

Instant and Rapid Paddy Drying Techniques: A Review of Engineering Developments and Applications

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Abstract - *Post-harvest losses in paddy reach 20–30% due to fungal and insect damage from improper drying, with traditional open-sun methods causing uneven moisture removal, cracking, and mycotoxins like aflatoxins (up to 88% in undried grains). This comprehensive review synthesizes global advances in instant paddy drying technologies—defined as rapid reduction of moisture from 20–25% to safe storage levels of 12–15% within minutes to one hour using fluidized bed dryers (FBDs), microwave-infrared hybrids, superheated steam, and solar-biomass integrations. Key performance metrics include drying times reduced from 7 hours (convective hot air) to under 1 hour, specific energy consumption (SEC) lowered from 4–8 MJ/kg water to 1–4 MJ/kg, and energy efficiencies improved by 20–80% through heat recovery and closed-loop systems.*

Keywords—*Paddy drying, fluidized bed dryer, hybrid drying technologies, energy*

efficiency, post-harvest losses, rice quality assessment, exergy analysis, psychrometrics, ANFIS modeling.

I. INTRODUCTION

A. Background and Global Significance

Paddy (*Oryza sativa*), or rough rice, is a staple for over 3.5 billion people, with global production exceeding 500 million tons annually. However, freshly harvested paddy at 20–25% moisture content (wet basis) is highly perishable, suffering 20–30% post-harvest losses from fungal growth (e.g., *Aspergillus*), insect infestation (e.g., *Rhyzopertha dominica*), germination, and biochemical degradation if not dried rapidly to 12–15%. In developing regions like sub-Saharan Africa and South Asia, these losses equate to 100–200 million tons yearly, undermining food security. For instance, in Ebonyi State, Nigeria, rice processing technologies (milling, drying, packaging) directly correlate with food availability, where 45.2% of respondents

strongly agreed modern drying reduces losses (Spearman's $\rho=0.417$, $p=0.043$).

Traditional open-sun drying on concrete floors or mats exposes grains to erratic weather, dust, animals, and contaminants, leading to uneven moisture removal, discoloration, cracking, and mycotoxin accumulation—e.g., 88% aflatoxin prevalence in Ethiopian undried maize analogs. Aggregate losses reach 20–40%, with 15–25% occurring during storage due to improper initial drying. This review focuses on "instant" paddy drying: rapid, on-demand processes using high-efficiency technologies to achieve safe moisture levels in minutes to hours, preserving milling quality (head rice yield >60%), nutritional value, and market price

B. Scope and Structure of the Review

Drawing from the attached document's outline, this paper structures content around: (1) fundamentals of moisture management and psychrometrics; (2) traditional challenges; (3) advanced technologies like FBDs and hybrids; (4) operating parameters and mathematical models; (5) energy/exergy analyses; (6) quality/economic assessments; (7) innovations (solar-biomass, IoT); and (8) future research gaps. Experimental benchmarks include FBD diffusivity ($2.9\text{--}5.9 \times 10^{-9} \text{ m}^2/\text{s}$), SEC (0.8–8.6 kWh/kg water), and ANFIS accuracy (98.58%). Emphasis is on scalable solutions for agricultural engineering students prototyping AgriTech in resource-constrained settings like Coimbatore, India.

C. Rationale for Instant Drying

Instant drying addresses time sensitivity: conventional methods take hours-days, prolonging exposure to microbes; advanced systems (microwave, infrared, FBD, superheated steam) cut times to <1 hour while saving 75% energy via multimodal integration. SEC drops from 4 MJ/kg (convective) to 1

MJ/kg (optimized steam), with moisture targets met without compromising antioxidants or breakage rates.

II. FUNDAMENTALS OF PADDY DRYING AND MOISTURE MANAGEMENT

A. Importance of Moisture Content

Moisture content (MC) critically governs paddy quality during drying, storage, and milling. Safe storage requires 12–15% MC (wet basis) to inhibit microbial growth, spoilage, germination, and degradation like cracking/discoloration. Excess MC (>15%) fosters fungi; deficits (<12%) cause stress cracks, reducing head rice recovery by 10–20%. Moisture stratification in bulks creates temperature/humidity gradients, modeled via coupled heat-moisture transfer for ventilation optimization. Advanced methods like graphene far-infrared drying enhance efficiency while minimizing losses.

B. Psychrometrics in Drying Air

Drying air properties—temperature ($T=40\text{--}140^\circ\text{C}$), relative humidity ($RH=50\text{--}70\%$), velocity ($v=0.5\text{--}2.0 \text{ m/s}$), and enthalpy—dictate heat/mass transfer. High T accelerates evaporation but risks thermal damage ($>90^\circ\text{C}$); high RH reduces driving force; velocity boosts convective coefficients ($h \propto Re^{0.93}$, Nusselt correlation). Saturation during evaporation lowers efficiency; optimal air maintains gradients. Energy efficiency ranges 30–60% with recirculation/heat recovery.

C. Heat and Mass Transfer Mechanisms

Empirical constants (Nusselt Nu , Sherwood Sh) link v and grain dimensions to rates:

$$Nu = cRe^{0.93}Pr^{1/3}, Sh = c'Re^{0.93}Sc^{1/3}$$

Drying kinetics:

$$\frac{dM}{dt} = -k(M - M_e)$$

where $M=MC$ (dry basis), $k(T,v)$, M_e =equilibrium MC. High-temp rapid drying (150°C) reduces time to <1 hour for parboiled paddy.

