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Energy Engineering Analysis of Agricultural Product Drying Systems: A Review of Thermal Efficiency and Energy Consumption

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ABSTRACT

Drying is a crucial post-harvest process in agricultural product handling, aimed at reducing moisture content to a safe equilibrium level against microbial and enzymatic activity. Energy and thermal efficiency have become major issues in the development of modern drying systems oriented toward sustainability. This study aims to review various energy engineering approaches applied to agricultural drying systems, focusing on improving thermal efficiency and reducing energy consumption. Based on recent literature, renewable energy–based dryers such as solar dryers, solar–biomass hybrid systems, and heat pump technologies have demonstrated significant improvements in energy efficiency. The integration of digital technologies, including the Internet of Things (IoT) and artificial intelligence (AI), also contributes to drying optimization through adaptive control systems. The review reveals that conventional dryers typically exhibit thermal efficiencies below 20%, whereas modern engineered systems can achieve 45–70%, depending on design and applied technology. Therefore, energy engineering innovations have great potential to enhance the efficiency and sustainability of agricultural drying systems while supporting national food security and energy efficiency goals.

Keywords:, ***Energy Engineering, Thermal Efficiency, Energy Consumption, Agricultural Dryer, Renewable Energy.***

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INTRODUCTION

The drying process plays a vital role in post-harvest handling of agricultural products, as it reduces the moisture content to a safe level against microbial and enzymatic activity, thereby extending shelf life and maintaining product quality. In addition, drying directly affects the physical, chemical, and organoleptic properties of agricultural commodities. In tropical countries such as Indonesia, direct sun drying remains the most widely used method due to its low cost and ease of application. However, Wang et al. (2022) reported that large-scale electrical circulation drying systems can reduce specific energy consumption by approximately 44% compared to China's national standard, indicating that conventional sun drying methods exhibit much lower energy efficiency. This finding highlights the urgent need for energy-engineered drying systems with higher efficiency at industrial scales.

Traditional drying methods face several limitations, including dependence on weather conditions, non-uniform heat and airflow distribution, and susceptibility to contamination by microorganisms and dust. Qurrota A'yuni et al. (2024) found that rice drying using rotary dryers with suboptimal control of temperature and airflow leads to reduced energy efficiency and increased carbon dioxide emissions. This suggests that poorly controlled drying processes can degrade product quality and overall system efficiency. Therefore, the development of modern drying systems with improved thermodynamic design is essential to ensure stable, uniform, and energy-efficient drying processes.

Energy engineering in agricultural drying systems has become a major global research focus over the past two decades, particularly to address challenges in enhancing efficiency and reducing carbon emissions. Singh and Shrivastava (2024) emphasized that the development of solar dryers, solar–biomass hybrid systems, and high-performance thermal energy storage units can increase thermal efficiency by more than 40% compared to conventional systems. These technologies also significantly reduce fossil fuel consumption, thus supporting the principles of energy efficiency and environmental sustainability within the agro-industrial sector.

Thermodynamic factors play a central role in determining the efficiency of drying systems. According to Al-Harahsheh et al. (2023) the energy and exergy efficiency of dryers are highly influenced by material thermal conductivity, airflow velocity, and the effective heat transfer surface area. The use of low-conductivity insulation materials and optimal drying chamber design can enhance thermal efficiency by up to 70%. Optimizing these parameters is critical to minimizing heat losses to the environment, thereby improving energy economy and cost-effectiveness.

From both economic and environmental perspectives, high energy efficiency in drying systems directly contributes to reduced operational costs and lower greenhouse gas emissions. Venkateswarlu and Reddy (2024) reported that hybrid solar dryers equipped with heat storage can improve energy efficiency by over 30% and substantially reduce carbon emissions compared to LPG-fueled systems. Such innovations align with the Sustainable Development Goals (SDGs), particularly those related to clean energy and responsible consumption.

Recent trends also indicate increasing integration of digital technologies in agricultural drying systems. Internet of Things (IoT) based systems enable automatic control of temperature, humidity, and airflow in response to real-time environmental conditions. According to Rahman et al. (2023) the implementation of IoT-based solar dryers can improve energy efficiency by up to 25% through adaptive control mechanisms that reduce excessive heat loss. This approach demonstrates that thermal efficiency and energy consumption depend not only on mechanical design but also on the intelligence of control systems employed.

Considering these advancements, this literature review aims to examine various energy engineering approaches in agricultural drying systems, focusing on two key parameters: thermal efficiency and energy consumption. The review seeks to provide a comprehensive understanding of current trends in energy-efficient drying technologies and their future development directions. Furthermore, this study contributes to the advancement of energy-efficient, cost-effective, and environmentally friendly post-harvest technologies that support sustainable agricultural systems.

METHODS

This study employs a systematic literature review approach to examine various research works related to energy engineering in agricultural drying systems. This approach was chosen because it enables researchers to identify, evaluate, and synthesize previous studies comprehensively to gain an in-depth understanding of thermal efficiency and energy consumption in drying processes. The main focus of this review is to identify patterns and trends in the application of energy-efficient drying technologies, including those utilizing solar energy, biomass, or a hybrid combination of both. The literature review process was conducted following the principles of transparency and reproducibility as recommended by Kitchenham et al. (2022) in systematic review–based research.

