**JMM: Journal of Mechanical and Manufacture**
Vol. 5 No 2, October 2025 , pp. 1-9
DOI: 10.31949/jmm.v5i1.16113
e-ISSN: 2829-4424

# HYBRID GREENHOUSE SOLAR DRYER PERFORMANCE FOR CASSAVA CRACKER DRYING WITH BIOMASS HEATING

**La Ode M. Firman[1], Ade Ruhama[1], Engkos Koswara[2]**
[1] Department Master of Mechanical Engineering, Universitas Pancasila, Jakarta, Indonesia
[2] Department of Mechanical Engineering, Universitas Majalengka, Majalengka, Indonesia
[1]mtmpancasila@gmail.com

***Abstract***
*This study evaluated the performance of a Hybrid Greenhouse Solar Dryer (HGSD) integrating a modified-arch greenhouse design, forced convection via a solar-PV–driven blower, and supplementary biomass heating for cassava cracker drying. Experiments compared open sun drying (OD), HGSD without biomass, and HGSD with biomass (HB). Environmental parameters (temperature, humidity, solar radiation, wind speed) and mass-loss rates were monitored using a K-type thermocouple data logger, hygrometer, solar power meter, anemometer, and digital scale. Drying rates were 0.830 kg/h (OD), 0.956 kg/h (HGSD without biomass), and 1.151 kg/h (HB). Average chamber temperatures reached 41 °C (no biomass) and 44 °C (with biomass), with relative humidity maintained at 50–60% during the constant-rate phase. Economically, OD suits low-capital, HGSD without biomass yields high ROI, and HB ensures stable drying despite lower ROI. Integrating solar and biomass energy in HGSD improves drying efficiency and offers a sustainable solution for small-scale food processors*

***Keywords:*** *Biomass; Convection; Dryer; Greenhouse; Solar PV*

| Submitted: 2025-10-11 | Revised: 2025-10-12 | Accepted: 2025-10-15 |
|---|---|---|

## Introduction

Cassava is not merely a source of carbohydrates but is also rich in essential nutrients such as ascorbic acid, carotenoids, calcium, potassium, iron, magnesium, copper, zinc, and manganese. Its high carbohydrate content allows for versatile processing and application (Li et al., 2017). Processing cassava yields various food products, ranging from those that can be consumed immediately after a simple process to those further processed as ingredients in diverse foods and beverages (Alves De Oliveira et al., 2020). The non-food industry also utilizes cassava in the production of alcohol, organic acids, pharmaceuticals, paper manufacturing, and as an additive. Traditionally, cassava is consumed boiled or cooked, with preparation methods varying across regions and countries (Muibat Omolara, 2017).

Cassava is one of the important food crops in Indonesia, following rice, maize, soybean, peanut, and mung bean. It is utilized as a raw material for human food, animal feed, and industrial applications in both the upstream and downstream sectors. Cassava productivity in Indonesia has increased significantly from 1980 to 2019. During this period, the average growth rate reached 2.66% per year, with productivity increasing from 97.51 quintals per hectare in 1980 to 260.23 quintals per hectare in 2019. The volume of Indonesia's cassava exports showed an average growth of 72.63% per year between 2000 and 2020. The export value also saw a significant rise, averaging 89.89% per year. Cassava is exported in fresh and processed forms, including cassava starch (tapioca), dried cassava chips, and cassava pellets, with main destination countries being Taiwan, the Philippines, Australia, Malaysia, the United Kingdom, and Brunei Darussalam (Pertanian Subsektor Tanaman Pangan, 2020).

Dried cassava chips are a product resulting from cassava processing that requires the removal of moisture content immediately after harvest. The drying process of cassava, before further processing or consumption, plays a crucial role in extending the shelf life of the food material. Optimal drying is capable of inhibiting the growth of microorganisms and detrimental chemical reactions during storage. According to the provisions set by the Indonesian National Standardization Agency (BSN), the maximum allowable moisture content in cassava derivative products like tapioca flour, as well as processed ingredients such as cassava stored before frying or further processing, is 14% on a wet basis. This regulation is stipulated in the Indonesian National Standard (SNI) 3451:2011 concerning tapioca products (Badan Standardisasi Nasional, 2011). Meeting this moisture content threshold is vital for maintaining product quality and stability during distribution and storage. Drying, or dehydration, is a method for removing a portion of water from a material through evaporation. Reducing the moisture content lowers the food material's humidity, inhibits microbial development, inactivates enzymes, and prevents various potential substances and biochemical responses that degrade food quality. Therefore, the drying process is an important stage in food processing as it can extend shelf life (Mohana et al., 2020).

