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REVOLUTIONIZING RICE PROCESSING: THE ROLE OF INNOVATIVE DRYING AND MILLING TECHNOLOGIES IN ENHANCING QUALITY AND ECONOMIC OUTCOMES

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Abstract:

Rice, as a staple food for more than half of the global population, faces persistent challenges in post-harvest processing, particularly during drying and milling. Traditional drying methods often result in excessive energy consumption, grain fissuring, and nutrient degradation. At the same time, conventional milling practices frequently compromise head rice yield and overall product quality. These inefficiencies limit both the economic returns for producers and the sustainability of rice value chains. Addressing this gap, the present study aims to investigate how innovative drying and milling technologies can enhance rice quality, improve milling efficiency, and support economic sustainability. Using a narrative review methodology, data were systematically collected through the Scopus database and analyzed using an integrative thematic approach to identify key technological advancements, concepts, and theoretical perspectives. The findings indicate that advanced thermal drying technologies and IoT-assisted solar drying systems have been shown in experimental and pilot-scale studies to improve moisture control, reduce grain fissuring, and better preserve nutritional quality compared to conventional methods. Collectively, the literature suggests that these innovations may contribute to economic sustainability by improving processing efficiency, reducing energy intensity, and increasing value-added output. Theoretically, the study advances agricultural innovation scholarship by integrating diffusion of innovation and socio-technical systems perspectives to explain how adoption factors mediate technological and sustainability outcomes. Practically, the review highlights the importance of targeted investment,

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capacity building, and phased implementation strategies. The study concludes by identifying financial, technical, and knowledge-based adoption barriers and recommends future research on techno-economic assessments, pilot implementation, and digital integration strategies to optimize rice processing systems.

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Keyword:

Innovative Drying Technologies, Milling Efficiency, Economic Sustainability, Agro-processing Industry, Technology Adoption

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Introduction

Rice remains a fundamental staple food for more than half of the world's population, making its quality and economic value crucial for global food security. Post-harvest processing, particularly drying and milling, plays a decisive role in determining both the nutritional and commercial attributes of rice. Following this, conventional drying methods, such as sun drying and hot-air drying, are still widely practiced. However, they are often associated with longer processing times, high energy consumption, and inconsistent quality outcomes. Similarly, traditional milling practices often compromise rice yield, texture, and nutrient retention, thereby limiting overall economic efficiency. Together, these challenges underscore the need to explore innovative technologies that can enhance both the efficiency and quality of rice processing in an era of rising demand and sustainability concerns (Mahmood et al., 2024; Tong et al., 2019).

Over the past decade, research has introduced advanced drying technologies, including Radio Frequency (RF), Microwave (MW), and Infrared (IR) drying, that demonstrate potential in reducing processing time, improving heating uniformity, and preserving rice quality. Furthermore, studies indicate that these methods can enhance the physicochemical properties, nutritional stability, and sensory attributes of products compared to conventional methods (Mahmood et al., 2023; Jimoh et al., 2025). Likewise, developments in milling, such as the application of machine vision systems, Discrete Element Method (DEM) simulations, and precision-based milling equipment, have demonstrated improvements in yield, texture, and nutrient retention (Tie et al., 2024; Yu et al., 2024). Despite these advances, widespread adoption remains limited, and further optimization is necessary to strike a balance between cost, scalability, and long-term economic outcomes.

Although numerous studies have examined drying and milling technologies separately, there is still a lack of an integrative review that comparatively evaluates both stages in relation to process efficiency, grain quality, economic performance, and sustainability outcomes. This fragmented body of literature limits the development of a unified framework capable of guiding stakeholders in making informed technological investment decisions across the rice value chain.

This study aims to bridge this gap by proposing a conceptual framework that integrates innovative drying and milling technologies to enhance rice quality while ensuring economic efficiency. Specifically, the framework emphasizes optimization of operating conditions, technology integration, and evaluation through both quality indices and cost-effectiveness analyses. Thus, by combining multidisciplinary insights from food science, engineering, and economics, the study seeks to contribute to the modernization of rice processing and establish pathways for sustainable practices (Jimoh et al., 2025; Yu et al., 2024). Moreover, the findings are expected to provide practical implications for policymakers, researchers, and industry stakeholders engaged in rice production and processing.

