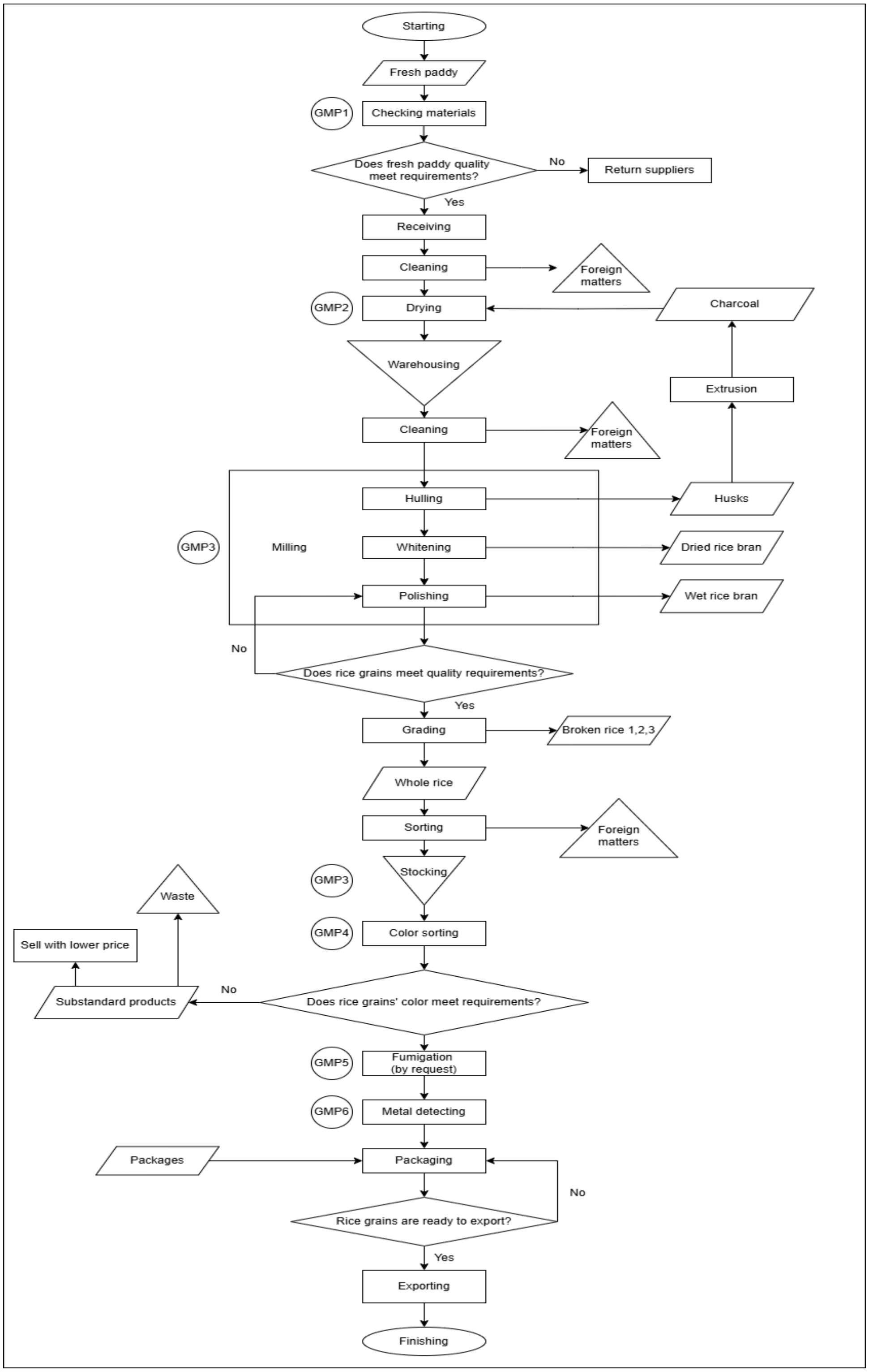

*Figure 1: CDo's rice processing flow chart*

### 4.3.2 Processing description

Even though all rice varieties follow the processing diagram, their calibration for quality requirements differs.

#### 4.3.2.1 Checking and receiving materials

**Transportation and delivery operations**

CDo company receives freshly harvested paddy through barge transportation via the Cai Son River at docks placed in front of factory (Figure 2). Standard shipments consist of 30 metric tons arriving within 20-24 hours of post-harvest. This transportation method utilizes traditional boats and barges, representing typical delivery practices among Mekong Delta rice processors.

*Figure 2: Docks to receive rice paddies*

**Reception and inspection procedures**

The facility employs standardized reception procedures coordinated by procurement, production, and quality control teams. Inspection protocols include transportation hygiene verification, raw material quality assessment, and equipment functionality checks for conveyor systems and screening equipment. The company follows Good Manufacturing Practice (GMP) standards and maintains digital documentation for all inspection activities.

**Quality acceptance standards**

Incoming paddy is evaluated according to variety-specific quality criteria before processing approval. Table 17 presents the acceptance thresholds applied to different rice categories.

*Table 17: Standards for receiving materials*

| Varieties | Moisture (%) | Immature grains (%) | Impurities (%) | Mixed grains (%) | Cracked grains (%) | Damaged grains (%) | Yellow grains (%) |
|---|---|---|---|---|---|---|---|
| White | ≤ 28 | ≤ 3 | ≤ 3.5 | ≤ 10 | ≤ 3 | ≤ 3 | ≤ 0.5 |
| Fragrant | ≤ 28 | ≤ 5 | ≤ 5 | ≤ 10 | ≤ 4 | ≤ 2 | ≤ 0.5 |
| Japanese | ≤ 30 | ≤ 5 | ≤ 5 | ≤ 3 | ≤ 5 | ≤ 2 | ≤ 2 |

**Data collected from CDo company*

The facility maintains differentiated acceptance standards for white, fragrant, and Japanese rice varieties. Approved materials proceed to processing operations, while non-compliant batches are returned to suppliers. All quality assessments are recorded in digital logs following standard industry traceability practices.

#### 4.3.2.2 Cleaning 1

**Primary cleaning and screening process**

Following acceptance, paddy is transported via Vigan screw conveyor to the impurity screening system manufactured by Bui Van Ngo. The cleaning system operates with 10 mm diameter sieves and conveyor speeds of 10-20 meters per minute to separate coarse and fine impurities including plant debris, plastic materials, stones, and metals. This primary cleaning stage protects downstream processing equipment and ensures product safety compliance. Figure 3 illustrates screening process in practice.

*Figure 3: Screening in CDo factory*

**Quality monitoring and batch management**

Cleaned paddy is weighed and transferred to dryers with 20-35 tons capacity. Quality control teams conduct visual and sensory inspections for odor, visible damage, and mold presence before dryer loading. Non-conforming batches undergo corrective procedures including segregation, priority drying, or isolation for separate processing to prevent cross-contamination and quality degradation.

**Cleaning standards**

The facility maintains zero-tolerance policies for specific contaminants including wet paddy, oils, metals, and glass materials. Quality standards for the cleaning stage follow the same variety-specific criteria established during material reception at Table 17.

#### 4.3.2.3 Drying

**Equipment configuration and capacity**

CDo facility operates 12 flatbed dryers, each with 30-ton capacity, providing total daily throughput of 360 tons. Each dryer consists of a drying bin, plenum chamber for air distribution, centrifugal fan, and furnace powered by rice hull charcoal (Figure 4 and Figure 5). The system heats air to 40-50°C in furnace and distributes it by fan through the plenum chamber to reduce paddy moisture content to approximately 14.5%. A circular screw conveyor with vertical and horizontal blades provides paddy agitation to ensure uniform moisture distribution throughout the grain mass (Figure 6). Figure 4, Figure 5, and Figure 6 provide dryers' operations and equipment status in practice at CDo factory.

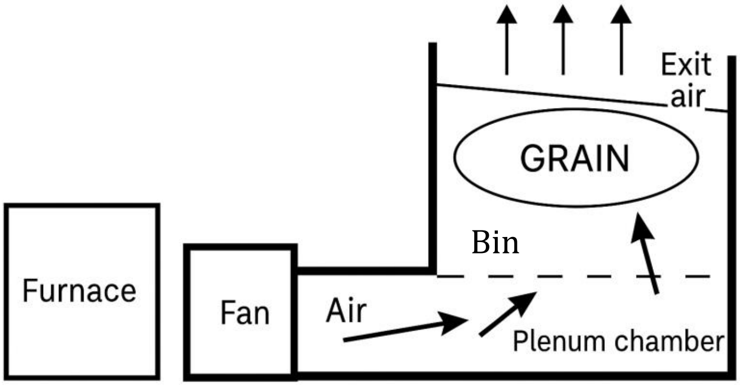

*Figure 4: Flat-bed dryer structure*

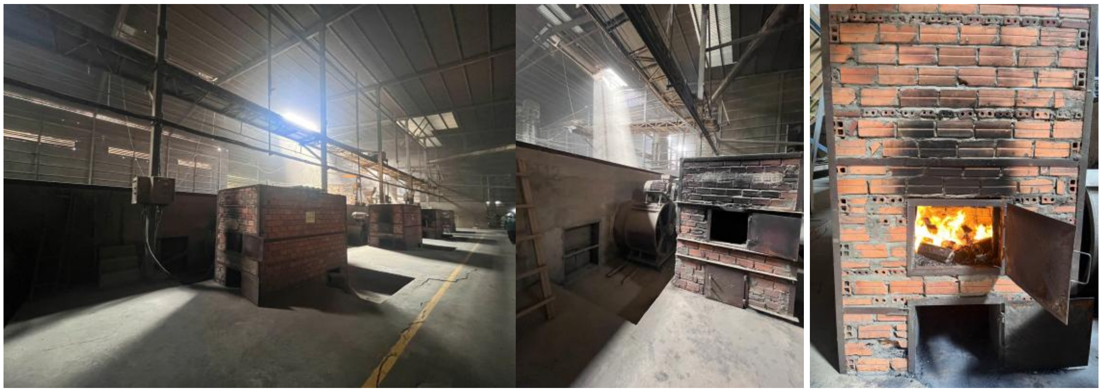

*Figure 5: Furnace at CDo factory*

*Figure 6: The circular screw conveyor and bin at CDo factory*

### Operational procedures

#### *Pre-drying preparation*

Operators prepare the system by validating fuel ratios and ensuring fan and plenum chamber components are free from blockages. Personnel wear protective equipment including dust masks and insulated gloves following safety protocols. Paddy is loaded into grain bins and distributed evenly across 25-40 centimeters depth layers according to manufacturer specifications.

#### *Drying process stages*

The drying operation follows a two-stage process:

- **Air drying (2 hours)**: Natural air circulation using centrifugal fan at 12-15 $m^3$/min per ton to stabilize moisture distribution.
- **Heat drying (18-24 hours)**: Heated air application at 40-50°C to achieve target moisture content of 14.5%.

Rice husk charcoal serves as the primary fuel source, with consumption rates of approximately 30 kg charcoal per hour per 30-ton batch. In the meantime, air temperature is monitored to prevent exceeding 50°C, which could cause grain fracturing.

### *Process monitoring and control*

Drying aims to dry paddy to target moisture content. Therefore, moisture content is measured using Wile 55 moisture testers with three replicates every 2 hours, increasing to 30-60 minutes intervals as the target moisture approaches. The circular screw conveyor operates intermittently based on moisture readings and operator assessment. Drying duration varies according to initial moisture content: 18 hours for 23-24% initial moisture and 24 hours for 28-30% initial moisture.

### *Drying performance specifications*

Table 18 presents the operational parameters for CDo's drying system.

*Table 18: Heat-drying performance specifications at CDo factory*

| Specification | Details |
|---|---|
| Equipment type | Flatbed dryer, capacity 30 tons/batch capacity |
| Grain/Paddy depth | 25-40 cm |
| Drying air temperature | 40-50 °C |
| Drying duration | ~18 hours (initial moisture content at 23-24%) |
| | ~24 hours (initial moisture content at 28-30%) |
| Fan speed | 12–15 $m^3$/min per ton of paddy |
| Target moisture content | 14.5% (dry matter) |
| Fuel consumption | 30 kg rice hull charcoal/hour/30 tons |

**Data collected from CDo company*

### 4.3.2.4 Warehousing

### Storage transportation and facility management

Following drying operations, paddies are transported to storage silos as Figure 7 using automated conveyor and chain systems equipped with magnetic separators for metal removal. Storage silos undergo cleanliness verification before loading, with batch documentation maintained for traceability and ISO 22000:2018 compliance.

*Figure 7: Silos for warehousing at CDo factory*

#### Tempering process

CDo employs a standardized 12-30-hour tempering period for all rice varieties to achieve moisture equilibration within the kernel before milling operations. The facility maintains documented tempering protocols with batch segregation for different rice varieties in designated storage areas.

#### Operational management

Storage operations accommodate processing flexibility based on production requirements. Approximately 10% of batches may have adjusted tempering duration for immediate milling needs, while 15% of paddy batches undergo extended storage periods up to one month for inventory management purposes.

### 4.3.2.5 Cleaning 2

#### Pre-milling cleaning process

Dried paddy undergoes secondary cleaning using a Vigan screw conveyor and Bui Van Ngo impurity screening system equipped with 8 mm screening holes. This pre-milling cleaning stage provides impurity removal to protect downstream milling equipment from potential damage caused by remaining foreign materials.

#### Two-stage cleaning system

The facility employs a two-stage cleaning approach combining the initial post-reception cleaning with this pre-milling cleaning operation. This sequential cleaning process ensures comprehensive impurity removal before paddy enters the milling stages, supporting equipment protection and product quality requirements.