The use of inefficient natural drying also presents several drawbacks, including its strong dependence on weather conditions, which leads to longer drying times and greater susceptibility to product loss or defects. Furthermore, uneven distribution of air temperature, humidity, and airflow velocity means that optimal drying is typically only achieved during the dry season, especially due to low ambient air temperatures. In contrast, using artificial dryers can enhance drying efficiency. Advantages of artificial drying include: the process can be carried out at any time, independent of weather or season; properly dried products can prevent warping, mold growth, and other defects; the distribution of air temperature, humidity, and airflow velocity within the drying chamber can be controlled and evenly distributed; and the temperature of the drying chamber can be increased optimally to support smooth production.

Currently, many drying methods in food processing utilize renewable energy. Solar drying is widely used in tropical regions due to abundant solar energy, ease of design and construction, and cost-effectiveness (Muibat Omolara, 2017). Direct-type solar drying is a variation of the traditional open-sun drying method, where the material is directly exposed to sunlight and protected by a transparent cover (Ameri et al., 2018). The mixed-type solar dryer combines the principles of direct and indirect solar drying. They feature a transparent drying chamber and a facility to preheat the air before it enters the chamber. In this type of dryer, heat is transferred via convection from the dry air to the food surface and through radiation from the drying chamber (Dhalsamant et al., 2018). Consequently, mixed-type solar dryers have a higher thermal efficiency compared to the previously mentioned systems. Lakshmi et al. (Lakshmi et al., 2018) analyzed the drying efficiency of a forced convection mixed-type solar dryer compared to open sun drying. Their results indicated that the overall dryer efficiency and the average exergy efficiency for the forced convection mixed-type solar dryer were 33.5% and 59.1%, respectively.

Solar dryers are categorized into two types based on air circulation: passive and active flow. In passive mode solar dryers, air circulation occurs naturally through buoyancy, pressure differences, or a combination of both. Most cabinet and greenhouse dryers use this passive mode. The design includes a drying chamber with air inlets and outlets and a transparent cover. Solar energy passes through the insulated drying chamber and hits opaque walls, creating a greenhouse effect that aids in drying food products. Passive mode solar dryers are suitable for drying small quantities of fruits and vegetables. However, there is a risk of overheating and product quality degradation. Grains like rice, wheat, and thin vegetables such as potatoes and tomatoes are commonly dried using passive mode dryers. The drying efficiency of passive mode solar dryers ranges from 20% to 40%, depending on the food material, dryer location, temperature, airflow rate, and weather conditions. When hot airflow circulation is driven by a fan or blower, the solar dryer is referred to as an 'active dryer (Udomkun et al., 2020).

The air velocity in a forced convection cassava drying machine depends on its design and capacity. Generally, the forced convection velocity can range between 0.7 m/s to 1.0 m/s (Titahelu & Litiloly, 2018). Sari R. (Sary, 2016) conducted an experimental study on coffee bean drying using the forced convection method with three variations of air velocity. An air velocity of 3.15 m/s at an average temperature of 60°C reduced the moisture content by 31% over 4 hours from an initial value of 42%, with a fuel consumption of 1.2 kg. Meanwhile, an air velocity of 3.75 m/s at an average temperature of 60°C reduced the moisture content by 33% in the same time from the initial 42% content (Sary, 2016). This type of dryer is highly suitable for products with high moisture content, such as cassava, papaya, cabbage, cauliflower, tomatoes, kiwi, and others. With better air circulation, active dryers provide a faster drying rate. Drying outside of direct sunlight can also be achieved by integrating an appropriate air heating system. This can ensure better product quality with minimal risk of damage and fungal contamination. Modern dryers are also designed with additional components to store solar heat absorbed during the day, which can then be released and utilized at night (Mishra et al., 2019).

