
DESIGN AND THERMAL PERFORMANCE OF A HYBRID SOLAR-BIOMASS DRYER FOR DRYING FISH

Igbinosa Ikpotokin^{1,*}

¹*Department of Mechanical and Mechatronics Engineering, Faculty of Engineering, Federal University Otuoke, Bayelsa State, Nigeria*

Email: ikpotokinii@fuotuoike.edu.ng*

*Corresponding author: Igbinosa Ikpotokin

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ABSTRACT

Fish dryers are heat-transfer devices designed to remove moisture from fish undergoing drying in order to improve the fish's shelf life. However, a dryer that relies only on thermal energy from solar power often performs poorly at night and on cloudy or raining days. These conditions reduce the solar collector's effectiveness and limit the drying rates. To address this, a hybrid dryer was developed, which uses solar energy as its main heat source and combusts biomass to make up for the absence of solar radiation. This study aimed to create a hybrid solar-biomass dryer that can sustain stable drying conditions regardless of the solar availability. The dryer, which consists of a flat-plate solar collector, biomass combustion chamber, and heat exchanger, was fabricated with low-cost, locally sourced materials. Performance test was conducted outdoors at the Federal University Otuoke, Bayelsa State, using one kilogram of catfish over seven effective daylight hours. To avoid drying interruption, biomass-fueled heating was used in the evening. The results demonstrated that the hybrid dryer reduced the fish drying time from 48 hours to 10 hours and decreased the moisture content from 75% to 15%. Effective conversion and use of renewable energy is demonstrated by the dryer's overall thermal efficiency, which ranges from 45 to 50%, and its average solar collector efficiency of 40%. This study highlights the potential of the hybrid dryer as an efficient, economical, and sustainable approach to enhance fish preservation, food security, small-scale business assistance, and reduce post-harvest losses.

Keywords: Thermal performance; Hybrid dryer; Biomass; Solar energy; Fish drying

1.0 INTRODUCTION

Dryers are devices designed to facilitate the removal of certain amount of liquid, usually water, from materials or products to reduce the residual liquid content to an acceptably low level using thermal energy. They are widely used in numerous applications such as paper mill, food processing, pharmaceuticals, textiles, and manufacturing industries. In agriculture, dryers are used for processing and preservation of post-harvest produce, including fish through drying. This increases their shelf life, preserves quality and prevent microbial growth that causes spoilage (Hao *et al.*, 2021).

Among the numerous techniques for preserving fish, drying is the most popular and more economical. This method involves the application of dryers that operate with heat energy source to reduce the moisture content of the fish to a level that limits microbial growth and enzymatic reactions, thereby extending the fish's shelf life (Nwakuba *et al.*, 2025).

Traditionally, fish are dried by exposing them directly to the sun and is commonly used in rural areas because of low capital cost and operational simplicity of the drying system (Vengsungnle *et al.*, 2020). However, this practice has many disadvantages. One of the disadvantages is that significant amount of the thermal energy generated from solar irradiation is lost to the environment due to its dispersion, variability and relatively low intensity. This energy loss results in low drying efficiency, limiting the effectiveness of open sun solar-based dryers. Additionally, product dried using open sun solar-based dryer may be contaminated with dust and insects that compromises the product's quality and economic worth (Prabhu *et al.*, 2023).

Conventional dryers that operate solely on fossil fuels are often more efficient, but their high fuel consumption makes them unaffordable for rural people, especially those with low agricultural output ability. Additionally, increasing fossil fuel prices, sporadic supply interruptions, and the related environmental effects such as greenhouse gas emissions that cause climate change have inspired a

search for efficient and sustainable renewable energy sources (Ambaye *et al.*, 2021). Solar and biomass have been identified as the two primary renewable energy resources most suitable for drying applications (Lingayat *et al.*, 2021; Anyaoha *et al.*, 2025; Younis *et al.*, 2025).

In recent years, researchers have developed solar dryers to surmount the problem of traditional fish drying. These dryers employ solar collector to heat the air and move it through the drying chamber, which acts as a controlled environment to increase drying efficiency, shield the fish from contaminants, and enable more reliable drying (Yuwana *et al.*, 2020). However, solar energy is only available on sunny days. This condition limits solar fish dryers' capacity to operate continuously at night and during cloudy or raining weather (Murali *et al.*, 2023).

