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Analyzing the Performance of a Solar-Assisted Grain Dryer

Daniel Parenden[1], Frederik H. Sumbung[2], Peter Sahupala[1*]

[1]*Department of Mechanical Engineering, Musamus University, Merauke, Papua, Indonesia*
[2]*Department of Electrical Engineering, Musamus University, Merauke, Papua, Indonesia*
**Corresponding author: pieter@unmus.ac.id*

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ABSTRACT

This study evaluates the drying performance and energy efficiency of a solar-powered rice cabinet dryer equipped with two distinct airflow mechanisms: free convection (chimney-assisted) and forced convection (fan-assisted). Field experiments were conducted under tropical conditions in Merauke, Indonesia, comparing drying efficiency, moisture reduction, and air mass flow across three rice grain loads: 1 kg, 3 kg, and 5 kg. The experimental design incorporated both thermal analysis and statistical evaluation (ANOVA and t-tests) to assess the effects of airflow method and grain weight on drying outcomes. Results indicate that the chimney system demonstrated more stable and efficient performance at lower grain weights (1–3 kg), with range efficiency of 32.07% - 37.5% compared to 28.26% - 32.67% using the fan-assisted method. Drying efficiency increases with grain load, reaching a maximum of 43.75% for chimney-assisted drying and 43.44% for fan-assisted drying at 5 kg. However, the fan-assisted system provided superior performance at higher loads due to improved heat and moisture transfer. Although the fan method yielded faster drying rates and more effective moisture reduction, it exhibited slightly greater variability. Despite limitations related to experimental scale and real-time solar radiation monitoring, the findings confirm that solar-powered cabinet dryers—especially those with adaptive airflow control—offer a cost-effective, energy-efficient, and scalable drying solution for smallholder rice producers. Future work should prioritize scaling up capacity, integrating hybrid energy sources, and automating temperature regulation to enhance system performance under fluctuating weather conditions.

Keywords: *Chimney, collector, drying, fan, grain, moisture content.*

I. Introduction

As of 2023, Merauke Regency possesses over 1.2 million hectares of potential agricultural land, with 67,612.49 hectares actively cultivated for horticultural and food crops—primarily rice. The region's favorable climate, soil characteristics, and water availability contribute to its strong potential for rice production. According to the Merauke Regency Agriculture and Horticulture Service's Master Plan for Rice Plantation Development, 206 wetland clusters have been designated as Rice Production Center Areas (KSP), with a planting target of 63,785 hectares for the 2024 season—an increase of 2,000 hectares compared to 2023 [1].

Despite Merauke's high rice production potential, post-harvest handling—particularly rice drying—remains a critical challenge. Inadequate drying methods often result in poor grain quality, undermining the benefits of increased yields. Traditional manual sun drying is unreliable and frequently leads to a high proportion of broken or damaged grains [2]. To improve rice quality and advance food self-sufficiency, there is an urgent need for

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agricultural mechanization and the development of efficient, field-adapted post-harvest drying systems. Enhanced drying technologies can reduce post-harvest losses and increase the commercial value of rice.

In response, recent research has explored eco-friendly rice drying technologies, particularly those utilizing renewable energy sources such as biomass and solar power. However, adoption among smallholder farmers in underdeveloped or remote areas remains limited due to infrastructure and resource constraints. Sharma *et al*. [3] reported that a solar tunnel dryer improved thermal efficiency by 22–28% compared to open-air drying, although the study was confined to small, laboratory-scale loads and did not account for airflow effects. Rachmat *et al*. [4] developed a biomass-powered flat-bed dryer capable of reducing rice moisture to 14% in under six hours, but its applicability to variable grain volumes and reliance on fuel and electricity limit its practicality in off-grid areas. Nguyen *et al*. [5] found that a hybrid LPG–solar dryer enhanced efficiency by up to 38% and accelerated the drying process, yet lacked a direct comparison of forced versus natural convection across different drying loads. Similarly, Ali *et al.* [6] concluded via simulation that appropriate ventilation and solar collector design improve the efficiency of natural convection solar dryers, though the model has yet to be validated under field conditions.