Cleaned paddy from this stage proceeds directly to the husking operations, completing the preparation phase of the processing sequence.

#### 4.3.2.6 Milling: husking – whitening – polishing

**Husking process**

***Equipment configuration***

CDo employs rubber roll huskers installed in 2011, consisting of two parallel rubber-coated rollers operating at 1000-1350 RPM with 10 HP motor capacity. The system is shown in Figure 8 with 6 huskers. The system features one fixed and one adjustable roller with inclined plane design, adjustable chute, and vibrator mechanisms for feed rate control. Processing throughput operates at 3 tons per hour capacity.

*Figure 8: Huskers at CDo factory*

***Operational process***

The husking process removes paddy husks through friction and pressure between rotating rollers, producing a mixture of brown rice, unhulled paddy, and husk materials. Integrated compartment-type paddy separators continuously separate these components based on specific gravity and kernel size differences. The system maintains continuous operation throughout processing periods.

***Process management***

Production operators manage roller gap adjustments, feed rates, and processing speeds to optimize husking outcomes. Adjustments are made based on operator assessment of rice variety characteristics and processing conditions. The facility processes multiple rice varieties requiring different operational parameters for optimal husking performance.

***Quality standards***

CDo maintains quality benchmarks for brown rice production following Vietnamese national standards (TCVN 11888:2017) and international guidelines (FAO, 2017). Quality parameters include whole rice yield targets and broken rice rate thresholds established for different rice varieties processed at the facility.

*Table 19: Quality standards and outcomes in husking stage*

| **Grade** | **Moisture (%)** | **Whole Rice (%)** | **Broken Rice (%)** | **Cracked Grains (%)** |
|---|---|---|---|---|
| Class A | 14.5 | 80 | 4 | 3 |
| Class B | 14.5 | 80 | 4.5 | 3 |
| 5% broken rice grains | 14.5 | 75 | 7 | 5 |
| 10% broken rice grains | 14.5 | 70 | 12 | 6 |

**Data collected from CDo company*

**Whitening Process**

***Equipment configuration***

The whitening operation utilizes a vertical rice mill with cylindrical stone shaft equipped with rubber rotary bars that remove bran layers and germ from brown rice kernels (Figure 10). Together with a control panel to control speed, gaps of bars and stone, and gaps of bars, the whitening chamber features a cylindrical perforated sieve with multiple compartments and directional ribs that guide rice flow to designated exit points (Figure 9). Each compartment operates with separate vacuum suction systems for bran dust removal.

*Figure 9: Whitener and its control panel*

*Figure 10: Inside structure of whiteners*

***Operational process***

Brown rice is transported through magnetic-equipped pipes for metal contamination removal before entering the whitening chamber. The facility employs a four-pass whitening process to achieve optimal bran removal. Operators monitor whitening chamber conditions, grain breakage levels, and whiteness achievement, making real-time adjustments to machine settings including stone shaft speed and rubber roller positioning.

### Polishing operations

#### *Equipment and process flow*

Whitened rice moves through a 10-meter cooling pipe before entering the polishing stage, which operates at 3 tons per hour capacity. Illustrated in Figure 11, the polishing machine combines sharp blades, mesh screens, and fine water mist application to enhance rice grain gloss and texture. The facility typically employs seven polishing passes to achieve maximum gloss levels.

*Figure 11: Polishers and their structure at CDo factory*

#### *Process management*

Operators control water flow, pressure, and machine settings to maintain consistent rice quality while preventing moisture-related damage. Temperature monitoring ensures grain cooling to prevent breakage and enhance gloss development. Polished rice undergoes moisture content testing and visual quality assessment before proceeding to cooling silos.

#### *Quality control standards*

Quality control procedures monitor moisture content, glossiness, and broken rice ratios within ±1% tolerance windows. Rice does not meet moisture and gloss criteria returns to polishers for additional processing. The combined whitening and polishing operations produce white rice meeting established purity, color, and breakage standards for consumer and industry requirements.

#### *Process integration*

The whitening and polishing stages operate as integrated mechanical and environmental systems producing polished white rice that meets facility quality specifications. Both operations rely on manual equipment settings and operator expertise for process optimization across different rice varieties processed at the facility.

## Grading operations

### *Grading process and equipment*

Following milling completion, rice undergoes grading operations to ensure uniformity and market standard compliance. The facility employs length graders that classify milled rice based on kernel length using rotating cylinders with indentations. This continuous process operates at 3 tons per hour capacity, separating head rice (whole kernels) from smaller fragments and broken grains.

### *Quality classification standards*

CDo maintains established quality standards for graded rice products based on moisture content, whole rice percentage, and broken rice ratios. Table 20 presents the quality requirements following polishing operations and Figure 12 shows rice quality after grading.

*Table 20: Quality requirement after polishing*

| **Brown rice** | **Moisture** | **Whole rice (weight)** | **Broken rice (weight)** |
|---|---|---|---|
| Class A | 14.0% | >60% | 4.1% |
| Class B | 14.0% | >60% | 4.6% |
| 5% broken rice grains | 14.0% | >60% | 7.2% |
| 10% broken rice grains | 14.0% | >55% | 12.3% |

**Data collected from CDo company*

*Figure 12: Grading after polishing at CDo factory*

These quality classifications align with Vietnamese national standards and international guidelines (FAO, 2017; ISO, 2018), providing product categories suitable for different market segments and customer requirements.

***Output segregation***

The grading process produces segregated rice categories that proceed to packaging operations based on quality classification. Each grade category maintains specific moisture and breakage thresholds to meet designated market specifications and customer quality expectations.

#### 4.3.2.7 Stocking

**Storage process and facility management**

Following grading operations, rice is packaged in bags as semi-finished products and organized in rows within warehouse facilities to prevent contamination as shown in Figure 13. Storage duration varies from hours to weeks depending on order logistics and customer requirements. The facility conducts fumigation treatments when required by clients or as precautionary measures during storage periods.

*Figure 13: Stocking at CDo factory*

**Storage conditions and standards**

CDo maintains storage conditions with rice moisture content at 14.5% for storage periods up to 12 months. For rice with moisture content between 14.5-15.5%, storage duration is limited to 3 months. The facility operates within the Mekong Delta's tropical climate conditions, requiring moisture management to prevent environmental absorption and quality deterioration.

**Storage management procedures**

Bagged rice is arranged systematically in warehouse facilities with appropriate spacing and ventilation considerations. Storage areas are monitored for environmental conditions including temperature and humidity levels. The facility implements pest control measures to minimize risks from insects and birds during storage periods.

**Quality maintenance**

Storage operations maintain rice quality through controlled environmental conditions and regular monitoring protocols. The facility documents storage duration and conditions for each batch to ensure compliance with established quality standards and customer specifications.

Storage represents the final stage of CDo's processing sequence before packaging and distribution operations, maintaining product integrity until order fulfillment and shipment to customers.

#### 4.3.2.8 Color sorting

**Equipment and technology**

CDo employs optical color sorters equipped with high-resolution cameras and pneumatic ejectors for export-designated rice products. The sorting system operates continuously at 5 tons per hour capacity, processing rice in thin layers for optimal grain detection and separation.

**Sorting process**

The color sorting mechanism identifies discolored, immature, or defective grains through camera detection systems. Targeted air jets remove unacceptable grains from the product stream through pneumatic ejection. Rejected grains can undergo re-sorting for potential recovery or allocation to alternative markets.

**Quality requirements**

Color sorting ensures visual uniformity and defect removal for export market specifications. The process separates qualified rice meeting export standards from rejected materials, maintaining consistent grain appearance required for premium product categories.

Qualified rice from color sorting proceeds to final packaging operations, while the sorting stage represents the final quality enhancement operation before export preparation.

#### 4.3.2.9 Fumigation

**Fumigation process and equipment**

When requested by clients, CDo conducts fumigation operations in airtight storage facilities using phosphine gas generators or fumigation tablets. The fumigation process duration ranges from 24 to 72 hours depending on infestation levels and phosphine type employed.

**Operational procedures**

Following phosphine exposure, storage facilities undergo aeration procedures to ensure safe entry conditions. The fumigation process eliminates insect pests and ensures rice safety for human consumption and international trade requirements. Fumigation services are provided on a client-request basis rather than as standard processing protocol.

**Safety and compliance**

Fumigation operations follow established safety protocols for phosphine handling and facility ventilation. The process ensures treated rice meets safety standards for export markets and client specifications requiring pest-free products.

Fumigation represents an optional service within CDo's processing capabilities, available when specific client requirements or market conditions necessitate pest elimination treatments.

#### 4.3.2.10 Metal detecting and packaging

**Metal detection**

CDo employs conveyor belt-type industrial metal detectors with automated reject systems to remove metal-contaminated rice before packaging.

**Packaging process**

Automated weigh-and-fill machines measure and dispense rice into bags or consumer containers. The process includes sealing and labeling before preparation for transport. Packaging lines operate continuously at several tons per hour capacity.

**Product standards**

Packaged containers meet regulatory and market requirements. Metal detection and packaging complete the final processing stages before distribution.

#### 4.3.2.11 Exporting

Shipment represents the final stage in CDo's post-harvest processing sequence, involving rice preparation for export delivery to destination countries. Therefore, export preparation includes final quality inspection, documentation processing, and container loading operations. These activities require several hours to a full day depending on shipment size and destination requirements. Shipment operations complete CDo's integrated processing sequence from paddy reception through export delivery preparation.

# 5 Results and discussion

## 5.1 Loss quantification and economic impact

### 5.1.1 Descriptive statistics overview

The loss quantification across 36 batches of DT8 rice processed over three collection dates (December 12, 17, and 25, 2024) is presented in Table 21. Each batch averaged approximately 30,044 kg of paddy input with moisture content ranging from 27% to 30%. The formulas used are from

Section 3: Materials and Methodology. Table 21 presents losses at cleaning, drying, milling, and sorting stages while other stages such as receiving and packaging have no loss. Moreover, the storage loss with (-0.0002% ± 0.0004) was negligible since it was likely measurement error, and humidity absorption (14.5% ± 0.3 moisture) could also contribute to the error.

*Table 21: Summary statistics for processing losses (n=36 batches)*

| Parameter | Mean | SD | SE | 95% CI | Min | Max | CV (%) | Contribution (%) |
|---|---|---|---|---|---|---|---|---|
| **Cleaning Loss (%)** | 2.1 | 0.152 | 0.025 | ±0.049 | 1.95 | 2.57 | 7.0 | 10 |
| **Drying Loss (%)** | 6.0 | 0.981 | 0.163 | ±0.320 | 4.25 | 8.26 | 16.5 | 28 |
| **Milling Loss (%)** | 12.7 | 0.403 | 0.067 | ±0.132 | 11.92 | 13.49 | 3.2 | 58 |
| **Sorting Loss (%)** | 1.0 | 0.241 | 0.040 | ±0.079 | 0.10 | 1.44 | 24.4 | 5 |
| **Total Loss (%)** | 21.8 | 1.197 | 0.199 | ±0.391 | 19.60 | 24.74 | 5.5 | 100.0 |

**Data collected from CDo company*

***Drying loss is based on dry matter difference.*

Total processing loss reached 21.8% across 36 batches. While this falls within Vietnam's reported range of 14–35% (United Nations, cited in Enternews, 2023), it exceeds typical losses of 10–14% by 55–118% and surpasses World Bank (2020) benchmarks by over 200%, indicating substantial inefficiency (VietnamNet, 2018; World Bank, 2020). Small SE and narrow width of 95% CI in Table 21 show confidence of means within this range. Moreover, the overall low CV (5.5%) confirms that total processing losses are structurally embedded in CDo's operations, providing methodological confidence in the measurements and supporting the conclusion that losses are systematic rather than random.

Throughout each stage, milling contributes the highest loss at 12.7%, representing 58% of total losses with highly stable process performance (CV=3.2%). This was followed by drying loss at 6.0% (28% of total, CV=16.5%), cleaning loss at 2.1% (10% of total, CV=10%), and color sorting at 1.0% (5% of total, CV=24.4%).

Figure 14 shows loss at processing stages contributing to total loss.

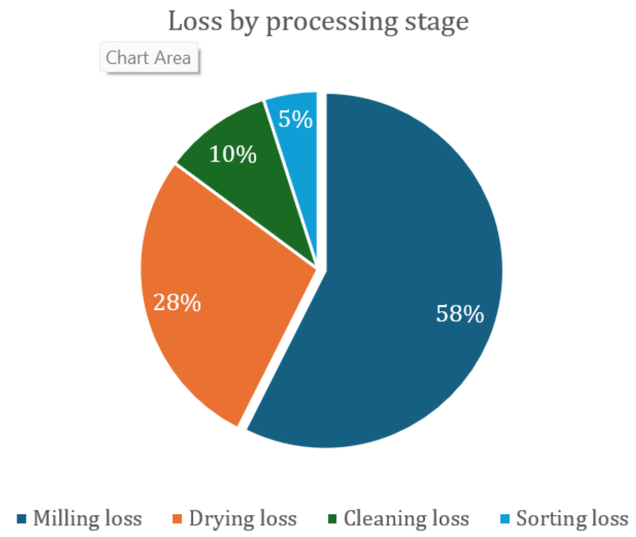

*Figure 14: Contribution of processing stage to total loss*

With 86% losses concentrated in milling and drying, CDo should focus improvement efforts on these stages to bring losses closer to industry norms (Singh & Basu, 2021; IRRI, 2025).

