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Comparative Evaluation of Drying Kinetics, Energy Performance, Quality Attributes and Mathematical Modeling of Nile Tilapia in Natural and Forced Convection Greenhouse Solar Dryer System

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ABSTRACT: This study investigates the drying kinetics and performance of a Parabolic Greenhouse Solar Dryer (PGSD) for Nile Tilapia during the winter season in Thailand (December–January). Two operation modes were tested: passive (natural convection) and active (forced convection) at air velocities of 1–3 m/s. Results showed that while the average temperature rise decreased to 23.8% with increasing wind speed, relative humidity reduction reached 32.4%, confirming the effectiveness of forced convection in accelerating moisture removal under cooler conditions. At 3 m/s, the drying time was reduced to 9 hours to reach water activity ($a_w < 0.85$), This is a 50% improvement compared to open sun drying, which took 18 hours. Under these conditions the system reached the drying rate of 0.211 kg/hour. The Specific Moisture Extraction Rate or SMER was 51.156 kg/kWh. The overall efficiency was 27.45 percent. Product quality also improved. Fish dried at velocity had the highest lightness, with an L^* value of 44.96. It also showed the total color change at $\Delta E = 8.55$. Mathematical modeling supported these findings: the Page model was most accurate for forced convection ($R^2 = 0.994189$, RMSE = 0.004883), while the Logarithmic and Wang & Singh models better fit natural convection. At 3 m/s, the behavior index ($n = 1.255336$) indicated accelerated internal moisture diffusion driven by enhanced airflow within the parabolic greenhouse. Overall, the PGSD system with forced convection provides an efficient and sustainable solution for high-quality fish processing

1. INTRODUCTION

Nile tilapia (*Oreochromis niloticus*) is recognized globally and regionally as one of the most economically important freshwater fish species (Geletu & Zhao, 2023). It is an excellent source of protein with high nutritional value, rich in essential amino acids and beneficial fatty acids, while also being inexpensive (Basak *et al.* 2023; Guan *et al.* 2013). However, tilapia is a highly perishable

food product due to its high moisture content and the enzymatic and microbial activity that occurs after harvest. Without effective preservation strategies, the quality of tilapia deteriorates rapidly (Wu *et al.*, 2024; Sroy *et al.* 2023). Among various food preservation methods, drying is the most important and widely used because it reduces water activity (a_w) to a safe level, effectively inhibits microbial growth, and slows down chemical reactions that cause deterioration. This results in a longer shelf life and more efficient transportation (Schmidt and Fontana 2020; Senas *et al.* 2026).

Despite its importance, small-scale processors often rely on traditional open sun drying, which faces several constraints. Primarily, it poses food safety and hygiene risks as the products are directly exposed to contaminants such as dust, insects, and animal vectors (Natarajan *et al.* 2022; Singh and Gaur 2024).

Furthermore, weather unpredictability leads to excessively long drying durations and inconsistent environmental conditions. These limitations not only result in the loss of sensory quality but also significantly impact the chemical composition and nutritional value, particularly through lipid oxidation and protein degradation, which alter the flavor and appearance of the final product (Fitri *et al.* 2022; Fei *et al.*, 2026). Moreover, uncontrolled processing conditions increase the susceptibility to pathogenic microbial contamination and the accumulation of undesirable compounds, posing a direct threat to consumer safety (Chan *et al.* 2023). Consequently, developing a more efficient drying system is imperative to enhance the sustainable and safe production of dried Nile Tilapia.

To overcome the drawbacks of traditional open sun drying, greenhouse solar drying technology has been implemented as a highly efficient alternative (Fernandes & Tavares, 2024; Youthao *et al.*, 2026). A primary advantage is its ability to create a greenhouse effect which traps thermal energy within the enclosure, maintaining internal temperatures significantly higher than the ambient environment (Maraveas *et al.*, 2023). This accelerates the moisture evaporation rate from the fish muscle (Janjai 2012; Sandali *et al.* 2024). Moreover, the enclosed structure acts as a barrier against external pollutants, such as dust, insects, and airborne microbes, ensuring that the dried product meets international hygiene standards (Natarajan *et al.* 2022; Aissa *et al.* 2024).

From a sustainability perspective, utilizing solar energy aligns with global shifts toward green energy and carbon footprint reduction in food processing (Suherman *et al.* 2020; Singh and Gaur 2024). The implementation of greenhouse solar drying systems optimizes the utilization of renewable resources and, from a techno-economic standpoint, significantly reduces long-term operational costs compared to conventional electric or fossil fuel-based systems (Chavan and Thorat 2022).

Furthermore, recent advancements in solar drying technology such as the integration of hybrid thermal sources and improved indirect airflow designs not only enhance production efficiency by shortening drying cycles but also minimize post-harvest losses while preserving the nutritional and sensory attributes of the product (Afzal *et al.* 2023; El-Sebaey *et al.* 2023). Consequently, these innovations promote food security and sustainable manufacturing for Small and Medium-sized Enterprises (SMEs) in the fishery industry, empowering them to produce high quality dried Nile Tilapia that meets international safety standards (Bariuan, 2025).

The airflow mechanism within a greenhouse solar dryer is a fundamental factor determining heat and mass transfer efficiency. Generally, these are classified into natural and forced convection (Aissa *et al.* 2024; Fernandes and Tavares 2024). In natural convection systems, air movement is buoyancy-driven, resulting from density gradients between internal and external air (Haddad *et al.* 2024). However, such systems often suffer from low and non-uniform moisture removal rates, potentially leading to localized "hot spots" and inconsistent temperature distribution. These limitations can significantly degrade product quality, especially in sensitive commodities like Nile Tilapia (Ghafar *et al.* 2025; Basiouny 2014).

To enhance productivity, forced convection utilizing mechanical fans to circulate air is employed to maintain a constant and uniform airflow rate. Increasing the air velocity over the product surface reduces mass transfer resistance and significantly accelerates moisture evaporation (Ghafar *et al.* 2025; Hussain *et al.* 2021). This approach effectively minimizes drying duration and mitigates microbial risks during the critical early stages of the process, when the high moisture content makes the product most susceptible to spoilage (Basak *et al.* 2023).

In the aquatic processing industry, the ultimate goal of drying transcends mere moisture reduction, the preservation of quality attributes is the decisive factor for market value and consumer acceptance (Nuwanthi *et al.* 2016; Pathare *et al.* 2013). Physical attributes, particularly color, serve as primary indicators of quality, where changes during drying are often driven by non-enzymatic browning and pigment degradation (Pathare *et al.* 2013; Senas *et al.* 2026). Furthermore, safety parameters such as

water activity (a_w) and microbial loads must comply with industrial standards to ensure consumer safety and shelf stability (Schmidt and Fontana 2020).

The disparity between natural and forced convection significantly impacts these quality factors. Natural convection, with its slower dehydration rate, may cause "case hardening" the premature hardening of the surface which traps internal moisture and increases microbial risks (Basak *et al.* 2023; Guan *et al.* 2013). Conversely, while forced convection ensures rapid and uniform drying, excessive airflow may lead to muscle shrinkage and sensory alterations, such as lipid oxidation (Senas *et al.* 2026; Wu *et al.* 2024).

Despite extensive research on solar drying for agricultural residues (Ali *et al.* 2022; Olimat 2017), comprehensive comparative analyses focusing on natural vs. forced convection specifically for Nile Tilapia in greenhouse environments remain scarce (Deef *et al.* 2023; Nasrat *et al.* 2024). Nile Tilapia possesses a unique muscle structure and lipid composition that influences moisture diffusivity and chemical changes differently than other species (Basak *et al.* 2023; Guan *et al.* 2013). Furthermore, many studies emphasize engineering efficiency while overlooking the correlation between airflow mechanisms, quality standards, and precise mathematical modeling for local production (Chavan and Thorat 2022; Obayopo and Alonge 2018).