Various dryer designs exist, such as the greenhouse-type dryer. This dryer is simple to manufacture and has a wide geographical scope. The greenhouse dryer can also be used in a mixed-type drying system. The 'greenhouse' concept is often used for crop cultivation, soil solarization, aquaculture, and poultry farming, with the goal of creating ideal air conditions for agricultural activities. The development of this controlled environment concept has been applied to food drying. Based on design, greenhouse systems can be divided into dome-shaped structures and roof structures. Dome structures maximize the use of incoming solar energy, while roof structures are effective for mixing drying air. Greenhouse dryers can operate in both active and passive modes. Forced convection greenhouse dryers are suitable for drying crops with high moisture content, whereas natural convection is more appropriate for crops with low moisture content (Solar Drying Technology, 2017).

The selection of a solar greenhouse dryer varies depending on the location, and it is not possible to apply a single design standard for a specific shape and orientation. Among the various shapes considered in greenhouse dryer design, the even span and Quonset shapes are commonly used worldwide. The even span shape is preferred because it receives higher solar radiation during both winter and summer. East-west orientation is preferred over others because it requires less energy for heating and cooling and is capable of absorbing more solar radiation into the dryer. Low-density polyethylene sheeting, commonly used for its stability against ultraviolet light, infrared, and anti-dripping properties, is often used as the greenhouse covering material (Srinivasan & Muthukumar, 2021).

In this research, the study will combine the use of a modified arch-shaped greenhouse dryer, forced convection, and the utilization of a solar PV system as the blower's power source for drying cassava. Furthermore, biomass material will be utilized as an additional heat source channeled through a heat exchanger tube. The hot air is transferred through pipes and distributed into the drying chamber.

## Research Method

The experimental study was conducted in Lurah Village, Plumbon District, Cirebon Regency, West Java, Indonesia, where the Hybrid Greenhouse Solar Dryer (HGSD) prototype was fabricated and tested. The research site was selected due to its high solar irradiation potential and proximity to small-scale cassava cracker (opak singkong) producers in Majalengka, ensuring realistic operating conditions for the trials. The experiments were designed to compare three drying methods: conventional open sun drying (OD), HGSD without biomass heating, and HGSD with biomass heating (HB). Each method was tested under similar daytime conditions to ensure comparability.

The HGSD unit was constructed with a modified-arch greenhouse design, measuring 2000 mm in length, 1000 mm in width, and 1500 mm in height. The frame was made of hollow steel profiles for structural rigidity, with side walls and doors fabricated from 1.4 mm aluminium sheets lined with 4 mm aluminium-foil bubble insulation to reduce heat loss. The roof and front wall were made from 1

mm transparent polycarbonate sheets to maximize solar transmittance. Inside the chamber, four rack levels held eight aluminium mesh trays (980 × 920 mm), each capable of supporting cassava cracker samples in a single layer to ensure uniform airflow. A 170 W blower, powered primarily by two 150 Wp monocrystalline solar PV panels via a 12 V/5 Ah battery and inverter, provided forced convection. For the HB configuration, a biomass-fired heat exchanger with 16 steel tubes (Ø 73 mm) supplied additional hot air (200–300 °C) from teak wood waste combustion.
The test material consisted of 5 kg of freshly boiled cassava crackers per cycle, with two thickness categories: thick (± 2 mm) and thin (± 1 mm), each with a diameter of ± 80 mm.