Several previous studies on rice drying have been conducted using laboratory-scale setups or small prototypes, which do not fully represent the technical challenges encountered under real field conditions. This constitutes a general limitation of earlier research. Moreover, many studies provide only descriptive data without conducting formal statistical validation, such as t-tests or ANOVA, to scientifically assess the effectiveness of the drying methods, indicating a lack of significant statistical analysis. Another key limitation is the limited examination of variable grain loads; very few studies explore how drying efficiency changes with different quantities, such as 1 kg, 3 kg, or 5 kg. In addition, there is a notable absence of direct comparative evaluations between free convection (chimney) and forced convection (fan) systems using standardized performance indicators [7]. Although a number of studies have investigated rice drying technologies in the context of post-harvest improvement, several important knowledge gaps remain. These include the lack of field-based application under varying natural sunlight intensities (field application gap), direct comparisons between chimney and fan convection methods for different rice weights (convection method comparison gap), comprehensive analysis of how drying efficiency varies with grain load (efficiency vs. rice weight gap), and the limited use of statistical tools to validate experimental results (statistical validation gap). This study addresses these gaps by conducting field trials using a solar-powered rice dryer, comparing chimney and fan airflow systems across three grain loads (1 kg, 3 kg, and 5 kg), and applying t-tests and two-way ANOVA to statistically assess drying efficiency, duration, and performance.

While numerous studies employ diverse drying techniques in post-harvest rice technology, several knowledge gaps remain. This review identifies critical gaps, including: a lack of comparative studies on fan and chimney drying efficiency across different rice weights (convection method comparison gap); insufficient field research on solar-based rice drying systems under varying natural light intensities, such as in Merauke, Papua (field application gap); and an incomplete understanding of system efficiency variations relative to rice weight (efficiency gap versus rice weight). This research addresses these gaps by directly field-testing a solar-based rice dryer using chimney and fan methods with rice weight variations. So, the purpose of this study is to evaluate the performance of solar-powered rice dryers using fan-assisted and chimney-based airflow methods; to compute and compare drying efficiency across different rice weights; to apply t-tests and two-way

ANOVA for statistically validating the differences between methods; and to support local farmers—particularly in remote areas—in designing effective, affordable, and field-adaptable drying systems.

II. Material and Methods

1. Materials

The material used in this study includes newly harvested rice in the Merauke region. The type of rice was IR-64 with an initial moisture content of approximately 24.6%. Drying equipment used a closed solar dryer unit with a collector and drying chamber, a DC fan for forced convection, and a vertical chimney for natural ventilation produced by Musamus University, Papua, with dimensions and components, as shown in Figure 1.

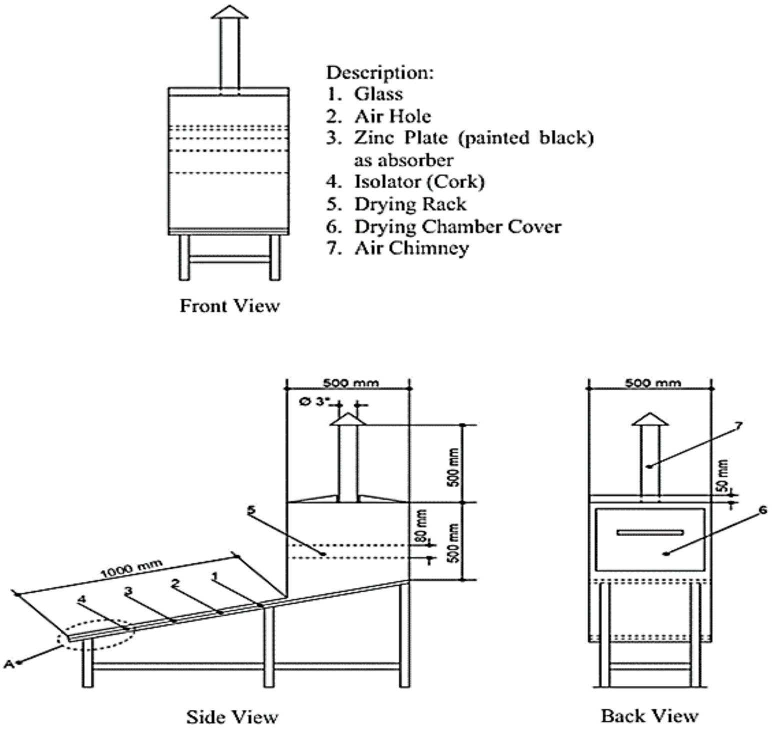

Fig. 1. Design of a grain dryer using solar energy

2. Research Design

This study employed a quantitative experimental approach using a factorial design to evaluate the performance of a solar-powered rice cabinet dryer under field conditions. The primary objective was to compare the drying efficiency of two airflow mechanisms: free convection (chimney-assisted) and forced convection (fan-assisted), across three rice grain weights: 1 kg, 3 kg, and 5 kg. The experiment was conducted under tropical climatic conditions in Merauke, Indonesia, during August 2024—a period chosen due to its stable solar radiation, alignment with post-harvest periods, and typically dry weather [8],[9].