This study aims to perform a comparative performance analysis of passive mode (natural convection) and active mode (forced convection) greenhouse solar dryers for dried Nile Tilapia production, focusing on three core objectives: (i) To investigate and compare the drying kinetics under both convection systems to understand moisture reduction behavior. (ii) To evaluate and compare color changes and water activity (a_w) to ensure product quality. (iii) To determine the most suitable mathematical models for predicting drying behavior and supporting future system development.

2. MATERIALS AND METHODS

The experimental framework of this study was developed to rigorously evaluate the impact of a Parabolic Greenhouse Solar Dryer (PGSD) on the dehydration kinetics and quality attributes of Nile Tilapia. By incorporating parabolic reflectors, the PGSD system facilitates enhanced solar radiation concentration, thereby optimizing thermal energy distribution within the drying chamber. This research provides a systematic analysis of drying characteristics and physicochemical properties, complemented by the validation of various thin-layer mathematical models to establish an efficient and sustainable drying protocol.

2.1 Nile Tilapia preparation

The objective of sample preparation was to standardize the raw material for precise drying kinetic analysis. Fresh Nile Tilapia with a uniform weight ranging from 250 to 300 g. were selected to minimize experimental variability and ensure consistent heat and mass transfer (Guan *et al.* 2013; Younis *et al.* 2025), as shown in Figure 1. Fresh Nile Tilapia 250–300 g. per fish. The preparation process involved descaling, gutting, and thorough washing to remove impurities and visceral organs (Basiouny 2014). Subsequently, the samples were immersed in a 10% (w/v) sodium chloride (NaCl) solution for 30 minutes to enhance drying efficiency through osmotic dehydration (Kituu *et al.* 2009; Basak *et al.* 2023). This optimal brine concentration helps maintain physical quality, prevents case hardening, and preserves an appropriate color profile (Pathare *et al.* 2013; Senas *et al.* 2026). Furthermore, this pre-treatment improves the protein structure to minimize nutrient loss and retain the nutritional value of the product (Nuwanthi *et al.* 2016; Sroy *et al.* 2023). as shown in Figure 2. Nile Tilapia after preparation.



Fig 1. Fresh Nile Tilapia 250–300 g. per fish



Fig 2. Nile Tilapia after preparation

2.2 Drying experiment using a parabolic greenhouse solar dryer (PGSD)

The drying experiments were conducted to evaluate the influence of the PGSD system on the drying kinetics and quality attributes of Nile Tilapia. The solar drying facility features a parabolic geometry with external dimensions of $0.85 \text{ m} \times 1.10 \text{ m} \times 0.35 \text{ m}$ (width $\times$ length $\times$ height), constructed from high-strength steel and enveloped with 6 mm thick polycarbonate sheets to maximize the greenhouse effect (Aissa *et al.* 2024; Sandali *et al.* 2024). For enhanced operational flexibility, the dryer is designed as a cart-like structure for easy mobility. The floor is composed of 3 mm thick steel sheets, integrated with thermal insulation underneath to minimize heat loss to the environment (Ghafar *et al.* 2025).

To facilitate sample handling, the dryer is equipped with side-opening panels. The ventilation system includes two air intakes fitted with high-efficiency filters to prevent contamination from dust and insects. Two internal fans are installed to maintain air circulation, where the system can be adjusted to operate under natural or forced convection modes to effectively remove moisture from the product (Hussain *et al.* 2021; Ghafar *et al.* 2025). Real-time monitoring of the drying environment is achieved through calibrated temperature and relative humidity sensors installed within the PGSD (Janjai 2012).

The configuration and components of the PGSD system utilized in this study as shown in Figure 3. To monitor the drying conditions accurately, K-type thermocouples were strategically installed at multiple locations within the dryer to measure air temperature gradients. Relative humidity sensors were also integrated to track moisture levels during the process. Solar radiation intensity was measured using a high-precision pyranometer (Model CMP11, Kipp & Zonen, Netherlands), ensuring accurate monitoring of solar radiation throughout the experiments. All thermal, humidity, and solar radiation data were continuously recorded using a high-precision data logger (Model GL820, Graphtec, Japan). Air velocity was monitored using a digital anemometer (Model UT363, UNI-T, China) with a specified accuracy of $\pm 0.5\%$. Furthermore, the weight loss of the Nile Tilapia samples was measured at regular intervals using a high-precision digital balance (Model GF-3000, A&D, Japan) with an accuracy of $\pm 0.02 \text{ g}$ to determine the drying rate and moisture content changes throughout the experiment.

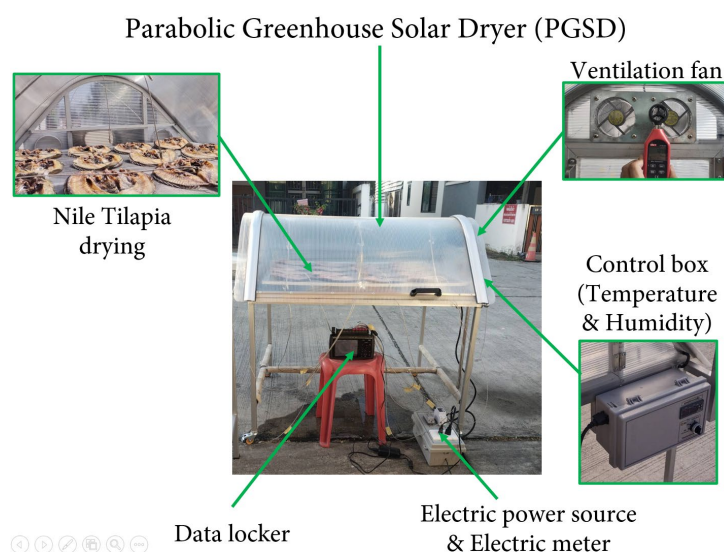


Fig 3. Parabolic greenhouse solar dryer (PGSD)

2.3 Product quality assessment

The final quality of the dried Nile Tilapia was comprehensively evaluated through physical and chemical analyses to determine the effectiveness of the PGSD system. The following key quality indicators were assessed:

2.3.1 Moisture content measurement

The initial and dynamic moisture content of the Nile Tilapia samples were determined using the gravimetric method in accordance with standard protocols (Basiouny, 2014; Ghanem *et al.* 2025). The wet basis moisture content (MC_{wb}) was measured by drying the samples in a hot air oven by drying at 105°C for 36 hours until a constant weight was achieved, according to the AOAC (2000) standard method (Loemba *et al.*, 2024) as shown in Figure 4. Hot air oven drying.



Fig 4. Hot air oven drying (Lab Companion OF-11E, Jeio Tech, Korea)

The initial weight of the fish fillets was recorded prior to the drying process, and weight changes were monitored at regular intervals throughout the experiment. Upon completion, the final weight was recorded to determine the final moisture content. The moisture content was calculated on a wet basis (%wb) using Equation 1, as follows (Kituu *et al.* 2009; Ye *et al.* 2025).

$$MC_{wb} = \frac{W_i - W_f}{W_i} \times 100 \quad (1)$$

Where MC_{wb} is the moisture content on a wet basis (%), W_i is the initial weight (g) and W_f is the final weight of the dried sample (g). The drying duration was strictly determined by monitoring the water activity (a_w), which was required to be below 0.85 to ensure product safety and microbial stability (Chan *et al.* 2023; Fitri *et al.* 2022). Maintaining an a_w level below 0.85 is critical as it effectively inhibits the growth of most pathogenic bacteria and limits biochemical reactions, thereby extending the shelf life and preserving the quality of the dried fish (Fitri *et al.*, 2022). Furthermore, the moisture reduction efficiency was compared between samples processed using the PGSD and those dried via the traditional open sun drying method to evaluate the comparative performance of the systems (Sinuhaji *et al.*, 2025).