Importantly, the significance of this study lies in its potential to revolutionize rice processing by aligning technological innovation with economic and sustainability goals. Employing a theoretical lens grounded in systems integration and process optimization, this study positions rice processing as a value chain where technological choices directly influence quality outcomes and market performance. Accordingly, the structure of this paper is as follows: the next section presents a comprehensive literature review on drying and milling technologies. This is followed by a methodology section outlining experimental approaches, simulation models, and economic analysis. The results and discussion section then evaluates the quality and economic performance of the integrated technologies. Finally, the paper concludes with implications for rice processing and directions for future research.

Background

The drying stage is one of the most critical operations in rice post-harvest processing, as it directly influences both quality and marketability. Traditional drying methods, such as sun drying or hot-air drying, remain the standard in many rice-producing countries; however, they often result in prolonged drying durations, high energy consumption, and inconsistent quality outcomes. To address these limitations, researchers have explored several innovative drying technologies, including RF, MW, IR, Vacuum Drying (VD), Superheated Steam (SHS), and Fluidized Bed (FB) drying. These methods have been demonstrated to significantly enhance drying efficiency, maintain nutritional integrity, and improve the cooking and sensory properties of rice (Mahmood et al., 2024). For instance, RF drying enhances uniform heating, reducing fissuring, whereas MW drying has demonstrated the potential to drastically shorten drying times without compromising quality (Mahmood et al., 2023).

Advancements in milling technologies have also garnered increasing attention, as milling remains a crucial factor in determining the final quality and economic value of rice. Notably, conventional milling practices often result in over-polishing and nutrient losses, which reduce both yield and quality. Recent innovations include semi-dry milling methods, which strike a balance between water conservation and flour performance, and precision-based milling systems that utilize hot air or mechanical treatments to enhance efficiency (Yu et al., 2024). Additionally, the integration of digital technologies, including machine vision and Artificial

Intelligence (AI), has enabled real-time monitoring and quality control during milling operations. Collectively, these advancements preserve essential nutrients, improve flour consistency, and reduce waste. This ultimately contributes to higher economic returns for producers and processors (Panigrahi et al., 2025).

Despite these promising developments, challenges persist in the widespread adoption of innovative drying and milling technologies. Key barriers include the high capital costs of advanced equipment, scalability issues, and performance variability across different rice varieties. For example, while FB drying has demonstrated efficiency improvements, studies highlight the need for further research to optimize its operational parameters and minimize uneven drying (Luthra & Sadaka, 2020). In addition, discrepancies in findings across studies indicate a lack of consensus on the comparative advantages of specific methods. This suggests that further empirical and applied research is essential to refine these technologies and facilitate their adoption in both large-scale and smallholder settings (Panigrahi et al., 2025).

Another important strand of research focuses on the economic and environmental dimensions of innovative processing technologies. The adoption of modern drying systems, such as IoT-enabled portable dryers, has demonstrated reductions in energy consumption and post-harvest losses, thereby improving both quality and profitability (Austria et al., 2024). Similarly, environmental assessments of rice production chains suggest that the adoption of advanced drying and milling technologies could reduce greenhouse gas emissions and water consumption compared to traditional practices (Motevali et al., 2019). In essence, the integration of by-product utilization strategies, such as converting rice bran and husk into value-added products, further supports sustainability by promoting a zero-waste bioindustry model (Onwusiribe et al., 2025).

Overall, the literature indicates that innovative drying and milling technologies have the potential to transform rice processing by improving quality, reducing losses, and enhancing economic outcomes. Nevertheless, the integration of these technologies into a unified framework remains underexplored. Most studies focus on either drying or milling technologies in isolation, and few address their combined potential in optimizing the entire rice processing value chain. This highlights the need for a comprehensive conceptual framework that aligns technological innovations with sustainability and economic efficiency goals. Remarkably, such an approach would enhance rice quality and profitability and support broader food security and environmental sustainability agendas.