## 5.1.2 Stage-by-stage loss analysis

### 5.1.2.1 Receiving materials and cleaning stage

The zero physical loss during reception aligns with mechanized handling systems achieving <0.1% losses in comparable facilities (Nguyen & Tran, 2021). The 2.1% loss during cleaning operations aligns with typical impurity removal rates of 1.5-3.0% in comparable rice processing facilities (FAO, 2019; Nguyen & Tran, 2021). The cleaning stage loss of 2.1% represents a 40% deviation above optimal cleaning efficiency of 1.5% baseline recommended by international processing standards (World Bank, 2019). However, the cleaning stage shows high stability (CV = 7.0%), indicating systematic, equipment-driven performance. Therefore, this loss may potentially originate excessive spillage during grain transport due to being overloaded, mechanical screening operations and suboptimal equipment calibration for the processed rice varieties (World Bank, 2019).

### 5.1.2.2 Drying stage

The 6% actual loss on a dry matter basis during drying operations exceeds the 3.4-4.2% range reported in comparable Mekong Delta facilities (Dao & Nguyen, 2017; Nguyen et al., 2013) but remains below the 9% loss documented in recent regional studies (Nguyen, 2023). However, the total mass reduction in drying represents the largest single contributor to the overall 21.8% processing loss sequence. This agreed with previous findings that drying is identified as the most significant loss point in studies by Dao & Nguyen, 2017; Nguyen et al., 2013; Nguyen, 2023. However, CDo's dry matter loss of 6% is higher than the benchmark value of 3% set by India, where using computer-controlled dryers with real-time sensors and closed systems to mitigate the drying losses (Ashari et al., 2024; Navasayam Dandekar, 2025). The moderate CV (16.5%) could indicate influence might come from both equipment factors and upstream variables. Particularly, equipment factors could be temperature control failures and airflow distribution inefficiencies in CDo's flatbed dryers (installed in 2011) and upstream variables include input moisture content and batch-specific conditions. Those factors could contribute to excessive dry matter loss.

#### 5.1.2.3 Milling stage

The milling stage accounts for 58% of total processing losses. The 0.1% direct physical loss during milling operations aligns with Vietnamese milling facilities achieving 0-1.5% containment losses (MARD, 2021; Nguyen & Tran, 2021). However, the milling stage performance demonstrates significant relative deviations from industry benchmarks across multiple efficiency indicators. Particularly, CDo's head rice yield (HRY) of 46.0% falls significantly below the 55% industry benchmark (IRRI, 2025), representing a 16.3% deviation that translates directly to economic loss. 19.7% CDo's broken rice (HRY) is significantly higher than the 10% industry benchmark (Chen & Zhang, 2020), representing a 97% deviation that translates directly to economic loss. Details of the milling stage performance compared with industry standards summarized in Table 22.

*Table 22: Milling stage performance vs. industry standards*

| **Performance indicator** | **CDo results** | **Industry standard** | **Relative deviation** | **Source** |
|---|---|---|---|---|
| Direct physical loss | 0.1% | 0-1.5% | Within range | MARD, 2021 |
| Milled rice yield (MRY) | 57.3% | 68-72% | -15.7% to -20.4% | Pham, 2020 |
| Head rice yield (HRY) | 46.0% | 55% minimum | -16.4% | IRRI, 2025 |
| Whole grain ratio | 80.3% | 90% optimal | -10.8% | World Bank, 2019 |
| Broken rice (of milled) | 19.7% | 10% modern mills | +97% | Chen & Zhang, 2020 |
| Husk percentage | 23.9% | 20% standard | +19.5% | IRRI, 2025a |

**Data collected from CDo company*

The low CV (3.2%) combined with high absolute value (12.7%) suggests systematic equipment-related inefficiency rather than random operational variation or incoming material quality. This finding supports the hypothesis that obsolete milling equipment (installed 2011) creates consistent, predictable losses regardless of operator skill or batch characteristics. The stability of losses indicates that interventions targeting milling equipment will yield predictable improvements.

#### 5.1.2.4 Sorting stage

The 1.0% loss during color sorting operations aligns with typical optical sorting rejection rates of 0.5-2.0% documented in export-oriented rice facilities (IRRI, 2025; Chen & Zhang, 2020). The sorting stage shows the highest variability (CV = 24.4%), indicating strong dependence on upstream quality factors. In other words, the loss represents quality control segregation rather than processing inefficiency. This suggests that sorting loss is heavily influenced by the quality of rice entering the color sorter, including defects, discolored kernels, or foreign matter from earlier processing stages such as drying and milling operations. This could make sense when color sorters are one of newest equipment in the factory, equipment might not be the important factor making high variability.

### 5.1.3 Quality-related losses metrics

#### 5.1.3.1 Quality-related losses by low HRY and high broken rice rate

CDo's head rice yield of 46.0% represents a critical quality metric. The extremely low CV (0.6%) indicates that HRY is highly consistent. This could explain that the true population HRY is very likely within this narrow range, suggesting equipment-driven rather than upstream-driven determination. This finding is also confirmed by the non-significant relationship between HRY and input moisture content (see Section 5.2.3.3).

HRY rate being low and broken rice rate being high represent a significant underperformance, leading to severe economic consequences. Compared with Japan and EU's requirements, level of breakage of all 36 batches exceed these requirements, which are 10% limit of broken rice and 12-14% threshold of broken rice respectively. In other words, DT8 rice after processing might be ineligible for premium export markets, making economic losses. To solve this problem, normally, the company could downgrade the markets or mix whole rice and broken rice with the required rates. However, these solutions still lead to losing profitability, or costing time, human resources, and other expenses without ensuring required rice rate and even rice quality.

#### 5.1.3.2 Quality-related losses by existing contamination

Quality non-conformity analysis of CDo's annual production revealed 3,869 kg of rice failing regulatory standards across five contamination categories, as detailed in Table 23. This total represents systematic quality losses beyond standard processing operations, with contamination levels consistently exceeding quality standards in Vietnam and EU.

*Table 23: Quantity of non-conformity whole rice*

| Quality/Contaminant Factor | Quantity of whole rice (Kgs) | Observed level | Measurement uncertainty | Regulatory threshold (Vietnam/EU) |
|---|---|---|---|---|
| Discoloration | 1,620 | N/A | N/A | Visual standards |
| Heavy metals (Pb) | 265 | 0.3 mg/kg | ±0.03 mg/kg (±10%) | 0.2 mg/kg (Codex) |
| Pesticide residues | 1058 | 0.05 mg/kg | ±0.01 mg/kg (±20%) | 0.01 mg/kg (VN/EU) |
| **Fungi** | | | | |
| Aflatoxin B1 | 264 | ≥2.8 µg/kg | ±0.4 µg/kg (±15%) | 2 µg/kg (VN/EU) |
| Ochratoxin A | 662 | ≥5.4 µg/kg | ±0.8 µg/kg (±15%) | 3 µg/kg (EU) / 5 µg/kg (VN) |
| **Total quantity of non-confirmity** | | **3,869** | | |

**Data collected from CDo company*

Distribution patterns reveal discoloration as the dominant quality issue, accounting for 41.8% of total non-conforming rice (1,620 kg), followed by pesticide residues at 27.3% (1,058 kg), mycotoxin contamination at 23.9% (926 kg combined), and heavy metal contamination at 6.8% (265 kg).

Comparation with regulatory benchmarks shows substantial deviations: heavy metal contamination (0.3 mg/kg) exceeded Codex standards (0.2 mg/kg) by 50%, pesticide residues (0.05 mg/kg) surpassed both Vietnamese and EU limits (0.01 mg/kg) by 400%, Aflatoxin B1 levels (≥2.8 µg/kg) breached Vietnamese and EU thresholds (2 µg/kg) by 40%, and Ochratoxin A concentrations (≥5.4 µg/kg) exceeded EU standards (3 µg/kg) by 80% while marginally surpassing Vietnamese limits (5 µg/kg) by 8%.

With measurement uncertainty estimated in Table 23, contamination levels such as heavy metals, pesticide residues, Aflatoxin B1, and Ochratoxin A remain significantly above regulatory thresholds even at the lower bounds of measurement uncertainty. For example, pesticide residues at the lower uncertainty bound (0.04 mg/kg) still exceed Vietnamese and EU limits (0.01 mg/kg) by

300%. This indicates that the quality non-conformities represent genuine compliance failures rather than measurement artifacts.

Discoloration rejection is based on visual quality standards and visual assessment using color sorter thresholds. The sorters would separate unqualified rice for quantitative measurement. This means that sorting depends on sorter thresholds, introducing potential subjectivity in classification if sorters are calibrated properly.

### 5.1.4 Economic loss assessment

CDo's rice exports reached 18,000 tons with average prices of 520 USD/ton for DT8 whole rice and 312 USD/ton for DT8 broken rice (CDo data, 2024). However, internal processing and quality-related losses significantly reduce potential revenue.

#### 5.1.4.1 Losses from milling inefficiency

CDo's milling of a 30,044 kg paddy batch yielded 10,606 kg of head rice (46.0% HRY) and 2,605 kg of broken rice (19.7%), compared to industry benchmarks of 55% HRY and 10% broken rice (IRRI, 2025; Pham, 2020). At 520 USD/ton for head rice and 312 USD/ton for broken rice, this deviation translates to a loss of 686.82 USD per batch (Table 24), or 1,165,632 USD annually for DT8 production (18,000 ton/year). Measurement precision of ±0.53% on milled weights ensure these estimates reliably represent major economic impacts while acknowledging minor variation limits.

*Table 24: Economic impact of milling inefficiency (one batch)*

| | Whole rice Quantity (Kgs) | Whole rice Price (US$/Kgs) | Broken rice Quantity (Kgs) | Broken rice Price (US$/Kgs) | Value (US $) |
|---|---|---|---|---|---|
| Theoretical quantity | 12,672 | 0.520 | 1408 | 0.312 | 7,028.736 |
| Empirical quantity | 10,606 | 0.520 | 2605 | 0.312 | 6,341.92 |
| **The difference** | | | | | **686.816** |

**Data collected from CDo company*

#### 5.1.4.2 Losses from quality non-conformities

Annual quality rejections totaled 3,869 kg, incurring 2,011.88 USD at 520 USD/ton. Testing followed TCVN 5799:2010 protocols (measurement reliability ±1%).

#### 5.1.4.3 Total economic loss

Combined, milling inefficiency and quality rejections cost CDo approximately 1,167,644 USD in 2024. This represents 12% of DT8 export revenue potential and underscores critical inefficiencies in milling and quality control compared to industry norms (VNA, 2023; Axmann et al., 2022).

## 5.2 Root cause analysis – statistical evidence

This part aims to determine why losses are happening by quantifying upstream factors (input MC, collection date) and equipment contributions (specific status equipment)

### 5.2.1 Temporal consistency analysis (ANOVA by collection date)

One-way ANOVA was conducted to determine whether processing losses differ systematically by collection date, testing measurement reliability and temporal consistency.

*Table 25: ANOVA Results - Processing losses by collection date*

| Outcome Variable | F-statistic | p-value | $\eta^2$ | Effect size | Significant |
|---|---|---|---|---|---|
| Drying Loss | 0.1104 | 0.8958 | 0.007 | Small | No |
| Milling Loss | 0.0884 | 0.9156 | 0.005 | Small | No |
| Total Loss | 0.1961 | 0.8229 | 0.012 | Small | No |
| HRY | 1.4970 | 0.2386 | 0.083 | Medium | No |

Drying loss, milling loss, and total loss do not differ significantly by collection date because of small effect size and p-value. In other words, drying losses are structurally consistent across the observation period. This supports the hypothesis that losses are caused by systematic equipment factors rather than day-to-day operational variation. No significant date effects at drying and milling stages (all $p > 0.05$) confirmed that

- Data collection was consistent throughout all three observation days.
- Processing conditions remained stable throughout the study period.
- Observed variations are attributable to factors other than temporal/seasonal effects.
- The 36-batch sample provides reliable estimates of typical processing performance.

However, despite the small p-value, effect size of HRY is medium, collection dates may impact the results.

### 5.2.2 Input moisture content effects (ANOVA by input MC)

*Table 26: ANOVA Results - Processing losses by input moisture content*

| **Outcome Variable** | **F-statistic** | **p-value** | **$\eta^2$** | **Effect Size** | **Significant** |
|---|---|---|---|---|---|
| Drying Loss | 8.2206 | 0.0003 | 0.435 | Large | Yes |
| Milling Loss | 6.2834 | 0.0018 | 0.371 | Large | Yes |
| Total Loss | 9.8879 | <0.0001 | 0.481 | Large | Yes |
| HRY | 1.2750 | 0.2996 | 0.107 | Medium | No |

Table 26 shows that while input MC significantly affects drying loss ($p = 0.0003$), milling loss ($p = 0.0018$), and total loss ($p < 0.0001$), with all large effect sizes ($\eta^2 > 0.14$), HRY shows no significant relationship with input MC ($p = 0.300$). This proves that HRY is independent of MC, confirming equipment-driven determination. In the meanwhile, different input MC contributes to different losses at drying and milling stages (Table 27 and Figure 15).