2.3.2 Color measurement

The surface color of the dried fish was quantified using a colorimeter to evaluate the impact of thermal treatment on the product's visual appearance. Results were recorded based on the CIELAB color space, providing L^* (lightness), a^* (redness/greenness), and b^* (yellowness/blueness) values (Leon *et al.* 2006). Accurate color assessment is essential for determining consumer acceptability and monitoring physicochemical changes during dehydration (Pathare *et al.* 2013; Senas *et al.* 2026). Surface color (L^* , a^* , b^*) was measured at multiple locations on each fish fillet using a colorimeter, as shown in Figure 5. Measurements were conducted on both fresh and dried samples to ensure data representativeness and consistency.



Fig 5. Portable colorimeter (NH310, 3nh, China)

Both fresh and dried samples were analyzed to evaluate color shifts post-processing. The color parameters were measured using the L^* , a^* , and b^* color space, and the total color difference (ΔE) between the fresh and dried samples was calculated using Equation 2 (Pathare *et al.* 2013; Shreelavaniya *et al.* 2021).

$$\Delta E = \sqrt{(L^* - L_0^*)^2 + (a^* - a_0^*)^2 + (b^* - b_0^*)^2} \quad (2)$$

Where L_0^* , a_0^* , and b_0^* represent the color parameters of the fresh samples, and L^* , a^* , and b^* represent the color parameters of the dried samples.

2.3.3 Water activity

Water activity (a_w) was determined using a calibrated water activity meter, as shown in Figure 6, at a controlled temperature. Maintaining a low a_w level is critical for the microbial stability and shelf-life of dried seafood (Nuwanthi *et al.* 2016). Along with moisture content, this parameter indicates the effectiveness of the PGSD system in producing a safe and stable final product (Basak *et al.* 2023). Moreover, monitoring a_w is essential for ensuring food safety and preventing quality degradation, as it directly influences the growth of spoilage microorganisms and the rate of biochemical reactions during storage (Sroy *et al.* 2023; Schmidt and Fontana 2020).



Fig 6. Water activity meter (AQUALAB PRE, USA)

The a_w values of Nile Tilapia dried via PGSD and traditional open sun drying were compared, with the target threshold established to be below 0.85 to ensure product safety and microbial stability (Chan *et al.* 2023; Fitri *et al.* 2022).

2.4 Moisture ratio

The moisture ratio (MR) of Nile Tilapia during the drying process was determined to analyze the drying kinetics under different experimental conditions. The MR was calculated using the following Equation 3 (Andreas *et al.* 2019; Ragasudha *et al.* 2024).

$$MR = \frac{M_t - M_e}{M_o - M_e} \quad (3)$$

Where M_t is the moisture content at any specific drying time, M_o is the initial moisture content of the fresh sample, and M_e is the equilibrium moisture content, which is often considered negligible in solar drying calculations. This mathematical modeling approach follows standard procedures for evaluating thin-layer drying characteristics and is used to assess the performance of the PGSD system.

In many solar drying applications, the value of M_e is relatively small compared to M_o and M_t , allowing the equation to be simplified to $MR = M_t / M_o$ without significant loss of accuracy (Ghanem *et al.* 2025; Guan *et al.* 2013). This mathematical modeling approach is a standard procedure for evaluating the thin-layer drying characteristics of aquatic products (Wu *et al.* 2024). The resulting MR values were further utilized to determine the effective moisture diffusivity and to assess the performance of the PGSD system (Aissa *et al.* 2024; Basak *et al.* 2023).

2.5 Drying rate

The drying rate (DR) of Nile Tilapia fillets was determined to evaluate the mass of water removed from the sample per unit of time during the drying process. The drying rate was calculated using the following Equation 4 (Ye *et al.* 2025).

$$DR = \frac{W_t - W_{t+\Delta t}}{\Delta t} \quad (4)$$

Where DR is the drying rate (g/min), W_t is the mass of the sample at time t (g), $W_{t+\Delta t}$ is the mass of the sample at time $t + \Delta t$ (g), and Δt is the time interval between consecutive weighings (min). The weights of the fish fillets were recorded at regular intervals using a digital balance to ensure the accuracy of the drying kinetics analysis. This parameter is essential for comparing the efficiency of the PGSD system against traditional open sun drying methods, as it reflects the moisture removal capability under varying thermal conditions (Basak *et al.* 2023). The drying rate data were further utilized to understand the constant and falling rate periods during the thin-layer drying of the aquatic products (Ghanem *et al.* 2025; Guan *et al.* 2013; Wu *et al.* 2024).

2.6 Specific moisture extraction rate

The specific moisture extraction rate ($SMER$) was determined to evaluate the energy efficiency of the PGSD system. $SMER$ represents the ratio of the amount of water evaporated from the fish fillets to the total energy consumed during the drying process (Ghanem *et al.* 2025; Zeng *et al.* 2024). The $SMER$ value was calculated using the following Equation 5 (Kang *et al.* 2022).

$$SMER = \frac{M_w}{E_{total}} \quad (5)$$

Where $SMER$ is the specific moisture extraction rate (kg/kWh), M_w is the mass of moisture removed from the Nile Tilapia fillets (kg), and E_{total} is the total energy input into the drying system (kWh), including solar radiation and electrical energy used for fans in forced convection mode (Ghafar *et al.* 2025; Ghanem *et al.* 2025). This parameter is a key indicator for assessing the techno-enviro-economic performance and sustainability of solar dryers in aquatic product processing (Alsakran *et al.* 2025; Ghanem *et al.* 2025). A higher $SMER$ value indicates a more energy efficient drying system with lower operational costs and environmental impact (Younis *et al.* 2025; Zeng *et al.* 2024).

2.7 Specific energy consumption (SEC)

The specific energy consumption (SEC) was determined to evaluate the amount of energy in megajoules (MJ) required to remove a unit mass of water from the Nile Tilapia fillets. The SEC value (MJ/kg) was calculated using the following Equation 6 (Metwally *et al.* 2024).

$$SEC = \frac{E_{total} \times 3.6}{M_w} \quad (6)$$

Where SEC is the specific energy consumption (MJ/kg), M_w is the total mass of moisture removed from the fish samples (kg), and E_{total} is the total energy consumed during the drying process in kilowatt-hours (kWh). A conversion factor of 3.6 was applied to transform the energy unit from kWh to MJ (1 kWh = 3.6 MJ). This parameter serves as a critical indicator for assessing the energy intensity and economic viability of the PGSD system. A lower SEC value signifies a more efficient drying process with optimized energy utilization. Furthermore, SEC is inversely related to the $SMER$, where a decrease in SEC directly reflects an improvement in the system's moisture extraction efficiency (Metwally *et al.* 2024).