Materials And Methods

Research Design – Narrative Review Methodology

This study adopts a narrative review design to critically examine and synthesize existing knowledge on innovative drying and milling technologies in rice processing. A narrative review approach was selected because the technologies examined vary substantially in experimental design, performance indicators, rice varieties, and contextual applications, making statistical meta-analysis inappropriate. The narrative approach allows interdisciplinary synthesis across engineering, food science, and sustainability perspectives while maintaining analytical transparency and rigor.

Unlike systematic reviews, which employ rigid protocols for data extraction and meta-analysis, the narrative review methodology emphasizes a thematic and conceptual synthesis of relevant literature. Accordingly, this approach facilitates a more in-depth examination of emerging technologies in rice processing and their implications for quality improvement, economic viability, and sustainability. Furthermore, it allows the integration of technological, economic, and environmental aspects, which are often reported separately in empirical studies.

Key Steps in Conducting a Narrative Review

The review process followed a structured yet flexible sequence of steps to ensure rigor and comprehensiveness:

Step 1: Defining the Scope and Objectives

The research scope was clearly defined to focus on post-harvest rice processing, with an emphasis on two critical stages: drying and milling. The primary objective was to evaluate the potential of innovative technologies (e.g., RF, MW, IF, vacuum, FB, semi-dry milling, precision-based milling, and AI-enabled systems) in enhancing rice quality, reducing losses, and promoting sustainability.

Step 2: Literature Search Strategy

Data collection was conducted using the Scopus database, given its broad coverage of peer-reviewed journals, conference proceedings, and high-impact publications in agricultural engineering, food science, and sustainability studies. The search was limited to publications between 2019 and 2025 to capture the most recent advancements in the field. However, earlier seminal works were also considered where relevant.

Step 3: Screening and Selection of Sources

The initial search results were screened by reviewing titles and abstracts to ensure relevance to rice processing technologies. Full-text articles were then assessed for their contribution to understanding the effects of drying and milling innovations on quality, efficiency, economic outcomes, and environmental sustainability. Note that only peer-reviewed studies, review papers, and high-quality conference proceedings were included.

Step 4: Data Extraction and Organization

Key information, such as technology type, experimental design, findings, limitations, and implications, was systematically extracted and organized into thematic categories (e.g., drying innovations, milling innovations, sustainability perspectives). This thematic categorization allowed for the identification of common findings, contrasting evidence, and research gaps.

Step 5: Thematic Synthesis and Critical Analysis

The extracted data were synthesized into thematic narratives, highlighting patterns, trends, and divergences across studies. Emphasis was placed on linking technological advancements to their practical implications in rice processing. This includes product quality, milling yield, nutrient retention, energy efficiency, and environmental impacts.

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Step 6: Identification of Gaps and Future Directions

The final stage involved identifying areas of consensus, unresolved debates, and gaps in the literature. As such, special attention was given to challenges in technology adoption, scalability, and integration of drying and milling innovations into a unified framework for sustainable rice processing.

Through these structured steps, the narrative review offers a comprehensive, integrated, and critical evaluation of the role of innovative drying and milling technologies in transforming rice processing practices.

