INTERNATIONAL JOURNAL OF ADVANCED INNOVATIVE TECHNOLOGY IN ENGINEERING

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A Comprehensive Review of Agricultural Seeds Drying Technologies: Trends, Challenges, and Future Directions

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Article History

Received on: 10 Feb. 2025

Revised on: 28 Feb. 2025

Accepted on: 30 March 2025

Keywords: Agricultural Seeds, Drying Technologies, Energy Efficiency, Seed Quality, Artificial Intelligence, IoT, Future Trends

e-ISSN: 2455-6491

DOI: 10.5281/zenodo.15423806

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ABSTRACT

Efficient drying of agricultural seeds is a critical post-harvest process that ensures seed viability, quality, and storage longevity. Various drying technologies, including conventional and advanced techniques, have been developed to optimize moisture removal while preserving seed properties. This review provides a comprehensive analysis of existing agricultural seed drying methods, including hot air drying, vacuum drying, microwave-assisted drying, and hybrid techniques. The study examines recent advancements in drying technologies, their impact on seed quality, energy efficiency, and drying kinetics. Additionally, the integration of Artificial Intelligence (AI) and the Internet of Things (IoT) in drying systems is discussed, highlighting their potential in real-time monitoring and process optimization. The review identifies key challenges such as high energy consumption, uneven drying, and the need for technology adaptation in different agricultural settings. Future research directions emphasize the development of energy-efficient, intelligent drying systems tailored for specific seed types. This study aims to provide insights for researchers and industry stakeholders to enhance drying technology, ensuring sustainable and high-quality seed preservation.

1. INTRODUCTION

A. Importance of seed drying in agriculture

Seed drying is essential for preserving seed viability, preventing spoilage, and ensuring long-term storage stability. Proper drying inhibits mold, fungal growth, and pest infestations, reducing post-harvest losses. It enhances seed handling, processing efficiency, and compliance with market standards. Additionally, drying improves energy efficiency in further processing, such as oil extraction, and supports sustainable agriculture by minimizing waste. Advanced drying technologies play a crucial role in optimizing seed quality, ensuring better agricultural productivity and food security [1].

B. Role of Seed Drying in Maintaining Seed Viability, Germination, and Storage

Maintaining Seed Viability: Proper drying prevents physiological and biochemical deterioration, preserving the seed's ability to sprout and grow. Excess moisture leads to microbial activity, enzyme degradation, and reduced seed vigor.

Enhancing Germination Potential: Seeds dried to optimal moisture levels maintain high germination rates. Over-drying or under-drying can negatively impact embryo health, reducing seedling emergence and crop productivity.

Ensuring Long-Term Storage Stability: Drying seeds to the recommended moisture content prevents mold, fungal growth, and insect infestation. It extends storage life by reducing metabolic activities that cause spoilage, making seeds viable for future planting seasons [2].

C. Objectives and Scope of the Review

This review aims to analyze conventional and advanced seed drying technologies, assessing their impact on seed viability, germination, and storage. It explores the integration of Artificial Intelligence (AI), IoT, and automation for optimizing drying processes while identifying key challenges such as energy consumption and quality degradation. Additionally, the review highlights future research directions to develop efficient, cost-effective, and sustainable drying methods. The scope includes an overview of drying principles, various drying techniques, their effects on seed quality, and the role of smart drying technologies. By addressing current trends and challenges, this review provides valuable insights for researchers and industry professionals to enhance seed drying efficiency and sustainability.

D. Fundamentals of Seed Drying

Seed drying is essential for maintaining viability, storage stability, and germination potential by removing excess moisture. It relies on heat and mass transfer, achieving equilibrium moisture content (EMC) to prevent spoilage or damage. Drying methods include convective (hot air), conductive (direct contact), and radiative (infrared/microwave) techniques, influenced by factors like temperature, airflow, and humidity. Natural, mechanical, and hybrid drying approaches ensure efficiency, with advanced systems integrating AI and IoT for precision control. Proper drying enhances seed quality, longevity, and sustainability in agriculture.

2. Literature Survey

Various drying techniques have been studied to enhance seed drying efficiency, optimize energy consumption, and maintain seed quality. Research on vibrating tray drying in the infrared field demonstrated that optimizing oscillation frequency ($f = 100\, s^{-1}$) improves seed transportation, but excessive motor speed reduces efficiency [3]. Thin-layer drying of sprouted wheat in a tray dryer at 50–80°C showed that the Wang and Singh model best predicts drying behavior, with moisture diffusivity increasing with temperature [4]. A tray dryer for groundnut drying was developed to replace traditional sun drying, achieving 77.54% to 79.32% drying efficiency and reducing moisture content from 20% to 9% within 7 hours [5]. In humid climates, artificial drying of grass seeds using rotary dryers was found to be energy-intensive but effective when layer-by-layer unloading every 2.5 hours was implemented to maintain seed viability [6].

