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Optimization of Drying Time and Thermal Performance of Solar Dryer for Tekwan Products Based on Energy Balance Analysis

Devina Sanchia Samosir[1*], Yohandri Bow[2], Arizal Aswan[3]

[1] *Heavy Equipment Study Program, Balikpapan State Polytechnic, Indonesia, devinasanchia@poltekba.ac.id*
[2] *Energy Engineering Study Program, Sriwijaya State Polytechnic, Indonesia, yohandri@polsri.ac.id*
[3] *Energy Engineering Study Program, Sriwijaya State Polytechnic, Indonesia, arizal_aswan@polsri.ac.id*

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ABSTRACT

Energy requirements for production efficiency can be obtained from fossil fuels or renewable energy sources. The traditional drying process in Tekwan production is often inefficient and weather-dependent. Solar-powered drying technology using photovoltaic panels can improve cleanliness, efficiency, and product quality, and is suitable for application in Indonesia. Traditional drying faces challenges in terms of time efficiency and product quality due to weather dependence. This study designed a drying device with tiered racks and an automatic motor for heat distribution. Tests were conducted at 40°C for 1 to 5 hours to analyze moisture content, energy efficiency, and exergy. Results showed a decrease in moisture content from 57.21% to 34% after 5 hours, although it did not meet the SNI 11 standard. The highest thermal efficiency was achieved at 4 hours (84.42%), exergy efficiency was 77.61%, and the lowest exergy loss was 0.520 kJ/mol. Environmental factors, such as humidity and airflow speed, influence performance. Heat loss through convection and radiation remain the main challenges. Design improvements are needed to reduce heat loss and achieve optimal drying.

Keywords: Energy, Exergy, Humidity, Drying, Tekwan

ABSTRAK

Kebutuhan energi untuk efisiensi produksi dapat diperoleh dari bahan bakar fosil atau sumber energi terbarukan. Proses pengeringan tradisional pada produksi Tekwan seringkali tidak efisien dan tergantung cuaca. Teknologi pengeringan berbasis tenaga surya menggunakan panel fotovoltaik dapat meningkatkan kebersihan, efisiensi, dan kualitas produk, serta cocok diterapkan di Indonesia. Pengeringan tradisional menghadapi tantangan efisiensi waktu dan kualitas produk akibat ketergantungan cuaca. Penelitian ini merancang perangkat pengering dengan rak bertingkat dan motor otomatis untuk distribusi panas. Uji coba dilakukan pada suhu 40°C selama 1 hingga 5 jam untuk menganalisis kandungan air, efisiensi energi, dan eksergi. Hasil menunjukkan penurunan kandungan air dari 57,21% menjadi 34% setelah 5 jam, meskipun belum memenuhi standar SNI 11%. Efisiensi termal tertinggi tercapai pada 4 jam (84,42%), efisiensi eksergi 77,61%, dan kehilangan eksergi terendah 0,520 kJ/mol. Faktor lingkungan, seperti kelembapan dan kecepatan aliran udara, mempengaruhi kinerja. Kehilangan panas melalui konveksi dan radiasi tetap menjadi tantangan utama. Perbaikan desain diperlukan untuk mengurangi kehilangan panas dan mencapai pengeringan yang optimal.

Kata kunci: Energi, Exergi, Kelembaban, Pengeringan, Tekwan

INTRODUCTION

In this modern era, human activities cannot be separated from the need for energy. Energy is used to increase the efficiency of the production process, cost, and output with high selling value (Sioshansi, 2008). The energy can be obtained directly or in the process of converting energy resources from fossil and renewable sources (Adellea, 2022). Energy can also be utilized in primary form, namely the sun and fossil fuels, while energy utilized in secondary form is electricity and synthetic fuels (Solikah & Bramastia, 2024). One of the major applications of energy in the food industry is the drying process, which removes most of the water content from solid materials to make the product more durable and ready to be packaged (Hariyadi, 2018).