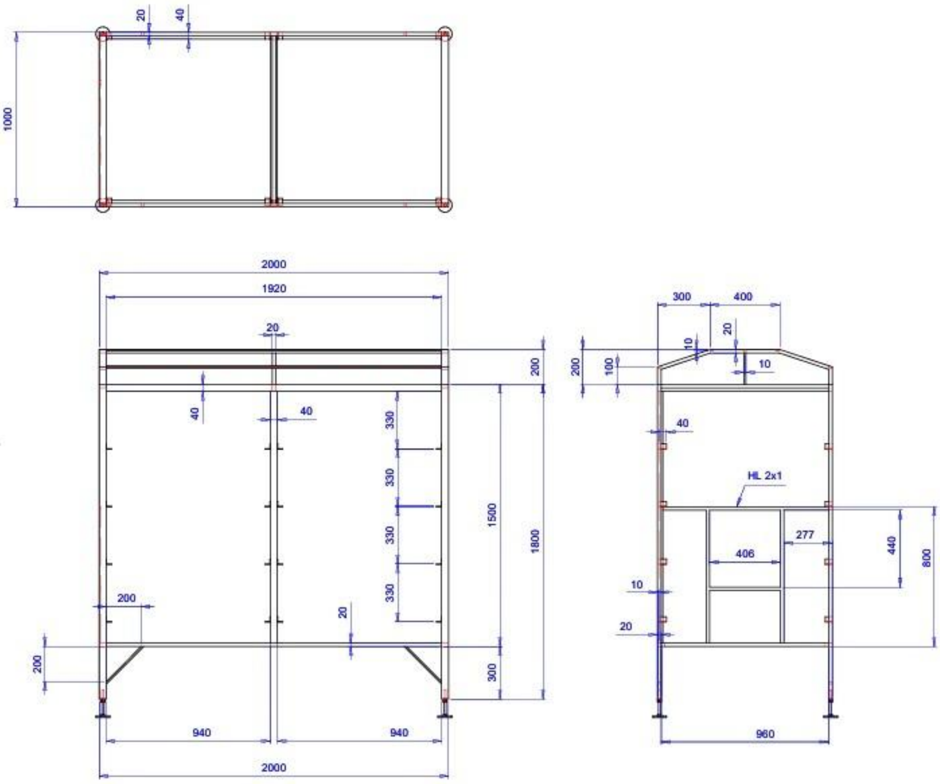

**Figure 1.** Dimension Detail Drawing Green House Solar Dryer

Samples were arranged with a 20 mm gap between pieces to promote even airflow. Prior to drying, samples were stabilised at ambient temperature (26–28 °C) for two hours.

- Environmental and process parameters were measured using calibrated field instruments:
- Solar irradiation: Solar power meter (resolution 0.1 W/m²) placed outdoors.
- Air velocity: vane anemometer for both ambient and chamber airflow.
- Temperature: K-type thermocouples connected to an 8-channel data logger, positioned under each tray to capture vertical and horizontal gradients.
- Relative humidity (RH): digital hygrometers placed at multiple chamber points.
- Sample mass: digital hanging scale (±1 g) with tare function to subtract tray weight.
- Moisture content: pin-type moisture meter (0–99.9%, ±0.5%).

Measurements were taken every 30–45 minutes for OD and HGSD without biomass, while for HB, mass was recorded at the start and end to minimise heat loss from frequent door opening.

Moisture content on a wet basis (WB) and dry basis (DB) was calculated using (Saravanan et al., 2014):

$$M_c(WB)=\frac{m_i - m_d}{m_i}$$

$$M_c(DB)=\frac{m_i - m_d}{m_d}$$

Where $m_i$ is the initial sample mass (kg) and $m_d$ is the dried sample mass (kg).
Drying rate $R_d$ was determined by:

$$R_d=\frac{m_i - m_d}{t}$$

where $t$ is the drying time.

## Results and Discussion

During the open sun drying (OD) and Hybrid Greenhouse Solar Dryer (HGSD) trials without biomass heating, the average solar irradiation recorded was 459.1 W/m², with a peak value of 857.1 W/m² occurring around midday. Ambient temperatures during the tests ranged from 34.1 °C to 35.8 °C, while relative humidity fluctuated between 42% and 50%. Wind speeds in the open environment reached up to 0.7 m/s. Inside the HGSD chamber, the forced convection system maintained an average air velocity of approximately 0.35 m/s, which contributed to raising the internal temperature to around 41 °C and stabilising the relative humidity between 50% and 60% during the constant-rate drying phase. These controlled conditions provided a more consistent drying environment compared to OD, where temperature and humidity were entirely dependent on fluctuating weather patterns. Setup of the experiment shown in the image below.

