Jurnal Asiimetrik: Jurnal Ilmiah Rekayasa Dan Inovasi
Terakreditasi "**Peringkat 3**" berdasarkan SK Dirjendiktiristek, Nomor: 225/E/KPT/2022
Volume 6 Nomor 1 Tahun 2024, Juli 2024, Halaman 227-240
Website : http://journal.univpancasila.ac.id/index.php/asiimetrik/

p-ISSN 2655-1861
e-ISSN 2716-2923

Characteristics of Multi-tier Hybrid Dryer for Drying Corn Grains

Karakteristik Pengering Hybrid Tipe Rak Bertingkat Untuk Pengeringan Butiran Jagung

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Article information:

Received:
19/03/2024
Revised:
03/04/2024
Accepted:
19/04/2024

Abstract

The type of drying device known as a hybrid dryer is a tool that harnesses solar energy and the heat generated by a biomass fuel-powered heat exchanger. This study was conducted to assess the performance of the hybrid dryer by analyzing the parameters of the device itself and the dried material. The research was carried out experimentally using a solar collector and a biomass furnace (as a heat exchanger) to heat the air. The solar collector used consists of 0.35 mm thick black-painted zinc, coated with 5 mm thick glass, and installed at a 20-degree angle. The heat exchanger pipe used has a diameter of 1.25 inches and is made of galvanized pipe. The tested sample is corn seeds with an initial moisture content of about 24.6%. The experimental results show that in the drying process using a solar dryer, the initial moisture content of 24.8% was successfully reduced to 14% at 5.50 h (rack 1), 6.50 h (rack 2) and 7.00 h (rack 3) with a thermal efficiency of 24.25%. Meanwhile, in the hybrid drying process, the required time is approximately 5.00 h (rack 1), 5.50 h (rack 2) and 6.00 h (rack 3), with a efficiency of the drying equipment used is 21.048±5.690% (hybrid) and 22.706±6.437% (solar).

Keywords: hybrid dryer, multi-tiered rack, solar collector, biomass furnace, corn grains.

***SDGs*:**

12 RESPONSIBLE CONSUMPTION AND PRODUCTION

Abstrak

Tipe perangkat pengering yang disebut pengering hibrida merupakan alat yang memanfaatkan energi panas dari matahari serta udara panas yang dihasilkan oleh pemanasan penukar kalor menggunakan bahan bakar biomassa. Penelitian ini dilaksanakan untuk mengevaluasi prestasi pengering hibrida dengan menganalisis parameter dari alat itu sendiri dan bahan yang dikeringkan. Penelitian ini dilakukan secara eksperimental dengan memanfaatkan kolektor surya dan tungku biomassa (sebagai penukar panas) untuk memanaskan udara. Kolektor surya yang dipakai terdiri dari seng setebal 0,35 mm yang dicat hitam, dilapisi kaca setebal 5 mm, dan dipasang dengan kemiringan 20 derajat. Pipa penukar panas yang digunakan berdiameter 1,25 inci dan terbuat dari pipa galvanis. Sampel yang diuji adalah biji jagung yang memiliki kadar air awal sekitar 24,6%. Hasil eksperimen menunjukkan bahwa dalam proses pengeringan menggunakan pengering surya, kadar air awal sebesar 24,8% berhasil dikurangi menjadi 14% dalam waktu 5,50 jam (rak 1), 6,50 jam (rak 2), dan 7,00 jam (rak 3) dengan efisiensi termal mencapai 24,25%. Sementara itu, pada proses pengeringan hibrida, waktu yang diperlukan adalah sekitar 5,00 jam (rak 1), 5,50 jam (rak 2), dan 6,00 jam (rak 3) dengan efisiensi alat pengering yang digunakan adalah 21.048±5.690% (hybrid) dan 22.706±6.437% (surya).

Kata Kunci: pengering hybrid, rak bertingkat, kolektor surya, tungku biomassa, butiran jagung.

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1. INTRODUCTION

Solar dryers are essential tools for farmers, who harness solar energy to efficiently dry agricultural products. These dryers typically consist of solar collectors, drying chambers, and exhaust systems (Rizalman *et al.*, 2023; Sethy *et al.*, 2023). The collectors heat the air, which is then directed into the drying chambers to remove moisture from the products, thus reducing their moisture content (Watson *et al.*, 2024). Solar drying offers a cost-effective and sustainable alternative to traditional drying methods, providing benefits for small-scale farmers by reducing operational costs and utilizing renewable energy sources (Devi *et al.*, 2023). Although solar drying technology has advanced over the years, further refinement is needed to optimize the drying process and improve overall efficiency, ensuring better preservation of agricultural products (Daksa and Tolesa, 2023).

Hybrid drying is a method devised to address the limitations of solar drying by amalgamating two or more conventional drying techniques into a singular, intricate process. This approach aims to enhance drying efficiency, energy efficiency, and the overall quality of dried products. Hybrid drying can be achieved by combining techniques such as convection, microwaving, freeze drying, and ultrasonics. The integration of these techniques allows for better control over the drying process, resulting in superior product quality and reduced energy consumption (Hii *et al.*, 2021; Banerjee *et al.*, 2022; Ciurzyńska *et al.*, 2022; Nwankwo *et al.*, 2023).

The integration of drying technology can expedite the drying process, reducing the overall processing time. This not only enhances production efficiency but also minimizes the risks of contamination and spoilage. Hybrid drying facilitates quicker completion times without compromising product quality, making it an attractive choice for industries with tight time constraints. Hybrid drying systems offer flexibility by allowing adjustments to drying parameters to suit different products. Whether it's fruits, vegetables, or grains, the adaptive capabilities of hybrid drying ensure optimal results for various agricultural and food products.

Hybrid drying technology combines various drying methods, such as solar drying, heat pumps, and microwave radiation, to enhance the quality of food products while simultaneously reducing energy consumption and environmental impact. This technology is designed to be more energy-efficient and utilize renewable energy sources, such as solar energy, to preserve food products without compromising their nutritional value or contributing to greenhouse gas emissions (Puchkov, Perov and Solovyov, 2023; Matin *et al.*, 2024). Moreover, hybrid drying systems can be optimized to improve energy efficiency and reduce the risk of food contamination, thereby contributing to a more sustainable food industry (Matin *et al.*, 2024).

Several research studies have examined the effectiveness of hybrid dryers versus traditional solar dryers. Hybrid solar dryers have exhibited promising outcomes regarding drying efficiency and temperature regulation. Reports indicate that the drying efficiency of hybrid solar dryers reaches approximately 35%, with a peak drying temperature of 80°C (Behera, Mohanty and Mohanty, 2023). Conversely, a hybrid photovoltaic thermal (PV/T) system has demonstrated an overall efficiency ranging from 35% to 52%, along with a thermal efficiency spanning from 50% to 70% (Olaoye *et al.*, 2023). Furthermore, the incorporation of an evacuated water tube solar water heater into a hybrid solar drying setup has resulted in a reduction of drying duration from 3.5 to 2.5 hours compared to open sun drying, indicating enhanced drying performance (Agrawal, Varshney and Kumar, 2023). Kiburi et al., found that an improved solar-biomass hybrid dryer, incorporating a back pass solar collector and a biomass heating stove, significantly increased drying efficiency (Kiburi *et al.*, 2023). Similarly, Devi et al., reported that a hybrid solar dryer, using both solar and electrical energy, outperformed direct open sun drying and solar drying (Devi *et al.*, 2023). Daksa and Tolesa, also observed that a hybrid solar dryer was 10% faster than a conventional solar dryer (Daksa and Tolesa, 2023). A hybrid solar-gas dryer can maintain a drying efficiency similar to that of a traditional gas dryer, while also achieving a notable decrease in fuel consumption (Kamarulzaman, Hasanuzzaman and Rahim, 2021).