*Table 27: Group means by input moisture content*

| **Input MC** | **n** | **Drying Loss (%)** | **Milling Loss (%)** | **Total Loss (%)** | **HRY (%)** |
|---|---|---|---|---|---|
| 27% | 2 | 4.85 (0.84) | 12.47 (0.21) | 20.48 (0.76) | 45.99 (0.34) |
| 28% | 10 | 5.55 (0.81) | 12.29 (0.24) | 20.95 (0.96) | 45.96 (0.24) |
| 29% | 15 | 5.76 (0.64) | 12.81 (0.37) | 21.71 (0.83) | 45.99 (0.24) |
| **30%** | **9** | **7.01 (0.91)** | **12.86 (0.38)** | **23.02 (0.98)** | 46.18 (0.34) |

*Values shown as Mean (SD)*

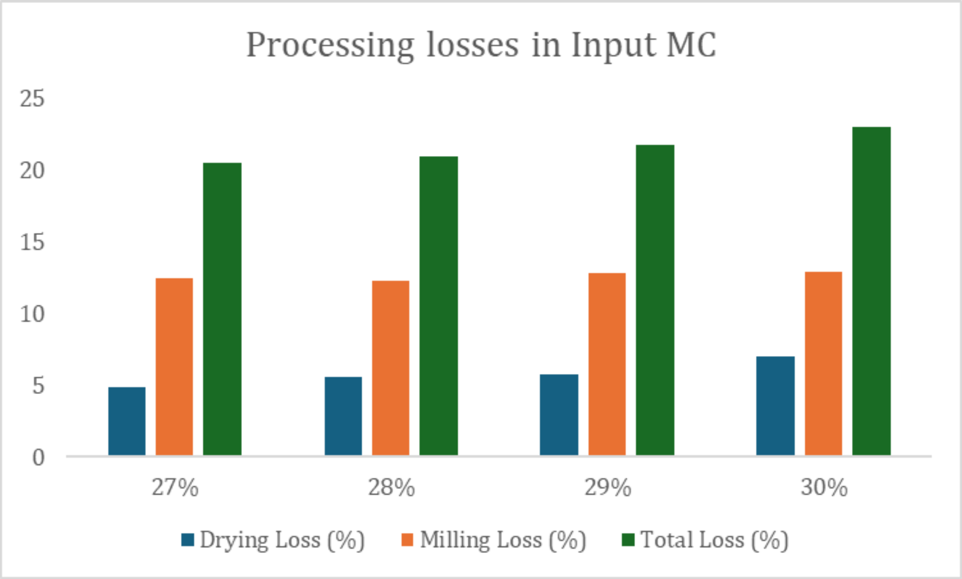

*Figure 15: Processing losses in Input MC*

Tukey HSD post-hoc analysis was conducted to find significant pairwise differences (Bonferroni $p < 0.05$). The results are in Table 28.

*Table 28: Summary of significant pairwise differences*

| **Outcome variable** | **Significant comparisons** | **Key finding** |
|---|---|---|
| Drying Loss | 28% vs 30% (p=0.011), 29% vs 30% (p=0.004) | 30% MC significantly higher than 28-29% |
| Milling Loss | 28% vs 29% (p=0.004), 28% vs 30% (p=0.006) | 28% MC significantly lower than 29-30% |
| Total Loss | 27% vs 30% (p=0.047), 28% vs 30% (p=0.001), 29% vs 30% (p=0.012) | 30% MC significantly higher than all others |

With information in Table 27, Figure 15, and Table 28, processing losses increase with input moisture content, in which 30% MC shows significantly higher losses. This pattern reveals a clear positive relationship: higher input MC consistently leads to higher losses. It could estimate that each 1% increase in input MC could make ~0.72% increase in drying loss, ~0.13% increase in milling loss, and ~0.85% increase in total loss. Therefore, controlling moisture contents plays an important role in reducing the total loss.

### 5.2.3 Quantification of root cause contributions (regression analysis + variance decomposition)

Linear regression analysis was conducted to model predictive relationships between input moisture content and processing losses, enabling variance decomposition into reasons as upstream (Input MC) versus equipment contributions.

#### 5.2.3.1 Drying loss model

Model: Drying Loss (%) = 0.684 × Input MC - 13.769

*Table 29: Drying loss model*

| **Statistic** | **R** | **$R^2$** | **F** | **p-value** | **β (slope)** |
|---|---|---|---|---|---|
| **Value** | 0.604 | 0.365 | 19.55 | <0.0001 | 0.684 |

Drying loss model (Table 29) shows that for each 1% increase in input MC, drying loss increases by 0.68 percentage points. Input MC explains 36.5% of drying loss variance, while equipment factors explain 63.5%.

#### 5.2.3.2 Total loss model

Model: Total Loss (%) = 0.933 × Input MC - 5.164

*Table 30: Total loss model*

| **Statistic** | **R** | **$R^2$** | **F** | **p-value** | **β (slope)** |
|---|---|---|---|---|---|
| **Value** | 0.676 | 0.457 | 28.58 | <0.0001 | 0.933 |

Total loss model (Table 30) proves that for each 1% increase in input MC, total loss increases by 0.93 percentage points. Input MC explains 45.7% of total loss variance, while equipment factors explain 54.3%.

#### 5.2.3.3 Head rice yield model

Model: HRY (%) = 0.085 × Input MC + 43.583

*Table 31: Head rice yield model*

| **Statistic** | **R** | **$R^2$** | **F** | **p-value** | **β (slope)** |
|---|---|---|---|---|---|
| **Value** | 0.267 | 0.071 | 2.60 | 0.116 | 0.085 |

Head rice yield model (Table 31) illustrates that input MC has no significant effect on HRY (p=0.116). Moreover, 92.9% of HRY variance is explained by equipment factors, confirming that improving HRY requires milling equipment optimization rather than upstream quality control.

### 5.2.4 Integration: Upstream vs. Equipment factors

Figure 16 shows variance decomposition of Input MC vs Equipment factors.

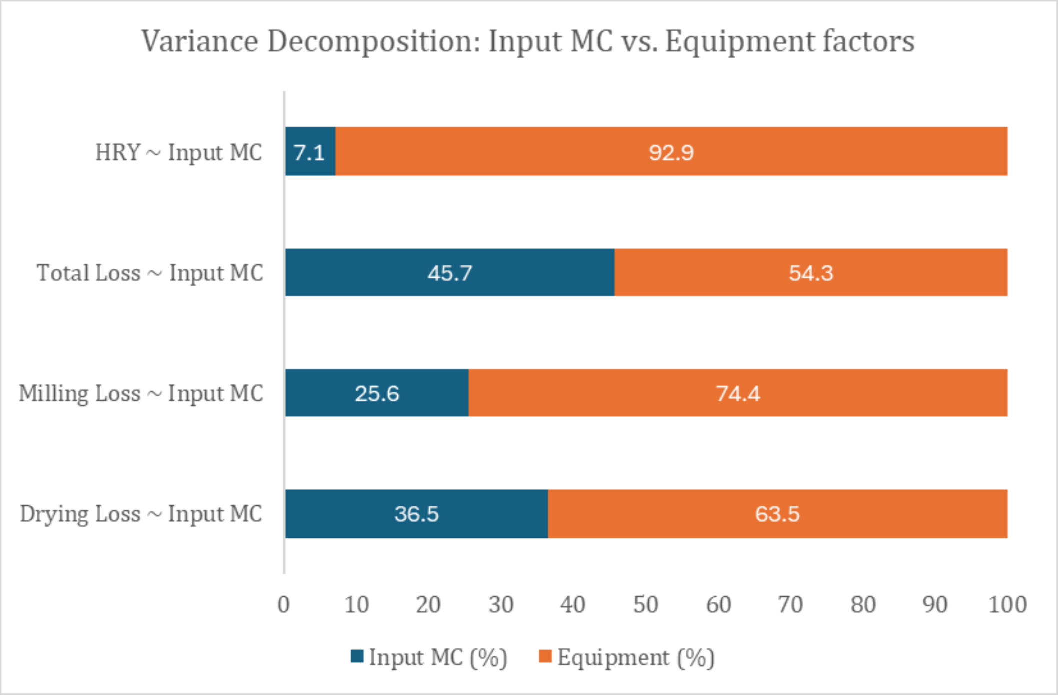

*Figure 16: Variance Decomposition - Input MC vs Equipment factors*

*p-value: <0.0017**

**Significant at α = 0.05*

Figure 16 illustrates that equipment factors dominate all processing losses, explaining 54-93% of variance across all parameters. Therefore, intervention implications should be primary focus on equipment optimization both for drying and milling stage and then input moisture content.

## 5.3 Root cause analysis - mechanistic identification

### 5.3.1 Mechanistic causes at cleaning stage

The cleaning stage shows high stability (CV = 7.0%) in Table 21, indicating systematic, equipment-driven performance. This statement aligned with plant visit observation. Particularly, this loss might come from spillage during grain transport. During the transport, Vigan screw conveyor and Bui Van Ngo screening equipment is sometimes overloaded, grain overflows from sieves and becomes lost as waste rather than being properly processed. This aligns to studies' findings (Swinderman, 1987; MLT Group, 2025; Feeco, 2025; Martin Engineering, 2025) assessing conveyor belt maintenance. They demonstrated that material spillage happens when bulk materials fall off a conveyor belt, primarily caused by misaligned belts, excessive loading, or ineffective transfer points. The reason for this could be inadequate maintenance, manual operations, or operational pressure that creates a trade-off between production volume and processing efficiency. Financial constraints and training gaps could be the underline causes of those actions. This might explain why the company accepts the loss at cleaning stage without trying to minimize the loss. However, research on conveyor spillage costs indicates that improvement of carryback spillage management can achieve more than 10% difference in cleaning efficiency (Tega, 2024).

On the other hand, the high level of loss at cleaning could be partly because of the high level of input impurities from harvesting and post-harvesting. According to CDo standards for receiving materials at Table 17 state that acceptance level for impurities is ≤ 3.5%. This might explain that 2.1% losses are from impurities. Research on rice post-harvest operations confirms that many types of foreign matters including soil pieces, sand, small stones, metal debris, plastic pieces, twigs, and weed seeds can appear in the input and unnecessarily increase processing costs (NDAL & JICA, 2015; Ishaq Ibrahim, 2018). However, Mekong Delta has applied mechanization into harvesting, enhancing rice quality, mitigating losses, and eliminating impurities before processing since 2013 (Bich Huyen, 2013; Ha Anh & Tran, 2025), thereby gaining significant improvement. As a result, CDo's cleaning losses may reflect processing rather than input quality issues.

### 5.3.2 Mechanistic causes at drying loss

Statistical evidence on 5.2.3.1 Drying loss model shows 36.5% variance depending input MC and 63.5% variance depending on equipment factors.

#### 5.3.2.1 Input moisture content

All observed batches had high input MC (over 26%) which is higher than input moisture content in previous studies (Kok et al., 2024; Nguyen et al, 2013; Dao & Nguyen, 2017), impacting drying loss. According to section 5.2.2 Input moisture content effects, each 1% increase in input MC could make ~0.72% increase in drying loss. This could be because when the input moisture content of grains is high, the drying duration takes longer than batches with low input moisture contents when keeping the same temperature. Consequently, excessive water removal and quality-related losses may occur if not controlled well, especially when the factory has been using flat-bed drying in

2011 which is hard to control temperature and airflow. This might lead to immediate mass reduction from excessive water removal, aligning to findings conducted by Kok et al., (2024); Nguyen et al, (2013); Dao & Nguyen, (2017); and Nguyen, (1999). Particularly, excessive water removal starts from temperature control failures and airflow distribution inefficiencies in the context of various MC's ranges (Kok et al., 2024; Nguyen et al, 2013; Dao & Nguyen, 2017; and Nguyen, 1999).

#### 5.3.2.2 Temperature control failures

CDo factory operates drying at 40-50°C air temperature, which potentially exceed 43°C threshold during peak operations as recommendations in studies conducted by Champ et al., 1995; Dong et al., 2010; Kumoro et al., 2025; Barthwal, 2025; IRRI, 2025. Studies conducted by Dong et al., 2010; Kumoro et al., 2025 concur that drying temperatures at 45-50°C create severe internal moisture gradients within rice kernels. Other studies confirm that samples dried at 50-60°C show maximum fissuring rates after 12 hours, while air temperature of 40-45°C is normally recommended for flatbed dryers with grain layer heights of 25-40cm (Cnossen et al., 2003; Siebenmorgen & Matsler, 2006; Hung et al., 2018).

*Table 32: Comparation of drying performance at CDo practices with India*

| **Parameter** | **CDo Practice** | **India Benchmark** |
|---|---|---|
| Dryer Type | Flatbed | Continuous flow/fluidized |
| Batch Size | 30 tons | 30–50 tons |
| Drying Temperature | 40–50°C | 38–45°C |
| Moisture Monitoring | Manual, 2h | Automated, real-time |
| Drying duration | 18-24h | 18-24h |
| Energy Source | Rice husk charcoal | Rice husk, LPG, biomass |
| Mixing System | Screw conveyor | Automated/multi-point |

**Data collected from CDo company,* Ashari et al., 2024; Navasayam Dandekar, 2025

A CDo staff reported that 10 years ago, CDo used to measure temperature by placing some thermometers inside plenum chamber. The company found that when heated air was at 40-50°C, drying temperature in plenum chamber could be around 45°C. Since then, CDo has just kept heated air at 40-50°C. This could be because CDo's drying system uses heated air in furnace to distribute it through the plenum chamber underneath grains bin, heated air might reduce temperature during this distribution.

However, during the observation, there is no sensor or thermometer remained in furnace and plenum chamber to inspect temperature. This makes sense with CDo's drying status which use flatbed dryers installed in 2011. The flatbed driers without any thermometers or sensors or control panels might hinder temperature and airflow control and real time feedback for timely responses in practices, creating a bottleneck in temperature management and impacting efficiency. Moreover, CDo's furnace lacks precise temperature control by CDo's staff to manage temperature generated by rice hull charcoal during 24-hour-drying. All practices result in not only over drying that making grains brittle, but also inadequate drying that making grains fissured (Dong et al., 2010; Kumoro et al., 2025). Those grains prone to breakage in subsequent handling, creating dual loss effects (Champ et al., 1995; Dong et al., 2010; Kumoro et al., 2025; Barthwal, 2025; IRRI, 2025).