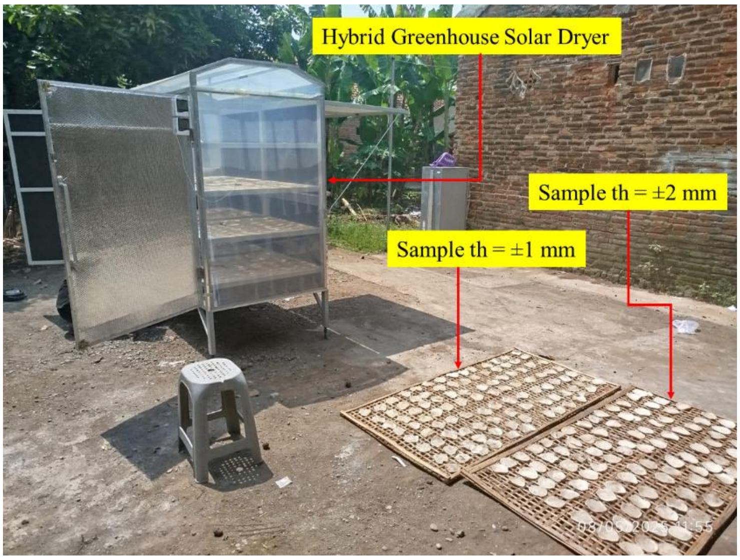

**Figure 2.** Simultaneous Testing of Open Drying and Hybrid Greenhouse Solar Dryer (HGSD)

In the OD method, the average drying rate achieved was 0.830 kg/h. The drying process was highly dependent on solar intensity, with rapid moisture loss occurring during peak irradiation hours, followed by a noticeable slowdown as the product's moisture content approached equilibrium with the surrounding air. In contrast, the HGSD without biomass heating achieved a higher average drying rate of 0.956 kg/h, representing a 15% improvement over OD. This increase was attributed to the higher and more stable chamber temperatures, as well as the controlled airflow provided by the blower system. The constant-rate drying phase was extended in the HGSD, and moisture removal was more uniform across all trays, reducing the variability in final product quality.

**Figure 3.** Sample Arrangement on Each Tray

When biomass heating was integrated into the HGSD system, chamber temperatures were maintained at approximately 44 °C, and relative humidity was kept within the range of 45% to 55%, even during periods of reduced solar radiation. The addition of biomass heating also increased air velocity within the chamber to between 0.7 and 1.4 m/s in certain zones, further enhancing heat and mass transfer. Under these conditions, the drying rate reached 1.151 kg/h, which was 20% higher than the HGSD without biomass heating. The biomass-assisted system extended the constant-rate drying phase and shortened the total drying time. The final moisture content achieved was 11.2% (wet basis), which complies with the Indonesian National Standard (SNI) requirement of ≤14% for tapioca-based products.

The comparative shown in table evaluation of the three drying methods revealed clear performance differences. In terms of temperature, OD reached a maximum of approximately 35.8 °C, HGSD without biomass heating maintained around 41 °C, and HGSD with biomass heating achieved about 44 °C. Relative humidity control was absent in OD, whereas HGSD without biomass maintained 50–60% RH, and HGSD with biomass maintained 45–55% RH. Air velocity in OD was limited to ambient wind speeds below 0.7 m/s, while HGSD without biomass maintained around 0.35 m/s, and HGSD with biomass reached up to 1.4 m/s. Correspondingly, drying rates improved from 0.830 kg/h in OD to 0.956 kg/h in HGSD without biomass, and further to 1.151 kg/h in HGSD with biomass heating.