The optimal temperature for hybrid drying can vary depending on the type of product being dried and the specific hybrid drying system used. For drying corn kernels, it's generally crucial to maintain a sufficiently high temperature to ensure fast and uniform drying without causing damage to the kernels. The traditional drying temperature for corn kernels typically ranges between 60-80°C (140-176°F) depending on the drying method and equipment used. The recommended drying air temperature for a hybrid system with a moisture content of 20-15% is set at 82°C. Excessively high temperatures can lead to cracking and reduce the germination rate of corn seeds, especially if the corn is intended for planting (Mykola *et al.*, 2021).

In the case of drying in general, an optimal temperature range has been reported between 40-80ºC, with the final moisture content decreasing as the temperature increases (Suherman, Hadiyanto, *et al.*, 2020). Hybrid drying systems are often classified into low and high-temperature dryers, with the working temperature levels varying depending on the specific system (Suherman, Widuri, *et al.*, 2020).

This research aims to compare the performance of solar dryers and hybrid dryers in reducing the moisture content of corn seeds. In the case of hybrid drying, an additional heat source combines heat from solar collectors and a heat exchanger with a biomass combustion furnace.

2. METHODOLOGY

2.1. Descripts

The hybrid dryer developed in this research is of the tiered rack type, utilizing indirect heating (see Figure 1), incorporating both a solar collector and a biomass combustion furnace as sources of drying air, along with a turbine ventilator. The technical specifications of the hybrid dryer include the number of racks (3 levels), a solar collector made of black matte coated zinc plate measuring (132 cm x 160 cm) with a 4mm thick absorbing glass. The biomass combustion furnace, constructed from a used drum with a diameter of 59 cm, is equipped with a heat exchanger made of 1.25-inch galvanized iron pipe and features a temperature control valve in the outlet pipe to manage air temperature. The turbine ventilator (non-electric blower) used has a diameter of 12 inches and is made of aluminium plate material. The dimensions of each drying rack are (60 cm x 60 cm x 15 cm), allowing the tool to accommodate approximately 30 kg of corn. The inner walls are made of 9mm thick plywood covered with a silver-coloured zinc plate for durability. The frame (support structure), made of merbau wood, ensures stability and longevity. To prevent heat loss, the bottom and sides of the collector, as well as the drying chamber walls, are insulated with cork material (Styrofoam). In addition, all holes and connections are sealed with silicone glue and rubber layers to ensure no air leakage from the dryer.

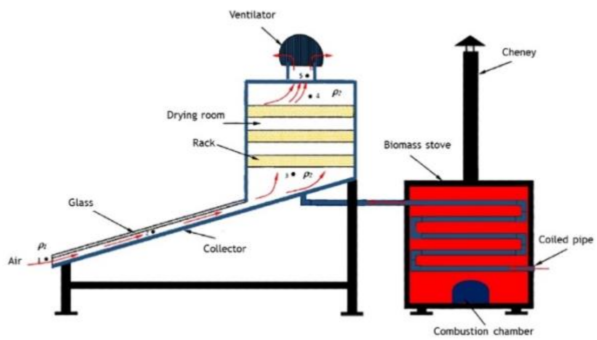


Figure 1. Hybrid dryer.

The necessary instruments for this experiment include the Krisbow Electronic Kitchen Scale 5 kg Slim Plate digital scale (accuracy ±0.1 g), Bonad SM-206 Solar Power Meter for measuring solar intensity (accuracy ±0.1 W/m2), Krisbow KW-0600561 Digital Temperature and Relative Humidity Meter (each accurate to ±0.1°C and ±0.01%), Krisbow KW-0600562 Flexible Thermo Anemometer Unit (accuracy ±0.01 m/s), and the Fluke 117 True RMS Original Digital Multimeter (accuracy ±0.1 A and ±0.1 V). Air temperature is monitored at the primary solar collector, drying chamber, and chamber exit door using type K thermocouple sensors with an accuracy of ±1.1°C.

A total of 30 kg of dried corn seeds was purchased from farmers in Keerom Regency, Papua, Indonesia. Each drying tray contained 5 kg of corn seeds, with 15 kg allocated for solar drying and the remaining 15 kg for hybrid drying. Solar drying did not involve the use of heated air from burning wood sawdust, whereas for hybrid drying, hot air from a heat exchanger and solar energy were utilized. The moisture content of the corn before drying was 24.8%. The research implementation stages can be seen in Figure 2.

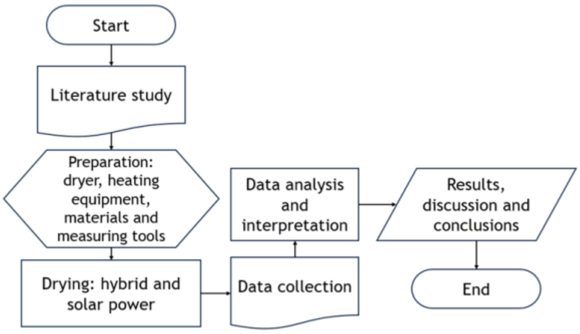


Figure 2. Research flowchart.

2.2. Performance Analysis of the Dryer

The performance testing of the hybrid dryer was conducted based on the required parameters. After data collection, an analysis of the comparative characteristics of both drying tools will be performed. To facilitate analysis, the obtained test data obtained will be processed using Microsoft Excel. The parameters include: the corn stack thickness on the rack at 5 cm, the initial weight of dried corn at 5 kg, and its moisture content of 24.8% (basis wet). Meanwhile, biomass for the heat exchanger heating is achieved using Merbau wood sawdust.

Here are the equations employed to analyze the performance of the hybrid dryer, which is a combination of a heat collector as the heat source and air as the heat exchanger.

2.2.1. Moisture content (M_w)

The percentage of water in the grain relative to the total seeds weight is denoted as moisture content on a wet basis (Putri, Pratama and Ifmalinda, 2023). The dry weight, or dry matter, of the grain is determined by the disparity between the wet weight and the total weight. In the commercial grain sector, a calibrated moisture meter is commonly utilized for measuring wet-basis moisture content (Delahunt *et al.*, 2020).

Alternatively, the wet-basis moisture content can be computed when both wet and dry weights are available (Delahunt *et al.*, 2020):

$$M_w = 100 \times \frac{(wet\ weight - dry\ weight)}{wet\ weight} \quad (1)$$

Here, M_w represents the moisture content on a wet basis, expressed as a percentage. The drawback of employing wet-basis moisture content lies in the fact that the wet weight undergoes alterations during the drying process. Consequently, the values of wet-basis moisture content cannot be directly employed in addition or subtraction to determine the weight change or moisture shrinkage resulting from the drying process.

2.2.2. Moisture Shrink

The drying procedure of grains, like corn and wheat, causes a decrease in both wet and overall weights, termed as moisture shrinkage loss (Suherman, Hadiyanto, *et al.*, 2020). This reduction is affected by factors such as initial moisture content and handling losses (Yuwana, Silvia and Sidebang, 2020). Additionally, this process results in alterations in grain characteristics, including an uptick in test weight and susceptibility to breakage (Yuwana, Silvia and Sidebang, 2020). Moisture shrinkage denotes the volume of water discharged during the grain's drying process to achieve a specified moisture content, typically set at 15% for corn and 14% for wheat. The formula to calculate moisture shrinkage is as follows (Suherman, Widuri, *et al.*, 2020):

$$M_s = \frac{100 \times (M_o - M_f)}{100 - M_f} \quad (2)$$

where, M_o is the original and M_f the final moisture content in percent.

