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Development and Performance Assessment of Sensor-Mounted Solar Dryer for Micro-Climatic Modeling and Optimization of Dried Fish Quality in Cambodia

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Abstract: Fish are one of the main sources of protein in Cambodia but they are highly perishable. This requires immediate consumption or processing for later use. In processing, fish drying is very common, but most processors practice traditional drying methods although solar dryers have been introduced, or gradually used, in Cambodia. There is a large variation in terms of drying efficiency due to large differences in solar radiation, temperature, and humidity conditions in traditional drying methods and solar dryers. However, there is limited information on the actual variation in these two systems, which should be documented in Cambodia. Using sensors to monitor micro-climatic changes inside the drying chamber will be useful to improve efficiency and performance. Therefore, the objectives of this research were to (1) design a fish dryer from locally available inputs; (2) determine changes in solar radiation over time; (3) compare relative humidity and temperatures between traditional sun-drying and the solar dryer; (4) determine the relationship among the climatic parameters; and (5) compare some physical, chemical, and biological properties of dried fish in both drying techniques with the Cambodian dried fish standards. The study was conducted in collaboration with a fish processor in the Siem Reap Province between December 2023 and January 2024 using a sensor-mounted solar dryer fabricated by the Royal University of Agriculture to dry fish and compared with traditional sun-drying. Three experiments were carried out from 8:00 to 16:00 following the common drying practices in Cambodia. In each experiment, 80–100 kg of raw giant snakehead, or 56–70 kg of prepared fish (1.04 $\pm$ 0.05 kg each fish), was prepared for drying. Data on environmental conditions were measured and analyzed. The results show that the solar dryer had higher temperatures (almost 60 °C) and lower relative humidity (about 20%) during peak hours when compared with traditional sun-drying (36.8 °C and 40%, respectively). In all cases, relative humidity decreased with rising solar radiation and temperatures. The final weight and moisture of dried fish in the solar dryer were lower than those in traditional sun-drying in eight hours. Salmonella was detected with traditional sun-drying but *E. coli* was not. Bacterial presence may be harmful to human health. Nevertheless, the time spent for drying in both techniques was the same, so future studies should focus on improving ventilation to remove moisture faster out of the solar dryer, which can help with faster drying and more time saving. Hybrid solar dryers should also be considered to maintain high temperatures at night, while bacteria should be counted for safety reasons.

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Keywords: fish drying; protein; humidity; solar radiation; temperature; sensor

1. Introduction

Fish provide a source of food that contains necessary protein for body growth, and it is part of the daily diet of Cambodian people [1–3]. Due to the abundance of rivers across Cambodia [4,5], both wild and farmed fish are major sources to meet the needs of human consumption. Fish are considered highly perishable [6,7]; thus, preserving methods are needed to ensure their availability over a longer time period [8]. There are many ways of preserving fish for long-term use and one of those is drying [9]. In Cambodia, fish are dried directly on the open field due to the abundance of sunlight, but this practice is subject to many issues associated with quality, safety, and nutrition.

Many studies have shown that traditional fish drying is ineffective, unhygienic, and poor in nutrients [10,11]. This is because sun-dried fish are exposed to dust, flies, and ultraviolet radiation, all of which reduce the quality and nutrients while increasing contamination with microbes, thereby leading to health hazards such as diarrhea [12–14]. Low-quality fish products result in low selling prices [15]. Despite the abundance of sunshine, the temperature obtained is not high enough to effectively and uniformly dry the fish under the sun. In most cases, even during the hottest hours of the day, temperatures are about 40 °C, which results in delayed drying [16]. More importantly, during the rainy season, drying cannot be executed properly and needs more time to achieve the desired moisture due to greater ambient relative humidity and cloudy conditions [17]. These issues can be solved by utilizing solar dryers, because they have transparent plastic covers to protect fish, while increasing the temperature inside for faster drying [18].

There are many kinds of solar dryers designed, tested, and used for drying fish, both freshwater and marine, and other products [17,19,20]. Basically, they are categorized into four: direct solar dryers, indirect solar dryers, mixed-mode solar dryers, and hybrid solar dryers [21]. They are found to be superior to open sun-drying in terms of the time efficiency, appearance, quality, and hygiene of products [20,22]. Comparing different dryers, the indirect option is better because products intended for drying are kept separately inside a drying chamber, while hotter air is pushed through a solar collector [23]. For example, Basunia et al. [24] found that solar tunnel dryers are better than sun-drying because they can decrease fish moisture from 66.5% to 15.5% more rapidly, and they did not cause discoloration and physical damage to fish, unlike open sun-drying techniques [10]. Solar dryers also provide greater protection from insects, dust, and rain, when compared to sun-dried fish [25,26]. Some designs of solar tunnel dryers can dry 120–150 kg of fish each time and can decrease fish moisture from 90% to 15% in 9 h, while open sun-drying may take over 20 h [27].