Drying tests using the chimney system began on August 3, 2024, followed by fan-assisted drying tests on August 20, 2024. Both tests commenced at 10:00 WIT and were performed under sunny conditions. Each treatment (airflow method × grain weight) was repeated three times to ensure data reliability.

The drying chamber measured 2 meters in length and 60 cm in width, with a total capacity of 10 kg of rice grains. Temperature and humidity were monitored using a thermohygrometer; airflow velocity was measured using a digital anemometer, and grain weight was recorded using a digital scale. Temperature data were collected at three key points: ambient air before entering the collector, after exiting the collector, and just before leaving the drying chamber [10].

The independent variables were: Drying method: chimney-based (free convection) and fan-assisted (forced convection), Grain weight: 1 kg, 3 kg, and 5 kg, Sunlight intensity: categorized by time of day (morning: 300–500 W/m²; midday: 700–900 W/m²; afternoon: 200–400 W/m²) [11]. Dependent variables included: final grain moisture content (%), drying efficiency (%), calculated as the ratio of heat used to evaporate water versus total solar heat input, Mass of evaporated water (kg), drying time (hours), air temperature distribution, grain quality indicators (visual appearance, cracking level, and storage suitability index). Control variables were carefully maintained across tests to ensure experimental consistency. These included the grain type, starting time (08:30 WIT), dryer design and surface area, ambient weather conditions, distance from the heat source to the grain surface, and overall dryer configuration.

A randomized block design was applied, with treatment factors consisting of airflow method, rice load, and sunlight intensity. Periodic measurements were recorded every 30 minutes for drying chamber temperature and hourly for grain moisture content. Temperature uniformity within the chamber was assessed at five distributed points to evaluate thermal consistency [12]. To ensure the reliability and statistical validity of the results, each experimental condition was repeated five times. This allowed for the calculation of standard deviations and analysis of variability in the rice drying process. The experimental factors included three rice weight levels (1 kg, 3 kg, and 5 kg) and two drying methods (chimney-assisted and fan-assisted), with five replicates for each combination. In total, 3 (rice weights) × 2 (drying methods) × 5 (repetitions) resulted in 30 experimental runs, providing a robust dataset for the comprehensive evaluation of drying performance.

3. Data Analysis

This comprehensive and controlled experimental framework enables accurate evaluation of the solar dryer’s performance and supports rigorous statistical analysis. The results were analyzed using both descriptive and inferential statistical methods. Descriptive statistics, including mean, standard deviation, and range, were applied to key parameters such as drying chamber temperature, moisture content, drying time, and post-drying grain quality. Inferential analysis involved the use of t-tests and two-way ANOVA to determine the statistical significance of differences between drying methods (chimney and fan) and grain loads (1 kg, 3 kg, and 5 kg). Additionally, correlation analysis was conducted to assess the relationship between drying chamber temperature and final grain moisture content, while linear regression analysis was used to model the influence of solar intensity and drying time on moisture reduction. The evaluation criteria focused on achieving target storage moisture content (12–14%), reducing drying time relative to traditional methods, preserving grain quality (e.g., minimal cracking or discoloration), and ensuring uniform temperature distribution within the drying chamber. These analyses provide scientifically validated insights for optimizing solar drying systems, particularly for smallholder rice farmers in remote or resource-limited areas.

III. Results and Discussions

Based on the data analysis, the relationship between grain moisture content, drying time, and drying air mass flow rate is summarized in Table 1 and illustrated in Figure 2. In this study, the drying process commenced at 08:30 WIT. The results indicate an inverse relationship between drying time and grain moisture content, whereby longer drying durations correspond to lower final moisture levels in the rice grains.

Figure 2 illustrates that grain moisture content decreases as drying time increases across all tested grain weights (1 kg, 3 kg, and 5 kg), primarily due to the evaporation of moisture from within the grains. At the initial time point (t = 0, or 08:30 WIT), no drying has occurred, and the moisture content remains at the initial level of 24.6%. The drying process aims to reduce this moisture content to the target range of 12–14% for safe storage and quality preservation [13]. The graph demonstrates that extended drying time facilitates greater moisture loss, as the continuous flow of heated air through the grain bed accelerates evaporation.