2.2.3. Drying Rate

A drying rate is the rate at which a substance loses its moisture content. It's typically measured as a percentage of moisture per unit time. The following equation is used to calculate the drying rate (Suherman, Hadiyanto, *et al.*, 2020):

$$R_c = \frac{(X_i - X_f)}{t_c} \quad (3)$$

where R_c is the drying rate (%/s); X_i is the initial moisture content (%); x_f is the final moisture content (%); and t_c is the total time elapsed (s).

2.2.4. Drying air requirements (m_a)

In order to ascertain the requisite amount of drying air for the corn grain drying procedure, it's essential to compute the volume of air necessary to extract a specific quantity of water from the corn grains over a defined timeframe. This calculation is impacted by various factors including the initial and final moisture content of the grains, the targeted drying rate, environmental air conditions, and the effectiveness and capacity of the drying apparatus. The needed mass flow rate of drying air can be established employing the formula (Naigam *et al.*, 2021):

$$m_a = \frac{m_w \times L}{Cp_a (T_i - T_o)} \quad (4)$$

where, m_a is the drying air (kg); m_w is the mass of evaporated water mass (kg); Cp is the specific heat of the drying air (kJ/kg. K); and L is the latent heat of evaporation (kJ/kg).

2.2.5. Mass flow rate of drying air

The typical equation utilized to determine the mass flow rate of drying air in dryers where the air is warmed and circulated over the grains is (Naigam *et al.*, 2021):

$$\dot{m}_a = \frac{m_a}{3600 \times t} \quad (5)$$

where, t is the drying time (s)

2.2.6. Drying air velocity

The air velocity can be calculated using the volumetric flow rate of the air and the cross-sectional area of the air duct or space through which the air is moving (Yuwana, Silvia and Sidebang, 2020):

$$v_a = \frac{\dot{m}_a}{\rho_a \times A_c} \quad (6)$$

Where t is the drying time (s); v_a is the drying air velocity (m/s), and an is the drying air density (kg/m^3). A_c represents the collector's cross-sectional area (m^2).

2.2.7. Heat for water evaporation (Q_p)

The drying process involves the evaporation of water, which requires heat to transform liquid water into steam. Heat is crucial in this process as it supplies the energy needed to break the bonds between water molecules, facilitating their transition from liquid to gas phase. The heat necessary for water evaporation is known as latent heat (Suherman, Hadiyanto, *et al.*, 2020):

$$Q_p = \dot{m}_w \times h_{fg} \quad (7)$$

with,

$$\dot{m}_w = \frac{m_w}{t} \quad (8)$$

h_{fg} = the latent heat for water evaporation is evaluated at T_3.

2.2.8. Total heat absorbed by the collector for drying (Q_c)

The total heat absorbed by the solar collector for drying can be calculated provided you have information about the collector efficiency, collector area, and exposure to solar radiation on the collector. The formula for calculating the absorbed heat is (Naigam *et al.*, 2021):

$$Q_c = A_c \times I_g \quad (9)$$

where A_c is the cross-sectional area of the collector ($p_c \times l_c$, m^2); I_g is the global intensity of solar.

2.2.9. Drying apparatus efficiency (η_{th})

To determine drying efficiency, it is required to account energy intake and output during the drying process (Suherman, Hadiyanto, *et al.*, 2020):

$$\eta_{th} = \frac{Q_p}{Q_c} \quad (10)$$

3. RESULTS AND DISCUSSION

Test results of a hybrid dryer and solar power to dry corn grains with the same weight of 5 kg on each three-tiered shelf at a moisture content of

24.8%. Data on the temperature, weight, and humidity of dried corn grains were collected for 16 hours (from 8:00 to 16:00 local time). These results are shown in Tables 1 and 2, and then analyzed in terms of drying characteristics such as water content after drying (M_W), amount of water vapor produced from corn (mw), amount of drying air required (ma), and rate of corn mass flow. Drying air (*m*), drying air speed (v_a), water evaporation heat (Q_p), collector heat absorbed (Q_c), and dryer efficiency (η_{th}).

3.1. Temperature Distribution in the Dryer

Analysis of temperature and solar radiation measurements based on Table 1 reveals that the maximum solar irradiance value reaches 800 W/m². The solar-powered dryer achieves a higher maximum temperature, reaching 90°C, whereas the hybrid dryer peaks at 79°C. Conversely, the minimum solar radiation value reaches 455 W/m². The average minimum environmental temperature stands at 28°C. Measurements of the average minimum solar drying values when using the solar-powered dryer are at 660 W/m², while the hybrid dryer is slightly higher at 662 W/m². The average maximum temperature during operation, the solar dryer is slightly higher at 33°C compared to the operation of the hybrid dryer at 32°C.

For solar radiation, the standard deviation measures the spread of values around the mean, indicating how much the solar radiation measurements deviate from the average. The Solar Dryer exhibits a standard deviation of 119.29 W/m², suggesting a moderate level of variability in solar radiation readings. Conversely, the Hybrid Dryer shows a slightly lower standard deviation of 116.33 W/m², indicating a slightly narrower spread of solar radiation values around the mean.

Table 1. Dryer temperature measurement data at 0.5-hour intervals.

Time (h)	Measurement time interval (h)	Hybrid dryer							Solar dryer						
		I_g W/m²	T_o °C	T_1 °C	T_2 °C	T_3 °C	T_4 °C	T_5 °C	I_g W/m²	T_o °C	T_1 °C	T_2 °C	T_3 °C	T_4 °C	T_5 °C
08:00	0.0	455	28.4	28.9	50.2	88	85	83	455	28.4	28.5	49.7	38	36	39.2
08:30	0.5	511	30.3	30.8	55.9	88	85	83	511	30.3	30.5	54.7	45	42	44.9
09:00	1.0	553	31.2	31.7	58.4	90	87	83	553	31.2	31.4	58.0	49	47	48.4
09:30	1.5	649	32.9	33.4	61.7	90	88	84	649	32.9	33.1	61.0	53	51	51.7
10:00	2.0	677	33.3	33.8	64.0	89	88	85	677	33.3	33.5	63.0	54	53	54.0
10:30	2.5	758	33.5	34.0	72.5	88	87	85	758	33.5	33.6	70.0	62	59	62.5
11:00	3.0	779	33.7	34.5	76.3	89	88	86	779	33.7	33.9	74.0	67	65	67.3
11:30	3.5	794	34.0	34.8	77.2	90	89	87	794	34.0	34.2	76.0	68	67	68.4
12:00	4.0	798	34.5	35.3	78.4	90	89	87	800	34.5	34.7	79.0	70	69	69.6
12:30	4.5	800	34.4	35.2	78.1	90	89	88	800	34.4	34.7	78.5	71	69	69.1
13:00	5.0	781	34.1	34.9	76.6	90	88	88	781	34.1	34.4	75.9	69	68	67.6
13:30	5.5	720	33.8	34.6	74.4	90	88	87	720	33.8	33.9	73.3	67	66	66.4
14:00	6.0	688	32.5	33.3	71.7	89	87	86	688	32.5	32.6	70.4	65	63	63.7
14:30	6.5	650	31.9	32.5	68.2	87	86	86	650	31.9	31.9	67.0	61	59	60.2
15:00	7.0	574	30.1	30.7	65.5	88	87	86	574	30.1	30.3	64.0	59	57	57.5
15:30	7.5	549	29.7	30.3	61.9	88	87	85	549	29.7	29.7	59.0	55	52	53.9
16:00	8.0	480	29.5	30.1	57.0	88	87	85	516	29.5	29.6	55.0	50	47	49.0
	Max	800	35	35	78	90	89	88	800	35	35	79	71	69	70
	Min	455	28	29	50	87	85	83	455	28	29	50	38	36	39
	Average	660	32	33	68	89	87	86	662	32	32	66	59	57	58
	Std	119	1.97	2.06	8.96	1.03	1.22	1.62	116	1.97	2.02	9.15	9.75	10.1	9.49

This suggests that solar radiation measurements in the Hybrid Dryer may be slightly more consistent than those in the Solar Dryer.