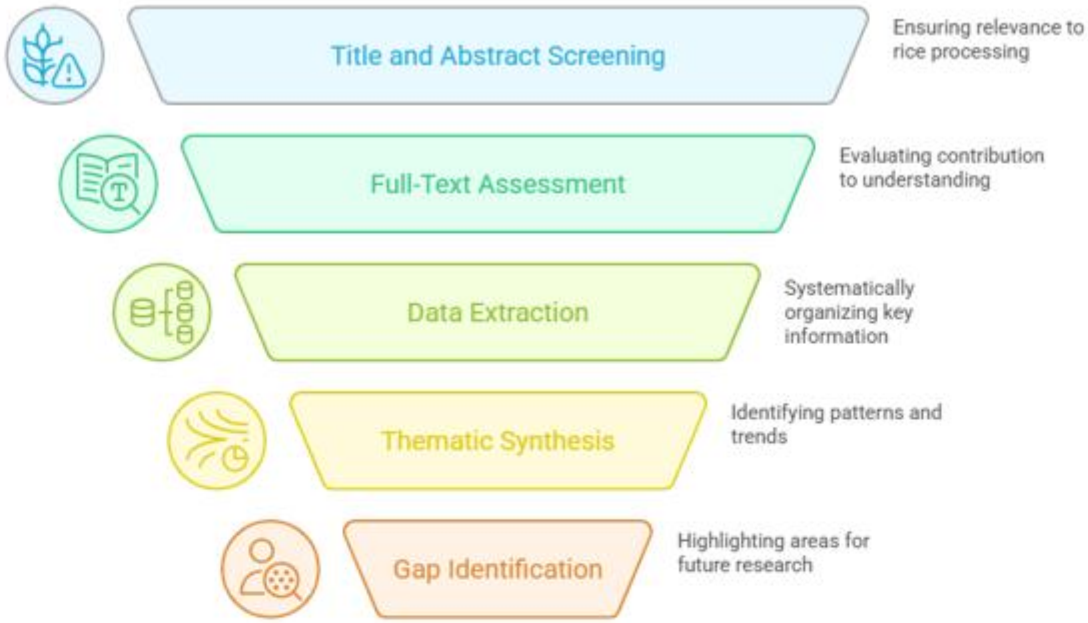

Figure 1: Refining Research on Rice Processing

Data Collection and Review Strategy

The data collection process for this narrative review was designed to ensure comprehensiveness, transparency, and academic rigor. Specifically, the Scopus database was selected as the primary source due to its extensive coverage of peer-reviewed journals, conference proceedings, and high-impact publications across the fields of food science, agricultural engineering, and sustainability studies. Following this, to capture the breadth of literature related to rice processing technologies, a structured search string was developed:

Search String:
(“drying” OR “dehydration” OR “moisture removal” OR “air drying”) AND (“milling” OR “grinding” OR “crushing” OR “pulverizing”) AND (“rice” OR “paddy” OR “grain” OR “cereal”) AND (“processing” OR “treatment” OR “manufacturing” OR “production”) AND (“technology” OR “innovation” OR “method” OR “technique”)

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This search string was carefully constructed using Boolean operators to capture both traditional and emerging terminology in rice drying and milling technologies. The inclusion of multiple synonyms (e.g., "drying"/" dehydration," "milling"/" grinding") broadened the search scope. At the same time, the combination of keywords across domains (e.g., "processing," "technology," "innovation") ensured that both technical and applied perspectives were represented.

The initial search query generated a large number of results, which were systematically refined using defined criteria. The inclusion criteria comprised peer-reviewed journal articles, high-quality review papers, and indexed conference proceedings published between 2015 and 2025, written in English, and explicitly focused on post-harvest rice drying and milling technologies. Studies focusing solely on cultivation or pre-harvest practices, non-scientific reports, opinion papers without empirical grounding, and studies unrelated to rice processing technologies were excluded. Titles, abstracts, and keywords were screened to identify relevant studies, and full-text reviews were conducted for articles that aligned with the research objectives. Additional backward and forward citation tracking was employed to ensure that influential studies not captured by the search string were also considered.

To synthesize the selected literature, an integrative thematic analysis approach was employed. This method was selected as it facilitates the identification, organization, and interpretation of recurring themes and concepts across diverse sources, allowing for both descriptive mapping and critical interpretation. The process involved the following steps:

1. Data Familiarization: Each selected study was carefully read to understand its objectives, methods, findings, and contributions.
2. Initial Coding: Key concepts, methodologies, technological innovations, and findings were manually extracted and coded. Codes were applied to reflect both explicit results (e.g., drying rates, milling yields) and implicit themes (e.g., sustainability, economic outcomes, technology adoption challenges).
3. Theme Development: Codes were clustered into broader categories, including *innovative drying technologies, advanced milling methods, quality outcomes, economic performance, and sustainability dimensions*.
4. Theoretical Integration: The identified themes were synthesized into higher-level conceptual insights, linking technical outcomes with theoretical perspectives from food science, engineering, and sustainable development.
5. Validation and Refinement: Themes were iteratively refined through comparison across studies, ensuring that overlapping ideas were consolidated and that divergent perspectives were highlighted.