In addition, Figure 2 shows that drying time (t) is directly related to grain layer thickness (h), which increases with grain weight. Thicker grain layers, corresponding to higher grain loads, contain more water and exhibit greater resistance to heat and moisture transfer. As a result, they require more time to reach the desired moisture content, explaining the longer drying durations observed for the 5 kg samples compared to the 1 kg and 3 kg samples.

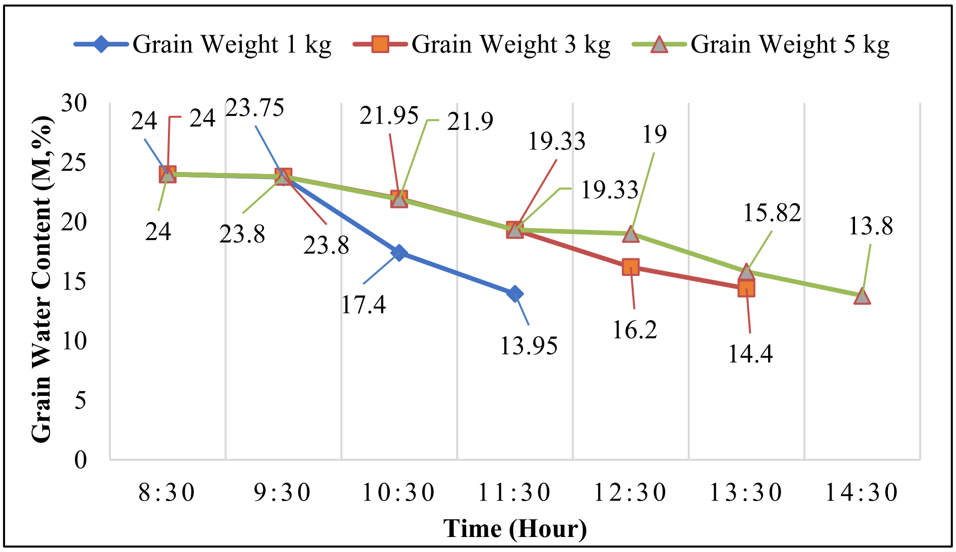

Fig. 2. Graph of the relationship between grain moisture content (M) and drying time (t)

Table 1. Decrease in water content

Grain weight (kg)	Decreased water content (Chimney)	Decreased water content (Fan)
1	24 - 13.5 = 10.5%	24 - 13.5 = 10.5%
3	24 - 13.7 = 10.3%	24 - 13.2 = 10.8%
5	24 - 13.5 = 10.5%	24 - 13.2 = 10.8%

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Table 1 indicates that the fan-assisted drying method is more effective than the chimney-based approach in reducing grain moisture content, particularly for larger grain weights. The fan-assisted system consistently results in lower average final moisture content compared to the chimney method. This effect is especially pronounced at 3 kg and 5 kg grain loads, suggesting that forced convection enhances drying efficiency by improving heat and moisture transfer within thicker grain layers. These findings highlight the advantage of the fan-assisted approach for handling larger volumes of grain in solar drying applications.

To evaluate the effectiveness of the chimney and fan-assisted drying methods, the average final moisture content was calculated and is presented in Figure 3. The bar chart illustrates the final moisture content for each drying method across different grain weights, with standard deviation values displayed above each bar [14]. The results show that chimney drying yields relatively consistent final moisture content across all grain weights, with a lower standard deviation of 0.115, indicating higher reliability and repeatability in moisture readings. In contrast, fan-assisted drying achieves slightly lower average final moisture content—suggesting better moisture removal—but with a higher standard deviation of 0.173, reflecting greater variability in drying outcomes.

Overall, while fan-assisted drying demonstrates greater effectiveness in reducing moisture content, chimney drying offers more uniform results. This trade-off highlights the efficiency advantage of forced convection, especially for larger grain loads, alongside the stability and consistency of natural convection. The corresponding data on moisture reduction for each condition is summarized in Table 1.