2.8 Thermal efficiency of the drying system

The thermal efficiency (η_{th}) was evaluated to determine the effectiveness of the PGSD system in converting solar radiation into useful energy for moisture evaporation. The thermal efficiency was calculated using the following Equation 7.

$$\eta_{th} = \frac{M_w \cdot h_{fg}}{(I \cdot A \cdot t) + E_{elec}} \times 100 \quad (7)$$

Where η_{th} is the thermal efficiency (%), M_w is the mass of moisture evaporated from the Nile Tilapia fillets (kg), h_{fg} is the latent heat of vaporization of water (kJ/kg), I is the average solar irradiance (W/m²), A is the collector or greenhouse floor area (m²), t is the drying time (s) and E_{elec} is the total electrical energy consumed by the ventilation fans during the drying process (kJ). This parameter is a vital indicator of the dryer's performance, as it reflects the system's ability to harness solar energy for the drying process while minimizing heat losses to the environment (Hussain *et al.* 2021). Higher thermal efficiency values indicate superior system design and optimized heat transfer mechanisms within the drying chamber (Ghanem *et al.* 2025; Hussain *et al.* 2021). Furthermore, evaluating thermal efficiency is essential for assessing the overall sustainability and techno-economic viability of solar drying technologies for aquatic products (Alsakran *et al.* 2025; Ghanem *et al.* 2025).

2.9 Mathematical modeling

The drying kinetics of Nile Tilapia fillets in a PGSD system were investigated by analyzing experimental moisture ratio (MR) data. To understand the underlying mass and heat transfer phenomena, the MR data were fitted into eleven well-known thin-layer drying models commonly used to predict the moisture loss behavior of food and agricultural products (Ghanem *et al.* 2025; Onwude *et al.* 2016).

The application of these mathematical models not only elucidates the mechanisms of water mobility within the fish fillets but is also crucial for the design and optimization of solar drying systems. This ensures the production of high-quality products while maintaining maximum energy efficiency (Noshad *et al.* 2025). The mathematical expressions for the eleven models are summarized in Table 1.

Table 1

Mathematical models applied to the drying curves of Nile Tilapia fillets

No.	Model name	Equation
1	Newton (Lewis)	$MR = \exp(-kt)$
2	Page	$MR = \exp(-kt^n)$
3	Modified Page	$MR = \exp(-(kt/L^2)^n)$
4	Henderson and Pabis	$MR = a \exp(-kt)$
5	Modified Henderson and Pabis	$MR = a \exp(-kt) + b \exp(-gt) + c \exp(-ht)$
6	Logarithmic	$MR = a \exp(-kt) + c$
7	Two-term	$MR = a \exp(-k_0t) + b \exp(-k_1t)$
8	Two-term exponential	$MR = a \exp(-kt) + (1 - a) \exp(-kat)$
9	Wang and Singh	$MR = 1 + at + bt^2$
10	Diffusion approach	$MR = a \exp(-kt) + (1 - a) \exp(-kbt)$
11	Simple approx. of diffusion	$MR = a \exp(-c(t/L^2))$

2.9.1 Model validation

To evaluate the accuracy and suitability of the mathematical models used to predict the drying kinetics of Nile Tilapia fillets, statistical analyses were performed to compare the experimental data with the predicted values. The performance of each model was assessed using the coefficient of determination (R^2), reduced chi-square (χ^2) and root mean square error ($RMSE$). These

parameters are crucial for selecting the best-fit model to describe the thin-layer drying behavior of food and agricultural products (Onwude *et al.* 2016).

Coefficient of Determination (R^2): This parameter evaluates the linear relationship between the experimental and predicted moisture ratio values, where a value approaching 1.0 indicates a higher degree of fit for the drying process (Noshad *et al.* 2025). The R^2 value was calculated using the following Equation 8.

$$R^2 = 1 - \frac{\sum_{i=1}^N (MR_{exp,i} - MR_{pre,i})^2}{\sum_{i=1}^N (MR_{exp,i} - \overline{MR}_{exp,i})^2} \quad (8)$$

Reduced Chi-square (χ^2): This measure represents the discrepancy between the experimental and predicted data points (Onwude *et al.* 2016). Lower values of χ^2 indicate a better fit of the model to the experimental drying curve. The calculation of χ^2 was calculated using the following Equation 9.

$$\chi^2 = \frac{\sum_{i=1}^N (MR_{exp,i} - MR_{pre,i})^2}{N - n} \quad (9)$$

Root Mean Square Error (RMSE): RMSE provides an estimate of the average deviation between the experimental and predicted moisture ratios, with lower values signifying higher precision in the model's predictive capability (Noshad *et al.* 2025). It was calculated using the following Equation 10.

$$RMSE = \sqrt{\frac{1}{N} \sum_{i=1}^N (MR_{exp,i} - MR_{pre,i})^2} \quad (10)$$

Where $MR_{exp,i}$ is the i^{th} experimental moisture ratio, $MR_{pre,i}$ is the i^{th} predicted moisture ratio, $\overline{MR}_{exp,i}$ is the average experimental moisture ratio, N is the number of observations, and n is the number of constants in the drying model.

The criteria for selecting the best-fit model for Nile Tilapia drying in a greenhouse solar system were based on the highest R^2 and the lowest χ^2 and RMSE values (Noshad *et al.* 2025). Validating these mathematical models is essential not only for understanding the mechanisms of water mobility within the fish fillets but also for the design and optimization of solar drying systems to ensure high-quality products and maximum energy efficiency (Noshad *et al.* 2025; Onwude *et al.* 2016).

3. RESULTS AND DISCUSSION

3.1 Thermal performance and drying kinetics analysis of Nile Tilapia

The thermal efficiency of the PGSD system was rigorously evaluated through drying experiments using fresh Nile Tilapia in Muang Subdistrict, Chonburi Province, Thailand (13.263° North, 100.959° East) from December 2025 to January 2026 to determine the solar to heat conversion efficiency and moisture removal characteristics. The samples consisted of 16 fresh Nile Tilapia (250–300 g each), which underwent standard preparation processes including scaling, gutting, butterfly cutting, and thorough cleaning to ensure sample uniformity and a constant surface area to volume ratio for mass transfer. After controlled brine treatment, the samples were uniformly arranged on tray inside the PGSD for optimal efficiency, as shown in Figure 7.

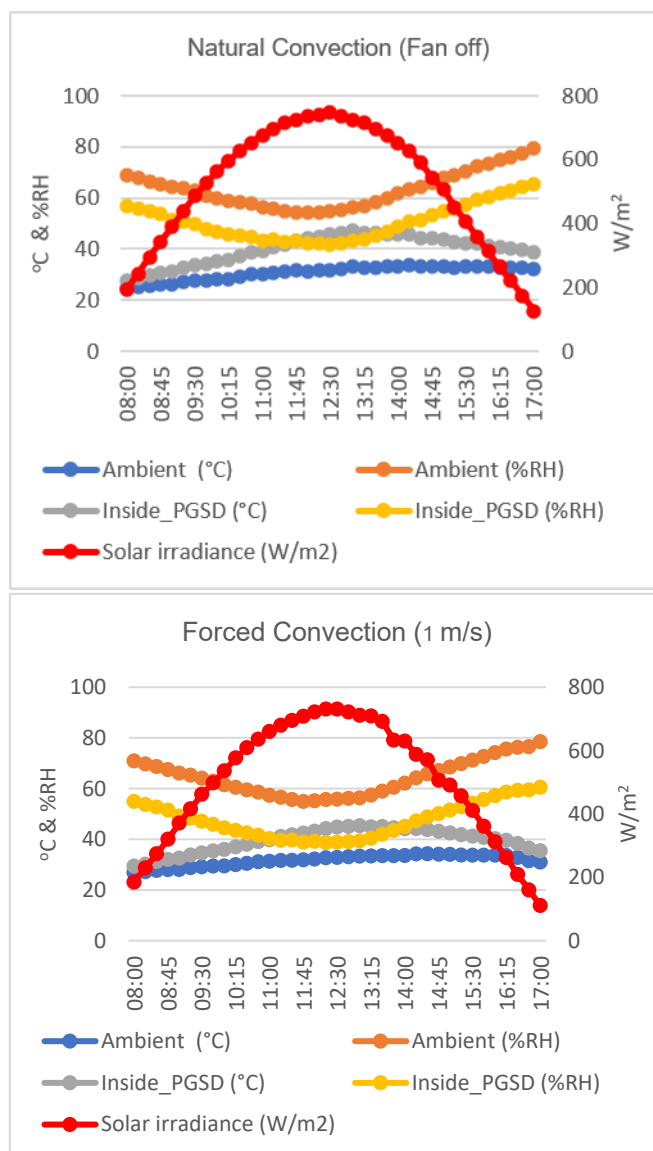
The experimental design focused on two different heat transfer modes: passive mode (natural convection with closed ventilation fans) and active mode (forced convection using ventilation fans at constant speeds of 1, 2, and 3 m/s.) The drying experiments

were repeated 3 times ($n = 3$) under the same operating conditions, and the average values were used for analysis. This repetition ensured statistical reliability, repeatability, and validation of the experimental results.