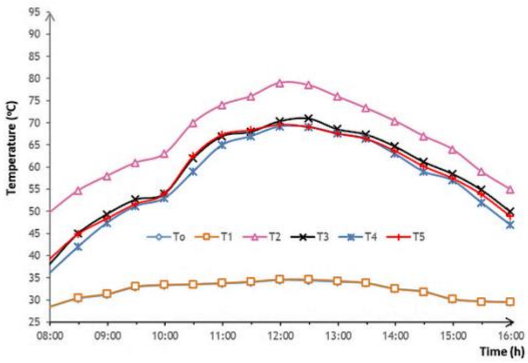
Similarly, for temperature measurements, the standard deviation indicates the degree of variability in temperature readings within each dryer. The Solar Dryer displays standard deviation values ranging from approximately 1.02°C to 2.06°C across different monitoring points, indicating relatively low variability in temperature measurements. In contrast, the hybrid dryer exhibits standard deviation values ranging from approximately 9.15°C to 10.11°C, suggesting higher variability in temperature readings compared to the solar dryer. This indicates that temperature control in the solar dryer is more consistent and reliable than in the hybrid dryer, where temperature fluctuations may be more pronounced.

The temperature distribution during the drying of corn kernels may not be predominantly influenced by the ambient air temperature and the solar radiation absorbed by the collector. Other factors, such as humidity levels and airflow within the dryer, exert a more substantial impact on the efficacy of the drying process (Li *et al.*, 2020).

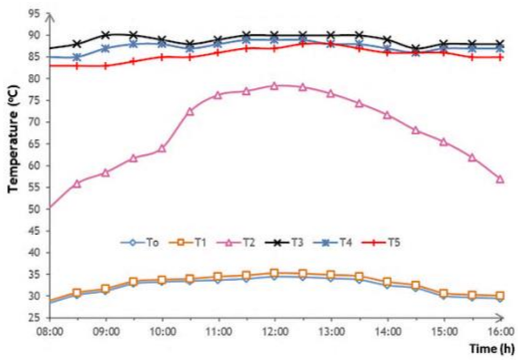
Crossflow dryers are renowned for their high temperatures and capacities, typically used for drying commodity grains within a specific temperature range, usually between 82.2 °C - 110°C (Puchkov, Perov and Solovyov, 2023). To achieve a market moisture content of 13-15%, depending on the grain varieties, temperatures need to be raised to match the drying air temperature, particularly along the inner layers of the crossflow dryer. However, it is imperative to ensure that the air temperature remains within acceptable thresholds to prevent adverse effects on the quality characteristics of corn kernels, applicable to another dryer designs as well.

Figure 3 depicts the temperature distribution throughout the day, from 08:00 to 16:00, when using solar-powered drying. Temperature data points T0 to T5 start at around 25°C at 08:00 and gradually increase to approximately 60°C by 14:00, then decrease to around 40°C by 16:00. Conversely, temperature data points T1 to T2 begin around 30°C at 08:00, experience a significant increase between 10:00 and 12:00, peaking at around 80°C, then gradually decrease to around 50°C by 16:00. Lastly, temperature data points T3 to T4 start at approximately 40°C at 08:00, maintain relative stability with slight increases, and peak at around 45°C by 16:00 (Figure 3a).

Temperature fluctuations during the observation period are delineated by T0 to T5. Figure 3b illustrates temperatures ranging around 25°C at 08:00 for T0 to T5, while T1 to T2 start slightly higher at around 30°C, and T3 to T4 begin at around 40°C. Over the subsequent hours, different patterns emerge, with T0 to T5 experiencing gradual increases, peaking at approximately 60°C by 14:00, followed by a decrease to around 40°C by nearly 16:00. Conversely, T1 to T2 undergo a significant spike between 10:00 and 12:00, with temperatures surging to around 80°C before declining to around 50°C by 16:00. In contrast, T3 to T4 remain relatively stable throughout the period, with only slight increases, ending at around 45°C by 16:00.



(a) Solar dryer



(b) Hybrid dryer

Figure 3. Temperature distribution during the drying process in a multi-tier rack dryer.

In the context of hybrid drying, this article highlights the benefits of integrating a biomass combustion furnace with a heat exchanger to stabilize and control temperatures within the drying chamber. Hybrid dryers, which combine solar energy with an additional heat source such as biomass, offer more consistent drying conditions compared to systems relying solely on solar power, particularly in variable weather conditions.

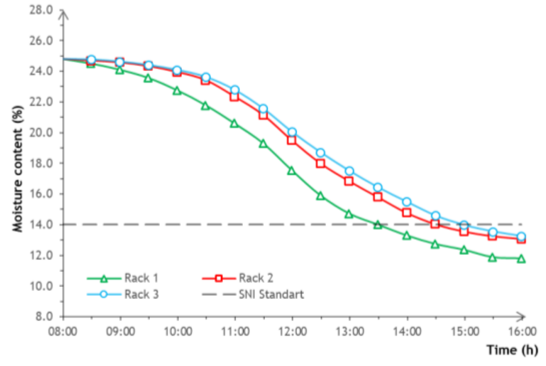
The addition of a heat exchanger in the system ensures that temperatures remain within the desired range, which is crucial for maintaining the quality of dried products. Hybrid dryers aim to keep air temperatures below the threshold of 90°C, as temperatures above this level may potentially damage the dried products or result in efficiency loss.

Temperature measurements taken at different points (T3, T4, and T5) serve as important indicators of thermal performance and drying regulation capability. These indicators demonstrate the hybrid system's ability to maintain a consistent and controlled drying environment through manual adjustments to airflow.

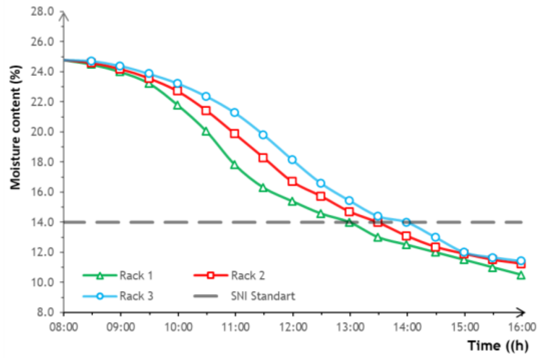
Manual control of the inlet valve of the heat exchanger is a crucial aspect of system operation as it allows operators to modulate the heat transferred from the biomass furnace to the drying air. Although effective, this approach has limitations in terms of precision and temperature control responsiveness compared to systems with automated controls driven by feedback. The ability to manually control temperature by adjusting valves provides a certain level of responsiveness to changes in environmental conditions or heat output from the biomass combustion furnace. However, it also implies the need for active monitoring and adjustment to ensure optimal drying temperatures are maintained.