Despite these advantages, most fish processors in Cambodia are still practicing traditional fish drying because they have poor understanding, insufficient technical support availability, and are unwilling to invest due to cost. Furthermore, many of the solar dryers available are expensive, so only a few are willing to purchase them with financial support [28,29]. Therefore, introducing a locally made solar dryer design could be a good option. However, it will require more information about the environmental conditions of the dryer and its performance and efficiency.

The objectives of this study were to (1) design a local fish dryer from inputs from producers; (2) determine changes in solar radiation over time; (3) compare relative humidity and temperatures between traditional sun-drying and the solar dryer; (4) determine the relationship among the climatic parameters; and (5) compare some physical, chemical, and biological properties of dried fish in both drying techniques with the Cambodian dried fish standards.

2. Materials and Methods

2.1. Study Location

The experimental process consisted of conducting a social survey to explore the socio-economic conditions of dried fish processors in Cambodia and developing a technical drawing of a suitable solar dryer, the incorporation of a micro-climatic sensor, fabrication, testing, modification, and experimentation, from May 2023 to January 2024. Firstly, a technical drawing of the solar dryer was developed based on the survey results, with the sensor coded from May to June 2023. The initial design, fabrication, and modifications were performed at the Faculty of Agricultural Biosystems Engineering (FABE), Royal University of Agriculture (RUA), Cambodia (11.51407° N, 104.90296° E). Later, from July to August 2023, the functionality of the solar dryer and its sensor were tested. Then, three subsequent experiments with 30–40 kg of giant snakehead (*Channa micropeltes*) each time, or 21–28 kg of prepared fish ready for drying, were carried out from September to October 2023 to determine how heat was generated inside the solar dryer and its influence on drying fish. After initial results, both the solar dryer and sensor were modified, and a final design was then developed, constructed, and field tested with a fish processor. The final solar dryer was evaluated with a family-run fish drying enterprise located in Aranh village, Siem Reap City, Siem Reap province (13.31097° N, 103.8474° E) starting 15 December 2023 using a series of experiments and compared with traditional sun-drying methods. This paper focused only on the results obtained from three subsequent experiments in collaboration with the fish processor in Siem Reap between December 2023 and January 2024, which was in the early dry season.

2.2. Materials

The solar dryer had three parts—a drying chamber, a heat collector, and a sensor—with a total weight of 300 kg. The drying chamber was 2.0 m wide, 4.0 m long, and 1.85 m high, with two shelves that can load up to 150 kg of fish (Table 1; Figure 1). The heat collector was 2.0 m wide and 2.3 m long, tilting at 30°. Inside the drying chamber were eight 8 W solar fans and one 50 W solar fan to ensure sufficient ventilation and remove moisture from the drying chamber. The solar dryer was mounted with a climatic sensor developed to detect temperatures; relative humidity; solar radiation, both inside and outside the drying chamber; and airflow in the drying chamber. All the fans and sensors were powered by a 180 W solar panel along with a 40 AH solar battery to supply energy in the case of clouds, or rain. The fabricated solar dryer was used to dry fish compared to traditional sun-drying (as a control).

Table 1. Correlation among climatic parameters inside and outside the solar dryer.

Parameter	Lower-Shelf Temp	Upper-Shelf Temp	Ambient Temp	Solar Dryer RH	Ambient RH	Solar Radiation
Lower-shelf Temp						
Upper-shelf Temp	0.99 ***					
Ambient Temp	0.93 ***	0.94 ***				
Solar dryer RH	−0.94 ***	−0.95 ***	−0.88 ***			
Ambient RH	−0.94 ***	−0.94 ***	−0.91 ***	0.93 ***		
Solar radiation	0.81 ***	0.79 ***	0.68 ***	−0.76 ***	−0.8 ***	

Note: "***" denotes significant differences at $\alpha < 0.001$. Abbreviations: "RH" and "Temp" refer to relative humidity and temperature, respectively.