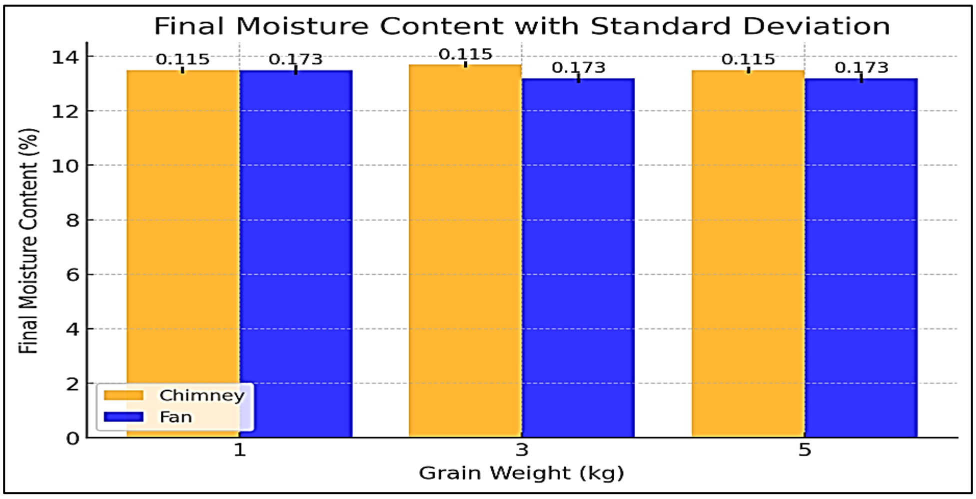

Fig. 3. Graph of grain moisture content before and after drying using a chimney and fan

As shown in Table 2, the fan-assisted drying method produced more consistent results than the chimney method, indicated by a lower standard deviation in drying time (1.25 hours compared to 1.53 hours for the chimney method). The drying time is directly related to the volume of air required to remove moisture from the grains; that is, the longer the drying duration, the more air is needed to facilitate moisture evaporation [15]. As drying progresses from an initial grain moisture content of 24.6% toward the target range of 12–14%, an increased amount of water must be removed. Consequently, a greater air mass flow is required to support prolonged drying times and ensure effective moisture reduction [16].

Drying rice grains using the chimney method requires an air mass of 130.40 kg for 1 kg of grain over 4 hours, 168.82 kg for 3 kg over 5.5 hours, and 203.18 kg for 5 kg over 6.5

hours. In comparison, the fan-assisted drying method requires 178.94 kg of drying air for 1 kg of grain over 3.5 hours, 210.56 kg for 3 kg over 5 hours, and 227.14 kg for 5 kg over 6 hours. These results demonstrate a clear trend: as both drying time and grain weight increase, the required air mass also increases. This reflects the greater airflow needed to facilitate moisture evaporation and achieve effective drying over longer durations and with larger grain volumes.

The mass of water evaporated from the grain is directly proportional to drying time—the longer the drying duration, the greater the amount of moisture removed. As the drying process progresses from an initial moisture content of 24.6% toward the target range of 12–14% in accordance with the Bulog standard, water is increasingly evaporated through the heat energy delivered by the airflow passing through the grain bed [17]. During the initial phase, the evaporation rate is relatively low, resulting in a gradual slope on the graph. Between approximately 2 and 5.5 hours, the evaporation rate accelerates as both drying time and air temperature increase. In the final hour, the graph begins to level off again, indicating a decline in moisture removal rate as the grain approaches its equilibrium moisture content within the desired range of 12–14% [18].

Table 2. Table of time required to dry grain

Grain Weight (kg)	Drying Time (hours)					
	Chimney			Fan		
	Time	Drying Time	Deviation	Time	Range	Deviation
1	2			1.5		
3	4.5			3.5		
5	6.5	4.5	1.53	5.0	2.5	1.25
Average	4.33			3.33		

Table 3 presents the mass of water evaporated during the drying process under different conditions. When using the chimney method, drying 1 kg of rice for 4 hours results in 0.3345 kg of water evaporated; drying 3 kg for 6.5 hours yields 0.8905 kg of evaporated water; and drying 5 kg for 5.5 hours results in 0.5786 kg of evaporated water. In comparison, the fan-assisted method yields 0.3183 kg of evaporated water for 1 kg of rice dried over 3.5 hours, 0.6054 kg of evaporated water for 3 kg over 5 hours, and 0.8954 kg of evaporated water for 5 kg over 6 hours. These results indicate a general increase in the mass of water removed with longer drying times and higher grain weights, highlighting the effectiveness of both drying methods in moisture reduction, with the fan-assisted approach showing a slightly higher water removal capacity for larger grain loads.