3.2. Moisture Content of Corn Seeds

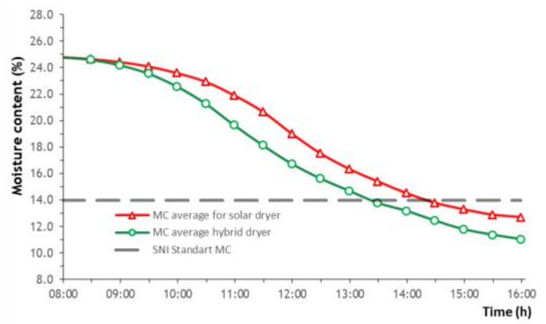
According to the Indonesian National Standard (SNI) 01-3481-1995, the moisture content for the dry corn category should not exceed 14%. In Figure 4, it can be observed that the moisture content decreases with increasing drying time. In the hybrid dryer, the time required to dry the sample (corn) from an initial harvest moisture content of approximately ±24.8% to the standard dry moisture content of 14% is shorter compared to drying with a solar dryer or outdoor drying (direct exposure to sunlight) (Table 2).



(a) Solar dryer



(b) Hybrid dryer



(c) Comparation average moisture content of dryer

Figure 4. Changes in corn seeds moisture content during the drying process.

Table 2 presents the moisture content measurements obtained from each drying apparatus. The hybrid dryer exhibits a more consistent and efficient drying process compared

Table 2. Weight and moisture content measurement data at 0.5-hour intervals.

Time (h)	Measurement time interval (h)	Hybrid dryer								Solar dryer							
		Weight of grain corn				Moisture content of grain corn				Weight of grain corn				Moisture content of grain corn			
		Rack 1	Rack 2	Rack 3	Average	Rack 1	Rack 2	Rack 3	Average	Rack 1	Rack 2	Rack 3	Average	Rack 1	Rack 2	Rack 3	Average
		kg	kg	kg	kg	%	%	%	%	kg	kg	kg	kg	%	%	%	%
08:00	0.0	5000.0	5000.0	5000.0	5000.0	24.8	24.8	24.8	24.8	5000.0	5000.0	5000.0	5000.0	24.8	24.8	24.8	24.8
08:30	0.5	4985.0	4990.0	4996.0	4994.0	24.5	24.6	24.7	24.7	4985.0	4995.0	4999.0	4992.0	24.5	24.7	24.8	24.6
09:00	1.0	4960.0	4970.0	4980.0	4986.0	24.0	24.2	24.4	24.5	4965.0	4989.0	4992.0	4984.0	24.1	24.6	24.6	24.5
09:30	1.5	4922.0	4939.0	4954.0	4975.0	23.2	23.6	23.9	24.3	4938.0	4977.0	4981.0	4975.0	23.6	24.3	24.4	24.3
10:00	2.0	4850.0	4896.0	4922.0	4955.0	21.8	22.7	23.2	23.9	4898.0	4958.0	4965.0	4956.0	22.8	24.0	24.1	23.9
10:30	2.5	4763.0	4832.0	4879.0	4925.0	20.1	21.4	22.4	23.3	4849.0	4931.0	4942.0	4923.0	21.8	23.4	23.6	23.3
11:00	3.0	4651.0	4754.0	4824.0	4886.0	17.8	19.9	21.3	22.5	4790.0	4878.0	4900.0	4889.0	20.6	22.4	22.8	22.6
11:30	3.5	4575.0	4675.0	4751.0	4835.0	16.3	18.3	19.8	21.5	4725.0	4818.0	4839.0	4839.0	19.3	21.2	21.6	21.6
12:00	4.0	4530.0	4595.0	4668.0	4770.0	15.4	16.7	18.2	20.2	4637.0	4735.0	4763.0	4774.0	17.5	19.5	20.1	20.3
12:30	4.5	4489.0	4547.0	4590.0	4711.0	14.6	15.7	16.6	19.0	4555.0	4660.0	4696.0	4715.0	15.9	18.0	18.7	19.1
13:00	5.0	4460.0	4495.0	4532.0	4656.0	14.0	14.7	15.4	17.9	4496.0	4602.0	4636.0	4660.0	14.7	16.8	17.5	18.0
13:30	5.5	4410.0	4459.0	4480.0	4610.0	13.0	14.0	14.4	17.0	4460.0	4550.0	4582.0	4612.0	14.0	15.8	16.4	17.0
14:00	6.0	4385.0	4414.0	4460.0	4568.0	12.5	13.1	14.0	16.2	4425.0	4499.0	4535.0	4569.0	13.3	14.8	15.5	16.2
14:30	6.5	4360.0	4378.0	4410.0	4531.0	12.0	12.4	13.0	15.4	4397.0	4462.0	4490.0	4535.0	12.7	14.0	14.6	15.5
15:00	7.0	4335.0	4355.0	4360.0	4500.0	11.5	11.9	12.0	14.8	4378.0	4438.0	4459.0	4504.0	12.4	13.6	14.0	14.9
15:30	7.5	4310.0	4335.0	4343.0	4475.0	11.0	11.5	11.7	14.3	4354.0	4423.0	4438.0	4477.0	11.9	13.3	13.6	14.3
16:00	8.0	4285.0	4322.0	4331.0	4461.0	10.5	11.2	11.4	14.0	4350.0	4414.0	4423.0	4458.0	11.8	13.1	13.3	14.0
	Max	5000	5000	5000	5000	25	25	25	25	5000	5000	5000	5000	25	25	25	25
	Min	4285	4322	4331	4461	11	11	11	14	4350	4414	4423	4458	12	13	13	14
	Average	4604	4644	4675	4755	17	18	18	20	4659	4725	4744	4757	18	19	20	20
	Std	257.85	253.26	252.5	203	5.1571	5.0652	5.05	4.0601	247.12	230.64	223.09	202.11	4.9424	4.6128	4.4618	4.0421

to the solar dryer. Specifically, the corn kernel weights across all three tiers of the hybrid dryer decrease from 5000 g to between 4285 g and 4331 g over an 8-hour period, whereas in the solar dryer, the weights decrease to a slightly higher range between 4350 g and 4423 g. Additionally, the moisture content of the corn kernels in the hybrid dryer decreases from an initial 24.8% to a range of between 10.5% and 11.4%, while the solar dryer achieves final moisture content between 11.8% and 13.3%.

The average weights and moisture content at the end of the drying period are also lower in the hybrid dryer compared to the solar dryer, indicating a more effective drying capacity. Moreover, the standard deviation for the hybrid dryer is smaller, indicating a more uniform drying process across different corn kernels on different tiers compared to the solar dryer. Overall, these data demonstrate that the hybrid dryer not only removes moisture more rapidly but also delivers more consistent drying results compared to the solar dryer.

The standard deviation values in the dataset serve as indicators of the uniformity of the drying process within the compared drying systems. A lower standard deviation suggests a more consistent drying experience across various tiers. The standard deviation values for weight loss in the hybrid dryer range from 203.002 to 257.853 g, while for the solar dryer, they range from 202.107 to 247.122 g. Similarly, the standard deviation of moisture content in the hybrid dryer (4.060% to 5.157%) is relatively smaller compared to that in the solar dryer (4.042% to 4.942%). These values indicate that the hybrid dryer provides a slightly more uniform drying process than the solar dryer, suggesting less drying variability across various trays in the hybrid system. Consistency in the data ensures that all corn kernels reach the desired dryness level simultaneously, thereby optimizing the drying process and potentially yielding better overall product quality.

The drying process of corn grains involves the utilization of various types of dryers, resulting in significant differences in moisture content that can fluctuate up to 30%. However, even after undergoing the drying procedure, the reduction in moisture content variation among grains only occurs partially and is not eliminated. The uniformity of water height distribution among corn particles exiting the crossflow or mixed-flow dryer is more consistent compared to the height observed in the crossflow dryer.