#### 5.3.2.3 Airflow distribution inefficiencies

Research on flatbed dryer operations confirms that even drying requires optimal distribution of airflow (Cnossen et al., 2003; Siebenmorgen & Matsler, 2006; Hung et al., 2018). As a result, fans on flat bed dryers take responsibility to achieve uniform moisture content across the bed height. Fan speed is set up at 12–15 $m^3$/min per ton of paddy with CDo's grain layer height at 25-40cm as recommendations in the study of Hung et al., (2018). However, CDo's practice of overfilling bins around 38-42cm depth, together with temperature control failures being able to limit heat and airflow penetration, creating uneven drying patterns with some layers over-dry, thereby making mass reduction (Arslan & Alibaş, 2024).

### 5.3.3 Mechanistic causes at milling loss

Statistical evidence on 5.2.3.2 Total loss model and 5.2.3.3 Head rice yield model shows variance depending on upstream factors (input MC) and equipment factors. As a result, the rice losses at CDo emerge from the interaction of three forces: weak grain condition (Fragile texture, fissures, moisture imbalance), poor equipment calibration (roller gap, roller hardness, excessive passes) due to old equipment, reliance on manual skill, and stage-by-stage damage accumulation. Each factor alone might elevate breakage modestly but combined they create a compounding effect that significantly lowers head rice yield. However, equipment factors play more important role in this impact (see section 5.2.3.2 Total loss model and 5.2.3.3 Head rice yield model).

#### 5.3.3.1 DT8's rice grain properties

***Fragile texture***

DT8’s fragile texture, including thin pericarp and bran layers and low amylose content (Vinaseed, 2025), attributes to cause CDo's milling losses. Low amylose content at 16.29% and thin pericarp and bran layers (Vinaseed 2025) together create structural vulnerabilities that act as multipliers of loss during every mechanical operation (husking, whitening, polishing). While low amylose content reduces mechanical resistance, making grains more likely to deform or fracture under pressure, thin pericarp makes them highly friable under mechanical stress (Kubík et al., 2021). Thin pericarp characteristics increase over-milling risks where bran removal continuously strips more than intended, damaging outer endosperm layers (Akter et al., 2025). Research confirms that grain breakage originates almost entirely from kernel defects, with negative correlation (r = -0.673) between grain defects and head rice yield (Kalpanadevi et al., 2019). Moreover, together with high DT8’s moisture content, sensitivity amplifies processing challenges (Kubík et al., 2021).

#### ***Fissures after drying***

While reducing moisture contents of paddies to target, it could simultaneously generate fissures. Moisture content acts as an important factor to grains quality during processing, impacting overall rice loss (Müller et al., 2022). Temperature control failures and airflow distribution inefficiencies mentioned in section 5.3.1.2 Cause analytics of drying loss might impact drying practices, leading to improper moisture removal, causing paddies fissured, thereby impacting overall loss.

During the observation, CDo accepted paddy with high moisture content at 29% while their standard stated at <28% MC in Table 17 and the international research recommends at 20-25% (IRRI, 2025a). This represents a 16% deviation above international best practices and 4% above their own standards. Although CDo was aware of the high initial MC of grains at receiving stage, the company had to receive them without a second choice. This is because the paddies harvested in December in Mekong Delta could be able to have moisture contents up to over 30%. In this situation, with drying conditions at Table 18 for 29% initial MC at 40-50°C for 24 hours, a rate of moisture removal in the outer cells could be faster than water migration from the center to outer layers. This forms intra-kernel moisture gradients with extreme difference. Therefore, the surface cells tend to shrink causing tension at the surface and compression at the center when failure strength of rice is exceeded. When drying paddies to 14.5% MC, transferring inside the paddies can change their structure, causing fissuring (Müller et al., 2022). These micro-cracks weaken the structural integrity of rice making it more susceptible to breakage during milling (Müller et al., 2022). Thus, head rice yield (HRY) reduced and broken rice ratio increased, making overall milling loss.

***Moisture imbalance***

After drying, the moisture variability range of 13.9-15.4% creates inconsistent processing conditions for subsequent milling operations. Particularly, 47% of the batches achieved the moisture content parameter of 14-14.5% after drying, 50% of the batches dried did not meet the standard and remained >14.5% moisture content. This batch-to-batch variability prevents consistent roller calibration and creates operational conflicts (Liu & Ren, 2023). Particularly, equipment settings optimal for 14% moisture cause excessive compression for 15.4% moisture grains, while settings for high-moisture grains can lead under effective process to drier batches. As a result, this moisture inconsistence potentially amplifies milling efficiency (Counce et al., 2000; Li et al., 2016).

The average 14.7% ± 0.4% moisture content significantly exceeds both 14% IRRI (2025) benchmark and CDo's stated 14.5% requirement (Table 18). APLMF (2017) states that moisture content above optimal range (14%) creates systematic milling problems. Particularly, while batches at 14-14.5% MC could operate near optimal range, batches >14.5% MC could deform more easily under stress and excessive plasticity, leading to poor husk separation, bran adhesion, and increased fragmentation under roller compression (Rehal et al., 2017). Liu & Ren (2023) indicate that 1% reduction of paddy moisture in the 10-14% range increased milling system performance by 0.7-3%. This could indicate that CDo's excess moisture directly reduces efficiency.

Fissured kernels from moisture imbalance are more sensitive to narrow roller settings, while heat produced by friction between rice kernel and roller machine enhances thermal stress (Kumoro et al., 2025). To CDo, the 14.7% moisture content amplifies these effects as water molecule migration from internal to external parts during milling creates additional thermal stress that compounds existing processing challenges.

CDo's justification for accepting 14.5% moisture instead of 14% to achieve "higher quantity of final product" contradicts established research. While staff claim this also prevents moisture reabsorption in Mekong Delta humidity, studies demonstrate that exceeding 14% MC fosters environment for microbes, aflatoxins, and mycotoxins, which decreases grain value (Atalla et al., 2003; IRRI, 2025; Tang et al., 2019). Moreover, Siebenmorgen and Matsler (2006) showed that kernels which are fissured are not only more easily broken but also exposed to higher rates of rancidity and microbial decomposition due to the absorption of excess oxygen and moisture.

#### 5.3.3.2 Equipment calibration and aging

a) *Roller gap generating over-compression*

Improper roller gap settings directly generate excessive compressive stress on rice kernels. When roller clearance is set narrower than optimal, excessive compression occurs, causing direct kernel fracture instead of gentle husk and bran removal (Gupta, 2025). This over-compression problem could explain why CDo's husk removal reached 23.9%, significantly exceeding the standard 20% husk weight per grain weight (Pode et al., 2015; PHilMech, 2020). This excess simultaneously indicates systematic mechanical damage, in which physical over-compression shatters fragile grains regardless of roller material composition.

CDo's huskers, whiteners, and polishers, installed in 2011, rely on roller gap adjustments performed by production operators to optimize milling outcomes. However, the equipment's age combined with manual adjustment procedures can cause losses through improperly calibrated roller gap settings that are unsuitable for DT8 variety characteristics. This leads to over-husking and over-bran removal, thereby resulting in quantifiable losses. Furthermore, when processing paddy with high levels of fissures caused during pre-milling stages, the milling losses become significantly more compounded.

### *b) <u>Hardened rollers eliminating cushioning protection</u>*

During processing, CDo's rubber rollers in huskers and polishers and rubber bars in whiteners could become hardened with age, transforming from flexible processing surfaces into rigid compression systems. When production operators recognize excessive rubber wear, equipment maintenance and rubber replacement are performed. However, these actions are based solely on production operators' experience and do not include evaluation of rubber hardness levels, creating a processing gap. A report by Merry (2023) demonstrates that sand roller rice mills provide advantages of soft collision and low broken rice rates compared to iron roller mills. Therefore, without timely replacement, CDo's hardened rollers/bars lose their cushioning effect, creating direct mechanical impact that transmits higher stress loads to already-vulnerable kernels, resulting in immediate kernel breakage.

In contrast, advanced mills in Thailand and Japan adopt precision automated controls that maintain constant pressure, roller clearance, and grain throughput (Baker, 2014; Nixma Group, 2021; Oshima, 2025). These facilities allow processors in these countries to overcome systematic variability and regularly achieve head rice yields far above traditional mills, with broken rates under 5% (Nixma Group, 2021; Oshima, 2025). The comparison highlights that CDo’s constraints are fewer technical limitations of rice than operational and systemic barriers: outdated machinery and limited capital to upgrade new equipment.

c) *Synergistic amplification creating catastrophic failure*

The two factors, roller gaps and hardened rollers, interact synergistically. Particularly, small errors in gaps become devastating when paired with overly hard or degraded rollers. For CDo's pre-fissured DT8 grains, this could create compound vulnerability, in which minor calibration deviations result in catastrophic mechanical failure because fissured grains from rapid drying are far more sensitive to narrow roller settings.

#### 5.3.3.3. Stage-by-stage damage accumulation

a) *Husking stage: fracture initiation*

Manual husking adjustments create losses by generating localized mechanical stress on rice kernels through uneven or excessive pressure (Baker et al., 2012; Kyani et al., 2025). The manually controlled huskers at CDo are not controlled by automated feedback systems, instead they rely on operator's experience rather than precision measurement. This approach could cause high inaccuracy, calibration errors, and pressure oversupply (Gupta, 2025) that initiate fractures in kernels, particularly those already weakened by pre-drying fissures.

b) *Whitening stage: damage propagation*

Narrow gaps between stone and rubber bar could crush or over-abrade kernels rather than properly peeling the bran, creating over-milling where not only bran is removed, but also parts of the endosperm. This finding also aligns with conclusion of Merry (2023). Moreover, CDo's manual whitening system often deploys four time of whitening passes to target specific brightness, which could multiply breakage risks, particularly in fissured or chalky rice. Moreover, according to findings of Kyani et al., (2025), temperature rise during whitening shows extremely significant correlation (r = -0.900) with reduced head rice yield, as thermal stress propagates micro-cracks exist. This partly explains why CDo's HRY reached 46%, significantly lower than the industry standard 55% (IRRI, 2025).

c) *Polishing stage: final damage completion*

Improper roller clearance and excessive firmness at polishing cause additional crack propagation in already stressed grains (El-Sheikha et al., 2010; Merry, 2023). Moreover, overusing water could produce re-wetting stresses and softens kernels unevenly, completing the fracture process instead of creating grain gloss as expected (C. Lague & B. M. Jenkins, 1991; Arafa & Abd El-Rahmam, 2017). While CDo has standardized amount of water for each batch, total water use per grain could be over because those grains have passed seven times of polishing. This finding is supported by Liu et al., (2022) and Sun et al., (2025) that frequent or overly rapid polishing cycles accumulate "mechanical fatigue", where each processing cycle adds cumulative stress that exceeds kernel failure thresholds.

### 5.3.4 Mechanistic causes of quality-related loss

The quality-related losses at CDo emerge from the interaction of three forces: suboptimal storage conditions (inadequate climate control, humidity exposure, temperature fluctuations, time of storage, moisture content) and supply chain contamination (pesticide residues, heavy metals, poor pre-harvest practices). Each factor alone might cause moderate quality degradation but combined they create a compounding effect that significantly increases rejection rates and post-processing losses.

#### 5.3.4.1 Suboptimal storage conditions creating systematic quality degradation

Together with humidity conditions in Mekong Delta, CDo's storage facility lacks climate-controlled infrastructure, attributing to discoloration and development of fungi like Aspergillus and Penicillium species during storage. On the one hand, tempering of dried paddies at silos during 12-30 hours under CDo’s condition might affect grains quality. Literally, tempering is necessary to balance moisture content which assists to reduce fissures and thermal stress created in drying. Moreover, 12-30 hours of tempering partly aligns to optimal tempering periods recommendations by Agriculture Institute (2025). However, type of silos for tempering could have detrimental impact to this stage. Those silos are like simple tanks without control panels to feedback/adjust thermal and moisture content. Therefore, when temperature and respiration in paddies increase, the factory might not have timely response, facilitating fungi development, discoloration, contraction, rot, oxidation and lipid production (Katta et al., 2019; Sgm-lektra, 2025). Moreover, this also could make under effective tempering step to balance moisture content, compounding thermal stress ratio in paddies (Katta et al., 2019; Sgm-lektra, 2025). On the other hand, CDo’s rice’s moisture content after millings and sorting is over 14% MC of IRRI recommendations (2015), fostering environment for microbes, aflatoxin, and mycotoxins, which decreases grain value (Katta et al., 2019).

Time of storage also impacts quality-related loss (Pan, 2024). The report’s findings state that 1% of losses are due to discoloration after 7 days of storage. Although the value of loss is around 1.03 to 2.90% loss per month as stated at Kim et al., (2023)’s study, these authors also indicated that their deterioration happened after 15 days of storage. This could be because of CDo’s improper facility, making a more significant degradation than levels of loss in study of Kim et al., (2023). Moreover, this emphasizes that the longer time of storage at CDo, the more degradation of rice that CDo has to face.

#### 5.3.4.2 Raw material contamination

Pesticide residues and heavy metals in rice detrimental impact in quality of rice in general. Although pesticide residues and heavy metals could create losses through biochemical disruption of rice structural matrix, these factors are often concerned due to economic loss for export rather than how they affect to the process (Bajwa & Sandhu, 2011; FAO, 2020; Zakaria et al., 2021; Persaud et al., 2024). This is because pesticide residues and heavy metals are basic standards that all processors need to comply with processing (FAO, 2020; Chen & Zhang, 2024; Persaud et al., 2024). Pesticide residues and heavy metals in rice often stem from farming practices (IJAAR, 2014; Hasan et al., 2022). Raw material contaminating pesticide residues and heavy metals reflects lack of supplier control and poor-quality management in pre-harvest stages (Rehal et al., 2017; Ledger Insights, 2019; Zhang et al., 2025; Department of Sanitary Engineering & EHT, 2025). CDo's endpoint detection and rejection policy fails to address root causes, creating systematic contamination risk that disadvantages competitiveness in high-value export markets. Leading processors in Thailand and China implement pre-harvest testing and traceability systems to mitigate paddies with pesticide residues and heavy metals enter their facilities, preventing economic losses from processing failed-to-export batches (Rehal et al., 2017; Ledger Insights, 2019; CNRRI, 2025).