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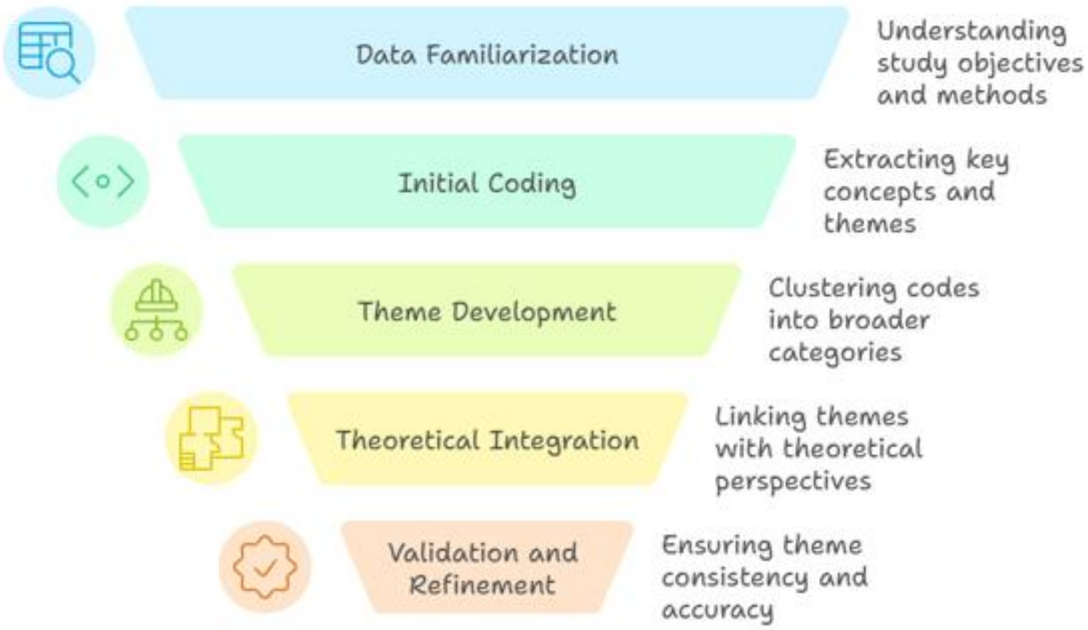

Figure 2: Integrative Thematic Analysis Process

By employing this integrative thematic analysis approach, the review was able to transcend a simple aggregation of findings. It also provides a cohesive conceptual framework that connects technological advancements in rice drying and milling with their implications for quality, efficiency, and sustainability. Furthermore, this strategy ensured that the review captured both the breadth of technological innovation and the depth of conceptual insights required to address the study's aims.

Key Findings from the Narrative Review

The narrative review identified a range of innovative drying and milling technologies that significantly influence rice quality and economic outcomes. Table 1 below presents the key findings, their descriptions, and associated implications.

Table 1: Key Findings on Rice Drying and Milling Innovations

Category	Key Finding	Description & Implications	References
Innovative Drying Technologies	Radio Frequency (RF) Drying	Improves drying rate, heating uniformity, crack reduction, and head rice yield, while enhancing viscosity and starch gelatinization.	Mahmood et al., 2024; Mahmood et al., 2023
Innovative Drying Technologies	Microwave (MW) Drying	Superior drying kinetics and energy efficiency, with lower environmental impact, require refinement to maintain nutrient retention and milling quality.	Jimoh et al., 2025
Innovative Drying Technologies	Infrared (IR) Drying	Enhances drying efficiency and technical maturity, especially with ultrasonic pretreatment, and is optimized with adjustments to radiation intensity.	Wang et al., 2025