The tools used in this study included a portable solar intensity meter (TM-206), a portable digital meat moisture meter (SKZ111C-2), digital electric scales, portable hygrometers, portable thermometers, and a laser thermometer (WURTH 0715 53 119). The solar intensity meter was used to detect solar radiation every hour from 8:00 to 16:00, while the moisture meter was utilized to measure the moisture of dried fish before and after drying. Electric scales were also used to weigh fish before and after drying to verify the results obtained from the moisture meter with respect to losses of fish weight and moisture. Portable hygrometers and thermometers were used to record relative humidity and temperatures in the ambient atmosphere and in the environment of the solar dryer.

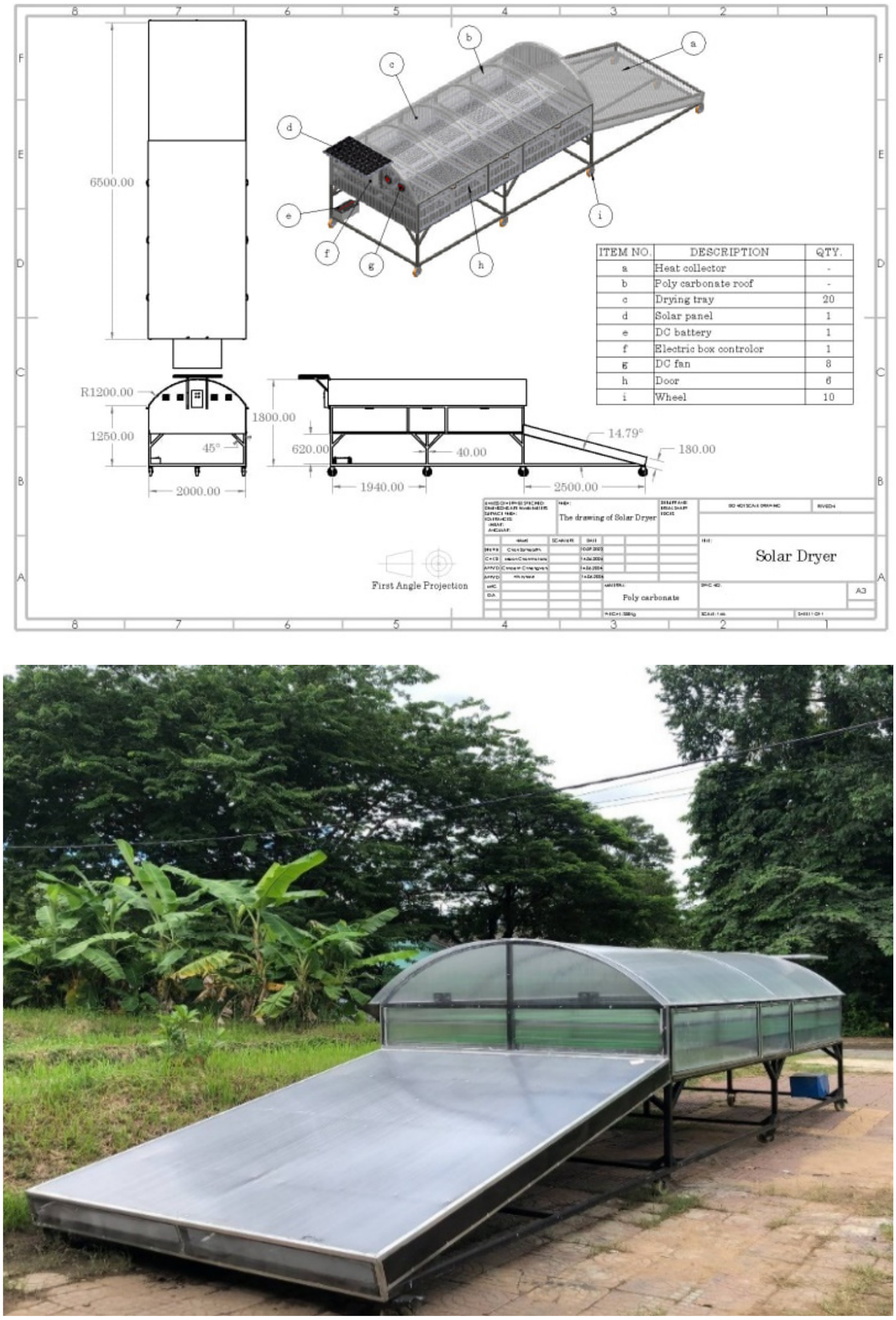

Figure 1. Technical drawing of the indirect solar dryer (**top**) and side view of the sensor-mounted solar dryer (**bottom**) tested in the Siem Reap Province.