Biomass drying systems employ burning of organic materials such as wood, charcoal, or agricultural waste. In many rural and coaster regions, biomass is a readily available and affordable source of energy. Researchers have demonstrated that biomass-fueled dryer provides a practical and effective solution for large-scale drying of marine post-harvest products (Alfiya *et al.*, 2025). The systems' scalability also makes it appropriate for commercial use, so as to enable higher production capacity while reducing fossil fuel consumption and environmental effect. However, inadequate utility management of biomass drying equipment may result in issues with pollution, fuel supply, and heat regulation.

The disadvantages inherent in each of the aforementioned thermal energy sources have stimulated the development of a hybrid drying equipment, which combines solar and biomass energy to provide continuous supply of heat even during periods of low solar radiation, such as cloudy days or nights (Pawar *et al.*, 2024). Researchers have shown that a temperature range of 40-50°C was effectively maintained within the drying chamber of a hybrid fish dryer continuously for a duration of 15 hours using a solar dryer in conjunction with biomass heater (Hamdani *et al.*, 2018). This range of temperatures promotes efficient moisture removal without causing the fish to deteriorate due to heat. Although studies have recognized the potential benefits of combining solar and biomass technologies earlier for drying, there is still a dearth of knowledge with respect to development and practical implementation of the hybrid equipment, especially for fish drying in rural communities.

Therefore, this study develops a hybrid solar-biomass fish dryer that uses a solar thermal collector in conjunction with biomass briquette source. The study also aims to evaluate the performance of the dryer.

2.0 METHODOLOGY

In this study, the deterministic approach, involving the application of energy and mass equations, was employed for the design. The drying equipment's materials were selected and sourced locally to ensure affordability and accessibility while satisfying the necessary structural and thermal requirements. These materials constituted components for solar collector, drying chamber, insulation and biomass heating system. Drying tests were conducted to evaluate the dryer's thermal performance.

2.1 Design Equations

The size of the solar collector was determined based on the drying area needed to dry a 1.0 kg load of 75% (wet basis) catfish between 9:00 AM and 5:00 PM. A target final moisture content of 12% (wet basis) was set for the dried fish. The design of the dry was carried out in accordance with the considerations listed in Table 1.

Table 1: Design considerations for the hybrid solar-biomass fish dryer

S/N	Parameters	Value
1	Drying material	Catfish
2	Initial mass of fish (m_w)	1.0 kg
3	Initial moisture content (M_i)	75% (wet basis)
4	Target final moisture content (M_f)	12% (wet basis)
5	Average solar irradiant (I_c)	600 W/m ²
6	Drying period (t_d) 9:00 AM and 5:00 PM	7 hours
7	Solar collector efficiency (η_c)	40%
8	Tilt angle	6°
9	Ambient Temperature (T_a)	30 °C
10	Drying chamber temperature range	45 – 52 °C
11	Biomass briquette Lower Calorific value (LCV)	15 MJ/kg

For the design and performance evaluation, equations 1 to 14 were applied.

The amount of moisture to be removed is expressed by equation 1.

$$m_w = m_i \frac{M_i - M_f}{100 - m_f} \quad (1)$$

where m_i is the initial mass of fresh to be dried (kg), m_i is the initial moisture content (% wet basis), and m_f is the final moisture content (% wet basis).

The thermal load required consists of the latent heat to evaporate the water (Q_{lat}) and the sensible heating of the fish tissue ($Q_{s,fish}$) as expressed in equation 2.

$$Q_{req} = Q_{lat} + Q_{s,fish} = m_w h_{fg} + m_i C_p (T_c - T_a) \quad (2)$$

The total design thermal load was calculated by adding 15% for heat losses through the dryer walls. This is expressed in equation 3.

$$Q_{load} = 1.15 Q_{req} = 1.15 (m_w h_{fg} + m_i C_p (T_c - T_a)) \quad (3)$$

where C_p is the specific heat capacity of fish (J/kg.°C), T_c is the target drying temperature (°C), T_a is the ambient air temperature (°C), and h_{fg} is the enthalpy of vaporization (J/kg).