**Table 1.** Parameter Comparison Table Method OD, HGSD and HB

| Testing Time | Drying Duration (hours) | Method | Sample | Environment / Tray | Avg. Solar Radiation (W/m²) | Avg. Temperature (°C) | Avg. Relative Humidity (%) | Kecepatan Angin rata-rata (m/s) | Avg. Wind Speed (m/s) | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | Avg. | Total |
| Simultaneous | 4,5 jam (10:30 ~ 15:00) | Open Drying (OD) | Th (± 2 mm) | Environment | 461,0 | 33,6 | 46,7 | 0,04 | 0,475 | 0,830 |
| | | | Th (± 1 mm) | | | | | | 0,355 | |
| | | Hybrid Greenhouse Solar Dryer without Biomass (HGSD) | Th (± 2 mm) | Tray 1 | | 32,8 | 61,2 | 0,97 | 0,110 | 0,956 |
| | | | | Tray 2 | | 33,6 | 61,1 | 1,47 | 0,114 | |
| | | | | Tray 3 | | 34,4 | 53,4 | 0,82 | 0,118 | |
| | | | | Tray 4 | | 37,8 | 51,6 | 0,00 | 0,104 | |
| | | | Th (± 1 mm) | Tray 5 | | 33,2 | 61,2 | 0,97 | 0,148 | |
| | | | | Tray 6 | | 33,2 | 61,1 | 1,47 | 0,118 | |
| | | | | Tray 7 | | 34,6 | 53,4 | 0,82 | 0,109 | |
| | | | | Tray 8 | | 37,1 | 51,6 | 0,00 | 0,134 | |
| Separate | 2,5 Jam (11:00 ~13:30) | Hybrid Greenhouse Solar Dryer with Biomass (HB) | Th (± 2 mm) | Tray 1 | 404,2 | 42,5 | 46,2 | 0,88 | 0,136 | 1,151 |
| | | | | Tray 2 | | 44,3 | 44,4 | 1,17 | 0,084 | |
| | | | | Tray 3 | | 42,7 | 42,6 | 1,10 | 0,088 | |
| | | | | Tray 4 | | 46,3 | 40,4 | 0,00 | 0,080 | |
| | | | Th (± 1 mm) | Tray 5 | | 43,4 | 46,2 | 0,88 | 0,207 | |
| | | | | Tray 6 | | 43,9 | 44,4 | 1,17 | 0,200 | |
| | | | | Tray 7 | | 46,7 | 42,6 | 1,10 | 0,209 | |
| | | | | Tray 8 | | 43,4 | 40,4 | 0,00 | 0,147 | |

The economic shown in the table analysis indicated that OD required minimal investment and generated an estimated annual profit of approximately IDR 38.88 million. The HGSD without biomass heating offered the highest return on investment (ROI) at 642%, with an estimated annual profit of IDR 77.76 million, primarily due to the doubling of daily production capacity. In contrast, the HGSD with biomass heating, while delivering the most stable drying performance, had a lower ROI of 57% and an annual profit of around IDR 6.9 million, largely due to the additional cost of biomass fuel. This highlights the trade-off between operational stability and economic return.

**Table 2.** Economic Comparison Table Mehtod OD, HGSD and HB

| Method | Cycles/day | Profit/cycle (IDR) | Profit/year (IDR) | Investment (IDR) | ROI (%) |
|---|---|---|---|---|---|
| Open Drying (OD) | 1 | 129.600 | 38.880.000 | 0 | - |
| HGSD tanpa biomassa | 2 | 129.600 | 77.760.000 | 12.110.800 | 642 |
| HGSD + biomassa (HB) | 5 | 4.600 | 6.900.000 | 12.110.800 | 57 |

## Conclusion

Based on the findings discussed in this study, it can be concluded that open drying achieves a drying rate of 0.830 kg/hour, while the HGSD method without biomass reaches 0.956 kg/hour for cassava chips. The addition of biomass combustion in the HB drying chamber significantly improves performance, achieving a faster drying rate of 1.151 kg/hour even under cloudy conditions compared to both HGSD without biomass and open drying. From an economic perspective, the open drying method is ideal for small-scale enterprises with limited capital. HGSD without biomass offers a high return on investment when supported by adequate photovoltaic systems, while the HB method ensures drying stability despite a lower ROI. The choice of method depends on available capital, energy supply, and production targets.

To enhance future system performance, it is recommended to add a battery with sufficient capacity to keep the blower fan running during low solar irradiation. Airflow within the drying chamber remains uneven and should be improved by installing necks and volume dampers to ensure uniform air distribution across all tray levels. Temperature consistency can be achieved by adding baffled air plenums, zonal dampers, circulation fans, and extra perforations on trays. Computational simulations are suggested to analyze airflow characteristics and optimize uniformity. Replacing aluminum plates with more effective heat-absorbing materials, increasing the number of trays to boost drying capacity, and integrating a cyclone spray scrubber combination in the heat exchanger exhaust line are also recommended to efficiently capture fine particles and neutralize gases without requiring large installation space.