In Indonesia, many food industries still rely on traditional drying methods, such as direct sunlight, to produce dried tekwan products. However, this method is considered inefficient and unhygienic, requires ample space, and is highly dependent on weather conditions, producing Tekwan with non-uniform moisture content (Asiah et al., 2023). The inconsistency in moisture levels not only affects the sensory quality of the product, such as texture, chewiness, and its appearance, but also poses significant risks to food safety and shelf life (Chang et al., 2021). Sections of the product that retain excess moisture are more susceptible to microbial growth, including molds and bacteria, which can lead to spoilage and health hazards for consumers (Mafe et al., 2024). Furthermore, this variability complicates packaging and storage, potentially resulting in economic losses due to reduced products acceptability and increased returns or waste (Pauer et al., 2019). Therefore, achieving uniform drying is essential to ensure product standardization, consumer satisfaction, and regulatory compliance in the food industry.

To solve these problems, solar energy-based drying technology is being applied as an alternative. Previous studies were conducted on the combination between solar-based drying process with Internet of Things (IoT) and sensor (Hridoy et al., 2025; Hin et al., 2024) and has shrotcomings such as high initial cost, dependence on reliable power and connectivity, vulnerable to cyberattacks, and limited local support on the technology. The new breakthrough regarding photovoltaic panels to convert solar radiation into electrical energy which in turn powers a heating system within a controlled drying chamber become the focus of scientists recently. By decoupling the drying process from direct exposure to weather variability, this system enhances the process, improve hygiene,maintain product quality consistency, and environmentally friendly because they do not require oil and gas energy sources (Tumbal et al., 2022; Usman 2020; Ananto et al., 2023). Moreover, solar drying systems contribute to environmental sustainability by utilizing renewable energy sources, aligning with global efforts to reduce carbon emissions in the food processing sector (Kamalanathan et al., 2018).

In the context of Tekwan production, integrating photovoltaic-based drying systems can significantly improve product quality and processing efficiency. Tekwan, a traditional Indonesian fish-based food, is sensitive to moisture content, which affects both shelf life and texture (Agustini et al., 2009). Conventional drying often results in uneven moisture distribution, making the final product susceptible to microbial growth and spoilage (Nakra et al., 2025). With controlled temperature and humidity conditions, solar dryers can help maintain optimal drying parameters, producing Tekwan with uniform quality that meets established food safety and quality standards (Nnamchi et al., 2025). Previously, thermal photovoltaic hybrid solar dryer for drying peanuts can effectively increasing the electrical and thermal efficiency while reducing the peanuts moisture content (Amirtharajan et al., 2024). Meanwhile, the cost effectiveness and high drying quality (Zachariah et al., 2020).

This study aims to design and build an efficient and space-saving prototype of a solar photovoltaic cell-based dryer equipped with a multilevel rack system and an automatic drive motor for heat distribution for Tekwan production. This design adopts the principles of previous developments on dual solar dryer systems and photovoltaic-thermal collectors (Shahsavar et al., 2012). The prototype proposes to achieve high thermal and exergy efficiency while minimizing energy losses due to convection and radiation, common challenges in open drying systems. By analyzing energy and exergy flows within the system, this research provides insights into the thermodynamic performance of the solar dryer. Energy analysis evaluates how effectively input energy is used for moisture removal, while exergy analysis assesses the system's capacity to convert available energy into useful work, considering irreversibilities. These assessments are essential in identifying performance bottlenecks.

METHODOLOGY

Tools and Materials

The materials used in this research were a mixture of ground cork fish and sago flour in a 1:1 ratio, along with a combination of spices and water to form the dough. The mixture was boiled until the Tekwan floated, indicating it was fully cooked. Several tools were used to support the process, including solar panels as the main energy source, two batteries connected in parallel to enhance power capacity, an electric heater, and a drying chamber equipped with temperature and humidity sensors. Additional measuring instruments included a digital thermometer, a psychrometer to measure humidity, an anemometer for airflow velocity, a digital weighing scale, and a stopwatch for time tracking.

Procedure

The procedure began by mixing all the ingredients to form the dough, which was then boiled until it floated. The cooked tekwan was then subjected to drying using a solar-powered heating system. The solar panel was installed in an open space and connected to the electrical system. Once the system was activated, the heater was turned on, and the drying chamber was heated until the desired temperature was reached. The tekwan was placed inside the chamber, and data collection began. Observations were recorded every 10 minutes, including inlet and outlet air temperature, temperatures at six surfaces of the drying chamber (front, back, left, right, top, and bottom), relative humidity, and the initial and final mass of the material. Airflow velocity was also measured using an anemometer.