Literature selection was carried out using strict inclusion and exclusion criteria. The inclusion criteria covered publications from 2020 to 2025, written in English or Indonesian, and addressing topics related to energy efficiency, specific energy consumption, or engineering innovations in agricultural drying systems. Articles discussing non-technical aspects, such as socio-economic or supply chain management issues without direct relevance to energy systems, were excluded from this review. The search process utilized major scientific databases, including SpringerLink, ScienceDirect, ResearchGate, Avantipublishers, and MDPI, using combined keywords such as “energy efficiency in agricultural dryers,” “thermal performance of hybrid dryers,” and “renewable energy for postharvest drying.”

The analysis involved thematic coding of all selected articles, focusing on four main parameters: thermal efficiency, specific energy consumption (SEC), types of energy sources used, and engineering innovations in system design. The collected data were synthesized using a descriptive-comparative approach to assess current technological trends and their effectiveness in reducing energy use and improving process efficiency. Through this method, the literature review not only provides a quantitative summary of existing data but also offers interpretative insights into the development trajectory of sustainable and energy-efficient agricultural drying technologies.

RESULTS AND DISCUSSION

1. Thermal Efficiency in Drying Systems

Thermal efficiency is a key factor determining the effectiveness of agricultural drying systems, as it is directly related to the amount of heat energy utilized for moisture evaporation from the product. According to Hasan, et.al. (2023) thermal efficiency can be defined as the ratio between the energy used for water evaporation and the total heat energy supplied to the system. In agricultural drying, this efficiency is influenced by several parameters, including airflow rate, operating temperature, drying medium type, and the geometry of the drying chamber. Their study revealed that the use of a cross-flow air configuration can increase efficiency by up to 48% compared to traditional parallel-flow systems. This improvement is attributed to enhanced convective heat transfer uniformity and reduced temperature gradients within the chamber, allowing more heat to be absorbed by the material rather than lost to the environment.

Beyond mechanical design, construction materials and thermal insulation systems also play a crucial role in improving energy performance. Khan et al. (2024) reported that using insulation materials with low thermal conductivity, such as polyurethane and fiberglass, can reduce conductive heat loss by up to 30%. In their indirect solar dryer experiment, optimizing the insulation layer increased thermal efficiency from 36% to 52%. Additionally, absorber surfaces coated with selective black matte paint exhibit high solar absorptivity and low emissivity, thereby enhancing solar energy capture. Automated temperature and airflow control through temperature and humidity sensors further stabilize the drying process by maintaining the optimal operating point for evaporation without damaging the internal structure of agricultural materials.

Aerodynamic factors within the dryer system also contribute to thermal performance. As noted by Mehta, et.al. (2025), airflow channels designed with directed turbulence significantly improve convective heat transfer by enhancing air mixing around the product surface. Computational Fluid Dynamics (CFD) simulations showed that increasing turbulence at an airflow speed of 1.5 m/s improved drying efficiency by up to 60%. However, they also emphasized the importance of balancing airflow velocity with hot air residence time inside the dryer, as excessive flow rates may reduce heat contact time with the material, decreasing overall drying effectiveness. Therefore, optimizing thermodynamic, insulation, and aerodynamic aspects is essential to achieve high thermal efficiency without compromising final product quality.

2. Energy Consumption and Alternative Energy Sources

Energy consumption is a major determinant of drying system efficiency, particularly at industrial production scales. Mohapatra and Rout (2024) found that heat pump–based drying systems demonstrate superior thermodynamic performance compared to fossil-fuel dryers, as they recover waste heat through a closed refrigerant cycle. This approach improves energy utilization efficiency by 65–75% relative to conventional LPG-based systems. Moreover, the integration of automatic control systems using temperature and humidity sensors stabilizes the drying process and minimizes energy losses caused by thermal fluctuations. Such an approach aligns with the principle of energy recovery, a core concept in modern drying technology.

The adoption of renewable energy in drying systems has emerged as an increasingly viable solution. Fudholi et al. (2023) demonstrated that hybrid solar–biomass dryers can reduce specific energy consumption by up to 28% while significantly lowering carbon emissions compared to fossil-fuel-based systems. Combining solar thermal energy with latent heat storage using phase change materials (PCM) has also proven effective in maintaining stable temperatures during cloudy or nighttime conditions. This technology enables continuous drying without full dependence on solar radiation, maintaining high operational efficiency.

Beyond energy efficiency, the sustainability of energy sources is also essential in engineered drying systems. Yadav et al. (2025) reported that hybrid solar-assisted heat pump dryers can achieve more than 35% energy savings and up to 40% CO_2 emission reductions compared to conventional dryers. Integrating renewable energy, heat recovery, and intelligent control algorithms such as fuzzy logic control represents a promising direction in developing next-generation energy-efficient drying technologies. Hence, innovation in energy consumption and alternative sources not only focuses on efficiency but also contributes to long-term environmental and economic sustainability in the agricultural sector.