## Reference

Alves De Oliveira, L., Da, J., Motta, S., Lopes, J., Fabiana, J., Cerqueira, F., & Eliseth De Souza Viana, S. (2020). *Processing of sweet and bitter cassava*. Embrapa. www.embrapa.br/fale-conosco/sac

Ameri, B., Hanini, S., Benhamou, A., & Chibane, D. (2018). Comparative approach to the performance of direct and indirect solar drying of sludge from sewage plants, experimental and theoretical evaluation. *Solar Energy*, *159*, 722–732. https://doi.org/10.1016/j.solener.2017.11.032

Badan Standardisasi Nasional (BSN). (2011). *SNI 3451: 2011 Tapioka*. BSN.

Dhalsamant, K., Tripathy, P. P., & Shrivastava, S. L. (2018). Heat transfer analysis during mixed-mode solar drying of potato cylinders incorporating shrinkage: Numerical simulation and experimental validation. *Food and Bioproducts Processing*, *109*, 107–121. https://doi.org/10.1016/j.fbp.2018.03.005

Lakshmi, D. V. N., Muthukumar, P., Layek, A., & Nayak, P. K. (2018). Drying kinetics and quality analysis of black turmeric (*Curcuma caesia*) drying in a mixed mode forced convection solar dryer integrated with thermal energy storage. *Renewable Energy*, *120*, 23–34. https://doi.org/10.1016/j.renene.2017.12.053

Li, S., Cui, Y., Zhou, Y., Luo, Z., Liu, J., & Zhao, M. (2017). The industrial applications of cassava: current status, opportunities and prospects. *Journal of the Science of Food and Agriculture*, *97*(8), 2282–2290. https://doi.org/10.1002/jsfa.8287

Mishra, L., Sinha, A., & Gupta, R. (2019). Recent Developments in Latent Heat Energy Storage Systems Using Phase Change Materials (PCMs)—A Review. In M. K. Sharma et al. (Eds.), *Lecture Notes in Mechanical Engineering*. Springer. (pp. 25–37). https://doi.org/10.1007/978-981-13-1202-1_2

Mohana, Y., Mohanapriya, R., Anukiruthika, T., Yoha, K. S., Moses, J. A., & Anandharamakrishnan, C. (2020). Solar dryers for food applications: Concepts, designs, and recent advances. In *Solar Energy* (Vol. 208, pp. 321–344). Elsevier Ltd. https://doi.org/10.1016/j.solener.2020.07.098

Muibat Omolara, G. (2017). Cost and Return Analysis of Cassava Flour (*Lafun*) Production Among the Women of Osun State, Nigeria. *Science Research*, *5(5)*, 72. https://doi.org/10.11648/j.sr.20170505.12

Pusat Data dan Sistem Informasi Pertanian Sekretariat Jenderal Kementerian Pertanian. (n.d.). *Outlook Ubi Kayu Subsektor Tanaman Pangan 2020*. Kementerian Pertanian.

Saravanan, D., Wilson, V. H., & Kumarasamy, S. (2014). Design And Thermal Performance Of The Solar Biomass Hybrid Dryer For Cashew Drying. *FACTA UNIVERSITATIS Series: Mechanical Engineering*, *12*(3).

Sary, R. (2016). Kajian Eksperimental Pengeringan Biji Kopi dengan Menggunakan Sistem Konveksi Paksa. *14*(2).

Solar Drying Technology. (2017). [Buku]. Springer. http://www.springer.com/series/8059

Srinivasan, G., & Muthukumar, P. (2021). A review on solar greenhouse dryer: Design, thermal modelling, energy, economic and environmental aspects. *Solar Energy*, *229*, 3–21. https://doi.org/10.1016/j.solener.2021.04.058

Titahelu, N., & Litiloly, S. J. (2018). *Oven Pengering Pati Sagu Kapasitas*. Paper dipresentasikan pada Seminar Nasional "Archipelago Engineering" (ALE).

Udomkun, P., Romuli, S., Schock, S., Mahayothee, B., Sartas, M., Wossen, T., Njukwe, E., Vanlauwe, B., & Müller, J. (2020). Review of solar dryers for agricultural products in Asia and Africa: An innovation landscape approach. *Journal of Environmental Management*, *268*, 110730. https://doi.org/10.1016/j.jenvman.2020.110730