The experimental procedure in this study began with the preparation of the raw Tekwan ingredients, which included minced snakehead fish and sago flour mixed in a 1:1 ratio, along with seasonings and water. These ingredients were stirred into a uniform dough, then shaped and boiled in hot water that had been mixed with a small amount of cooking oil. The boiling process continued until the tekwan pieces floated to the surface, indicating that they were fully cooked and ready for the drying process.

For the drying stage, the solar panels were first placed in an open area facing the sun. The batteries were connected in parallel by linking the positive terminals together and the negative terminals together using sockets. These batteries were then connected to the solar panels through a plug, and the connection status was confirmed using the display on the solar charge controller. The system was activated by switching on the power, and after a 10-minute preheating period, the airflow rate was adjusted using the control knob. The target drying temperature was set using the temperature controller, and the heater was then switched on. Once the drying chamber reached the desired temperature, the Tekwan was placed inside, and the drying process commenced. Measurements were taken every 10 minutes to monitor various parameters. After the drying process was complete, the heater was turned off, followed by the fan and the main power. The battery-to-panel connections were then unplugged and the battery circuit was disconnected. The drying chamber was cleaned, and the solar panels were returned to storage.

To measure the total mass of both wet and dry tekwan, trays were weighed before and after being loaded with the samples. The difference in weight was calculated for each tray, and the totals were summed. Sample masses were also measured using watch glasses, and six samples were taken both before and after drying. The averages of these samples were then calculated to determine the moisture loss during the process. Moisture content in the inlet and outlet air of the drying chamber was analyzed by recording the airflow rate, temperature, and relative humidity (RH). Using a psychrometric chart, specific humidity values were determined, and the mass of water vapor in the air was calculated for both entry and exit points.

The final stage of this research is energy and exergy analysis. The mass and energy balances of the drying chamber were calculated to determine the efficiency of thermal energy used in the drying process. Energy efficiency is calculated based on the heat energy used to evaporate water compared to the total energy from the heat source. An exergy analysis is performed to assess the thermodynamic efficiency of the system and determine the extent to which the available energy can be utilized effectively. The exergy damage value was also calculated to illustrate the energy quality loss due to irreversible drying processes. The systematic research conducted by the author is clearly and briefly contained in the Fish Bond Diagram in Figure 1.

Data Analysis

The collected data, including temperature, humidity, airflow, and sample mass before and after drying, were analyzed to assess the drying system's performance. Moisture loss was calculated by comparing the initial and final mass of the Tekwan. Energy efficiency was determined by comparing the energy used to evaporate water with the total input energy, while exergy analysis evaluated how effectively the energy was utilized, including calculations of exergy input, output, and destruction. These analyses helped measure both the effectiveness and quality of energy use in the system, and provided insights for improving the solar-powered dryer.