Innovative Drying Technologies	Hybrid Drying Systems	Combines multiple methods (e.g., vacuum freeze-drying with MW) to reduce microbial contamination, improve rehydration, and minimize heat damage.	Khatri et al., 2024
Innovative Drying Technologies	Solar-powered IoT Dryers	Reduces drying time, enables real-time monitoring, and lowers post-harvest losses, providing a sustainable solution for smallholder farmers.	Austria et al., 2024
Innovative Milling Technologies	Semi-Dry Milling	Reduces soaking and energy use, improving flour quality, but faces challenges in achieving continuous production scalability.	Yu et al., 2024
Innovative Milling Technologies	Parboiling and Improved Milling	Enhances milling characteristics, nutritional quality, and economic returns with optimized soaking and steaming conditions.	Ndindeng et al., 2025; Shaju et al., 2022
Innovative Milling Technologies	Precision Milling	Incorporates mechanized cleaning, AI-driven grading, and sensor-based quality control; improves value addition and food security.	Madhu, 2025
Quality Outcomes	Enhanced Grain Quality	Innovations improve physicochemical, nutritional, and sensory attributes, including color, flavor, crack ratio, antioxidant activity, and cooking quality.	Mahmood et al., 2024; Tong et al., 2019
Economic Outcomes	Higher Head Rice Yield & Milling Recovery	Leads to increased revenues for farmers and processors; optimized parboiling and milling achieve higher returns.	Butardo & Sreenivasulu, 2019; Okegbile et al., 2005
Sustainability Outcomes	Reduced Energy and Environmental Impact	Hybrid and solar-powered systems improve efficiency while lowering carbon footprint, aligning with sustainable rice production goals.	Jimoh et al., 2025; Khatri et al., 2024; Austria et al., 2024
Challenges	Adoption Barriers	High capital costs, infrastructure limitations, and technical skills shortages hinder the adoption of these technologies, especially in developing regions.	Madhu, 2025
Challenges	Research Needs	Mechanisms of quality changes require further exploration; optimizing parameters across contexts is essential.	Mahmood et al., 2024; Tong et al., 2019

The findings from the narrative review underscore that innovative drying technologies have been reported in controlled studies to provide improvements in drying efficiency, product quality, and energy savings compared to conventional methods. Among them, dielectric-based approaches appear particularly promising based on reported experimental findings. Similarly, innovative milling technologies, including semi-dry milling, optimized parboiling, and precision AI-based methods, play a crucial role in enhancing flour quality. This includes retaining nutritional value and increasing head rice yield while also mitigating environmental impacts.

In terms of economic outcomes, improved head rice yield and milling recovery directly enhance profitability for rice producers and processors, with optimized parboiling and milling strategies offering better returns than conventional methods. In addition, the sustainability dimension is strengthened through the use of energy-efficient technologies, such as solar-powered IoT dryers and hybrid systems, which reduce both drying time and environmental impact. Despite these benefits, significant barriers to adoption remain, primarily due to high initial investment costs, limited infrastructure, and a lack of technical capacity in developing regions. Moreover, the literature highlights the need for further mechanistic research and process optimization to fully leverage these technologies across diverse production environments.

In summary, the review reveals that innovative drying and milling technologies hold transformative potential for rice processing by simultaneously enhancing quality, boosting economic gains, and promoting sustainability. Nonetheless, realizing these benefits requires continued research, industry collaboration, and supportive policy frameworks to overcome adoption challenges and accelerate the implementation of large-scale solutions.

Theoretical Framework

This study integrates Diffusion of Innovation Theory (Rogers et al., 2014) and Socio-Technical Systems Theory (Bostrom & Heinen, 1977) to conceptualize how technological innovations influence rice processing outcomes. Diffusion theory explains adoption patterns based on attributes such as relative advantage, complexity, and trialability. Socio-technical systems theory emphasizes the interaction between technological systems and social, institutional, and economic structures. By combining these perspectives, the framework conceptualizes innovative drying and milling technologies as independent variables, adoption conditions as mediating factors, and quality, economic efficiency, and sustainability as outcome variables. This integration advances understanding of how technological improvements translate into value chain transformation.