The solar collector thermal efficiency η_c is expressed in equation 4.

$$\eta_c = \frac{Q_{load}}{t_d A_c I_c} \times 100 = \frac{\dot{m}_a C_{pa} (T_{co} - T_{ci})}{A_c I_c} \times 100 \quad (4)$$

The mass flow rate of drying air required to absorb the evaporated water is given by equation 5.

$$\dot{m}_a = \frac{m_w}{t_d (\omega_o - \omega_i)} \quad (5)$$

The collector area is expressed by equation 6.

$$A_c = \frac{Q_{load}}{I_c \eta_c t_d} \quad (6)$$

where I_c is the average solar irradiant (W/m^2), $\dot{m}_a$ is the air flow rate (kg/s), C_{pa} is the specific heat capacity of air at constant pressure ($J/kg.K$), t_d is the drying period or time (s), T_{co} is the collector air outlet temperature ($^{\circ}C$), T_{ci} is the collector air inlet temperature ($^{\circ}C$), ω_o is the relative humidity of exhaust air exiting the chamber (kg water/kg air), and ω_i is the relative humidity of inlet air (kg water/kg air)

The tray area is expressed in equation 7.

$$A_{tray} = \frac{m_i}{\rho_{fish}} \quad (7)$$

where ρ_{fish} is the loading density of fish (kg/m^2)

Energy generated by combustion of biomass is determine using equation 8.

$$Q_{bio} = \dot{m}_{bio} LHV \quad (8)$$

The biomass consumption rate is expressed in equation 9.

$$\dot{m}_{bio} = \frac{Q_{load}}{LHV \times \eta_{comb} t_d} = \frac{Q_{bio}}{LHV \times \eta_{comb}} \quad (9)$$

where $\dot{m}_{bio}$ is the biomass consumption rate (kg/hr), LHV is the biomass lower heating value (kJ/kg), and η_{comb} is the biomass combustion efficiency (%).

Equation 10 expresses the thermal efficiency, which measures how efficiently the total energy input is converted to heat for evaporating moisture.

$$\eta_d = \frac{Q_{lat}}{Q_{solar} + Q_{bio}} \times 100 \quad (10)$$

Equations 11 expresses the latent heat of vaporization.

$$Q_{lat} = m_w h_{fg} \quad (11)$$

The solar energy collected by the solar collector during the drying period is represented by Equation 12.

$$Q_{solar} = A_c I_c t_{d,solar} \quad (12)$$

Equation 13 represents the total heat energy of the burnt biomass fuel.

$$Q_{bio} = \dot{m}_{bio} LHV \times \eta_{comb} t_{d,bio} \quad (13)$$

Equation 14 represents the hybrid dryer's overall energy consumption, which is the sum of the energy contributions from the solar and biomass sources.

$$Q_{tot} = Q_{solar} + Q_{bio} \quad (14)$$

2.2 Construction of the Dryer

The dimensions of the constructed dryer according to design Equations 1 through 14 is shown in Fig. 1(a) - (d). The hybrid solar-biomass dryer consists of drying chamber, solar collector and biomass combustion unit. The drying chamber was fabricated as rectangular insulated box with timber studs and plywood cladding. All internal seams were sealed before applying the aluminum liner. The black absorber plate was fixed below the glazing at a shallow inclination to encourage buoyancy-driven flow. A 4 mm thick glass sheet was mounted in a wooden sash with rubber beading to limit leakage and allow maintenance. The biomass heater was constructed using mild steel and connected via an indirect hot-air duct to avoid smoke contact with fish. The duct entered near the chamber floor to mix incoming hot air before rising across the trays. A top flue maintained steady exhaust of warm, moist air. The solar collector was mounted directly on the chamber at 6° , which nearly matched the local latitude of Bayelsa State, Nigeria ((about $5^{\circ}N$ to $6^{\circ}N$). This orientation maximized solar energy capture for the area. The direct mounting of the solar collector also eliminated long ducts and reduced thermal losses across joints.

2.3 Performance Evaluation Test Procedure

A performance test of the fabricated hybrid solar-biomass fish dryer was conducted outdoor at the Faculty of Engineering, Federal University Otuoke, Bayelsa State, Nigeria using 1.0 kg of fresh catfish with approximately 75% (wet basis) initial moisture content. The tests were carried out over 7 hours drying period under ambient temperature ranging from 28-30°C with solar irradiance of 600 W/m² and moderate wind. During the drying period, the dryer was operated on solar mode for about 7 hours and then on biomass support through the evening to complete the drying process. The ambient and chamber temperatures were measured using thermometers. A hygrometer was used to measure the relative humidity trend. A digital weighing balance was used to measure the initial mass and subsequent mass of the fish at regular intervals.