A sensor was developed and mounted on the solar dryer to record data on solar radiation, relative humidity, and temperature inside and outside the drying chamber, while the airflow was measured only inside the drying chamber. In this study, the airflow was 3.4 m/s, on average (Figures 2 and 3).

Figure 2. Data recorded using the sensor (**left**), solar radiation measured using a hand-held solar meter (**middle**), and fish moisture measured using a portable meat moisture meter (**right**).

Figure 3. Activities of dried fish experiment with a fish processor in the Siem Reap province.

2.3. Data Sampling

In the study, conducted in Siem Reap (Figures 3 and 4), giant snakehead (*Channa micropeltes*) was used for the experiment, which was replicated three times at weekly intervals with a new batch of fish. Each time, 80–100 kg of raw fish was purchased and prepared for drying by mixing sugar, salt, and seasoning at 2%, 1%, and 0.5%, respectively, based on one kg of prepared fish, while the fresh weight of the fish was 1.25–1.45 kg/head. After fish preparation, the fish lost about 30% of their weight, and only 56–70 kg remained (1.04 $\pm$ 0.05 kg of each prepared fish). In each experiment, prepared fish were equally divided into two drying methods: traditional sun-drying from 8:00 to 16:00, commonly followed in Cambodia [28], and the newly fabricated solar dryer to determine the performance of the dryer.

The data collected included relative humidity, temperature, solar radiation, dried fish weight, and fish moisture losses. The climatic data were recorded using the sensor every minute for three weeks, while the meat moisture meter was used to measure the same 10 dried fish before and after drying in each experiment. To quantify the data on fish quality, three dried fish in the second and third experiments from both drying techniques were randomly selected, stored below 4 °C in an ice box, and then brought to the microbiology laboratory of the Faculty of Agro-industry (AI), RUA, to identify the physical (moisture, sugar, salt, water, and ash), chemical (protein), and biological (*E. coli* and *Salmonella*) properties of the dried fish according to the Cambodian standard of dried fish—CS 167:2015 [29,30]. The quality parameters were analyzed in both drying techniques.

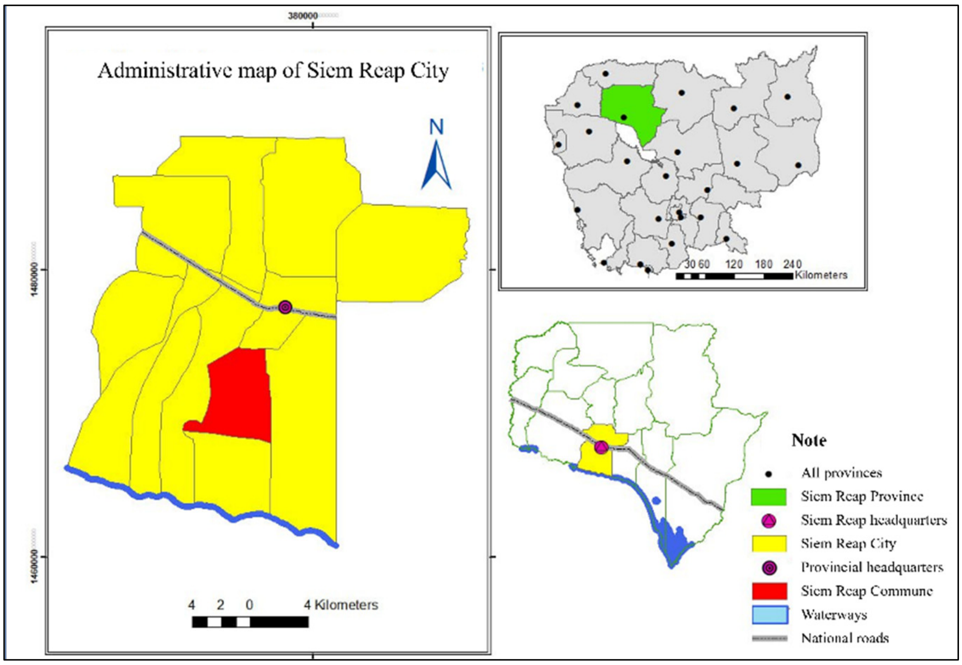

Figure 4. Map of the family-run fish drying enterprise located in the Siem Reap Province.