Applying these theories to the context of rice processing, the framework conceptualizes the relationship between innovative technologies (RF, MW, IR, hybrid, and solar drying; semi-dry and precision milling) and key outcomes, namely product quality, economic efficiency, and sustainability. Building on this, the integrative thematic analysis of the narrative review (Mahmood et al., 2024; Jimoh et al., 2025; Austria et al., 2024) revealed that the adoption of these technologies improves drying efficiency, enhances head rice yield, reduces energy costs, and supports environmental sustainability. At the same time, challenges such as high capital investment and limited technical expertise constrain diffusion, aligning with Rogers' attributes of innovation (relative advantage, complexity, and trialability). The conceptual framework, therefore, maps technological innovations as independent variables, adoption processes as mediating factors, and quality, economic, and sustainability outcomes as dependent variables.
From both theoretical and practical standpoints, this framework integrates insights from existing literature with applied perspectives, enabling a nuanced understanding of innovation in rice processing. It highlights that adoption is not merely a technical process. Rather, it is a

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socio-economic one shaped by market dynamics, farmer capacity, and policy support (Butardo & Sreenivasulu, 2019; Madhu, 2025). Theoretically, it advances scholarship on agricultural innovation by linking diffusion theory with socio-technical systems thinking. Practically, it informs stakeholders, including policymakers, technology developers, and industry players, about strategies to accelerate the adoption of innovations. Ultimately, the theoretical framework concludes that innovations in drying and milling technologies have the potential to be transformative. However, their benefits can only be fully realized when social, economic, and institutional contexts are aligned to support widespread implementation.

Proposition Development

Proposition Development 1: Innovative Drying Technologies and Milling Efficiency

Innovative drying technologies such as MW, RF, and IR drying have demonstrated significant effects on milling efficiency by improving the structural integrity and reducing moisture variability of rice grains. Traditional drying techniques often result in stress cracks, uneven moisture distribution, and higher breakage rates during milling. This, in turn, lowers head rice yield and reduces overall processing efficiency (Tong et al., 2019; Mahmood et al., 2023). In contrast, dielectric-based drying methods provide more uniform heating and controlled moisture removal, thereby minimizing grain fissures and enhancing milling recovery (Mahmood et al., 2024). Additionally, optimized drying parameters reduce mechanical losses during dehusking and polishing and enhance throughput and energy efficiency in milling operations (Jimoh et al., 2025). Hence, by stabilizing grain quality before milling, these innovative drying technologies directly contribute to higher yield, reduced waste, and enhanced process performance. *Proposition 1: The adoption of innovative drying technologies has a positive impact on milling efficiency in rice processing.*

Proposition Development 2: Milling Efficiency and Economic Sustainability

Milling efficiency plays a critical role in determining the economic sustainability of rice production, as it directly influences head rice yield, recovery rates, and overall profitability for farmers and processors. However, inefficient milling often results in higher breakage rates and reduced marketable output, which in turn diminishes revenue and increases waste (Tong et al., 2019). Conversely, efficient milling ensures greater retention of head rice, improved grain quality, and higher milling recovery, all of which contribute to enhanced market value and better economic outcomes (Butardo & Sreenivasulu, 2019). Advances in milling technologies, including semi-dry milling and precision milling, further optimize energy use, minimize grain losses, and promote value-added processes, thereby aligning economic performance with sustainability objectives (Yu et al., 2024). Furthermore, milling efficiency reduces costs in downstream processes. It enhances food security by making more high-quality rice available for consumption and trade (Ndindeng et al., 2025). *Proposition 2: Higher milling efficiency has a positive impact on economic sustainability in rice processing.*

Proposition Development 3: Innovative Drying Technologies and Economic Sustainability

Innovative drying technologies such as RF, MW, IR, and solar-powered systems have emerged as critical enablers of economic sustainability in rice processing by improving efficiency, reducing post-harvest losses, and lowering operational costs. Compared to conventional sun-drying, dielectric-based methods, such as RF and MW, accelerate drying time, enhance grain

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uniformity, and reduce cracking. This increases milling recovery and head rice yield, which directly translates into higher market value and profitability (Mahmood et al., 2024; Jimoh et al., 2025). On a similar note, solar-powered IoT dryers reduce dependency on fossil fuels and mitigate labor costs, while extending grain shelf life, making them more accessible and sustainable for smallholder farmers (Austria et al., 2024). From a broader perspective, these innovations reduce energy consumption and environmental impacts, aligning with sustainable production goals while enhancing competitiveness in the rice value chain (Khatri et al., 2024). In essence, by improving both cost-efficiency and product quality, innovative drying technologies play a pivotal role in sustaining economic returns for producers and processors. *Proposition 3: The adoption of innovative drying technologies has a positive impact on economic sustainability in rice processing.*