The relationship between solar intensity and the internal thermal response of the PGSD is shown in Figure 8. Throughout the experiment, all environmental parameters were recorded at 15-minute intervals to capture precise fluctuations in thermal behavior. Furthermore, the average thermal characteristics under both passive and active modes are summarized in Table 2.



Fig 7. Experimental setup and distribution of prepared Nile Tilapia specimens on the PGSD drying tray



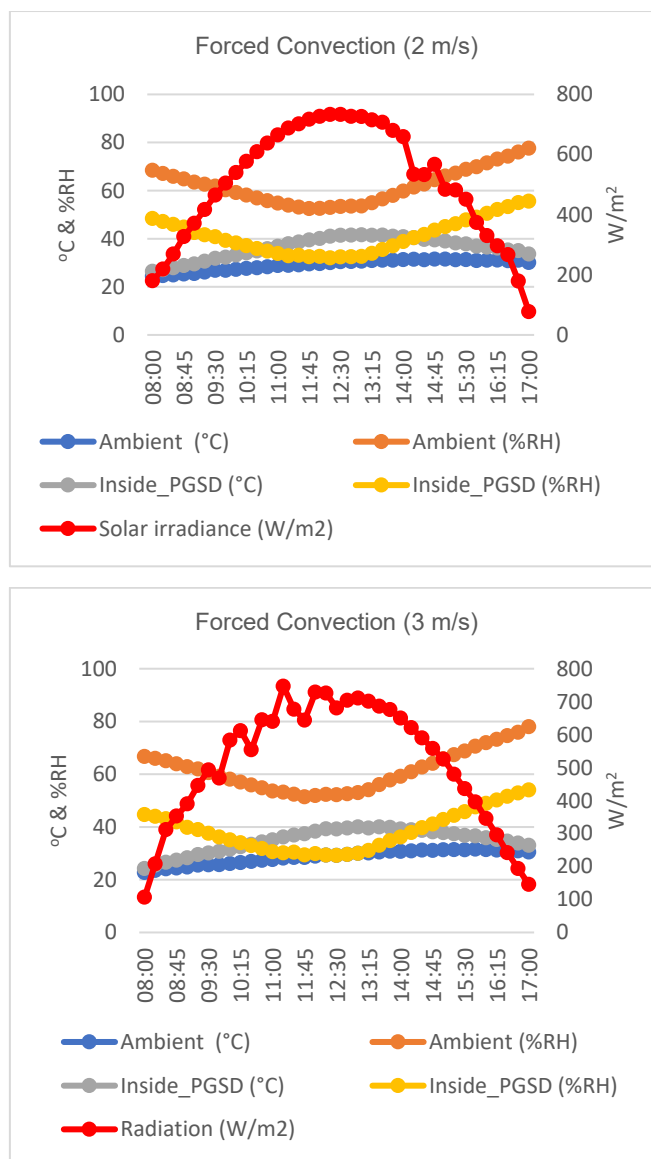


Fig 8. Profiles of internal temperature and relative humidity inside the PGSD during the Nile Tilapia drying process at different air velocities

Table 2

Summary of average thermal characteristics under passive (natural convection drying ; NCD) and active (forced convection drying ; FCD)

Mode	Ambient (°C)	Ambient (%RH)	Inside PGSD (°C)	Inside PGSD (%RH)	Solar irradiance (W/m²)
PGSD Fan off (NCD)	30.71	63.33	39.98	50.57	518.30
PGSD 1 m/s (FCD)	31.66	64.28	39.54	47.44	502.08
PGSD 2 m/s (FCD)	29.19	61.81	36.31	40.97	510.00
PGSD 3 m/s (FCD)	28.61	61.24	34.91	38.40	512.81

The experimental evaluation of the PGSD thermal performance under a full load of Nile Tilapia demonstrated significant energy efficiency in both passive and active modes. Under passive mode (ventilation fans closed), the system successfully increased the average internal temperature to 39.98°C at an average solar irradiance of 518.30 W/m², representing a 30.2% temperature rise above ambient conditions and a 20.1% reduction in relative humidity. These results align with the findings of previous studies (Ghafar *et al.* 2025), who reported that natural convection modes achieve higher heat accumulation due to lower air exchange rates. In active mode, with ventilation fan speeds at 1, 2, and 3 m/s, the average internal temperatures were recorded at 39.54°C, 36.31°C, and 34.91°C, respectively.

Although the average temperature rise decreased to 23.8% during the experiment when wind speed was adjusted between 1–3 m/s, the reduction in relative humidity reached as high as 32.4%. This is consistent with previous findings (Hussain *et al.* 2021), which reported that forced convection accelerates the moisture removal process from fish despite only slightly higher internal temperatures. Comparative analysis for practical application revealed that a wind speed of 3 m/s achieved the lowest internal relative humidity of 38.40%RH. Furthermore, the average solar irradiance during the trials (502.08–518.30 W/m²) provided sufficient energy for moisture evaporation from the 16 Nile Tilapia specimens (250–300 g. each). This outcome is in agreement with observed drying kinetics (Kituu *et al.* 2009), indicating that controlled environments in greenhouse solar dryers preserve product quality better than traditional open sun drying. To ensure statistical reliability and validate the stability of the results, all experimental conditions were performed in triplicate, utilizing the arithmetic mean for data analysis.

3.2 Comparative analysis of drying durations and correlation with quality compliance

In the experiment on drying Nile Tilapia, the drying duration was strictly determined by monitoring the water activity (a_w), which was required to be below 0.85 to ensure product safety and microbial stability (Chan *et al.* 2023; Fitri *et al.* 2022). The results of the study revealed that fresh Nile Tilapia had an initial moisture content of $81.45 \pm 0.20\%$ wb. with a water activity (a_w) of 0.987 ± 0.005 . After processing and brining according to the protocol, the moisture content decreased slightly to $80.15 \pm 0.25\%$ wb., and the a_w value was reduced to 0.968 ± 0.004 . This initial reduction in both moisture and a_w levels prior to the drying phase demonstrates the effectiveness of osmotic dehydration during the brining process, which helps prepare the fish structure for more efficient moisture removal. All values were obtained by repeating the measurements 3 times ($n = 3$) in each experimental cycle.

To determine the final moisture content, five fish samples were randomly selected from the PGSD chamber in each experimental run. Each sample was cut into small pieces and placed in moisture cans, followed by weighing before being dried in a hot air oven at 105 °C for 36 h until a constant weight was achieved. The samples were then reweighed to calculate the moisture content on a wet basis. All measurements were performed in triplicate for each sample.

For water activity (a_w) determination, five Nile Tilapia samples were also randomly selected under the same conditions, and each sample was measured in triplicate to ensure accuracy and repeatability.