### 5.3.5 Summary of causes

Summary of rice loss causes in CDo processing is show in Table 33.

*Table 33: Summary of rice loss causes in CDo processing*

| **Processing Stage** | **Root Causes** | **Direct Causes** | **Indirect Causes** |
|---|---|---|---|
| Cleaning<br>(2.1% loss) | Financial constraints<br>Training gaps<br>**Aging equipment** | Conveyor spillage<br>Equipment overloading<br>Aspiration over-removal<br>Manual operations | Input contamination<br>Inadequate maintenance<br>Operational pressure |
| Drying<br>(6% loss) | **Equipment obsolescence**<br>Lack of automated controls<br>Environmental pressure (Mekong Delta humidity) | Temperature control failures<br>Airflow distribution inefficiencies excessive moisture acceptance<br>Absence of sensors/thermometers | No tempering intervals<br>Spillage during collection system<br>Seasonal constraints<br>Manual temperature management |
| Milling<br>(12.7% loss) | Equipment-grain incompatibility<br>**Manual equipment**<br>Cash flow limitations<br>Reliance on manual skills | Week grain condition:<br>- DT8 fragile texture<br>- Pre-existing fissures<br>- Moisture imbalance<br>**Equipment failures**<br>- Roller gap errors<br>- Hardened rollers<br>- Manual calibration | Fissured grains<br>Equipment errors<br>Stage damage accumulation<br>Thermal stress<br>Mechanical fatigue |

| Processing Stage | Root Causes | Direct Causes | Indirect Causes |
|---|---|---|---|
| Quality-related (Variable rejections) | Infrastructure-environment mismatch<br>Supply chain control absence<br>Climate limitations (Mekong Delta) | Storage conditions<br>- No climate-controlled storage<br>- Simple tempering silos<br>- Fungal contamination<br>- Moisture content<br>Contamination<br>- Pesticide residues<br>- Heavy metals<br>- Endpoint detection only | Storage duration<br>Temperature/humidity fluctuations<br>Respiration increases<br>Supplier control gaps |

## 5.4 Limitations and methodological considerations

### 5.4.1 Measurement and data collection limitations

This study encountered difficulties in data collection, limiting direct quantitative data. Specifically, the temperature inside the drying plenum chamber could not be measured. Also, due to the large grain bed thickness, the actual temperature at the grain level may be very different. This therefore affects the certainty of the relationship between temperature control error and drying loss. The regression model showed that the equipment explained 63.5% of the variance in drying loss but could not quantify the exact contribution of temperature versus airflow versus other equipment factors. However, the key outcomes (HRY, broken rice) were measured directly using validated scales and standardized protocols, and the temperature hypothesis is strongly supported by the literature (Dong et al., 2010; Kumoro et al., 2025; IRRI, 2025) and is consistent with the observed batch-to-batch variations in final moisture content (range of 13.9–15.4%).

Cracks in rice kernels can affect rice quality, increasing the rate of broken rice in later stages of drying. However, cracks were not counted, photographed, or measured directly through optical or X-ray imaging. Although the rate of broken rice provides strong indirect evidence of rice kernel damage, the specific role of cracks compared to other damage mechanisms (e.g., inherent weakness of the kernel, over-compression) cannot be isolated. However, the consistency of findings across multiple indices (high broken rice, low broken rice, high husk removal) suggests that damage is systematic rather than random.

The drying duration time was not recorded precisely, only in the range of “18-24 hours”. This prevented a correlation analysis between drying duration and losses. However, as the regression models suggest, the majority of losses are due to outdated equipment. Therefore, in further research in the future or with other factories, drying duration could be used as an upstream factor to consider.

### 5.4.2 Economic estimate limitations

The economic impact calculation is based on market prices in November-December 2024. These prices may change in the future. Therefore, the damage estimate may be higher or lower depending on market prices. However, due to climate change in countries, rice prices may tend to increase, leading to more severe losses. In addition, the economic loss analysis only focuses on quantifying value, but excludes some other costs, such as labor, reprocessing, waste, and energy.

### 5.4.3 Implications for recommendations

Despite these limitations, the core findings are robust enough to support solid conclusions. Equipment factors clearly dominate all loss outcomes (54-93% of the variance), input MC shows a clear threshold effect at 30%, and milling equipment optimization is the main intervention lever. These conclusions are based on direct measurement of losses, outcomes and quantitative variance analysis with high confidence. Moderate to high confidence is applied to the mechanistic hypotheses (equipment calibration errors explain milling losses with an equipment contribution of 74.4%) supported by literature and field observations. Inferences about equipment parameters from CV and loss models provide moderate confidence for further solutions.

## 5.5 Recommendations and implementation roadmap

Vietnam's boom in rice exports is hampered by plant-level losses of 21.8% at CDo Company due to aged flat-bed dryers along with manual milling lines. Additionally, there are lapses in quality control, moisture control, and quality control. The overall economic losses exceed 1.17 million USD in annual losses from DT8 production. In this way, total plant losses are mitigated using this targeted value. Adopting new technologies and equipment shifts may require extensive resource allocation with regards to time, land, and facility retrofitting, making this the least ideal option for factory upgrades. Based on CDo's financial profile in Table 16 and to control losses, other more cost-effective solutions are IoT implementing controls which can actively monitor real-time data, manage and control parameters, and alert operators for real-time actions. This report proposes a three-phase IoT implementation project plan to manage primary and secondary quantitative loss in "hotspots" and the company could gradually adopt. At first, the factory could conduct three case studies as recommended in Table 34, Table 35, Table 36. This allows the company to have more solutions fitting their financial health instead of improving both drying and milling at the same time. However, expecting that intervention in both drying and milling could solve CDo's loss effectively. It is anticipated that implementing the multi-technology suite listed in Table 36, Table 37, and Table 38 will improve CDo's Head Rice Yield from 46% to a minimum of 54%, reduce broken grains to a maximum of 9%, and total processing loss to under 13.5% using the same data analytics methodologies.

The projected net revenue gain surpasses USD 1.7 million at 2025 FOB prices of USD 520 per ton. Additionally, other findings from this report can serve as a baseline study for continuous improvements in any other processes.

### 5.5.1 Three-phase IoT Implementation Strategy

#### 5.5.1.1 Phase 1: Basic IoT Sensors (6 months, US$85,000)

The first phase focuses on installing fundamental monitoring systems to address the most critical loss points, including moisture and temperature control.

Three case studies are suggested, including (i) only improving drying system, (ii) only improving milling system, (iii) improving both drying and milling systems.

*Table 34: Phase 1: Case study 1: Basic IoT sensors for drying monitoring (6 months, US$25,000)*

| Installing fundamental monitoring systems | Expected Benefits |
|---|---|
| **Drying System Improvements:** Implement a digital visibility strategy to address the 6% drying loss. For example,<br>• Deploy LoRa-IoT-based real-time controllers for precise thermal and moisture management.<br>• Implement LoRaWAN/4G/ connectivity for continuous data transmission.<br>• Create automated alerts for moisture deviations exceeding ±0.5%.<br>• Establish basic dashboard for operators to monitor drying progress. | 1)Reduce drying losses from 6.0% to 4.0%.<br>2)Lower discoloration incidents from 12% to 9%<br>3)Annual savings: $361,296<br>4) ROI period: 2.8 months |

*Table 35: Phase 1: Case study 2: Basic IoT sensors for milling monitoring (6 months, US$30,000)*

| Installing fundamental monitoring systems | Expected Benefits |
|---|---|
| **Milling Operations Enhancement:** Implement a digital monitoring strategy to address the 12.7% milling loss. For example,<br>• Install vibration sensors by LoRa-IoT-based real-time controllers on husking and whitening machines to detect wear and optimize performance.<br>• Deploy power consumption monitoring to identify inefficiencies. | 1)Reduce drying losses from 6.0% to 4.0%.<br>2)Lower discoloration incidents from 12% to 9%<br>3)Annual savings: $361,296<br>4) ROI period: 2.8 months |

| Installing fundamental monitoring systems | Expected Benefits |
|---|---|
| - Implement basic predictive maintenance alerts to prevent unexpected breakdowns. | |

*Table 36: Phase 1: Basic IoT sensors for both drying and milling monitoring (6 months, US$55,000)*

| Installing fundamental monitoring systems | Expected Benefits |
|---|---|
| **Drying System Improvements:** Implement a digital visibility strategy to address the 6% drying loss. For example,<br>• Deploy LoRa-IoT-based real-time controllers for precise thermal and moisture management.<br>• Implement LoRaWAN/4G/ connectivity for continuous data transmission.<br>• Create automated alerts for moisture deviations exceeding ±0.5%.<br>• Establish basic dashboard for operators to monitor drying progress.<br>**Milling Operations Enhancement:** Implement a digital monitoring strategy to address the 12.7% milling loss. For example,<br>• Install vibration sensors by LoRa-IoT-based real-time controllers on husking and whitening machines to detect wear and optimize performance.<br>• Deploy power consumption monitoring to identify inefficiencies.<br>• Implement basic predictive maintenance alerts to prevent unexpected breakdowns. | 1)Reduce drying losses from 6.0% to 4.0%.<br>2)Decrease milling losses from 12.7% to 11.2%<br>3)Lower discoloration incidents from 12% to 9%<br>4)Annual savings: $361,296<br>5) ROI period: 2.8 months |

Based on the same methodology to re-calculate the loss quantification in each case study to evaluate which case study gives the best result of improvement and which case study is the most suitable solution to the company and its finance.

#### 5.5.1.2 Phase 2: Advanced automation (12 months, US$80,000)

Building on Phase 1 infrastructure, this phase focuses on intelligent process control and introduces automated control systems.

*Table 37: Phase 2: Advanced Automation (12 months, US$80,000)*

| Automated control systems | Expected Benefits |
|---|---|
| **Smart Drying System:**<br>• Apply convolutional neural networks in moisture, multi-point temperature, and fan speed control. | 1)Further reduce drying losses to 2.5% |
| **Intelligent Milling:**<br>• Install pressure sensors for optimal rubber roll adjustment.<br>• Implement real-time grain flow monitoring and control.<br>• Deploy automated whitening speed control based on rice type.<br>• Integrate machine learning algorithms for continuous yield optimization. | 2)Decrease milling losses to 9.7%<br>3)Lower discoloration incidents to 6%<br>4)Reduce mycotoxin incidents by 50% |
| **Advanced Quality Management:**<br>• Install computer vision systems for automated grain quality assessment.<br>• Integrate with existing Satake color sorters for enhanced performance.<br>• Implement real-time mycotoxin risk prediction algorithms.<br>• Deploy environmental control systems in storage areas. | 5)Annual savings: $675,792<br>6)ROI period: 3.2 months |

### 5.5.1.3 Phase 3: Full integration (18 months, US$160,000)

The final phase creates a fully integrated smart rice mill, completing digital transformation.

The expected results after implementing full phases are shown in Figure 17.

*Table 38: Phase 3: Full Integration (18 months, US$160,000)*

| Full Integration | Expected Benefits |
|---|---|
| **Complete Process Automation:**<br>• End-to-end IoT integration across all processing stages.<br>• AI-powered process optimization using machine learning models.<br>• Automated quality control with intelligent reject handling.<br>• Real-time yield prediction and optimization algorithms. | 1)Achieve 2.0% drying losses (global best practice level)<br>2)Reduce milling losses to 8.2% |
| **Smart Storage & Logistics:**<br>• Automated storage systems with precise climate control and traceability. | 3)Improve head rice yield from 46% to 54% |

| | |
|---|---|
| • Predictive quality degradation models to optimize storage conditions.<br>• Integration with packaging lines for seamless operations.<br>**Business Intelligence Platform:**<br>• Real-time production dashboards for management oversight.<br>• Predictive analytics for market optimization.<br>• Automated cost optimization recommendations.<br>• Quality compliance monitoring for export standards. | 4)Lower discoloration incidents to 4%<br>5)Reduce mycotoxin incidents by 70%<br>6)Annual savings: $1,184,976<br>7)ROI period: 3.5 months |