Proposition Development 4: Innovative Drying Technologies, Milling Efficiency, and Economic Sustainability

Innovative drying technologies play a pivotal role in enhancing milling efficiency, which in turn drives economic sustainability in rice processing. Advanced drying methods, such as RF, MW, and IR drying, reduce moisture variability, minimize grain fissuring, and enhance kernel integrity. All these leads to higher head rice yields and improved milling recovery (Mahmood et al., 2024; Wang et al., 2025). Consistent with this, improved milling efficiency ensures reduced breakage, higher product quality, and greater marketable output, thereby strengthening revenue streams for both farmers and processors (Butardo & Sreenivasulu, 2019). Moreover, these technologies optimize energy use and reduce post-harvest losses, aligning with sustainable economic objectives while simultaneously enhancing food security (Ndindeng et al., 2025; Yu et al., 2024). Therefore, the integration of innovative drying and efficient milling reduces production costs and contributes to long-term economic resilience by promoting higher value addition and minimizing environmental impact (Jimoh et al., 2025). *Proposition 4: The integration of innovative drying technologies and enhanced milling efficiency has a positive impact on economic sustainability in rice processing.*

Conclusion

This study highlights the transformative role of innovative drying and milling technologies in revolutionizing rice processing by enhancing product quality, improving milling efficiency, and promoting economic sustainability. The findings also highlight how advanced drying methods, including RF, MW, IR, and hybrid drying systems, reduce grain fissuring, optimize moisture control, and preserve the nutritional quality of grains. In turn, improved milling efficiency increases head rice yield, enhances product value, and strengthens revenue streams for stakeholders across the rice supply chain. Collectively, these technological advancements demonstrate strong potential to address inefficiencies associated with traditional processing methods and contribute to sustainable agricultural practices.

From a theoretical perspective, this study advances understanding of the interconnected relationship between technology adoption, milling efficiency, and economic outcomes. By linking emerging processing technologies to sustainability and economic frameworks, the study conceptualizes how innovations can simultaneously enhance food quality, increase efficiency, and foster resilience in agri-food systems. Overall, this integration contributes to ongoing debates within agricultural and food processing research by offering a structured approach to studying technological innovations in post-harvest practices.

On a practical level, the study highlights the significance of adopting modern rice processing technologies to achieve higher productivity, improved product consistency, and reduced environmental impact. For policymakers and industry practitioners, the findings suggest that strategic investment in advanced drying and milling equipment can yield long-term economic benefits while aligning with sustainability objectives. Furthermore, the study emphasizes the importance of training programs and knowledge transfer initiatives in building technical capacity among farmers and processors, thereby ensuring that the benefits of these technologies are widely accessible. Policymakers are encouraged to design targeted financial incentives and capacity-building programs to reduce adoption barriers. Technology developers should prioritize scalable and cost-efficient designs suitable for small and medium-scale millers. Rice processors may adopt phased implementation strategies beginning with pilot-scale testing and techno-economic evaluation before full integration.

Despite its contributions, this study has several limitations. First, as a narrative review, it does not provide quantitative effect-size comparisons across technologies. Second, adoption barriers are discussed conceptually rather than empirically validated. Financial constraints (high capital investment), technical constraints (infrastructure and maintenance limitations), and knowledge gaps (limited technical skills and awareness) represent significant barriers, particularly in developing regions. Future research should prioritize pilot implementation studies, comparative techno-economic assessments, life-cycle environmental evaluations, and digital integration strategies such as AI-based monitoring and optimization systems.

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Ethics Statement:	This study did not involve any human participants, animals, or sensitive data requiring ethical approval. The authors confirm that the research was conducted in accordance with accepted academic integrity and ethical publishing standards.

Author Contribution Statement:	All authors contributed to the development of this manuscript. Muhammad Hanif Othman was responsible for conceptualization, research design, methodology development, literature synthesis, analysis, drafting, and overall supervision of the study. Noor Zahirah Mohd Sidek provided academic guidance, mentorship under the FRGS-EC grant framework, and contributed to the critical review and refinement of the manuscript. All authors read and approved the final version of the manuscript prior to submission.

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