The distribution of moisture content among corn particles exiting the crossflow or mixed flow dryer is more consistent compared to the crossflow dryer, indicating a greater difference (Sjechlad *et al.*, 2022; Jimoh *et al.*, 2023). To address uneven drying, mechanisms such as agitation systems have been proposed to enhance uniformity in moisture reduction during the drying process (Wang *et al.*, 2023). Additionally, optimizing the operation of tower dryers with downward-moving layers and hot air can significantly impact energy efficiency and drying uniformity, emphasizing the importance of convective heat transfer coefficients in achieving consistent moisture removal (Arsenoaia *et al.*, 2023).

Significant fluctuations in the initial moisture content of grain kernels entering the dryer contradict the positive outcomes of consistently applied drying processes (Shammi *et al.*, 2022). As a result, crossflow drying, which inherently produces uneven temperature and humidity gradients across the column width, does not alter kernel moisture variability to a greater or lesser extent compared to simultaneous drying and mixed flow drying (Jaganathan, Li and Liu, 2022). Meanwhile, the type of dryer has a significant effect on the stress crack value of grains. Corn dried in a crossflow dryer generally has the smallest stress crack, with the majority being dried in a crossflow dryer (Mabasso *et al.*, 2023).

The constant supply of hot air from the heat exchanger ensures that the dryer air temperature remains consistent during the drying process. This results in continuous drying unaffected by weather conditions, making the drying process in hybrid dryers faster compared to solar-powered drying. However, it's crucial to note that during the drying process, the dryer air temperature should not be too high as it can damage the dried product (corn). Therefore, temperature control valves on the heat exchanger outlet pipe are necessary.

3.3. Drying Efficiency

Drying efficiency is a critical parameter in the drying process, reflecting how effectively energy is utilized to remove moisture from a material. Factors such as temperature, energy source, and drying strategy significantly impact drying efficiency (Teymori-Omran *et al.*, 2023).

Table 3 and Table 4 present the heat values for hybrid dryers and solar dryers. Heat transfer primarily occurs through convection, where hot air is circulated through the drying chamber to remove moisture from the dried material. Table 3 and Table 4 illustrate the results of the analysis of data from hybrid dryers and solar dryers, with the average evaporation mass of corn grains being 0.00043±0.00016 kg/s (hybrid) and 0.00045±0.00014 kg/s, while the average drying air flow reaches 0.108±0.035 kg/s (hybrid) and 0.090±0.029 kg/s (solar). The heat generated by collectors in each dryer type is 480.00±71.58 Watts and 480.00±69.80 Watts, while the evaporation heat in hybrid dryers reaches 108,443±31.326 Watts, and in solar dryers is 108,986±32.472 Watts. The average heat value of sawdust powder used reaches 14100 kJ/kg to heat the air in the heat exchanger, with the average fuel consumption rate required during the process being 0.011±0.003 kg/s.

The allowable threshold of heat in this system varies, with the thermal efficiency of multi-directional solar collectors ranging from 50% to 70% . Additionally, the maximum efficiency of collectors in solar dryers for drying food products has been reported at 74.1% (Ponshanmugakumar and Rajavel, 2022). Different materials have different temperature tolerances, and agricultural products may have varying optimal temperature ranges for efficient drying while maintaining quality. For solar dryers, drying temperatures typically range from 25°C to 80°C (Behera, Mohanty and Mohanty, 2023), although these temperatures may vary depending on specific applications, designs, and dryer operations.

The comparison of average drying efficiencies in the utilized drying equipment is 21.048±5.690% (hybrid) and 22.706±6.437% (solar), indicating that only a small portion of the heat energy is used to evaporate water from corn grains. The rest is lost through various mechanisms such as conduction, convection, and radiation.

Figure 5 illustrates the comparison of drying efficiency, where the efficiency values increase with the duration of drying time until reaching midday at 12:00, then decrease as time progresses

Table 3. Heat values and efficiency of hybrid dryers.

	Mass of evaporation, m_w	Mass of evaporative flow, $\dot{m}_w$	Total mass of evaporation, m_{wtot}	Mass flow of average water evaporation, $\dot{m}_{wavg}$	Air density, ρ_a	Specific heat of air, Cp_a	Latent heat of vaporization, h_{fg}	Mass of air, m_a	Mass flow rate of drying air, $\dot{m}_a$	Drying air velocity, v_a	Heat of vaporization, Q_p	Solar collector absorption heat, Q_c	Calorific value of sawdust, LHV_{bb}	Fuel consumption, m_{bb}	Mass flow rate of fuel, $\dot{m}_{bb}$	Sawdust combustion heat, Q_{bb}	Drying efficiency, η
	kg	kg/s	kg	kg/s	kg/m^3	kJ/kg.K	kJ/kg	kg	kg/s	m/s	W	W	kJ/kg	kg	kg/s	W	%
	0	0	0	0	1.1704	1.007	2413.84	0	0	0	0	273	14100	0	0	0	0
	0.010	0.000005	0.013	0.00001	1.163	1.007	2406.70	7.70	0.004	0.050	12.92	306.60	14100	1.40	0.001	10.97	4.07
	0.020	0.000011	0.040	0.00002	1.159	1.007	2404.32	16.18	0.009	0.106	27.16	331.80	14100	2.10	0.001	16.45	7.80
	0.032	0.000018	0.081	0.00004	1.153	1.007	2401.94	37.77	0.021	0.250	42.26	389.40	14100	3.20	0.002	25.07	10.20
	0.049	0.000027	0.143	0.00008	1.151	1.007	2385.36	116.07	0.064	0.768	64.93	406.20	14100	4.05	0.002	31.73	14.83
	0.065	0.000036	0.223	0.00012	1.151	1.007	2394.80	153.79	0.085	1.018	86.04	454.80	14100	5.42	0.003	42.46	17.30
	0.082	0.000045	0.320	0.00018	1.150	1.007	2389.96	193.82	0.108	1.284	108.43	467.40	14100	6.10	0.003	47.78	21.05
	0.076	0.000042	0.407	0.00023	1.149	1.007	2385.12	180.01	0.100	1.194	100.71	476.40	14100	7.05	0.004	55.23	18.94
	0.069	0.000039	0.483	0.00027	1.147	1.007	2382.70	164.05	0.091	1.090	91.78	478.80	14100	7.95	0.004	62.28	16.96
	0.056	0.000031	0.543	0.00030	1.147	1.007	2382.70	131.71	0.073	0.875	73.69	480.00	14100	9.02	0.005	70.66	13.38
	0.046	0.000026	0.591	0.00033	1.148	1.007	2387.54	54.93	0.031	0.364	61.46	468.60	14100	11.81	0.007	92.54	10.95
	0.046	0.000026	0.638	0.00035	1.150	1.007	2389.96	54.59	0.030	0.362	61.08	432.00	14100	13.09	0.007	102.56	11.43
	0.030	0.000017	0.669	0.00037	1.155	1.007	2392.38	35.64	0.020	0.235	39.87	412.80	14100	14.37	0.008	112.59	7.59
	0.037	0.000021	0.705	0.00039	1.157	1.007	2399.56	88.17	0.049	0.581	49.32	390.00	14100	15.65	0.009	122.62	9.62
	0.033	0.000018	0.737	0.00041	1.164	1.007	2401.94	77.92	0.043	0.510	43.59	344.40	14100	16.93	0.009	132.64	9.14
	0.021	0.000011	0.757	0.00042	1.165	1.007	2406.70	49.39	0.027	0.323	27.63	329.40	14100	18.21	0.010	142.67	5.85
	0.017	0.000009	0.773	0.00043	1.166	1.007	2408.46	39.86	0.022	0.260	22.30	288.00	14100	19.49	0.011	152.70	5.06
Max	0.082	0.000045	0.773	0.00043	1.170	1.007	2413.84	193.82	0.108	1.284	108.433	480.00	14100.000	19.49	0.011	152.70	21.048
Min	0	0	0	0	1.147	1.007	2382.70	0.00	0	0	0	273.00	14100.000	0	0	0	0
Average	0.040	0.000022	0.419	0.00023	1.156	1.007	2396.12	82.45	0.046	0.545	53.716	395.86	14100.000	9.17	0.005	71.82	10.833
Std	0.024	0.000013	0.286	0.00016	0.008	0.000	10.00	62.59	0.035	0.415	31.326	71.58	0.000	6.25	0.003	48.99	5.690

Table 4. Heat values and efficiency of solar dryers.