2.4. Data Analysis and Interpretation

The climatic data stored in the memory of the sensor were coded in a text format, so it was first transformed to be readable using the R Program version 4.3.2. and RStudio version 2023.12.1+402, which are free and available online at https://posit.co/download/rstudio-desktop/ (accessed on 12 September 2023). These programs were also utilized to analyze the data along with Microsoft Excel when performing quadratic and exponential modeling to ensure the accuracy of the models. In this study, linear, quadratic, and exponential modeling were applied using the "lm" function in RStudio to create simple linear, second-order polynomial, and exponential regressions at the error level of 5% (95% confidence level). Meanwhile, a one-sample *t*-test, two-sample *t*-test, and Pearson's correlation were also performed using the "rstatix" package to make comparisons with the standard values and between the two drying techniques and to detect relationships among numerical variables at the error level of 5% (95% confidence level), respectively [31]. All the graphs were created using the "ggplot2" package, which is powerful in producing complex but beautiful graphs [32].

2.4.1. Simple Linear Regression

A simple linear regression was applied to detect the variation of temperatures measured inside and outside the drying chamber using the sensor with respect to different levels of solar radiation recorded during the daytime [33,34]. Assumptions of normality, linearity, homoscedasticity, and independence were checked, but because there were thousands of data for each parameter due to 24 h recordings documenting every minute for three weeks, the assumptions were met [35]. The result was presented on a scatterplot with a line of best fit, while its equation, P-value, and correlation coefficient (R) were shown on that graph only when significance was detected between the dependent and independent variables. R is used in a simple linear regression rather than the coefficient of determination (R^2) because it can show the sign of the relationship, either positive or negative.

2.4.2. Second-Order Polynomial Regression

A second-order polynomial regression [36] was performed to detect how solar radiation, temperatures, and relative humidity in both drying methods varied in time. This method is commonly used with only one independent variable [37]. Then, results were presented using a scatterplot with curve lines, and if significance between dependent and independent variables was detected, the equation, P-value, and the coefficient of determination (R^2) were shown on those graphs for prediction. In this model, R^2 is used rather than R because the relationship can be both positive and negative due to a quadratic shape [38]. All these quadratic equations are applicable with the time from 07:00 to 18:00.

2.4.3. Exponential Regression Model

Relationships between the temperature and relative humidity inside the drying chamber were also determined by running and observing different models in Microsoft Excel to generate one model with the highest R-squared. Then, the best model to predict the relationship was a simple exponential regression, which is considered one of the simplest non-linear regression models used for prediction [39,40]. The model was re-run using RStudio before the decision to plot a graph. Then, the result was presented using a scatterplot with a curve line, while the equation, P-value, and the coefficient of determination (R^2) were shown inside when significance was detected. The equation used in this study was based on the actual data collected using the sensor, and it is applicable only when the starting temperature was not less than 23 °C.

The following are the formulas of a simple linear regression [33], a second-order polynomial regression [36], and a simple exponential regression [39,40], respectively:

$$y = \beta_0 + \beta_1 x + \varepsilon \tag{1}$$

where

- y is the dependent variable;
- β_0 is the intercept constant;
- β_1 is the slope of the line;
- x is the explanatory variable;
- ε is the residual.

$$y = \beta_0 + \beta_1 x + \beta_2 x^2 + \varepsilon \tag{2}$$

where

- y is the dependent variable;
- β_0 is the intercept constant;
- β_1 is the linear effect parameter;
- β_2 is the quadratic effect parameter;
- x is the explanatory variable;
- ε is the residual.

$$y = \alpha e^{\beta x} + \varepsilon \tag{3}$$

where

- y is the dependent variable;
- α is the intercept constant;
- e is the exponential value (e = 2.7183);
- β is the exponential effect parameter;
- x is the explanatory variable;
- ε is the residual.