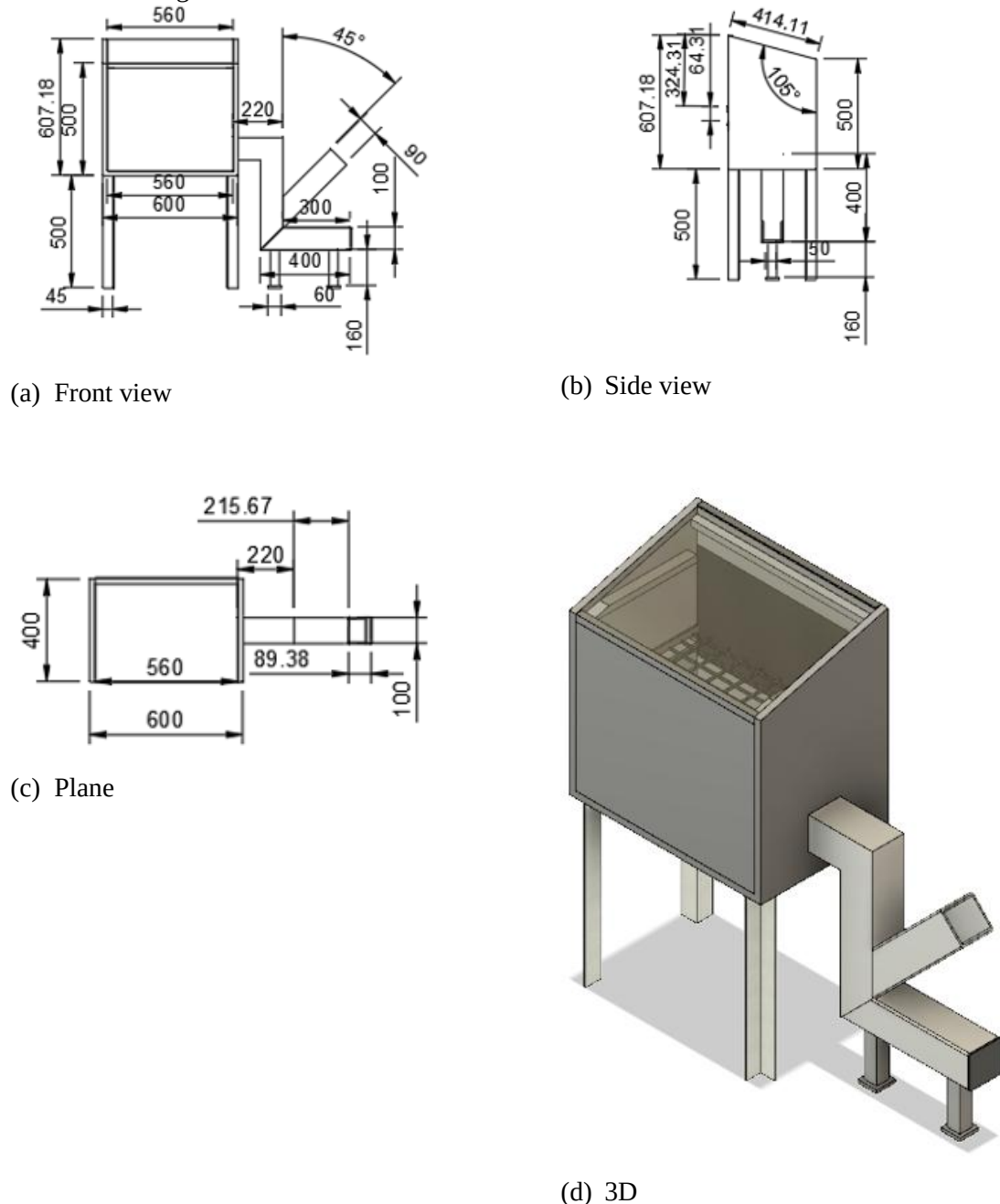


Figure 1: 2D and 3D of the hybrid dryer.

3.0 RESULTS AND DISCUSSION

The design results obtained using equations 1 through 14 are shown in Table 2. The results of moisture removal and weight loss during the test are depicted in Fig. 2(a) and (b), respectively. The

temperature trend results are presented in Fig. 3. Furthermore, the results of moisture removal and the drying chamber temperatures, which reveal the time of the solar energy utilisation phase and the biomass energy utilisation phase, respectively, are shown in Fig. 3(a) and (b).