The experimental results for various conditions are summarized in Table 3, showing that the time required to reduce moisture and a_w to the standard levels differed significantly depending on the drying conditions. For traditional open sun drying, the system required the longest duration of 18 hours to reach a moisture content of $64.12 \pm 0.57\%$ wb. and an a_w of 0.835 ± 0.014 . In contrast, using the PGSD system even in passive mode (fan off) reduced the duration to 16 hours, achieving a moisture content of $63.91 \pm 0.87\%$ wb. and an a_w of 0.833 ± 0.010 , which is consistent with the report that greenhouse structures provide better heat retention than traditional open sun drying (Janjai 2012).

However, under active mode (forced convection), wind speed directly enhanced the evaporation rate. At air velocities of 1 m/s and 2 m/s, the drying time was further reduced to 12 and 10 hours, respectively. The optimal performance was achieved at a maximum airflow of 3 m/s, requiring only 9 hours to reach a moisture content of $64.36 \pm 0.41\%$ wb. and an a_w of 0.832 ± 0.014 , meeting all standardized requirements. These results confirm that the PGSD system operating in active mode at 3 m/s can reduce drying time by up to 50% compared to traditional open sun drying.

This trend is consistent with the drying kinetics behavior reported in previous studies (Kituu *et al.* 2009). Which demonstrated that increasing airflow reduces mass transfer resistance at the product surface. Additionally, the pre-treatment brining process plays a crucial role in lowering water activity (a_w) to safe levels for consumption, as reported in a previous study (Basak *et al.* 2023).

Table 3

Drying duration, final moisture content (MC_{wb}) and water activity (a_w) of Nile Tilapia dried under different experimental conditions

Experimental condition	Drying hour (hr.) when $a_w < 0.85$	MC_{wb} (%wb) when $a_w < 0.85$	a_w
Traditional open sun	18	64.12 ± 0.57	0.835 ± 0.014
PGSD Fan off (NCD)	16	63.91 ± 0.87	0.833 ± 0.010
PGSD 1 m/s (FCD)	12	63.33 ± 0.77	0.834 ± 0.012
PGSD 2 m/s (FCD)	10	63.98 ± 0.51	0.836 ± 0.013
PGSD 3 m/s (FCD)	9	64.36 ± 0.41	0.832 ± 0.014

3.3 Energy performance and drying efficiency analysis

Based on the performance testing of the PGSD under varying convection conditions are summarized in Table 4, it was found that increasing air velocity directly improves all technical indicators. Considering the drying rate, forced convection at an air velocity of 3 m/s yielded the highest value of 0.211 kg/hr, which is 1.83 times higher than natural convection drying. This is consistent with the previous research (Ghafar *et al.* 2025), which states that forced convection systems are significantly more efficient at evaporating moisture from fish products compared to traditional open sun. The drying efficiency also showed an upward trend corresponding to air velocity, reaching a maximum of 27.45% at 3 m/s compared to 14.92% under natural convection. These results align with the PGSD development (Janjai 2012), which indicates that the parabolic shape combined with effective airflow management enhances thermal efficiency.

Furthermore, an analysis of the energy consumption indices in Table 4 reveals that the Specific Moisture Extraction Rate ($SMER$) increased to 51.156 kg/kWh, while the Specific Energy Consumption (SEC) decreased to only 0.070 MJ/kg. This indicates that increasing air velocity better reduces the specific energy load per unit mass of evaporated water, which is consistent with previous analyses regarding energy cost reduction in Nile Tilapia drying (Ghanem *et al.* 2025; Younis *et al.* 2025).

Consequently, the data in Table 4 concludes that an air velocity of 3 m/s is the optimal operating condition for both production rate and energy efficiency. This setting provides an ideal balance between rapid moisture removal and uniform thermal distribution, which is essential for achieving the target water activity (a_w) efficiently.

Table 4

Energy performance and drying efficiency of the PGSD at different convection drying conditions

Experimental condition	Drying rate (kg/hr)	$SMER$ (kg/kWh)	SEC (MJ/kg)	Drying eff. (%)
PGSD Fan off (NCD)	0.115	0.000	0.000	14.92
PGSD 1 m/s (FCD)	0.163	39.553	0.091	21.63
PGSD 2 m/s (FCD)	0.197	47.172	0.076	25.73
PGSD 3 m/s (FCD)	0.211	51.156	0.070	27.45

3.4 Color change analysis

Evaluating color variation in L^* , a^* , and b^* coordinates is a crucial indicator for assessing the physical quality and consumer acceptance of dried fish, as summarized in Table 5. All experimental data were statistically analyzed using one-way analysis of variance (ANOVA) (SPSS version 19, IBM Corp., Chicago, IL, USA), with a significance level of $P < 0.05$ considered statistically

significant. The overall color difference (ΔE), calculated from L^* , a^* , and b^* values relative to fresh samples, as summarized in Table 5.

For color measurements, five Nile Tilapia samples were randomly selected from the PGSD drying chamber. After each drying cycle, each fish was measured at three different locations on the inner muscle tissue: head, body, and tail, to consider localized color variation within the sample. The study results showed that forced convection drying (FCD) at an air velocity of 3 m/s significantly improved the color quality of dried Nile Tilapia compared to traditional open sun drying. The highest lightness value (L^*) of 44.96 ± 0.75 was obtained with forced convection drying (FCD), while the lowest value was 36.64 ± 1.35 for traditional open sun drying, indicating greater color degradation under long and uncontrolled drying conditions.

The higher L^* value obtained with forced convection drying (FCD) is due to the higher drying rate (0.211 kg/hr) and shorter drying time of 9 hours, which effectively reduces non enzymatic color degradation reactions and lipid oxidation. These findings are consistent with previous research (Senas *et al.* 2026), which reported that rapid moisture removal preserves the color of protein rich aquatic products. In terms of overall color difference (ΔE), traditional open sun drying had the highest value at 13.19, indicating severe color degradation. In contrast, PGSD (FCD) drying at 3 m/s resulted in a lower ΔE value of 8.55 while maintaining an a^* value similar to that of fresh samples (2.22 ± 0.58 compared to 1.96 ± 0.21). However, an increase in the b^* value to 11.79 ± 1.29 was observed, possibly related to fat migration on the surface, resulting in the desired golden yellow color.

The PGSD (FCD) system at 3 m/s produced superior quality dried Nile Tilapia, featuring a color closely resembling fresh fish while meeting all safety standards. By maintaining water activity (a_w) consistently below 0.85, the process effectively ensured microbial stability and preserved nutritional integrity. Consequently, forced convection at 3 m/s within the PGSD system is an efficient method for maintaining the physical quality and safety of the product.

Table 5

Effect of drying conditions on color quality (L^* , a^* , b^*) and total color change (ΔE) of Nile Tilapia

Experimental condition	L^*	a^*	b^*	ΔE
Fresh Nile Tilapia	49.01 ± 0.88^c	1.96 ± 0.21^a	4.26 ± 0.70^a	-
Traditional open sun	36.64 ± 1.35^a	4.02 ± 0.33^c	8.37 ± 0.66^b	13.19
PGSD Fan off (NCD)	40.75 ± 0.85^b	3.43 ± 0.59^{bc}	8.02 ± 0.93^b	9.19
PGSD 1 m/s (FCD)	41.63 ± 0.83^{bc}	3.60 ± 0.59^{bc}	8.11 ± 0.56^b	8.48
PGSD 2 m/s (FCD)	42.62 ± 0.78^c	2.96 ± 0.39^b	10.32 ± 1.05^c	8.86
PGSD 3 m/s (FCD)	44.96 ± 0.75^d	2.22 ± 0.58^a	11.79 ± 1.29^d	8.55

Note: Values are presented as mean $\pm$ standard deviation. Different superscripts in the same column indicate a statistically significant difference ($P < 0.05$)

The superior physical quality of the dried Nile Tilapia, processed within the PGSD for a duration of 9 hours under the optimal forced convection drying (FCD) at 3 m/s, is clearly as shown in Figure 9. The samples exhibit a highly desirable, uniform golden-yellow hue with excellent surface brightness. The texture retains its ideal elasticity without excessive toughness, which is a direct consequence of the precisely controlled moisture evaporation rate. This optimal drying condition successfully reduced the moisture content to below 65%wb. and achieved a water activity (a_w) of less than 0.85. This a_w level is required to ensure product safety and microbial stability (Chan *et al.* 2023; Fitri *et al.* 2022), effectively establishing a robust microbial barrier. These findings confirm that the finished product exceeds the essential quality and safety benchmarks for dried Nile Tilapia.