	Mass of evaporation, m_w	Mass of evaporative flow, $\dot{m}_w$	Total mass of evaporation, m_{wtot}	Mass flow of average water evaporation, $\dot{m}_{wavg}$	Air density, ρ_a	Specific heat of air, Cp_a	Latent heat of vaporization, h_{fg}	Mass of air, m_a	Mass flow rate of drying air, $\dot{m}_a$	Drying air velocity, v_a	Heat of vaporization, Q_p	Solar collector absorption heat, Q_c	Drying efficiency, η
	kg	kg/s	kg	kg/s	kg/m^3	kJ/kg.K	kJ/kg	kg	kg/s	m/s	W	W	%
	0	0	0	0	1.1704	1.007	2413.84	0	0	0	0	273.00	0
	0.007	0.000004	0.009	0.00001	1.16286	1.007	2406.70	5.58	0.003	0.329	9.36	306.60	3.05
	0.011	0.000006	0.024	0.00001	1.15944	1.007	2404.32	13.13	0.007	0.777	14.69	331.80	4.43
	0.017	0.000009	0.046	0.00003	1.15298	1.007	2401.94	26.50	0.015	1.576	22.24	389.40	5.71
	0.025	0.000014	0.078	0.00004	1.15146	1.007	2385.36	59.22	0.033	3.526	33.13	406.20	8.16
	0.033	0.000018	0.120	0.00007	1.1507	1.007	2394.80	26.16	0.015	1.559	43.90	454.80	9.65
	0.051	0.000029	0.184	0.00010	1.14994	1.007	2389.96	60.92	0.034	3.632	68.16	467.40	14.58
	0.062	0.000034	0.260	0.00014	1.1488	1.007	2385.12	146.85	0.082	8.764	82.15	476.40	17.24
	0.082	0.000046	0.356	0.00020	1.1469	1.007	2382.70	162.34	0.090	9.705	108.99	480.00	22.71
	0.075	0.000041	0.440	0.00024	1.14728	1.007	2382.70	92.99	0.052	5.557	98.84	480.00	20.59
	0.059	0.000033	0.505	0.00028	1.14842	1.007	2387.54	139.89	0.078	8.351	78.26	468.60	16.70
	0.047	0.000026	0.555	0.00031	1.14956	1.007	2389.96	112.34	0.062	6.700	62.85	432.00	14.55
	0.044	0.000025	0.601	0.00033	1.1545	1.007	2392.38	61.96	0.034	3.679	58.92	412.80	14.27
	0.037	0.000020	0.638	0.00035	1.15678	1.007	2399.56	39.71	0.022	2.354	48.88	390.00	12.53
	0.025	0.000014	0.663	0.00037	1.16362	1.007	2401.94	39.22	0.022	2.311	32.92	344.40	9.56
	0.020	0.000011	0.683	0.00038	1.16514	1.007	2406.70	16.48	0.009	0.970	26.74	329.40	8.12
	0.009	0.000005	0.692	0.00038	1.1659	1.007	2408.46	7.44	0.004	0.438	12.49	309.60	4.03
Max	0.082	0.000046	0.692	0.00038	1.170	1.007	2413.84	162.34	0.090	9.705	108.986	480.00	22.706
Min	0	0	0	0	1.147	1.007	2382.70	0.00	0	0	0	273.00	0.000
Average	0.036	0.000020	0.344	0.00019	1.156	1.007	2396.12	59.45	0.033	3.543	47.207	397.20	10.935
Std	0.025	0.000014	0.268	0.00015	0.008	0.000	10.00	52.89	0.029	3.162	32.472	69.80	6.437

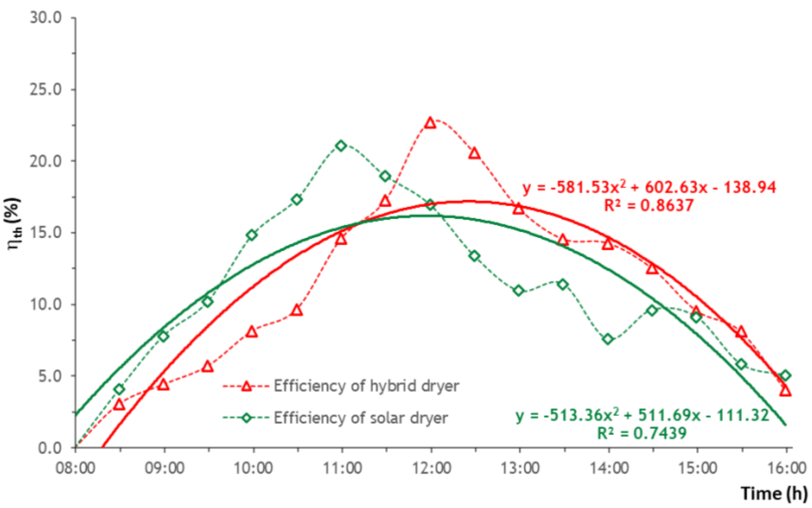


Figure 5. Thermal efficiency during the drying process.

until 16:00. This is due to fluctuations in air temperature inside the drying chamber, depending on the intensity of solar heat radiation received by the collector. The temperature gradient between the collector input, drying chamber, and chimney induces natural airflow due to pressure differences caused by variations in air density.

The representation in Figure 5 provides a comparison of the efficiency between solar dryers and hybrid dryers over a specific time period. In the graph caption, there are two equations displayed: $y = 581.53x^2 + 602.63x - 138.94$; $R^2 = 0.8637$ and $y = 513.36x^2 + 511.69x - 111.32$; $R^2 = 0.7439$. The R^2 value, also known as the coefficient of determination, indicates how well the regression line fits the data points. The R^2 value for the hybrid dryer (0.8637) is higher than that for the solar dryer (0.7439), suggesting that the trendline accurately predicts the efficiency of the hybrid dryer to a greater extent than that of the solar dryer. The efficiency of both dryers increases over time, reaching its peak around noon (12:00), and then gradually decreases. Throughout the day, the hybrid dryer demonstrates higher efficiency compared to the solar dryer.

4. CONCLUSION

Solar dryers have varying drying times due to fluctuating sunlight availability. Hybrid dryers utilize alternative energy sources to maintain drying time stability. The average evaporation mass of corn grains is 0.00043±0.00016 kg/s (hybrid) and 0.00045±0.00014 kg/s, while the average drying air flow reaches 0.108±0.035 kg/s (hybrid) and 0.090±0.029 kg/s (solar). The heat generated by collectors in each dryer type is 480.00±71.58 Watts and 480.00±69.80 Watts, while the evaporation heat in hybrid dryers reaches 108,443±31.326 Watts, and in solar dryers is 108,986±32.472 Watts. In hybrid dryers, the temperature and drying rate are relatively stable during the drying process, ranging from 70°C to 90°C. The drying time reaches 5 - 6 hours with an initial moisture content of 24.8% to achieve a final moisture content of 14%. The average drying efficiency of the drying equipment used is 21.048±5.690% (hybrid) and 22.706±6.437% (solar).