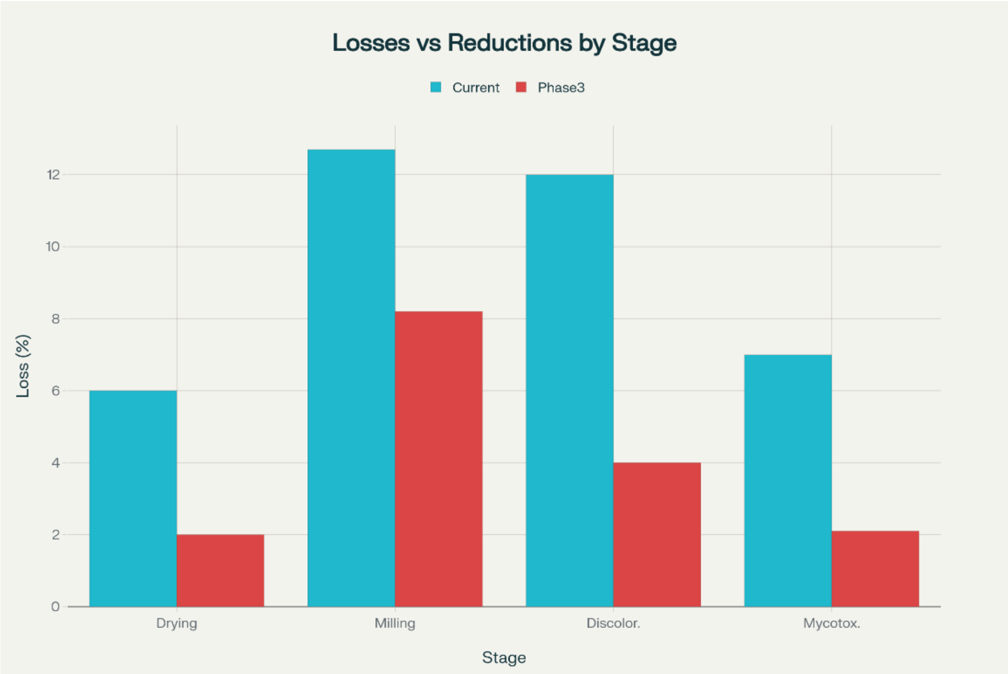

*Figure 17: IoT implementation proposal: Final loss reduction and ROI analysis*

### 5.5.2 Implementation timeline and resource requirements

*Table 39: Implementation timeline and resource requirements*

| Phase 1 (Months 1-6) | Phase 2 (Months 7-18) | Phase 3 (Months 19-36) |
|---|---|---|
| • Equipment procurement and installation: 3 months | • Advanced system integration: 6 months | • Complete system integration: 8 months |
| • System commissioning and testing: 2 months | • AI model development and training: 4 months | • Business intelligence platform deployment: 6 months |

| | | |
|---|---|---|
| • Staff training and documentation: 1 month | • Process optimization and validation: 2 months | • Comprehensive testing and optimization: 4 months |
| • Key personnel: 2 technicians, 1 IoT specialist | • Key personnel: 3 technicians, 2 software engineers, 1 process engineer | • Key personnel: 4 technicians, 2 data scientists, 1 systems integrator |

### 5.5.3 Risk mitigation strategies

*Table 40: Risk mitigation strategies for implementation roadmap*

| Technical Risks | Financial Risks | Operational Risks |
|---|---|---|
| • Gradual implementation reduces system integration complexity | • Phased investment approach allows for validation at each stage | • Comprehensive staff training programs ensure smooth adoption |
| • Redundant sensor systems ensure continuous operation | • Short ROI periods (less than 4 months) minimize financial exposure | • Parallel operation during transition periods maintains production continuity |
| • Local technical support partnerships minimize downtime | • Government incentives for agricultural technology adoption may be available | • 24/7 technical support during initial implementation phases<br>Long-term Benefits and Competitive Advantages |

### 5.5.4 Conclusion of recommendations and implementation roadmap

This proposal of a comprehensive implementation of IoT extends to CDo a pathway to evolve from a traditional rice mill to a smart digitally enabled facility. When CDo's capex is around $125,000-250,000, the project with total investment of $295,000 over three years could be suitable to deploy. Moreover, the proposal aims to generate cumulative savings exceeding $4.2 million over five years. Therefore, the proposal delivers exceptional returns while positioning the company for long-term competitive success in the global rice market.

The phased approach to implementation not only minimizes risk, but also maximizes opportunities for learning, ensuring all implementation stages build on the successes and findings of previous stages. Early wins in Phase 1 will build organizational confidence for the more comprehensive and impactful transformations planned for subsequent phases.

# 6. Conclusion and recommendations

This research aimed to identify and quantify the processing loss of rice for the CDo Company, a mid-scale mill of 45,000 MT annually located in CDo's Mekong Delta, Can Tho. The company's reliance on outdated automation and heavy manual controls processes revealed chronic underperformance at the mill, particularly in value recovery owing to aging automation and manual controls, when analyzed using meticulous mass balances, direct monitoring, and an extensive quality-control archive spanning twelve months.

As for the processing loss the evidence gathered suggests that the total quantitative loss is 21.8% for each 30MT DT8 batch. The components of die loss such as drying with a 6.0% dry-matter shrinkage and milling with a yield gap of 12.7% account for 86% of the total. During 2024, an additional 3,869 kg of processed grain was lost due to qualitative rejection as a result of discoloration, pesticide residues, heavy metals, and mycotoxins. Physical and quality loss was quite significant in the processing of rice, particularly, 1.17 million annually for DT8, a stark contrast to Vietnam's record export performance in the same year, underlining the discrepancy between observed and ideal revenue.

In addition to documenting losses, the thesis develops the first ever factory-level loss-and-value dashboard for a Vietnamese mill, demonstrates the relationship between some equipment settings and yield losses, and shows a replicable model that quantifies economically some technically inefficient operations. Such revelations furnish mill managers with a tangible rationale to modernize flat-bed dryers and the manual milling processes, while aiding policymakers as granular logic to justify technology-upgrade credit schemes.

Having a single site as the scope of study and primary measurements only collected in December poses limitations to statistical generalizability and calls for multi-site replication. Such limitations of generalizability were compounded by the unavailability of detailed export-rejection records due to confidentiality constraints, which may have understated the proportion of losses due to quality.

Relying on such narrow scope and set measurements, moving forward, research should embed life cycle costing to capture energy and carbon savings on a pilot study for IoT-enabled recirculating dryers and automated huskers. Expanding the study to analyze other varieties such as ST25 and OM5451 during wet and dry seasons would be beneficial. Additionally, to mitigate the risk of contaminants and enhance market differentiation, integrating traceability for sourcing raw paddy could be explored.

Conclusively, the CDo case substantiates that outdated technology is the primary reason for the losses incurred in rice processing in Vietnam. Improving drying uniformity and milling accuracy can eliminate about 20 percent of waste and recover over a million dollars a year in revenue per plant, reinforcing the country's position in high-value export markets. These insights provide a solid empirical foundation and a straightforward path for investment, guiding Vietnam's rice-processing industry towards a much overdue modernization that is data and efficiency focused.

Recommendations for future research:

1. Multi-site studies across Mekong Delta processors
2. Multi-variety comparisons (DT8 vs IR50404 vs fragrant varieties)
3. Longitudinal studies tracking seasonal and annual variation
4. Controlled experiments with IoT sensors to establish causal effects
5. Economic analysis of full value chain from farm to export

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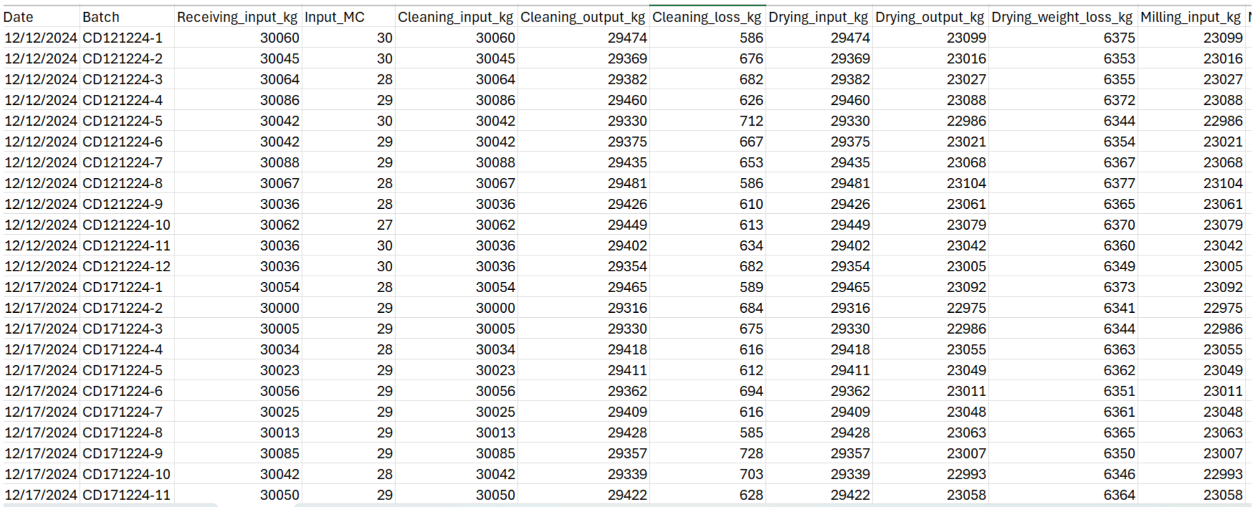
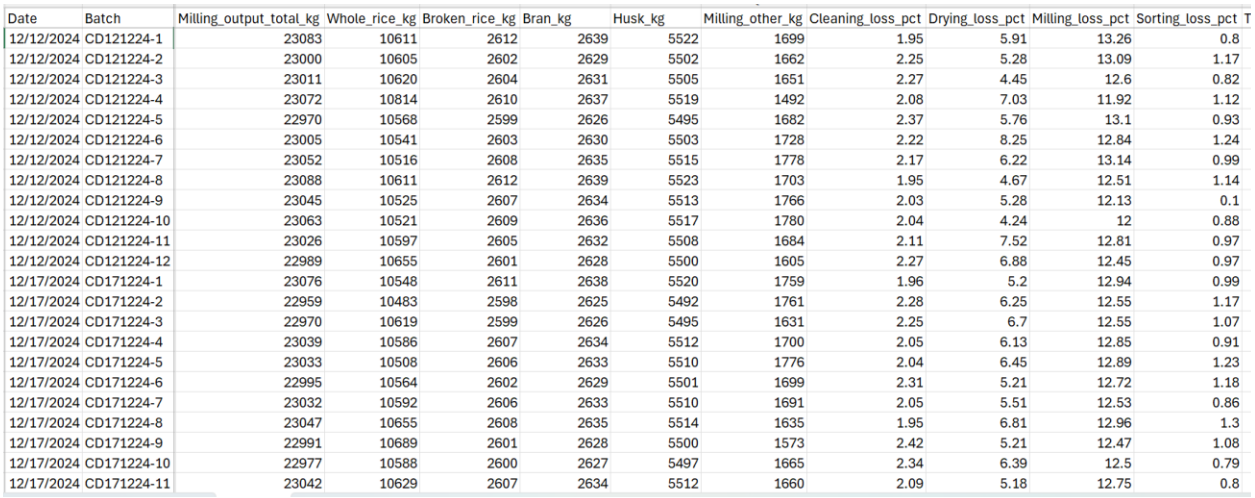
# 8. Appendix

Figure 18, Figure 19, Figure 20, and Figure 21 show data collected after plant visit on December 12, 2024, December 17 2024, and December 25 2024 during the company's processing of 36 batches of DT8 rice.



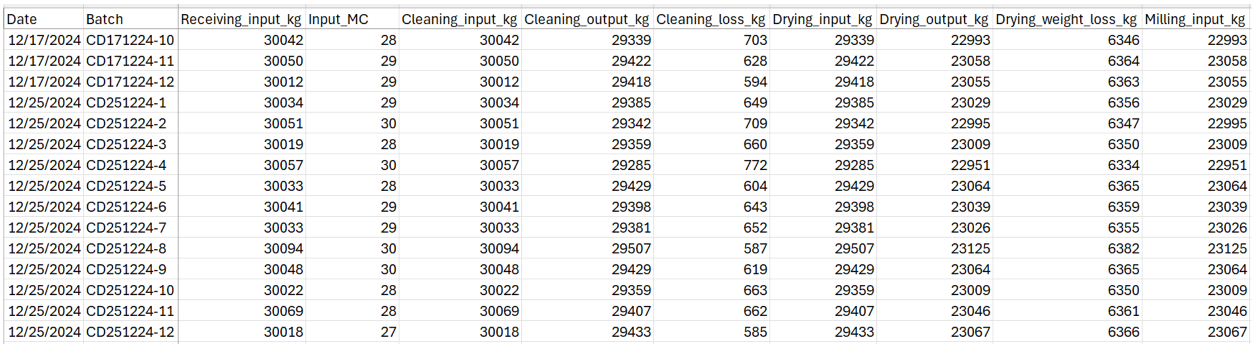
| Date | Batch | Receiving_input_kg | Input_MC | Cleaning_input_kg | Cleaning_output_kg | Cleaning_loss_kg | Drying_input_kg | Drying_output_kg | Drying_weight_loss_kg | Milling_input_kg |
|---|---|---|---|---|---|---|---|---|---|---|
| 12/12/2024 | CD121224-1 | 30060 | 30 | 30060 | 29474 | 586 | 29474 | 23099 | 6375 | 23099 |
| 12/12/2024 | CD121224-2 | 30045 | 30 | 30045 | 29369 | 676 | 29369 | 23016 | 6353 | 23016 |
| 12/12/2024 | CD121224-3 | 30064 | 28 | 30064 | 29382 | 682 | 29382 | 23027 | 6355 | 23027 |
| 12/12/2024 | CD121224-4 | 30086 | 29 | 30086 | 29460 | 626 | 29460 | 23088 | 6372 | 23088 |
| 12/12/2024 | CD121224-5 | 30042 | 30 | 30042 | 29330 | 712 | 29330 | 22986 | 6344 | 22986 |
| 12/12/2024 | CD121224-6 | 30042 | 29 | 30042 | 29375 | 667 | 29375 | 23021 | 6354 | 23021 |
| 12/12/2024 | CD121224-7 | 30088 | 29 | 30088 | 29435 | 653 | 29435 | 23068 | 6367 | 23068 |
| 12/12/2024 | CD121224-8 | 30067 | 28 | 30067 | 29481 | 586 | 29481 | 23104 | 6377 | 23104 |
| 12/12/2024 | CD121224-9 | 30036 | 28 | 30036 | 29426 | 610 | 29426 | 23061 | 6365 | 23061 |
| 12/12/2024 | CD121224-10 | 30062 | 27 | 30062 | 29449 | 613 | 29449 | 23079 | 6370 | 23079 |
| 12/12/2024 | CD121224-11 | 30036 | 30 | 30036 | 29402 | 634 | 29402 | 23042 | 6360 | 23042 |
| 12/12/2024 | CD121224-12 | 30036 | 30 | 30036 | 29354 | 682 | 29354 | 23005 | 6349 | 23005 |
| 12/17/2024 | CD171224-1 | 30054 | 28 | 30054 | 29465 | 589 | 29465 | 23092 | 6373 | 23092 |
| 12/17/2024 | CD171224-2 | 30000 | 29 | 30000 | 29316 | 684 | 29316 | 22975 | 6341 | 22975 |
| 12/17/2024 | CD171224-3 | 30005 | 29 | 30005 | 29330 | 675 | 29330 | 22986 | 6344 | 22986 |
| 12/17/2024 | CD171224-4 | 30034 | 28 | 30034 | 29418 | 616 | 29418 | 23055 | 6363 | 23055 |
| 12/17/2024 | CD171224-5 | 30023 | 29 | 30023 | 29411 | 612 | 29411 | 23049 | 6362 | 23049 |
| 12/17/2024 | CD171224-6 | 30056 | 29 | 30056 | 29362 | 694 | 29362 | 23011 | 6351 | 23011 |
| 12/17/2024 | CD171224-7 | 30025 | 29 | 30025 | 29409 | 616 | 29409 | 23048 | 6361 | 23048 |
| 12/17/2024 | CD171224-8 | 30013 | 29 | 30013 | 29428 | 585 | 29428 | 23063 | 6365 | 23063 |
| 12/17/2024 | CD171224-9 | 30085 | 29 | 30085 | 29357 | 728 | 29357 | 23007 | 6350 | 23007 |
| 12/17/2024 | CD171224-10 | 30042 | 28 | 30042 | 29339 | 703 | 29339 | 22993 | 6346 | 22993 |
| 12/17/2024 | CD171224-11 | 30050 | 29 | 30050 | 29422 | 628 | 29422 | 23058 | 6364 | 23058 |