2.4.4. One-Sample T-Test

One-sample *t*-test was used to compare the physical, chemical, and biological properties of fish dried with both drying techniques in compliance with the Cambodian standards for dried fish. The standards include moisture (<45%), water activity (<0.78), sodium chloride (<10% WB), sugar content (<8% WB), ash (<9% DB), and protein (40–45% WB), while biological properties, *E. coli* and Salmonella, have no clear values set by the standards [30]. The abbreviations "WB" and "DB" are referred to as wet basis and dry basis, respectively. Meanwhile, the ability of the AI laboratory, RUA, could just identify the presence of those bacteria in dried fish, without the ability to count their quantity. In a one-sample *t*-test, the assumptions of being numeric, of independence, of normality, and of having no outliers were tested [41]. In this study, the sample size of each parameter in both traditional sun-drying and solar drying was only six, when compared to the given standard values. However, many studies suggest that a small sample size ($\leq$6) is feasible for a *t*-test when the sample effect size is large [42,43], so the sample effect size was calculated before performing the one-sample *t*-test. Below are the formulas of sample effect size and the one-sample *t*-test performed against a given value [44,45]:

$$d = \frac{\overline{x} - \mu_0}{S} \quad (4)$$

where

- d, or Cohen's d, is the effect size;
- $\overline{x}$ is the mean value of each parameter;
- μ_0 is the given standard value;
- S is the sample standard deviation of x_i.

$$t = \frac{\overline{x} - \mu_0}{\frac{S}{\sqrt{n}}} \quad (5)$$

where

- t is the calculated t-test;
- $\overline{x}$ is the mean value of each parameter;
- μ_0 is the given standard value;
- S is the sample standard deviation of x_i;
- n is the sample number of x_i.

2.4.5. Independent Two-Sample T-Test

An independent two-sample *t*-test was performed to compare both initial and final weight and moisture losses of fish dried in traditional drying and in solar drying at an error level of 5% (95% confidence level). Assumptions of normality, homogeneity, independence, and randomness were tested first before performing this test [46,47]. In case the data were heterogenous, a two-sample *t*-test with unequal variance was applied. In such a case, Welch's test might also be performed to double-check the results to ensure their accuracy and reliability [48,49]. However, all the assumptions were met, so the formula of a two-sample *t*-test with equal variance is used and shown below:

$$t = \frac{\overline{x}_1 - \overline{x}_2}{S_p\sqrt{\frac{1}{n_1} + \frac{1}{n_2}}} \quad (6)$$

$$S_p^2 = \frac{(n_1 - 1)S_1^2 + (n_2 - 1)S_2^2}{n_1 + n_2 - 2} \quad (7)$$

where

- t is the calculated t-test;
- $\overline{x}_1$ is the mean value of variable 1;
- $\overline{x}_2$ is the mean value of variable 2;
- n_1 is the sample number of variable 1;
- n_2 is the sample number of variable 2;
- S_p^2 is the pooled variance of both variables;
- S_1^2 is the variance of variable 1;
- S_2^2 is the variance of variable 2.

2.4.6. Multivariate Correlation

Multivariate correlation was performed to detect individual relationships among climatic parameters: solar radiation, ambient relative humidity, ambient temperature, and both relative humidity and temperature inside the solar dryer. The analysis was carried out using Pearson's correlation with an error level of 5% (95% confidence level), while the assumptions of normality and absence of outliers were checked and verified first [50]. In this study, all the assumptions were met, so Pearson's correlation was used. In this test, a correlation coefficient (R) ranges from -1 to 1 and is defined as very weak ($R < |0.2|$), weak ($|0.2| \leq R < |0.4|$), moderate ($|0.4| \leq R < |0.6|$), strong ($|0.6| \leq R < |0.8|$), or very strong ($|0.8| \leq R \leq |1.0|$) [51,52]. The formula of correlation coefficient is presented as follows [53]:

$$R = \frac{\sum_{i=1}^{n}(x_i - \overline{x})(y_i - \overline{y})}{\sqrt{\sum_{i=1}^{n}(x_i - \overline{x})^2 \sum_{i=1}^{n}(y_i - \overline{y})^2}} \quad (8)$$

where

- R is the correlation coefficient;
- x_i is the individual value of the explanatory variable;
- y_i is the individual value of the dependent variable;
- $\overline{x}$ is the mean of x values;
- $\overline{y}$ is the mean of y values.

2.4.7. Akaike Information Criterion (AIC)

Akaike information criterion (AIC) was used to determine the best model for temperature, considered z, as a function of relative humidity (x) and solar radiation (y). Both temperature and relative humidity used for this function were parameters collected inside the solar dryer. In the process, several models were run using the "lm" function in RStudio and then applied with AIC. The best model could be selected with the lowest values of AIC [54], and then the result was presented in the form of a contour plot generated by "filled.contour" functions in RStudio.