REFERENCES

Agrawal, S., Varshney, T. and Kumar, J. (2023) 'Comparative Analysis of Hybrid Photovoltaic Thermal (PV/T) Solar Dryer', *Asian Journal of Water, Environment and Pollution*, 20(1), pp. 57–66.

Arsenoaia, V.N. *et al.* (2023) 'Drying Process Modeling and Quality Assessments Regarding an Innovative Seed Dryer', *Agriculture*, 13(2), p. 328.

Banerjee, B.B. *et al.* (2022) 'Role of Food Microwave Drying in Hybrid Drying Technology', in *A Comprehensive Review of the Versatile Dehydration Processes*. London, UK: IntechOpen.

Behera, D.D., Mohanty, R.C. and Mohanty, A.M. (2023) 'Thermal performance of a hybrid solar dryer through experimental and CFD investigation', *Journal of Food Process Engineering*, 46(8), p. e14386.

Ciurzyńska, A. *et al.* (2022) 'The Effect of Hybrid Drying Methods on the Quality of Dried Carrot', *Applied Sciences*, 12(20), p. 10588.

Daksa, T.W. and Tolesa, G.N. (2023) 'Review the Design of the Solar Dryer for the Dryer of Fruit and Vegetable Dryers', *International Journal of Food Engineering and Technology*, 7(1), pp. 1–11.

Delahunt, C.B. *et al.* (2020) 'Algorithms To Predict Moisture Content Of Grain Using Relative Humidity Time-Series', in *2020 IEEE Global Humanitarian Technology Conference (GHTC). 2020 IEEE Global Humanitarian Technology Conference (GHTC)*, pp. 1–8.

Devi, T.B. *et al.* (2023) 'Solar Dryer Using Evacuated Tube Solar Thermal Collector With Thermal Storage', *The Indian Journal of Agricultural Sciences*, 93(2), pp. 233–236.

Hii, C.L. *et al.* (2021) 'Hybrid Drying Of Food And Bioproducts: A Review', *Drying Technology*, 39(11), pp. 1554–1576.

Jaganathan, G.K., Li, J. and Liu, B. (2022) 'Low Constant Temperature Drying Can Be A Satisfactory Method To Determinethe Moisture Content Of Impermeable Seed Coated Species', *Southern Forests: a Journal of Forest Science*, 84(4), pp. 325-327.

Jimoh, K.A. *et al.* (2023) 'Recent Advances in the Drying Process of Grains', *Food Engineering Reviews*, 15(3), pp. 548-576.

Kamarulzaman, A., Hasanuzzaman, M. and Rahim, N.A. (2021) 'Global Advancement Of Solar Drying Technologies And Its Future Prospects: A Review', *Solar Energy*, 221, pp. 559–582.

Kiburi, F.G. *et al*. (2023) 'Exergetic Optimisation Of A Solar-Biomass Hybrid Greenhouse Dryer In Drying Banana Slices', *International Journal of Exergy*, 41(1), pp. 41–59.

Li, B. *et al*. (2020) 'Exergoeconomic Analysis of Corn Drying in a Novel Industrial Drying System', *Entropy*, 22(6), p. 689.

Mabasso, G.A. *et al*. (2023) 'The Effect Of Intermittent Drying With Variable Resting Times On Quality Parameters Of Corn Obtained After Storage', *LWT*, 182, p. 114855..

Matin, A. *et al*. (2024) 'Effect Of Conduction Drying On Nutrient And Fatty Acid Profiles: A Comparative Analysis Of Hazelnuts And Walnuts', *Frontiers in Sustainable Food Systems*, 8, pp. 1-12.

Mykola, K. *et al*. (2021) 'Influence of a New Energy-Saving Drying Method on the Quality of Corn Seeds', *American Journal of Agriculture and Forestry*, 9(1), pp. 1–6.

Naigam, A.P.V. *et al*. (2021) 'Design, Development And Performance Evaluation Of A Large-Scale Hybrid Solar Dryer', in *IOP Conference Series: Materials Science and Engineering. International Conference on Recent Innovations in Engineering and Technology (ICRIET 2020)*, Tamil Nadu, India: IOP Publishing, p. 012016.

Nwankwo, C.S. *et al*. (2023) 'Recent Developments in the Hybridization of the Freeze-Drying Technique in Food Dehydration: A Review on Chemical and Sensory Qualities', *Foods*, 12(18), p. 3437.

Olaoye, S.A. *et al*. (2023) 'Developmental Trend of Hybrid Solar Dryer: A Comprehensive Review', *Journal of Engineering Research and Reports*, 24(1), pp. 1–19.

Ponshanmugakumar, A. and Rajavel, R. (2022) 'Enhancement of Heat Transfer in Solar Dehydrator for Agriculture Products', in K. Mukherjee, R.K. Layek, and D. De (eds) *Tailored Functional Materials*. Singapore: Springer Nature, pp. 31–42.

Puchkov, E.M., Perov, G.A. and Solovyov, S.V. (2023) 'Innovative Technology Of Drying Seeds Of Small-Seeded Crops', *Agrarian science*, 9, pp. 161–165.

Putri, R.E., Pratama, W.E. and Ifmalinda, I. (2023) 'Application of Capacitive Sensor for Measuring Grain Moisture Content Based on Internet of Things', *Jurnal Keteknikan Pertanian*, 11(1), pp. 29–40.

Rizalman, M.K. *et al*. (2023) 'A Review Of Solar Drying Technology For Agricultural Produce', *Indonesian Journal of Electrical Engineering and Computer Science*, 30(3), pp. 1407–1419.

Sethy, S. *et al*. (2023) 'Development of a Solar Tray Dryer', *International Journal for Research in Applied Science and Engineering Technology*, 11(5), pp. 7576–7580.

Shammi, S. *et al*. (2022) 'Temporal And Spatial Representation Of Temperature And Moisture In Drying Chamber And Its Impact On Vertical Vacuum Dehumidifying Rice Seed Dryer Performance', *Journal of Agriculture and Food Research*, 10, p. 100424.

Sjechlad, D.Z. *et al*. (2022) 'Analyzing The Homogeneity In The Reduction Of Water Content During The Drying Process Of Grains Using A Flatbed Dryer Machine Equipped With A Stirring Mechanization System', *INMATEH Agricultural Engineering*, 68(3), pp. 201–210.

Suherman, S., Widuri, H., *et al*. (2020) 'Energy Analysis of a Hybrid Solar Dryer for Drying Coffee Beans', *International Journal of Renewable Energy Development*, 9(1), pp. 131–139.

Suherman, S., Hadiyanto, H., *et al*. (2020) 'Hybrid Solar Dryer For Sugar-Palm Vermicelli Drying', *Journal of Food Process Engineering*, 43(9), p. e13471.

Teymori-Omran, M. *et al*. (2023) 'Enhancing Energy Efficiency and Retention of Bioactive Compounds in Apple Drying: Comparative Analysis of Combined Hot Air–Infrared Drying Strategies', *Applied Sciences*, 13(13), p. 7612.

Wang, H. *et al*. (2023) 'Modeling and Experimental Study on Drying Characteristics of Corn Particles with Hot Air in Downward Moving Bed', *Fluids*, 8(2), p. 63.

Watson, A.G. *et al*. (2024) 'A Simple Solar Crop Drying And Pasteurizing System Appropriate For Smallholder And Subsistence Farmers In Tropical And Subtropical Regions', *Drying Technology*, 42(3), pp. 407–422.

Yuwana, Y., Silvia, E. and Sidebang, B. (2020) 'Drying Air Temperature Profile Of Independent Hybrid Solar Dryer For Agricultural Products In Respect To Different Energy Supplies (A Research Note)', *IOP Conference Series: Earth and Environmental Science*, 583(1), p. 012033.