Table 3. Mass of drying air and mass of water evaporated from grains in the drying process

Grain Weight (kg)	Chimney		Fan	
	Air mass (kg)	Water mass (kg)	Air mass (kg)	Water mass (kg)
1	130.8036	0.3345	178.9396	0.3183
3	168.6573	0.5786	208.5648	0.6054
5	203.1763	0.8905	227.1387	0.9278

Table 2 and Figure 4 illustrate an almost linear relationship between grain weight and drying time, indicating that an increase in grain weight results in a proportional increase in drying duration for both methods. As the grain load increases from 1 kg to 5 kg, the drying time correspondingly rises. When comparing the two drying methods, fan-assisted drying (represented by the green line with square markers) consistently achieves shorter drying times across all grain weights, demonstrating higher drying efficiency. In contrast, chimney-assisted drying (blue line with circular markers) requires more time to reach the target moisture content. The most significant time reduction with the fan method is observed at a grain weight of 5 kg, where it shortens the drying time by 1.5 hours compared to the chimney method.

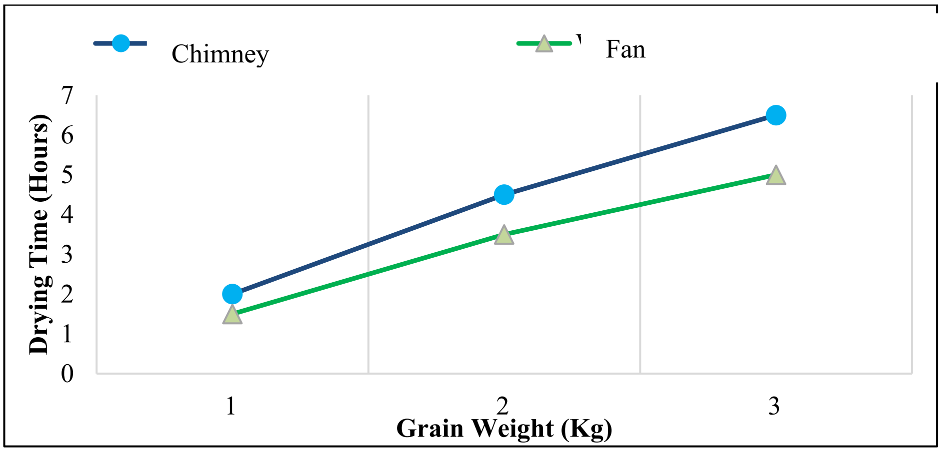

Fig. 4. Drying time for grain

The difference in drying efficiency between the chimney (free convection) and fan (forced convection) methods is primarily attributed to differences in airflow and heat transfer mechanisms. In the chimney method, heat transfer relies on natural convection, where air flows due to temperature and density differences between the solar-heated air in the collector and the ambient environment. This results in a stable but relatively slow airflow, which can be effective for smaller grain loads. In contrast, the fan method uses mechanically driven airflow to force hot air through the grain bed, significantly increasing the heat transfer rate and enhancing evaporation, especially when drying larger grain volumes. The air mass flow rate also plays a critical role: in chimney-based drying, airflow depends on solar intensity and varies throughout the day, whereas fan-assisted drying maintains a higher and more consistent airflow, improving its capacity to carry water vapor away from the grains [19]. Water vapor transport capacity also differs between the two methods: fans generate airflow that can carry moisture more efficiently, particularly in thicker grain layers (e.g., 5 kg), enhancing overall drying performance. However, for smaller grain weights (1–3 kg), the natural temperature and pressure differences are sufficient to drive airflow in chimney-based drying, making it more stable and energy-efficient, as it avoids additional power consumption for the fan. Additionally, fan-driven systems create a more uniform temperature and humidity distribution within the drying chamber, preventing localized moisture buildup on grain surfaces. Chimney drying tends to develop greater temperature and humidity gradients, particularly under heavier grain loads, which can reduce drying efficiency. Overall, fan-assisted drying is more effective for larger grain weights due to its forced airflow and improved moisture removal, while chimney drying remains more energy-efficient and reliable for smaller loads due to its passive operation without additional energy input.

Figure 5 illustrates the relationship between air mass flow rate and drying efficiency for two airflow methods: chimney-based (free convection) and fan-assisted (forced convection). The graph shows that drying efficiency generally increases with higher air mass flow rates, which correspond to increasing grain weights. The chimney method exhibits a steady, gradual improvement in efficiency, reflecting consistent heat transfer driven by natural temperature and density differences. In contrast, the fan-assisted method also demonstrates an upward trend in efficiency and surpasses the chimney method at a grain weight of 5 kg. This is attributed to the enhanced heat transfer and moisture removal capabilities of forced convection, where mechanically driven airflow accelerates the delivery of heat and the transport of water vapor from the grain surface. Higher air mass flow rates allow more thermal energy to reach the grain bed, promoting faster and more effective moisture evaporation.