Advanced drying technologies such as vibro-fluidized bed drying (VFBD) have shown improved efficiency, with Artificial Neural Networks (ANN) outperforming mathematical models in predicting drying behavior [8]. Fluidized bed drying for rice and soybean seeds enabled rapid drying but required careful control to avoid seed fissuring and maintain seed quality [9,10]. Microwave-assisted drying has proven to be highly energy-efficient, significantly reducing drying time and power consumption. Microwave drying of amaranth seeds at 40°C decreased drying time by 22% and energy consumption by 74%, preserving germination rates [11]. Similarly, microwave-vacuum drying of Camellia oleifera seeds improved drying kinetics while maintaining oil quality [12]. However, microwave drying of rapeseed exhibited uneven heating issues, requiring further optimization [13].

Infrared drying methods were studied for seed mucilage drying, demonstrating improved drying efficiency and color retention [14]. Microwave-assisted infrared drying of lentils revealed that microwave power had a greater influence on drying rate than infrared power, offering better control over drying kinetics [15]. Innovative drying technologies like graphene-based far-infrared drying for paddy seeds exhibited high moisture diffusion efficiency and thermal performance, achieving an activation energy of 47.44 kJ/mol with 71.11% heat efficiency [16]. Hybrid drying techniques, such as radio frequency-assisted hot air drying (RFHAD) for Camellia oleifera seeds, resulted in superior oil quality preservation compared to infrared drying [17]. RFHAD was also 25% more efficient than traditional hot air drying for corn kernels, reducing energy consumption and minimizing seed cracking [18].

3. COMPARATIVE ANALYSIS OF DRYING TECHNOLOGIES

Different drying technologies have been studied to improve seed drying efficiency, reduce energy consumption, and maintain seed quality. Table 1 shows comparative analysis of various techniques based on drying efficiency, energy consumption, drying time, seed quality impact, and suitability for different seed types. Following are some key findings from the comparison.

1. Infrared-assisted and microwave-vacuum drying offer high energy efficiency while preserving seed quality.
2. Fluidized bed drying is fast, but seed damage risks must be managed.
3. RFHAD is highly efficient, reducing drying time by 25% compared to hot air drying, making it suitable for cereals.
4. Vibrating tray and hot air-drying methods are effective but require optimization for uniform drying.

Table 1: Comparative analysis of various drying technologies

Sr. No	Drying Technology	Efficiency & Energy Consumption	Drying Time	Impact on Seed Quality	Suitability
1	Vibrating Tray Drying (Infrared-Assisted)	High efficiency with optimized oscillation frequency ($f = 100\ s^{-1}$)	Moderate	Enhances transportation, but excessive speed reduces efficiency [3]	Suitable for sunflower and similar seeds
2	Thin-Layer Drying (Tray Dryer)	Moderate energy consumption; varies by temperature (50–80°C)	Moderate to Long	Wang and Singh model best predicts drying; maintains germination	Effective for sprouted wheat and grains
3	Hot Air Tray Drying	Efficiency ranges from 77.54% to 79.32%	Long (~7 hrs for groundnut)	Reduces moisture from 20% to 9%; better than traditional methods [5]	Used for groundnut and oil seeds
4	Rotary Dryer (Grass Seeds)	High energy consumption due to continuous operation	Long	Layer-by-layer unloading every 2.5 hrs optimizes	Suitable for grass seeds in humid climates
5	Vibro-Fluidized Bed Drying	Optimized through Artificial Neural Networks (ANN)	Faster than tray drying	ANN provides better prediction; improves efficiency [8]	Suitable for pumpkin seeds and grains
6	Fluidized Bed Drying (Rice, Soybean)	High efficiency but risks overheating	Short	Improves drying rate, but may cause cracks and seed coat damage [9,10]	Suitable for rice, soybeans, and grains
7	Microwave-Assisted Drying	Reduces energy consumption by 74% (amaranth)	Short	Maintains viability at 35–40°C; minimizes germination loss [11]	Effective for amaranth and heat-sensitive seeds
9	Microwave-Vacuum Drying	Requires controlled conditions for optimal efficiency	Short	Maintains oil quality and nutritional properties [12]	Suitable for Camellia oleifera, rapeseed
10	Graphene Far-Infrared Drying	High efficiency (heat efficiency = 71.11%)	Short	Enhances moisture diffusion and thermal efficiency [16]	Suitable for paddy and cereals
	Radio Frequency-Assisted Hot Air Drying (RFHAD)	Reduces energy consumption at higher temperatures	25% shorter than hot air drying	Minimizes cracks and color changes [18]	Best for corn kernels and cereal grains

4. Challenges In Agricultural Seed Drying

Although advancements in seed drying technologies have been made, several challenges persist that impact efficiency, energy consumption, and seed quality. The major challenges identified from the literature are as follows:

High Energy Consumption: Many drying techniques, such as rotary dryers and fluidized bed drying, require significant energy input, making them costly for large-scale applications 4,74,74,7. Microwave and infrared-assisted drying have shown potential in reducing energy consumption, but their large-scale adoption remains limited due to initial investment costs [9,10].