3. Results

3.1. Changes in Daily Solar Radiation

Solar radiation was affected by the time during the day and had a concave parabolic shape ($p < 0.001$; $R^2 = 0.86$) (Figure 5). At 8:00, solar radiation was around 150 W/m^2, had a peak of 883 W/m^2 between 11:00 and 13:00, and then dropped back to 235 W/m^2 at 16:00. This finding shows that solar radiation available in Cambodia is high because the experiment was conducted in the early dry season. With such high solar intensity, it was good enough for drying agricultural products such as fish.

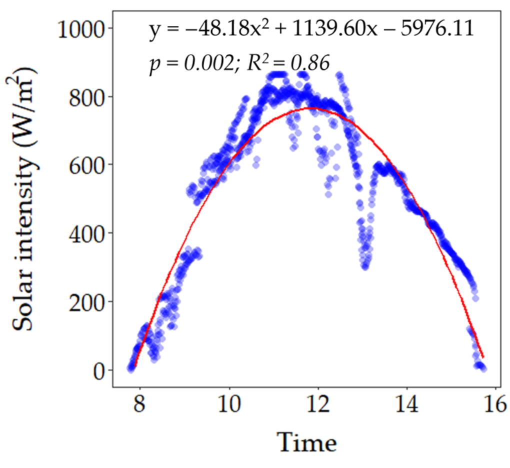

Figure 5. Changes in solar radiation recorded every minute from 8:00 to 16:00.

3.2. Relationship between Temperatures with Respect to Solar Radiation and Time

The results showed that both ambient temperature and temperatures in the lower and upper shelf inside the drying chamber were affected by solar radiation ($p < 0.001$, R = 0.68; $p < 0.001$, R = 0.80; and $p < 0.001$, R = 0.79, respectively) (Figure 6). There was a strong positive and linear relationship. The higher the solar radiation was, the higher the temperatures were. The ambient temperature remained lower than inside the solar dryer. Among the shelves inside the drying chamber, the lower shelf was a bit cooler than the upper shelf. Using the solar dryer, the temperature obtained was about 1.6 times higher than traditional sun-drying. Mathematically, with an increase in solar radiation by 100 W/m^2, the temperatures increased by 0.8, 2.4, and 2.5 °C for the ambient, lower shelf, and upper shelf, respectively.

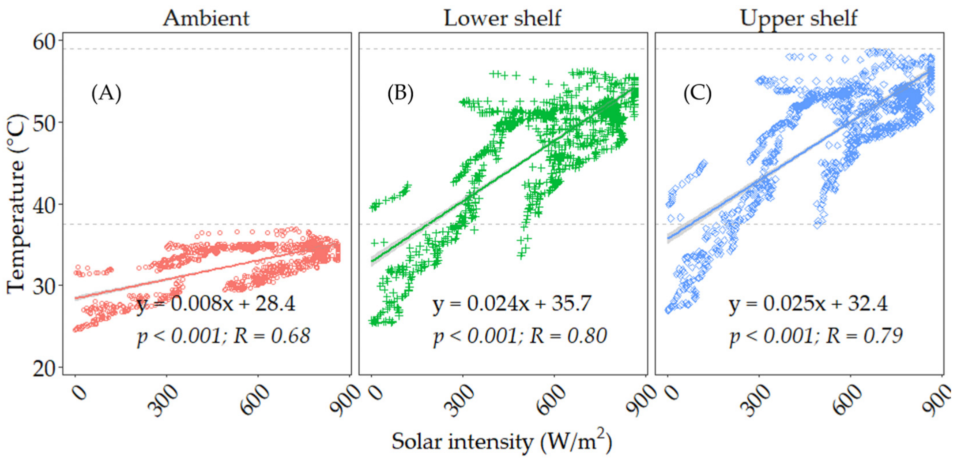

Figure 6. Comparison of changes in temperature outside and inside the solar dryer at the different levels of solar radiation recorded during the daytime. Letters (A), (B), and (C) refer to temperatures measured in the ambient condition, in the lower shelf, and in the upper shelf, respectively.

In addition to the determination of the solar radiation effect on temperatures, the relationship between the ambient, lower-shelf, and upper-shelf temperatures and time within the pre-determined period was also detected and was very highly significant ($p < 0.001$, $R^2 = 0.98$; $p < 0.001$, $R^2 = 0.97$; and $p < 0.001$, $R^2 = 0.98$, respectively) (Figure 7). In all cases, the relationship had a concave shape and, according to the graph, the highest temperatures were observed between 11:00 and 13:00, during which the temperatures were 36.8, 56.2, and 58.7 °C for the ambient, lower shelf, and upper shelf, respectively.