*Figure 18: Weight and moisture content at CDo stages (1)*



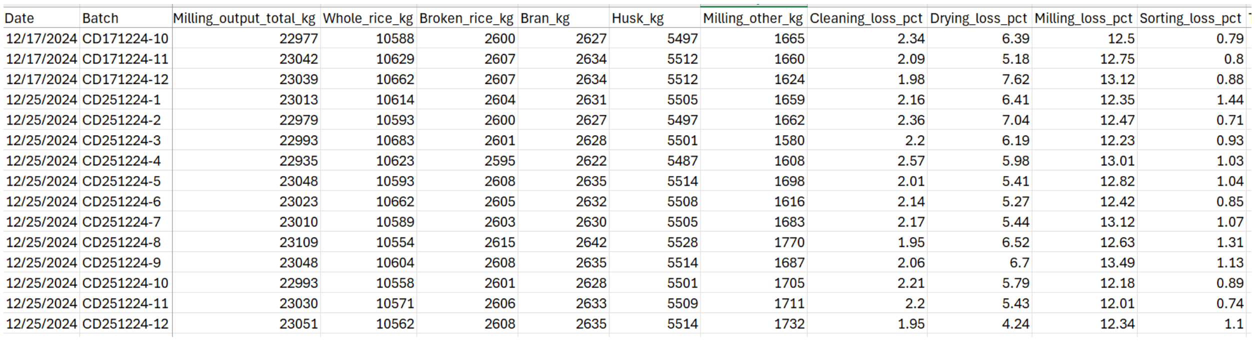
| Date | Batch | Milling_output_total_kg | Whole_rice_kg | Broken_rice_kg | Bran_kg | Husk_kg | Milling_other_kg | Cleaning_loss_pct | Drying_loss_pct | Milling_loss_pct | Sorting_loss_pct |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 12/12/2024 | CD121224-1 | 23083 | 10611 | 2612 | 2639 | 5522 | 1699 | 1.95 | 5.91 | 13.26 | 0.8 |
| 12/12/2024 | CD121224-2 | 23000 | 10605 | 2602 | 2629 | 5502 | 1662 | 2.25 | 5.28 | 13.09 | 1.17 |
| 12/12/2024 | CD121224-3 | 23011 | 10620 | 2604 | 2631 | 5505 | 1651 | 2.27 | 4.45 | 12.6 | 0.82 |
| 12/12/2024 | CD121224-4 | 23072 | 10814 | 2610 | 2637 | 5519 | 1492 | 2.08 | 7.03 | 11.92 | 1.12 |
| 12/12/2024 | CD121224-5 | 22970 | 10568 | 2599 | 2626 | 5495 | 1682 | 2.37 | 5.76 | 13.1 | 0.93 |
| 12/12/2024 | CD121224-6 | 23005 | 10541 | 2603 | 2630 | 5503 | 1728 | 2.22 | 8.25 | 12.84 | 1.24 |
| 12/12/2024 | CD121224-7 | 23052 | 10516 | 2608 | 2635 | 5515 | 1778 | 2.17 | 6.22 | 13.14 | 0.99 |
| 12/12/2024 | CD121224-8 | 23088 | 10611 | 2612 | 2639 | 5523 | 1703 | 1.95 | 4.67 | 12.51 | 1.14 |
| 12/12/2024 | CD121224-9 | 23045 | 10525 | 2607 | 2634 | 5513 | 1766 | 2.03 | 5.28 | 12.13 | 0.1 |
| 12/12/2024 | CD121224-10 | 23063 | 10521 | 2609 | 2636 | 5517 | 1780 | 2.04 | 4.24 | 12 | 0.88 |
| 12/12/2024 | CD121224-11 | 23026 | 10597 | 2605 | 2632 | 5508 | 1684 | 2.11 | 7.52 | 12.81 | 0.97 |
| 12/12/2024 | CD121224-12 | 22989 | 10655 | 2601 | 2628 | 5500 | 1605 | 2.27 | 6.88 | 12.45 | 0.97 |
| 12/17/2024 | CD171224-1 | 23076 | 10548 | 2611 | 2638 | 5520 | 1759 | 1.96 | 5.2 | 12.94 | 0.99 |
| 12/17/2024 | CD171224-2 | 22959 | 10483 | 2598 | 2625 | 5492 | 1761 | 2.28 | 6.25 | 12.55 | 1.17 |
| 12/17/2024 | CD171224-3 | 22970 | 10619 | 2599 | 2626 | 5495 | 1631 | 2.25 | 6.7 | 12.55 | 1.07 |
| 12/17/2024 | CD171224-4 | 23039 | 10586 | 2607 | 2634 | 5512 | 1700 | 2.05 | 6.13 | 12.85 | 0.91 |
| 12/17/2024 | CD171224-5 | 23033 | 10508 | 2606 | 2633 | 5510 | 1776 | 2.04 | 6.45 | 12.89 | 1.23 |
| 12/17/2024 | CD171224-6 | 22995 | 10564 | 2602 | 2629 | 5501 | 1699 | 2.31 | 5.21 | 12.72 | 1.18 |
| 12/17/2024 | CD171224-7 | 23032 | 10592 | 2606 | 2633 | 5510 | 1691 | 2.05 | 5.51 | 12.53 | 0.86 |
| 12/17/2024 | CD171224-8 | 23047 | 10655 | 2608 | 2635 | 5514 | 1635 | 1.95 | 6.81 | 12.96 | 1.3 |
| 12/17/2024 | CD171224-9 | 22991 | 10689 | 2601 | 2628 | 5500 | 1573 | 2.42 | 5.21 | 12.47 | 1.08 |
| 12/17/2024 | CD171224-10 | 22977 | 10588 | 2600 | 2627 | 5497 | 1665 | 2.34 | 6.39 | 12.5 | 0.79 |
| 12/17/2024 | CD171224-11 | 23042 | 10629 | 2607 | 2634 | 5512 | 1660 | 2.09 | 5.18 | 12.75 | 0.8 |

*Figure 19: Weight and moisture content at CDo stages (2)*



| Date | Batch | Receiving_input_kg | Input_MC | Cleaning_input_kg | Cleaning_output_kg | Cleaning_loss_kg | Drying_input_kg | Drying_output_kg | Drying_weight_loss_kg | Milling_input_kg |
|---|---|---|---|---|---|---|---|---|---|---|
| 12/17/2024 | CD171224-10 | 30042 | 28 | 30042 | 29339 | 703 | 29339 | 22993 | 6346 | 22993 |
| 12/17/2024 | CD171224-11 | 30050 | 29 | 30050 | 29422 | 628 | 29422 | 23058 | 6364 | 23058 |
| 12/17/2024 | CD171224-12 | 30012 | 29 | 30012 | 29418 | 594 | 29418 | 23055 | 6363 | 23055 |
| 12/25/2024 | CD251224-1 | 30034 | 29 | 30034 | 29385 | 649 | 29385 | 23029 | 6356 | 23029 |
| 12/25/2024 | CD251224-2 | 30051 | 30 | 30051 | 29342 | 709 | 29342 | 22995 | 6347 | 22995 |
| 12/25/2024 | CD251224-3 | 30019 | 28 | 30019 | 29359 | 660 | 29359 | 23009 | 6350 | 23009 |
| 12/25/2024 | CD251224-4 | 30057 | 30 | 30057 | 29285 | 772 | 29285 | 22951 | 6334 | 22951 |
| 12/25/2024 | CD251224-5 | 30033 | 28 | 30033 | 29429 | 604 | 29429 | 23064 | 6365 | 23064 |
| 12/25/2024 | CD251224-6 | 30041 | 29 | 30041 | 29398 | 643 | 29398 | 23039 | 6359 | 23039 |
| 12/25/2024 | CD251224-7 | 30033 | 29 | 30033 | 29381 | 652 | 29381 | 23026 | 6355 | 23026 |
| 12/25/2024 | CD251224-8 | 30094 | 30 | 30094 | 29507 | 587 | 29507 | 23125 | 6382 | 23125 |
| 12/25/2024 | CD251224-9 | 30048 | 30 | 30048 | 29429 | 619 | 29429 | 23064 | 6365 | 23064 |
| 12/25/2024 | CD251224-10 | 30022 | 28 | 30022 | 29359 | 663 | 29359 | 23009 | 6350 | 23009 |
| 12/25/2024 | CD251224-11 | 30069 | 28 | 30069 | 29407 | 662 | 29407 | 23046 | 6361 | 23046 |
| 12/25/2024 | CD251224-12 | 30018 | 27 | 30018 | 29433 | 585 | 29433 | 23067 | 6366 | 23067 |

*Figure 20: Weight and moisture content at CDo stages (3)*



| Date | Batch | Milling_output_total_kg | Whole_rice_kg | Broken_rice_kg | Bran_kg | Husk_kg | Milling_other_kg | Cleaning_loss_pct | Drying_loss_pct | Milling_loss_pct | Sorting_loss_pct |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 12/17/2024 | CD171224-10 | 22977 | 10588 | 2600 | 2627 | 5497 | 1665 | 2.34 | 6.39 | 12.5 | 0.79 |
| 12/17/2024 | CD171224-11 | 23042 | 10629 | 2607 | 2634 | 5512 | 1660 | 2.09 | 5.18 | 12.75 | 0.8 |
| 12/17/2024 | CD171224-12 | 23039 | 10662 | 2607 | 2634 | 5512 | 1624 | 1.98 | 7.62 | 13.12 | 0.88 |
| 12/25/2024 | CD251224-1 | 23013 | 10614 | 2604 | 2631 | 5505 | 1659 | 2.16 | 6.41 | 12.35 | 1.44 |
| 12/25/2024 | CD251224-2 | 22979 | 10593 | 2600 | 2627 | 5497 | 1662 | 2.36 | 7.04 | 12.47 | 0.71 |
| 12/25/2024 | CD251224-3 | 22993 | 10683 | 2601 | 2628 | 5501 | 1580 | 2.2 | 6.19 | 12.23 | 0.93 |
| 12/25/2024 | CD251224-4 | 22935 | 10623 | 2595 | 2622 | 5487 | 1608 | 2.57 | 5.98 | 13.01 | 1.03 |
| 12/25/2024 | CD251224-5 | 23048 | 10593 | 2608 | 2635 | 5514 | 1698 | 2.01 | 5.41 | 12.82 | 1.04 |
| 12/25/2024 | CD251224-6 | 23023 | 10662 | 2605 | 2632 | 5508 | 1616 | 2.14 | 5.27 | 12.42 | 0.85 |
| 12/25/2024 | CD251224-7 | 23010 | 10589 | 2603 | 2630 | 5505 | 1683 | 2.17 | 5.44 | 13.12 | 1.07 |
| 12/25/2024 | CD251224-8 | 23109 | 10554 | 2615 | 2642 | 5528 | 1770 | 1.95 | 6.52 | 12.63 | 1.31 |
| 12/25/2024 | CD251224-9 | 23048 | 10604 | 2608 | 2635 | 5514 | 1687 | 2.06 | 6.7 | 13.49 | 1.13 |
| 12/25/2024 | CD251224-10 | 22993 | 10558 | 2601 | 2628 | 5501 | 1705 | 2.21 | 5.79 | 12.18 | 0.89 |
| 12/25/2024 | CD251224-11 | 23030 | 10571 | 2606 | 2633 | 5509 | 1711 | 2.2 | 5.43 | 12.01 | 0.74 |
| 12/25/2024 | CD251224-12 | 23051 | 10562 | 2608 | 2635 | 5514 | 1732 | 1.95 | 4.24 | 12.34 | 1.1 |

*Figure 21: Weight and moisture content at CDo stages (4)*