Table I Quality Impacts

Type	Time	EE (%)	SEC (MJ/kg H2O)	Quality
Convective	7 hr	26–60	4–8	Moderate breakage
FBD	10–30 min	36 thermal	0.8–8.6 kWh/kg	Low damage
Microwave-Hybrid	<1 hr	+75 savings	1–4	High retention
Steam	Minutes	High	~1	Minimal loss
Lab	Varies	Low	20.87	Variable

D. Critical Moisture Levels and

Moisture content plays a key role in maintaining grain quality. When the moisture content exceeds 15%, grains become prone to mold growth, insect infestation, and unwanted germination, which reduces storage life and quality. For processing, a moisture level of about 12–13% is considered optimal, as it improves milling efficiency and reduces grain breakage. Maintaining this level also ensures safe storage and better product quality. Instant drying techniques, such as heating at about 98.5°C with air pulses for 2 minutes, rapidly remove excess moisture. This short exposure helps preserve antioxidants and nutritional compounds while preventing microbial growth. Proper moisture management therefore ensures better storage stability, milling yield, and nutritional retention.

III. CHALLENGES IN TRADITIONAL PADDY DRYING

Smallholder farms but yield 20–40% losses: uneven MC causes breakage/mycotoxins; labor-intensive (100–200 USD/tonne); contamination from dust/animals. In Nigeria/Africa, 15–25% storage losses stem from poor drying. Quality degrades: broken grains ↑, yield ↓. Economics suffer low B/C ratios vs. automated alternatives.

IV. ADVANCED AND INSTANT DRYING TECHNOLOGIES

A. Fluidized Bed Dryers (FBDs)

FBDs suspend grains in hot air (60–120°C, optimal <60°C for quality), achieving 10–30 min cycles, diffusivity $2.9\text{--}5.9 \times 10^{-9}$ m²/s. Metrics: thermal efficiency 36%, exergy 19%, SEC 0.8–8.6 kWh/kg water. Optimized at 98.5°C with pulses to minimize breakage.

B. Hybrid and Microwave-Infrared Systems

Microwave-hot air hybrid drying significantly reduces drying time compared to conventional methods. It can complete drying in less than 1 hour, whereas traditional convective drying may take around 7 hours. This method also provides about 75% energy savings, with a specific energy consumption (SEC) of 1–4 MJ/kg. Infrared assistance improves heat distribution and ensures more uniform drying of the product. Advanced systems like the LSU multi-stage drying method further enhance efficiency, achieving an SEC of about 2.58 MJ/kg while maintaining product quality.

C. Superheated Steam and Rapid-Flow Dryers

Closed-loop steam drying systems improve energy efficiency by recovering latent heat from the exhaust steam and reusing it in the drying cycle. This significantly reduces energy consumption, achieving a specific energy consumption (SEC) of around 1 MJ/kg. Since the system is closed, it minimizes contamination from dust and external air, ensuring cleaner processing. High-temperature operation (100–150 °C) makes this method particularly suitable for parboiled paddy drying, where rapid and hygienic moisture removal is required while maintaining grain quality.

D. Solar and Biomass Integrations

PV-powered fans with thermal energy storage help maintain consistent solar drying even during low sunlight periods by storing excess heat and ensuring continuous airflow. This improves drying reliability and reduces dependence on conventional energy sources. Biomass-based dryers can supply about 48% of the required energy, using agricultural residues as fuel. Such systems are economically attractive, with an estimated payback period of around 1.9 years, making them suitable for sustainable grain drying operations.

V. OPERATING PARAMETERS AND MODELING

Parameters: T, v, MC, time influence kinetics (k varies with T/v). Models: empirical ANFIS (98.58% accuracy, inputs: size 3–9 mm, color 0–1, weight 1000 g/L; 153 cycles, 5000 epochs).

ThermalEE:

$$\eta_{th} = \frac{\dot{m}_w h_{fg}}{\dot{Q}_{in}} \times 100$$

VI. ENERGY AND EXERGY ANALYSIS

Industrial drying systems typically have a specific energy consumption (SEC) ranging from 2.58 to 20.87 MJ/kg, depending on the drying technology and operating conditions. Hybrid drying systems improve energy efficiency (EE) by about 30–60% by combining multiple heat transfer methods. Exergy analysis is used to identify energy losses and system irreversibilities, helping optimize dryer design and improve overall thermal performance.

VII. QUALITY AND ECONOMIC ASSESSMENT

Neuro-fuzzy models are used to predict drying outcomes and grain quality by combining neural networks with fuzzy logic for better decision making. Hybrid drying systems also enhance processing efficiency and improve yield and benefit–cost (B/C) ratios in grain operations. Similar optimization concepts are seen in Alternate Wetting and Drying (AWD) irrigation methods, which can achieve around 20% water savings while maintaining crop productivity.

VIII. INNOVATIONS: IOT AND ML INTEGRATION

A DAS–HMI system built on Docker and Kubernetes enables efficient monitoring and control of drying operations. Containerization allows the system to be scalable, portable, and easy to deploy across different environments. The platform can achieve response times of around 30 seconds, ensuring timely data acquisition and process control. Such

architecture is particularly useful for prototype and pilot-scale systems, where flexibility and rapid updates are required.

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