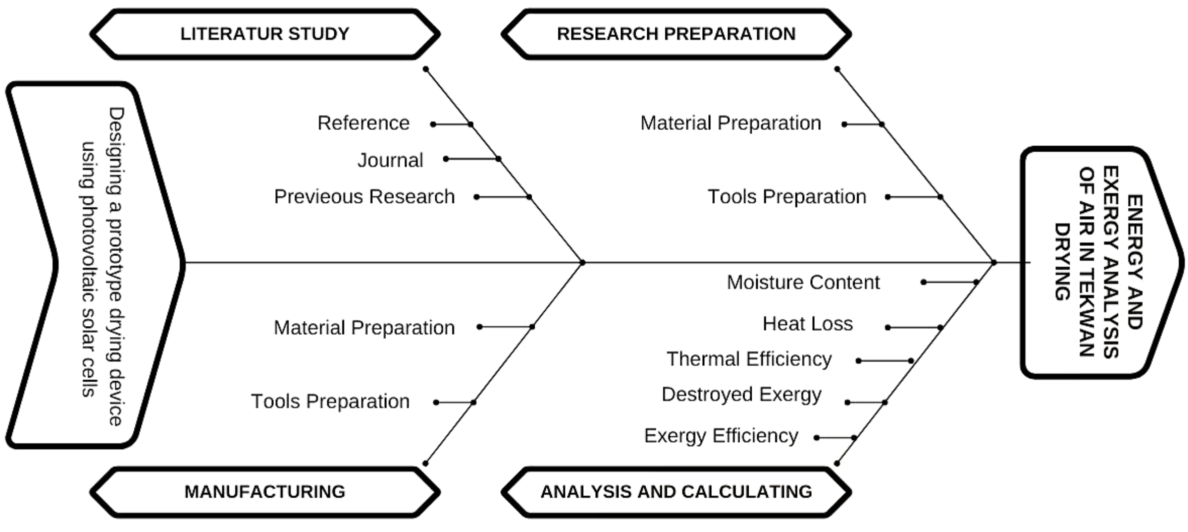

Figure 1. The systematic research

RESULTS AND DISCUSSION

Moisture Content Tekwan

The research was conducted with fixed variables, namely raw materials in the form of wet Tekwan, the number of raw materials 90 pieces and the weight of raw materials 846 grams, drying temperature 40ºC, and the unfixed variable taken is drying time. The collection was carried out for 4 days, with the first day of data collection varying by 1 hour and 2 hours of drying. The second day of data collection for variations of 3 hours of drying. On the third day, data was collected for the 4-hour drying variation. The fourth day of data collection for variations of 5 hours of drying.

Table 1. Reduction of tekwan moisture content

No	t_{Drying} (hour)	H_2O Level (%)		
		Start	End	Vaporized
1	1	57,21	54,57	2,64
2	2	57,21	50,77	6,44
3	3	57,21	48,14	9,07
4	4	57,21	38,85	18,36
5	5	57,21	34,00	23,21

Table 1. shows that the drying duration significantly affects the initial moisture content of Tekwan. At a constant temperature of 40 ˚C, the initial moisture content of 57.21% decreased to 34% after 5 hours of drying. Despite the decrease, the result has not met the maximum moisture content limit according to the SNI of fish crackers, which is 11% (BSN, 2009), indicating the need for additional drying time. The R2R2 analysis result of 0.9602 shows a high correlation between drying time and moisture content, but environmental variations such as humidity and temperature cause fluctuations. This could be due to data collection being done at different times. The curve in Figure 2 shows a positive linear relationship between drying duration and moisture content reduction. However, according to the SNI for fish crackers, it does not meet the maximum moisture content (≤ 11%). These findings support the convective drying theory, where moisture diffusion is governed by gradients in temperature and humidity between the product and the environment (Sablani, 2006). Setyawan et al. (2020) also found that inreased drying time and temperature significantly reduce moisture levels in fish-based products. However, the result of 34% moisture still exceeds the SNI threshold of 11% (BSN, 2009), indicating a need for either extended drying time or improve drying system efficiency.

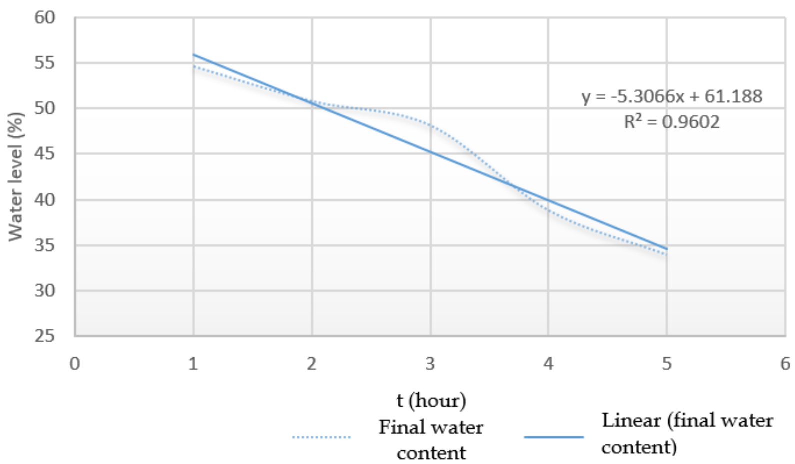

Figure 2. Decrease in evaporated H_2O content in each drying time variation

Change in Humidity and Water Vapor Mol Fraction (XT)