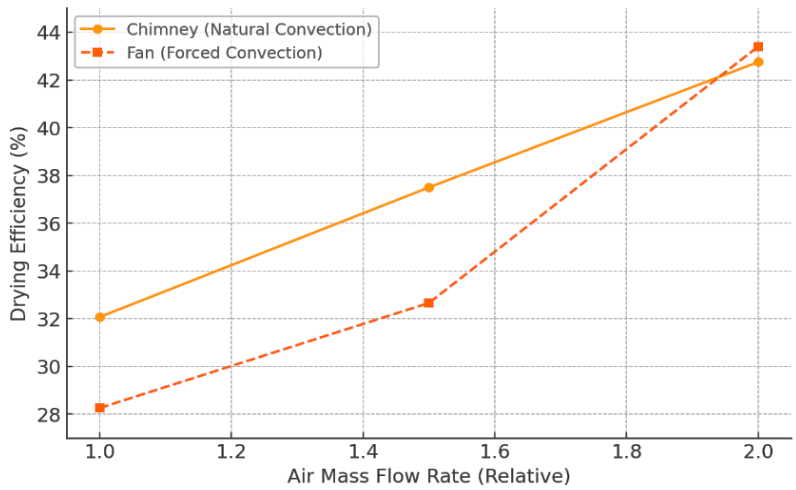

Fig. 5. Relationship between air mass flow rate and grain drying efficiency

The observed differences in efficiency between the two methods arise from their underlying airflow mechanisms. The chimney system depends heavily on solar intensity and natural convection, making its performance susceptible to environmental fluctuations. Meanwhile, the fan method maintains consistent airflow regardless of solar conditions, offering greater control over the drying process, albeit with additional energy input. The role of air mass flow rate is critical, as it not only facilitates heat delivery but also enhances the removal of water vapor. At higher grain loads, the benefits of forced convection become more pronounced: heat is distributed more uniformly across the grain layer, and energy is utilized more efficiently, resulting in higher drying efficiency.

The efficiency of the dryer increases with extended drying time, primarily due to the rise in air temperature entering the drying chamber as solar intensity intensifies throughout the day. This temperature increase enhances the thermal energy captured by the solar collector, resulting in a greater density difference between the ambient air and the heated air, thereby increasing the air mass flow rate into the drying chamber [20]. As a consequence, more heat energy is carried by the airflow, promoting greater evaporation of moisture from the rice grains and improving drying efficiency. However, after reaching peak efficiency, the system's performance begins to decline as the grain moisture content approaches the target range of 12–14%. At this stage, the remaining moisture is more tightly bound within the grain, and the heat energy is less effectively utilized, leading to reduced efficiency [21]. Experimental results from the chimney system showed that maximum efficiency was achieved after 6 hours for 5 kg of grain, 4 hours for 3 kg, and 2 hours for 1 kg. These time intervals correspond to the most effective use of heat energy for moisture removal, indicating optimal dryer performance. Chimney-based systems tend to be more energy-efficient than fan-assisted systems, as they operate solely on natural convection and do not require additional electrical energy to power a fan [22].

Table 4 shows that the chimney method is more efficient for drying 1 kg of rice, achieving an efficiency of 32.07%, compared to 28.26% with the fan-assisted method. At a grain weight of 3 kg, the chimney method remains more efficient, though the gap narrows. By 5 kg, the fan-assisted method reaches an efficiency of 43.44%, closely approaching the chimney's 43.75%, indicating that the fan performs better with larger grain volumes. The chimney's superior performance at lower grain weights (1–3 kg) can be attributed to sufficient natural temperature and pressure differentials, which are adequate for effective moisture removal without the need for forced airflow. In contrast, the improved performance of the fan at 5 kg suggests that forced convection becomes more beneficial as grain thickness increases, enhancing airflow penetration and heat transfer. To further contextualize the uniqueness of this design, a comparison with relevant studies is presented in Table 5.

Table 4. Grain dryer efficiency average and repeat data by method and weight

Method	Grain weight (kg)	Test 1	Test 2	Test 3	test4	Test 5	Average efficiency (%)
Chimney	1	32.07	32.06	32.07	32.08	32.07	32.07
Chimney	3	37.50	37.55	32.40	32.56	32.50	37.50
Chimney	5	42.75	42.55	42.80	42.65	43.00	43.75
Fan	1	28.26	28.21	28.25	28.26	28.25	28.26
Fan	3	32.66	32.67	32.73	32.56	32.67	32.67
Fan	5	43.40	43.45	43.40	43.45	43.50	43.44

Table 5. Comparison of different studies' grain dryer designs [23], [24].