Table 2: Design Calculation Parameters

S/N	Parameter	Value
1	Moisture to remove	0.7059kg
2	Moisture removed over 7hr	0.2896kg
3	Latent heat (Q_{lat})	1,595.3 kJ
4	Sensible heat ($Q_{s, fish}$)	92.5 kJ
5	Heat loss over 7hrs (Q_{loss})	540 kJ
6	Total heat (Q_{total})	2227.8 kJ
7	Solar collector surface area (A_c)	0.35 m ²

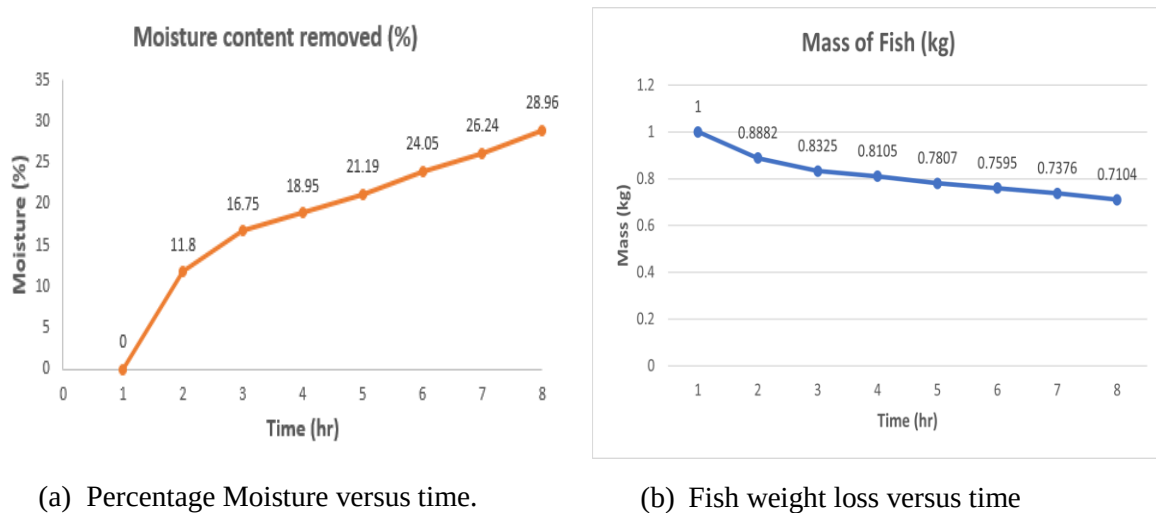


Figure 2: Percentage moisture and weight losses against drying time.

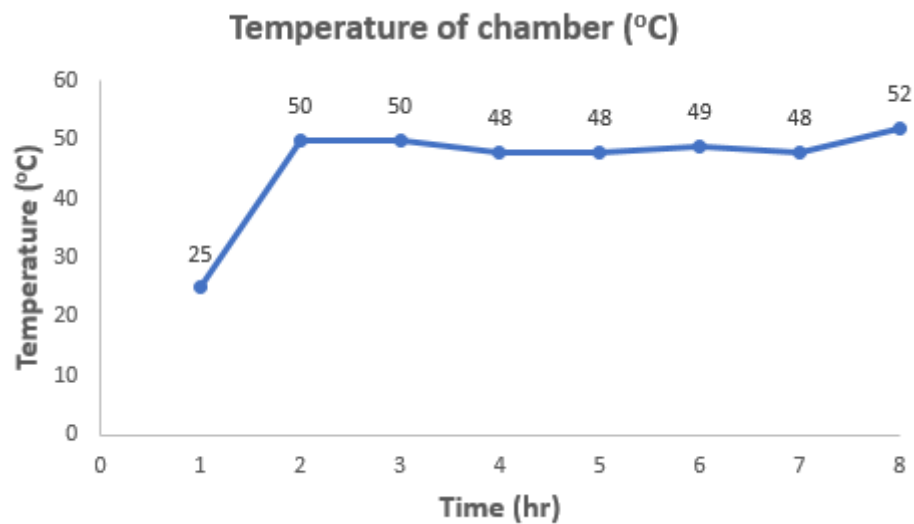


Figure 3: Drying chamber temperature profile.