Air relative humidity and water vapour mol fraction (XT) affect the drying rate. Low humidity tends to accelerate the water evaporation process (Hosseini & Shadmeri, 2016). The air humidities observed every 10 minutes showed dynamic fluctuations, reinforcing that environmental humidity plays an important role in the effectiveness of the drying process. Table X shows a gradual decrease in humidity over time, concistent with studies that emphasize the impact of ambient conditions on drying effieciency. This phenomenon is in acordance with the findings, who found that lower ambient humidity enhances drying by increasing vapor pressure differentials (Hosseini & Shadmeri, 2016). The environmental humidity fluctuations significantly impact the evaporations rate during food dehydration, undersorcing the importance of humidity control in drying system design (Kaveh et al., 2021). This result is similar to the findings that fluctuations in environmental air humidity directly impact evaporation rates during food drying (Kaveh et al., 2021).

Table 2. Combined H and XT on tekwan drying (1 to 5 hours)

t (minute)	H (1 hour)	XT (1 hour)	H (2 hour)	XT (2 hour)	H (3 hour)	XT (3 hour)	H (4 hours)	XT (4 hours)	H (5 hours)	XT (5 hours)
0	0.02671	1.33700	0.02667	1.33700	0.02671	1.33700	0.02658	1.33700	0.02671	1.33700
60	0.02847	1.20140	0.03273	1.18620	0.03033	1.20360	0.03203	1.16220	0.03230	1.16730
120			0.03230	1.03130	0.03011	1.06010	0.03428	0.98020	0.02636	1.00450
180					0.03230	0.92840	0.03037	0.80020	0.03208	0.84030
240							0.02838	0.63530	0.02649	0.67390
300									0.02649	0.51520

Dryer Performance Evaluation (Performance Test)

The performance of the device was tested through thermal and exergy analysis. Thermodynamically, the highest thermal efficiency at 4 hours of drying (84.42%) and the lowest at 1 hour (66.79%) is shown in Figure 3. The increase in efficiency is related to the airflow rate, which increased by 1.75 ms at 4 hours compared to 1.03 m/s at 1 hour; these results indicate accelerated convection heat transfer. Efficiency increases as heat convection increases, consistent with the thermodynamic principles of open systems (Mohammadi et al., 2020). Moreover, the extended drying time may lead to diminishing efficiency returns due to increased thermal losses via radiation and free convection (Kumar and Sahu, 2018). This aligns with the observed decline in efficiency at 5 hours in this study, suggesting that the optimum thermal perfomance was achieved at 4 hours of drying.

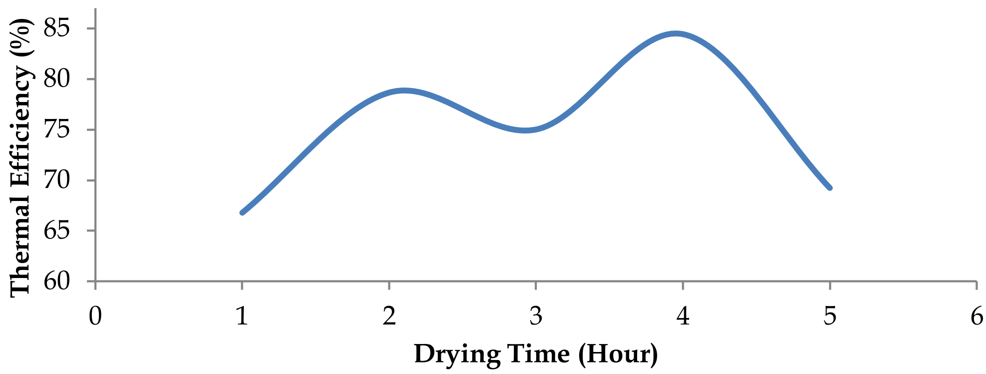

Figure 3. Graph of thermal efficiency in each drying time variation

The most significant reduction in efficiency is caused by heat loss through convection and radiation. External factors such as ambient temperature also accelerate heat transfer but cause increased potential energy loss. The decrease in efficiency at 5 hours is due to increased heat loss through radiation and free convection, supported by Kumar and Sahu (2018) on the performance of convection-type dryers.

Drying Energy Analysis

The Energy Analysis the researchers conducted was based on the air energy balance of Tekwan drying. The air energy balance of Tekwan drying in each variation of drying time can be seen in Table 3.