No	Dryer type	Energy source	Capacity	Drying time	Excess	Weakness
1	Batch dryer (Laboratory)	Rice husk	1.35 kg	Not specified	Eco-friendly and effective on a small scale	Low efficiency and unsuitable for large-scale
2	Rack-type dryer	Solar + biomass	Not specified	7 hours	Consistent temperature (±40°C), energy mix	The final water content remains high at almost 14%.
3	Axial fan blower flat bed dryer	Electricity (blower)	20 tons	20 hours	Able to manage high volumes	Excessive energy usage (8.4 x 10^6 kJ)
4	This research (chimney & fan)	Solar energy	1–5 kg	3.5 – 6.5 hours	Excellent performance, low energy, and appropriate for small farmers	Still small-scale; more research is required before going large-scale.

Based on the research findings presented in Table 4, a one-way ANOVA was conducted to assess the significance of differences in drying efficiency across different drying methods and grain weights. This test was appropriate as it compared more than two groups. The ANOVA results yielded an F-statistic of 148.15 with a P-value of 3.17×10^{-17}. Since the p-value is far below the conventional threshold of 0.05, the differences in efficiency between groups are significant. This indicates that both the drying method (chimney vs. fan) and grain weight have a significant effect on drying efficiency. As shown in Figure 5, the chimney method is more efficient than the fan-assisted method at grain weights of 1 kg and 3 kg. However, at 5 kg, the fan-assisted method demonstrates slightly higher efficiency, although the difference is marginal. Overall, there is a clear trend of increasing drying efficiency with increasing grain weight, regardless of the airflow method used.

The comparative analysis of this study reveals that the drying efficiency of both the fan-assisted and chimney-based methods (ranging from 32.07% to 43.75%) is substantially higher than that reported for laboratory-scale batch dryers, which typically range between 3.05% and 3.63%. In terms of drying capacity and duration, flat-bed dryers are capable of processing up to 20 tons of grain in approximately 20 hours. While the current study focused on smaller volumes, the observed increase in fan-assisted efficiency at the 5 kg level suggests that this method could perform even better at larger scales. However, further testing with greater drying capacities is needed to validate this potential. Regarding energy sources, a rack-type dryer achieved a final moisture content of 15.33% after 7 hours of drying, indicating effective use of combined biomass and solar energy. These findings suggest that hybrid energy systems can enhance overall drying efficiency. Notably, at the 5 kg grain weight, fan-assisted efficiency closely matched that of the chimney method, reinforcing the potential of both designs to deliver high performance when appropriately scaled and optimized.

These findings suggest that the fan-assisted drying method has the potential to perform more effectively at larger grain volumes; however, further testing at higher capacities is necessary to confirm this scalability. In terms of energy utilization, the rack-type dryer achieved a final moisture content of 15.33% after 7 hours, demonstrating good efficiency when using a combination of biomass and solar energy. This highlights the potential benefits of hybrid energy systems in enhancing overall drying performance. Both the fan and chimney designs exhibited high drying efficiency, particularly at a grain weight of 5 kg, where the fan's efficiency nearly matched that of the chimney. For small to medium grain loads, the chimney method is effective due to its reliance on efficient natural airflow without additional energy input. In contrast, the fan-assisted system accelerates evaporation and enhances air circulation, making it more suitable for larger quantities of grain. Based on these observations, the chimney method is recommended for small-scale applications (≤3 kg), while the fan-assisted method is more practical and efficient for larger-scale drying (≥5 kg).

IV. Conclusions

This study evaluated the efficiency of a solar-powered grain drying system using natural convection (chimney) and forced convection (fan). Both methods' drying efficiency was calculated and compared based on grain weight and drying time. Results indicated that efficiency increased with grain weight; the chimney method achieved a peak efficiency of 43.75% with 5 kg of grain, closely followed by the fan method at 42.40%. For smaller grain weights (1-3 kg), the chimney method consistently outperformed the fan method. The key finding is that natural convection is more efficient for small-scale drying due to passive airflow, whereas forced convection is more effective for larger grain loads due to enhanced air velocity. However, the electrical energy requirement of the fan should be considered. Therefore, solar dryers can be adapted based on user needs and energy availability. Chimney-based systems are better for small-scale, off-grid farmers, while fan-assisted systems are optimal for larger volumes if electricity is accessible. This study was limited to a 5 kg grain load and did not account for extreme solar intensity variations or hybrid energy use. Future research should test larger capacities under diverse environmental conditions.

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