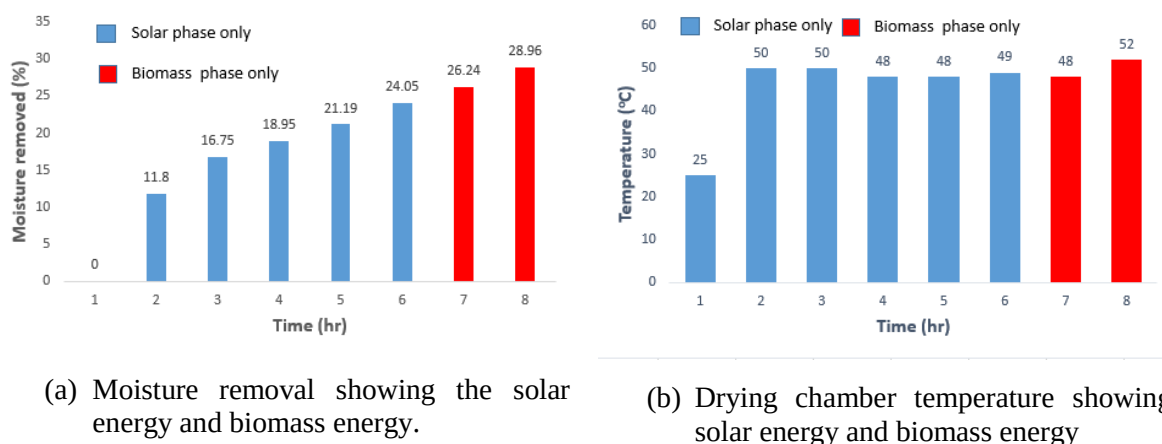


Figure 4: Moisture removal and chamber temperature showing solar energy and biomass energy supply.

Figure 2(a) shows the percentage of moisture content removed with time during the drying test. The moisture loss from the fresh fish increased from 0% to around 11.8% over the first hour of solar operation. The amount of moisture removed rises as the drying time increases, although more slowly and steadily to 24.05% during the solar phase as shown in Fig. 3(a). Approximately 28.96% of the

moisture content was removed within the other two hours of introducing biomass source of energy. After about 10 hours of total drying time, the fish's moisture decreased from 75% (wet basis) to 12-15%. This indicates that while the majority of the moisture may be eliminated in the early hours, it takes longer to achieve almost total drying because of decreasing returns.

The corresponding weight loss with time is depicted in Fig. 2(b). At first, when surface moisture evaporates, the mass decreases somewhat fast. As the residual moisture moves farther inside the fish and takes longer to reach the surface, the rate of mass loss gradually decreases. This pattern illustrates the usual drying behaviour, in which moisture loss is relatively faster at first and slows down as drying goes on. The fish's weight decreased from 1.0 kg to around 0.71 kg after 8 hours, in accordance with safe storage, and the steady fall shows efficient moisture removal. The pattern shows how well the drying process works to progressively reduce fish mass by gradually reducing the moisture content.

Fig. 3 shows the temperature profile of the chamber with respect to time. During the first hour, the temperature rises quickly, reaching 50°C and fluctuates slightly between 48 to 50°C within the duration of two to seven hours. The temperature marginally increase to 52°C after 8 hours due to activation of biomass source of energy as shown in Fig. 3(b). The temperature profile demonstrates that the chamber sustains a constant temperature for the majority of the drying time, which is suitable for reliable drying.

Energy analysis gave a batch design energy of about 2,227.8 kJ using equation 3. The hybrid solar-biomass drier provides an overall thermal efficiency ranging from 45%, demonstrating its ability to effectively convert and utilize thermal energy for the drying process. This efficiency is attributed to the combined performance of solar and biomass energy sources to maintain optimal drying temperatures and reduce energy losses. Additionally, the solar collector showed an efficiency of 40%, indicating that it can efficiently capture solar radiation and convert it into useful heat energy. The results also show that solar contributed approximately 60% of the dryer's energy consumption and biomass accounted for the remaining 40%. This complementing energy mix maximises the dryer's performance by ensuring consistent drying temperatures regardless of the weather conditions, including low solar irradiance or evening time.