Fig 9. Physical appearance of dried Nile Tilapia after 9 hours of drying in the PGSD under optimal forced convection drying (FCD) at 3 m/s

3.5 Mathematical modeling of drying kinetics of Nile Tilapia in PGSD system

The drying kinetics of Nile Tilapia were analyzed using a PGSD system by fitting experimental moisture ratio (MR) data to 11 widely accepted thin-layer drying models, as shown in Table 1. These models include the diffusion model, the Henderson-Pabis model, the logarithmic model, the modified Henderson-Pabis model, the modified Page model, the Newton model, the Page model, a simplified approximation of the diffusion model, the biterm model, the biterm exponential model, and the Wang-Singh model. The mathematical formulas of these models are widely used to describe the moisture transport behavior in food and agricultural products under various drying conditions.

Fitting the data to these models was performed using MATLAB software (R2016a, The MathWorks Inc., Natick, MA, USA), which provides robust nonlinear regression tools for parameter estimation and model optimization. The optimal mathematical models for each drying condition were selected based on statistical performance indicators, namely the coefficient of determination (R^2), root mean square error ($RMSE$), and chi-square (χ^2), to ensure that the models accurately represent the experimental drying behavior.

Furthermore, optimal mathematical models describing the drying kinetics of Nile Tilapia under different drying conditions are presented. The optimal models for natural convection drying (NCD), fanless PGSD drying, and forced convection drying in PGSD at air velocities of 1, 2, and 3 m/s are summarized in Tables 6. The parameters of the best fitting model for each experimental condition are summarized in Table 7. Moreover, a summary comparison of the optimal models under all drying conditions are summarized in Table 8, while a corresponding graphical representation of the experimental and predicted moisture ratio curves is shown in Figure 10.

The study of drying kinetics for Nile Tilapia under various convection conditions revealed that the optimal mathematical models for predicting drying behavior varied according to experimental parameters. Under natural convection drying (NCD) conditions, including traditional open sun drying and the PGSD with the fan off, the Logarithmic and Wang and Singh models provided the highest coefficients of determination (R^2), ranging from 0.985535 to 0.994015. These results align with the moisture ratio reduction patterns in aquatic products observed in recent studies (Ghanem *et al.* 2025).

Conversely, under forced convection drying (FCD) conditions with air velocities of 2–3 m/s, the Page model emerged as the most accurate, achieving an R^2 of up to 0.994189 and a remarkably low Root Mean Square Error ($RMSE$) of 0.004883. This consistency with established literature (Onwude *et al.* 2016) confirms that the Page model is highly effective for simulating air convection effects in thin-layer drying and provides the most reliable statistical values for high moisture food groups.

Regarding operational efficiency, the comparative data demonstrates that increasing air velocity significantly enhances the moisture removal rate. Specifically, the PGSD at 3 m/s reduced the moisture ratio (MR) to 0.80 within 8.82 hours, which is more than 52% faster than traditional open sun drying, which required 18.52 hours. This confirms the superior mass transfer efficiency of enclosed solar dryers equipped with ventilation systems, supporting modern industrial trends focused on reducing production time while maintaining quality (Younis *et al.* 2025; Janjai 2012).

Furthermore, the Page model parameters at maximum air velocity showed a behavior index (n) of 1.255336, reflecting an accelerated internal moisture migration mechanism stimulated by optimal airflow. This ensures consistent product uniformity and quality stability throughout the drying process. In conclusion, utilizing the Page model under forced convection provides the most precise prediction and time-efficient approach for the sustainable production of dried Nile Tilapia.

4. CONCLUSIONS

The experimental investigation of Nile Tilapia drying using a PGSD was conducted during the winter season in Thailand (December to January). This season is characterized by high solar irradiance but relatively high ambient humidity and cooler air temperatures compared to other seasons. The study successfully evaluated the drying kinetics, energy performance, and product quality under these specific climatic constraints, leading to the following conclusions;

Optimal drying model and kinetics: The drying characteristics of Nile Tilapia were effectively captured by mathematical modeling. For natural convection drying (NCD), the Logarithmic and Wang and Singh models provided the best fit. However, under forced convection drying (FCD) at 2–3 m/s, the Page model was superior, showing the highest R^2 of 0.994189 and the lowest $RMSE$ of 0.004883. The behavior index (n) reached 1.25533 at 3 m/s, indicating an accelerated internal moisture diffusion mechanism driven by the enhanced airflow.

System thermal performance: Despite the cooler ambient temperatures of the Thai winter (average 28.61–31.66 °C), the PGSD system was able to generate significant thermal gain, maintaining internal temperatures between 34.91 and 39.98 °C. The greenhouse effect within the dryer, coupled with solar irradiance levels averaging 502.08–518.30 W/m², reduced the internal relative humidity to a range of 38.40–50.57%RH.

Drying efficiency and time reduction: The forced convection mode at 3 m/s demonstrated the most significant operational advantage. It achieved the target water activity ($a_w < 0.85$) within only 9 hours, compared to 18 hours for traditional open sun drying, representing a 50% increase in productivity. This condition also yielded the highest drying rate of 0.211 kg/hr and a Specific Moisture Extraction Rate ($SMER$) of 51.156 kg/kWh, with an overall drying efficiency of 27.45%.

Product color quality: The rapid drying process at 3 m/s effectively preserved the physical quality of the fish. It maintained the highest lightness value ($L^* = 44.96$) and resulted in the lowest total color change ($\Delta E = 8.55$), whereas traditional open sun drying led to significant discoloration ($\Delta E = 13.19$) due to longer exposure times.

In summary, the PGSD system with forced convection at 3 m/s offers a highly efficient and sustainable technology for fish processing in tropical climates. This study demonstrates that the system can be effectively adapted for small-scale agricultural households as a low-cost food preservation method. By utilizing greenhouse solar dryers, farmers can achieve high-quality dried Nile Tilapia with minimal investment, providing a reliable and accessible solution for local food security and value-added production.