Non-Uniform Drying: Certain drying methods, particularly fluidized bed and microwave drying, can result in uneven moisture removal, leading to seed quality deterioration. For example, microwave-vacuum drying of rapeseed showed variations in moisture distribution due to non-uniform heating 111111. Similarly, radio frequency-assisted drying (RFHAD) exhibited temperature inconsistencies at different regions of corn samples [16].

Seed Quality Deterioration: Excessive heat exposure can cause cracking, seed coat damage, and reduced germination rates. Studies on fluidized bed drying of rice and soybeans highlighted risks of seed fissuring due to rapid moisture loss 7,87,87,8. Microwave-assisted drying, although energy-efficient, requires careful temperature control to prevent damage to nutrient composition and oil quality, as observed in Camellia oleifera seeds [10].

Process Optimization Challenges: Many drying techniques require precise temperature, airflow, and moisture control for optimal results. Studies on vibrating tray drying indicate that beyond 970 RPM, the efficiency of vibro-transportation decreases, requiring fine-tuned speed control 111. Similarly, thin-layer drying models need accurate parameter selection to maintain seed viability [2].

Long Drying Duration: Traditional methods like hot air and rotary drying take longer to achieve the desired moisture content. For instance, hot air tray drying of groundnut seeds required 7 hours to reduce moisture from 20% to 9% 333. This prolonged duration increases post-harvest losses and operational costs.

Technology Adaptation for Different Seed Types: Different seeds have varying moisture content and drying behavior, making it difficult to design a universal drying system. For example, amaranth seeds required lower drying temperatures (35–40°C) to maintain viability, whereas paddy drying using graphene far-infrared technology required higher temperatures for efficiency [9,14].

Cost of Advanced Drying Technologies: While AI and IoT-based smart drying systems offer better control and optimization, their high initial setup cost limits accessibility for small and medium-scale farmers. Technologies like ANN-based vibro-fluidized drying have shown better performance but require computational expertise and infrastructure.

5. Future Research Directions In Agricultural Seed Drying

To enhance the efficiency, energy sustainability, and seed quality preservation in agricultural seed drying, future research should focus on the following key areas:

Development of AI and IoT-Based Smart Drying Systems: The integration of Artificial Intelligence (AI) and the Internet of Things (IoT) can enable real-time monitoring and adaptive control of drying parameters, optimizing temperature, humidity, and airflow for different seed types. AI-driven models, such as machine learning-based predictive drying models, should be further explored for real-time adjustments and automation [6].

Optimization of Energy-Efficient Drying Techniques: *High energy consumption remains a major limitation in many drying technologies, particularly in rotary and fluidized bed dryers [4,7]. Future research should focus on hybrid drying techniques, such as the combination of solar, infrared, and microwave drying, to enhance energy efficiency while maintaining seed viability [10,14].*

Advancement in Non-Destructive Moisture and Quality Sensing: Real-time, non-invasive monitoring techniques such as near-infrared spectroscopy (NIRS) and hyper-spectral imaging should be investigated to assess moisture content and seed quality during drying without damaging the seeds. This can improve the precision of thin-layer drying models and vibrato-fluidized drying systems [1,2,6].

Development of Seed-Specific Drying Protocols: Different seeds exhibit unique drying behaviors, making it essential to develop customized drying protocols for specific seed types. Studies have shown that amaranth seeds require lower drying temperatures (35–40°C) to maintain viability, whereas paddy and rapeseed benefit from graphene far-infrared and microwave-vacuum drying [9,11,14]. Further research should focus on seed-specific moisture diffusivity, activation energy, and optimal drying conditions.

Investigation of Sustainable and Cost-Effective Drying Systems: Many advanced drying technologies, such as radio frequency-assisted drying (RFHAD) and microwave-assisted drying, have shown high efficiency but remain costly for large-scale implementation [16]. Future studies should focus on low-cost, scalable solutions for small and medium-scale farmers, such as solar-assisted hybrid dryers and biomass-powered drying systems [3,9].

Reduction of Non-Uniform Drying Effects: Issues like uneven moisture distribution in fluidized bed drying and microwave-assisted drying can cause seed quality deterioration [7,8]. Research should focus on improving heat and mass transfer mechanisms in drying systems to ensure uniform drying, reducing overheating and seed damage [1].

Exploration of New Drying Technologies: Emerging technologies such as graphene-based far-infrared drying, vacuum-assisted drying, and electrohydrodynamic drying should be explored for their potential to reduce drying time, improve thermal efficiency, and minimize seed damage [14]. These innovations could revolutionize high-value seed drying applications in precision agriculture.

Conclusion

Future research should aim at developing intelligent, energy-efficient, and cost-effective drying systems tailored to different agricultural seeds. Advancements in AI-driven monitoring, hybrid drying methods, and non-invasive quality assessment will play a crucial role in improving drying efficiency while ensuring sustainability in modern agriculture.

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