4.0 CONCLUSION

A hybrid solar-biomass dryer specifically for fish drying was designed and fabricated to address the disadvantages of traditional sun-based drying equipment as well those of solar energy or biomass or fossil fuel-operated dryers. The findings from the performance evaluation showed that the hybrid dryer lowered the moisture content from 75% to 15% and shortened the fish drying time from 48 to 10 hours. The hybrid dryer's overall thermal efficiency ranges from 45 to 50 percent, with an average solar collector efficiency of 40 percent, demonstrating its capacity to effectively convert and use thermal energy during the drying process. Solar energy accounts for about 60% of the dryer's energy needs, with biomass providing the remaining 40%, making the dryer a viable and sustainable solution for small-scale fish drying businesses. Therefore, this study emphasizes the potential of the hybrid dryer as a practical, affordable, and sustainable method to improve food security, fish preservation, small-scale business support, and post-harvest losses.

REFERENCES

- Anyaocha, C. O., Okoroigwe, F. C., Okoroigwe, C. N., Uzoagba, C. E., & Okoroigwe, E. C. (2025). A review of optimization strategies for solar-biomass dryers. *Sustainable Energy Technologies and Assessments*, 83, 104672.
- Hao, W., Zhang, H., Liu, S., & Lai, Y. (2021). Design and prediction method of dual working medium solar energy drying system. *Applied Thermal Engineering*, 198, 117153.
- Alfiya, P. V., Murali, S., Aniesrani Delfiya, D. S., & Samuel, M. P. (2025). Design and development of biomass-fueled convective dryer for marine products: energy, exergy, environmental, and economic (4E) analysis. *Biomass Conversion and Biorefinery*, 15(8), 12031–12042 . <https://doi.org/10.1007/s13399-024-06001-6>.

- Ambaye, T. G., Vaccari, M., Bonilla-Petriciolet, A., Prasad, S., Hullebusch, E. D., & Rtimi, S. (2021). Emerging technologies for biofuel production: A critical review on recent progress, challenges and perspectives. *Journal of Environmental Management*, 290, 112627.
- Hamdani, U., Rizal, T. A., & Muhammad, Z. (2018). Fabrication and testing of hybrid solar-biomass dryer for drying fish. *Case Studies in Thermal Engineering*, 12, 489-496.
- Lingayat, A., Balijepalli, R., & Chandramohan, V. P. (2021). Applications of solar energy based drying technologies in various industries – A review. *Solar Energy*, 229, 52-68.
- Murali, S., Alfiya, P. V., Delfiya, D. S., Samuel, M. P., & Ninan, G. (2023). Solar Hybrid Drying System for Marine Applications – A Comprehensive Review. *Journal of Aquatic Food Product Technology*, 32(1), 38–58.
- Nwakuba, N. R., Ofojioha, O. M., Ikechukwu, K. U., Ofoma, A. N., Chikwue, M. I., Oham, P. N., & Okorie, C. E. (2025). Development and Sustainability Assessment of a Fish-drying Kiln: Eco-thermodynamic Insights. *Agricultural Science and Food Processing*, 2(4), 176–196. <https://doi.org/10.62762/ASFP.2025.325927>.
- Pawar, R., Santara, S., Sircar, A., & Yadav, K. (2024). Design and development of hybrid solar–biomass drying system: An innovative approach. *MRS Energy & Sustainability*, 11(2), 409–433. <https://doi.org/10.1557/s43581-024-00083-5>.
- Prabhu, N., Saravanan, D., & Kumarasamy, S. (2023). Eco-friendly drying techniques: a comparison of solar, biomass, and hybrid dryers. *Environmental Science and Pollution Research*, 30 (42), 95086–95105 .
- Vengsungnle, P., Jongpluempiti, J., Srichat, A., Wiriyaart, S., & Naphon, P. (2020). Thermal performance of the photovoltaic–ventilated mixed mode greenhouse solar dryer with automatic closed loop control for Ganoderma drying. *Case Studies in Thermal Engineering*, 21, 100659.
- Younis, O. S., Oraiath, A. T., Metwally, K. A., Dessoky, E. S., Mahmoud, S. F., Rashed, M. N., . . . Elwakeel, A. E. (2025). Drying characteristics, environmental and economic analysis of a solar dryer with evacuated tube solar collector for drying Nile Tilapia slices. *Scientific Reports*, 15(1), 9822. <https://doi.org/10.1038/s41598-025-94194-9>.
- Yuwana, Y., Silvia, E., & Sidebang, B. (2020). Observed performances of the hybrid solar-biomass dryer for fish drying. *IOP Conference Series: Earth and Environmental Science* (pp. 583, 012032). Indonesia: IOP Publishing Ltd.