Table 3. Drying energy analysis

Component	1 hour	2 hour	3 hour	4 hour	5 hour
Input (kJ)	23,882.216	47,623.578	62,846.372	105,683.209	127,739.627
$Q_{dry\ air}$	15,876.495	37,292.093	46,918.082	88,835.738	87,987.687
$QH_2O_{Evaporated}$	74.435	166.932	222.979	385.027	452.594
$Q_{Convection\ and\ RadiationLoss}$	242.521	385.292	776.606	995.227	1,159.597
Q_{Loss}	7,688.764	9,779.261	14,928.704	15,467.217	38,139.739
Output (kJ)	23,882.216	47,623.578	62,846.372	105,683.209	127,739.627

The energy balance shows that the incoming energy increases with increasing drying duration, from 23,882 kJ (1 hour) to 127,739 kJ (5 hours). However, most of the energy is not used efficiently and is lost as thermal losses shown in Table X. This finding is consistent with Nasrullah et all. (2021), who emphasized the importance of optimizing insulation and temperature regulation to reduce energy loss. The energy used to evaporate the water remains relatively small compared to the total input, indicating optimization of the tool design. found The energy inefficiencies in drying systems can be minimized through better insulation and heat retention mechanisms (Nasrullah et al., 2021). The low proportion of energy directly utilized for water evaporation suggest that significant thermal losses occured, which should be addressed in future system improvement.

Drying Exergy Analysis

Energy analysis is based on air exergy balance in Tekwan drying and calculating the amount of destroyed exergy (Ėd). Analysis of air exergy in Tekwan drying in each variation of drying time can be seen in Table 4.

Table 4. Data from air exergy analysis on tekwan drying

No	T_{Drying} hour	$\dot{E}_{input}$ (kJ/kmol)	$\dot{E}_{output}$ (kJ/kmol)	$\dot{E}_{loss}$ (kJ/kmol)	$\dot{E}_{d}$ (kJ/kmol)	Efficiency (%)
1	1	8,211	3,663	2,806	1,742	65,83
2	2	7,394	3,663	3,105	0,626	58,00
3	3	7,575	4,253	2,518	0,805	66,76
4	4	7,852	5,574	1,758	0,520	77,61
5	5	7,327	4,264	2,105	0,958	71,28

The exergy analysis shows the effectiveness of energy conversion into work required. Table 4 shows that the highest exergy efficiency value was found in 4 hours of drying (77.16%), while the lowest was in 2 hours (58%). Table 5 shows the highest value of destroyed exergy (Ed) in 1 hour of drying (1,742 kJ/mol) and the lowest value in 4 hours of drying (0,520 kJ/mol). These results are in line with the research of Hassan et al. (2019), which explained that the smaller the Ed, the more thermodynamically efficient the system. Exergy analysis offers a more nuanced assessment of system perfomance compared to conventional energy analysis. It reflects the real usable energy converted in work, making it more sensitive to system imperfections, increasing exergy efficiency is essential in thermal food processing to reduce irreversbility and improve process sustainability (Rahman, 2021). This confirms the role of exergy efficiency as a sensitive indicator of system thermodynamic perfomance.

Table 5. Thermal efficiency in each drying time variation

No	T_{Drying} (hour)	Thermal efficiency (%)
1	1	66,79
2	2	78,66
3	3	75,01
4	4	84,42
5	5	69,23

CONCLUSION

A solar-powered dryer prototype designed for drying Tekwan products has successfully achieved the highest energy efficiency during a 4-hour drying duration, with an energy efficiency of 84.42% and exergy efficiency of 77.61%. Although a drying time of 5 hours resulted in the highest H_2O evaporation rate of 23.21%, this duration is not considered optimal due to significant energy and exergy losses caused by heat loss through convection and radiation. Environmental factors, such as air humidity and airflow velocity, influence the device's performance, while heat loss remains the primary challenge. To improve the device's performance, design improvements such as sealing gaps in the system and increasing the heater capacity are highly recommended. Although this solar-powered drying technology holds promise for enhancing food drying quality and efficiency, system optimization and increased heater capacity are essential to achieve better food drying standards and meet SNI requirements.

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