Table 6

Best fitting thin-layer drying models for Nile Tilapia under different drying conditions (NCD, PGSD fan-off, and FCD at 1–3 m/s)

Model	Experimental condition	R^2	χ^2	$RMSE$
Newton (Lewis)	Traditional open sun	0.857717	0.000456	0.021056
	PGSD Fan off (NCD)	0.946123	0.000259	0.015854
	PGSD 1 m/s (FCD)	0.995788	0.000017	0.004094
	PGSD 2 m/s (FCD)	0.988800	0.000057	0.007350
	PGSD 3 m/s (FCD)	0.975562	0.000106	0.010014
Page	Traditional open sun	0.977605	0.000074	0.008354
	PGSD Fan off (NCD)	0.968852	0.000154	0.012055
	PGSD 1 m/s (FCD)	0.995868	0.000018	0.004055

	PGSD 2 m/s (FCD)	0.992855	0.000038	0.005871
	PGSD 3 m/s (FCD)	0.994189	0.000027	0.004883
Modified Page	Traditional open sun	0.977605	0.000074	0.008354
	PGSD Fan off (NCD)	0.968852	0.000154	0.012055
	PGSD 1 m/s (FCD)	0.995868	0.000018	0.004055
	PGSD 2 m/s (FCD)	0.992854	0.000038	0.005871
	PGSD 3 m/s (FCD)	0.994188	0.000027	0.004883
Henderson and Pabis	Traditional open sun	0.928994	0.000234	0.014875
	PGSD Fan off (NCD)	0.953706	0.000229	0.014696
	PGSD 1 m/s (FCD)	0.995956	0.000017	0.004012
	PGSD 2 m/s (FCD)	0.992772	0.000038	0.005905
	PGSD 3 m/s (FCD)	0.985978	0.000064	0.007585
Modified Henderson and Pabis	Traditional open sun	0.994015	0.000022	0.004318
	PGSD Fan off (NCD)	0.984975	0.000085	0.008372
Model	Experimental condition	R^2	χ^2	RMSE
Modified Henderson and Pabis	PGSD 1 m/s (FCD)	0.995956	0.000021	0.004012
	PGSD 2 m/s (FCD)	0.992772	0.000048	0.005905
	PGSD 3 m/s (FCD)	0.985978	0.000084	0.007585
Logarithmic	Traditional open sun	0.994015	0.000020	0.004318
	PGSD Fan off (NCD)	0.984975	0.000077	0.008372
	PGSD 1 m/s (FCD)	0.995956	0.000018	0.004011
	PGSD 2 m/s (FCD)	0.992818	0.000040	0.005886
	PGSD 3 m/s (FCD)	0.988328	0.000057	0.006921
Two-term	Traditional open sun	0.994015	0.000021	0.004318
	PGSD Fan off (NCD)	0.984975	0.000079	0.008372
	PGSD 1 m/s (FCD)	0.995956	0.000019	0.004012
	PGSD 2 m/s (FCD)	0.992772	0.000043	0.005905
	PGSD 3 m/s (FCD)	0.985978	0.000073	0.007585
Two-term exponential	Traditional open sun	0.994015	0.000021	0.004318
	PGSD Fan off (NCD)	0.984975	0.000079	0.008372
	PGSD 1 m/s (FCD)	0.995956	0.000019	0.004012
	PGSD 2 m/s (FCD)	0.992772	0.000043	0.005905
	PGSD 3 m/s (FCD)	0.985978	0.000073	0.007585
Wang and Singh	Traditional open sun	0.991592	0.000028	0.005118
	PGSD Fan off (NCD)	0.985535	0.000072	0.008215

	PGSD 1 m/s (FCD)	0.995863	0.000018	0.004057
	PGSD 2 m/s (FCD)	0.990918	0.000048	0.006619
	PGSD 3 m/s (FCD)	0.991655	0.000038	0.005852
Diffusion approach	Traditional open sun	0.993818	0.000021	0.004389
	PGSD Fan off (NCD)	0.981151	0.000096	0.009378
	PGSD 1 m/s (FCD)	0.995854	0.000019	0.004062
	PGSD 2 m/s (FCD)	0.988800	0.000063	0.007350
	PGSD 3 m/s (FCD)	0.975562	0.000119	0.010014
Simple approx. of diffusion	Traditional open sun	0.928994	0.000234	0.014875
	PGSD Fan off (NCD)	0.953706	0.000229	0.014696
	PGSD 1 m/s (FCD)	0.995956	0.000017	0.004012
	PGSD 2 m/s (FCD)	0.992772	0.000038	0.005905
	PGSD 3 m/s (FCD)	0.985978	0.000064	0.007585

Table 7

Model parameters of the best fitting drying models for each experimental condition

Experimental condition	The best fitting model	k	a	b	c	n
Traditional open sun	Logarithmic	0.124289	0.214120	-	0.788490	-
PGSD Fan off (NCD)	Wang and Singh	-	-0.022257	0.000567	-	-
PGSD 1 m/s (FCD)	Logarithmic	0.018312	1.025595	-	-0.027361	
PGSD 2 m/s (FCD)	Page	0.018750	-	-	-	1.106897
PGSD 3 m/s (FCD)	Page	0.014500	-	-	-	1.255336

Table 8

Comparative summary of optimal drying models and statistical performance under all drying conditions

Experimental condition	Best model	R^2	χ^2	$RMSE$	$t@MR=0.90$ (h)	$t@MR=0.85$ (h)	$t@MR=0.80$ (h)
Traditional open sun	Logarithmic	0.994015	2.00×10^{-05}	0.004318	5.25	10.03	18.52
PGSD Fan off (NCD)	Wang & Singh	0.985535	7.20×10^{-05}	0.008215	5.18	8.65	13.95
PGSD 1 m/s (FCD)	Logarithmic	0.995956	1.80×10^{-05}	0.004011	5.50	8.52	11.73
PGSD 2 m/s (FCD)	Page	0.992855	3.80×10^{-05}	0.005871	4.76	7.03	9.37
PGSD 3 m/s (FCD)	Page	0.994189	2.70×10^{-05}	0.004883	4.85	6.85	8.82

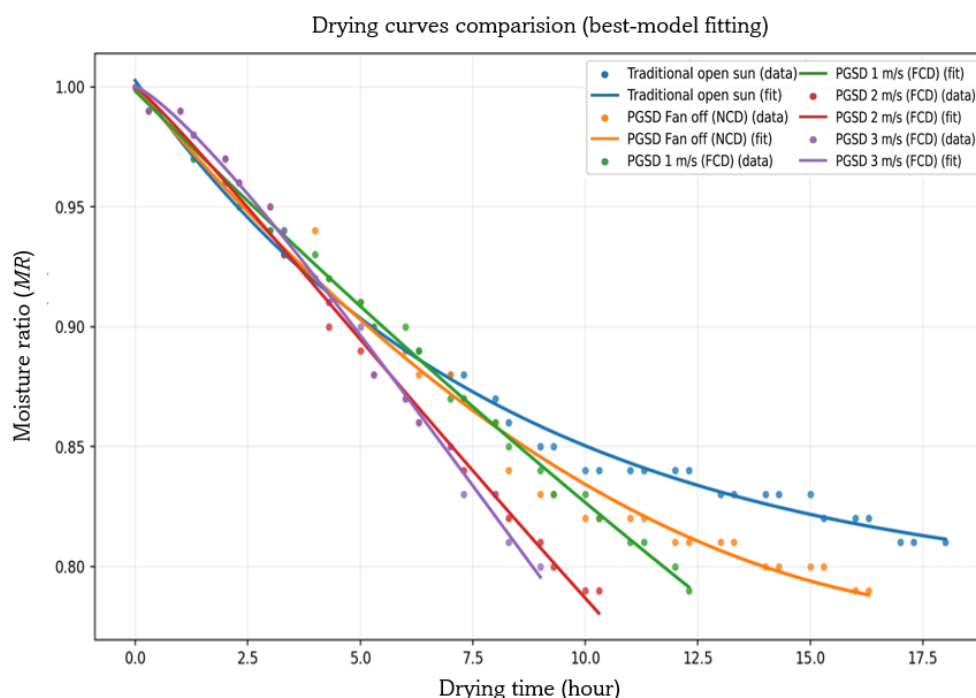


Fig 10. Comparison of experimental and predicted moisture ratio (MR) curves based on the best-fitting drying models for Nile Tilapia under different drying conditions

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