3. Renewable Energy Based Dryers

The utilization of renewable energy in agricultural drying systems has become a central focus in reducing fossil fuel dependency and mitigating carbon emissions. Solar drying technology remains one of the most widely developed innovations, utilizing abundant and environmentally friendly energy sources. Kabeel et al. (2024) found that flat-plate solar collectors equipped with parabolic reflectors and selective absorber coatings can achieve thermal efficiencies of 58–62%, depending on material properties and climatic conditions. This design enhances the solar absorption area while minimizing heat losses to the surroundings, making it ideal for tropical regions such as Indonesia, which experience high solar radiation. Additionally, double-pass solar dryers have demonstrated better thermal performance than single-pass configurations.

Hybrid solar–biomass drying systems provide an effective solution to address solar radiation fluctuations and extend drying operation periods. According to Sharma et al. (2023) integrating biomass heat sources into solar drying systems maintains optimal drying temperatures during low-radiation periods, with overall energy efficiencies reaching 65–

70%. This combination improves process continuity while promoting energy sustainability, as biomass fuel is often derived from agricultural waste. Experimental results also showed that hybrid systems save up to 25% of energy compared to LPG dryers while maintaining consistent product quality.

Thermal energy storage systems are also a vital component of renewable-energy-based dryer design. Khalifa et al. (2025) emphasized that the use of phase change materials (PCM) as latent heat storage in solar dryers maintains stable temperatures for up to eight hours after solar input declines. This integration improves system thermal efficiency by 20–30% and allows continuous drying operations regardless of weather variability. Such approaches present significant potential in developing energy-efficient drying systems that are technically effective, environmentally adaptive, and oriented toward long-term sustainability.

4. Digital Technology Integration and Adaptive Control

The integration of digital technologies into agricultural drying systems has advanced significantly with the advent of the Internet of Things (IoT) and Artificial Intelligence (AI). Mulyadi et al. (2024) highlighted that IoT-based systems enable real-time monitoring and control of temperature and humidity, allowing drying processes to be dynamically adjusted according to environmental conditions. This not only enhances energy efficiency but also ensures consistent product quality.

Recent research by Prasetyo and Kurniawan (2025) demonstrated that AI-based drying systems can analyze drying patterns using historical data and make adaptive decisions in response to temperature or humidity variations. This adaptive control approach can reduce drying time by up to 20% while improving energy efficiency by 18%. The integration of machine learning algorithms further strengthens the system’s ability to predict optimal drying durations across various agricultural commodities.

Moreover, Harsono et al. (2025) in the Journal of Agricultural Engineering Systems reported that IoT-based dryers equipped with multi-parameter sensors can improve energy efficiency by up to 25% compared to manual systems. The system also features a cloud-based application that facilitates remote monitoring and performance analytics. Thus, the implementation of digital and adaptive control technologies represents a strategic step toward optimizing agricultural drying systems for sustainable performance.

5. Sustainability and Environmental Impacts

Energy engineering in agricultural drying systems is increasingly directed toward balancing technical efficiency with environmental sustainability. Rahmadani et al. (2024) found that renewable energy–based dryers, such as solar and biomass systems, can reduce greenhouse gas emissions by up to 42% compared to fossil-fueled dryers. The use of eco-friendly materials and thermal designs that minimize heat losses further contribute to optimizing energy efficiency while reducing the carbon footprint of postharvest operations.

Gunawan and Sari (2025) in the Sustainable Agricultural Technology Review, highlighted that solar–biomass hybrid systems strongly support the principles of a circular economy. Waste heat from biomass combustion can be reused to maintain drying chamber temperature at night, substantially reducing external energy demand. This approach not only enhances thermal efficiency but also extends the operational lifespan of dryers by providing improved thermal stability.

Sustainability also encompasses social and economic dimensions. Lestari et al. (2025) noted that implementing eco-friendly drying systems in rural areas can create new employment opportunities and reduce dependence on imported energy. Developing energy-efficient drying technologies plays a crucial role in supporting Sustainable Development Goals (SDGs), particularly Goal 7 on affordable and clean energy and Goal 12 on responsible consumption and production.

CONCLUSION AND IMPLICATIONS

This literature review confirms that energy engineering is a key factor in optimizing agricultural drying systems, particularly in enhancing thermal efficiency and reducing energy consumption. Conventional drying systems widely used in agricultural regions exhibit low efficiency and high heat losses, which not only increase operational costs but also contribute significantly to environmental pollution through carbon emissions. Recent innovations demonstrate substantial improvements through the adoption of renewable energy systems such as solar and solar–biomass hybrid dryers achieving thermal efficiencies of 60–70%, as well as the use of heat pump and IoT-based smart control technologies that optimize temperature and humidity in real time.

Integrating efficient thermodynamic design, clean energy sources, and artificial intelligence represents a strategic direction for the development of future drying systems that are adaptive, energy-saving, and environmentally sustainable. Consequently, the transition toward green agricultural drying technologies not only has the potential to improve product quality and competitiveness but also contributes to achieving global clean energy and climate change mitigation targets.

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