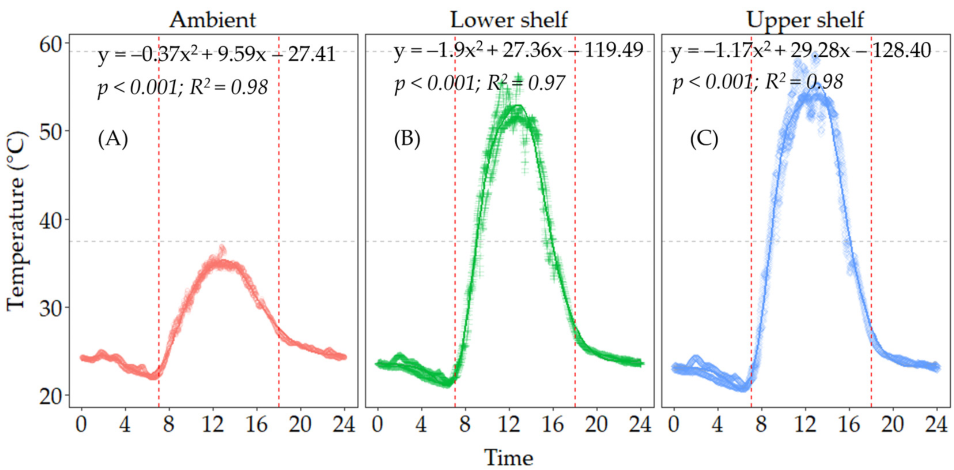

Figure 7. Comparison of changes in temperature outside and inside the solar dryer recorded every minute in 24 h. Letters (A), (B), and (C) refer to temperatures measured in the ambient condition, in the lower shelf, and in the upper shelf, respectively.

3.3. Comparison of Relative Humidity over Time

The relationship of relative humidity in both sun-drying and solar drying was found to be very highly significant with respect to the time ($p < 0.001$, $R^2 = 0.91$ and $p < 0.001$, $R^2 = 0.93$, respectively), having a convex parabolic shape (Figure 8). According to the graph, relative humidity in both drying techniques dropped over time during the experimental hours. Nevertheless, relative humidity inside the solar dryer dropped faster and was lower than in the open air. Ambient relative humidity decreased from 75% at 8:00 to about 40% between 13:00 and 16:00, while relative humidity inside the solar dryer dropped from about 100% at 8:00 to about 20% at 12:00 (Figure 8). Then, it increased slightly to 30% at 16:00. Technically, the higher the temperature, the drier the air. Because the temperature inside the solar dryer was higher, relative humidity became lower when compared to traditional sun-drying.

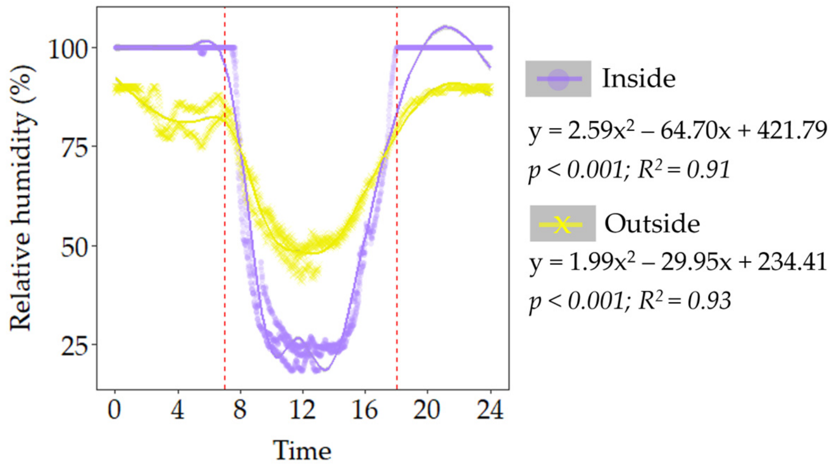

Figure 8. Comparison of relative humidity over time between traditional drying and the use of the solar dryer.

3.4. Relationship between Relative Humidity and Temperature in Solar Dryer

Temperature inversely affected relative humidity, and the shape was a descending exponential graph ($p < 0.001$, $R^2 = 0.98$; Figure 9A). Relative humidity dropped from about 90% at a temperature of 30 °C to 23% at an average temperature of nearly 60 °C. Using the function, an increase of one degree Celsius in temperature may lead to a 4% decrease in relative humidity inside the solar dryer.

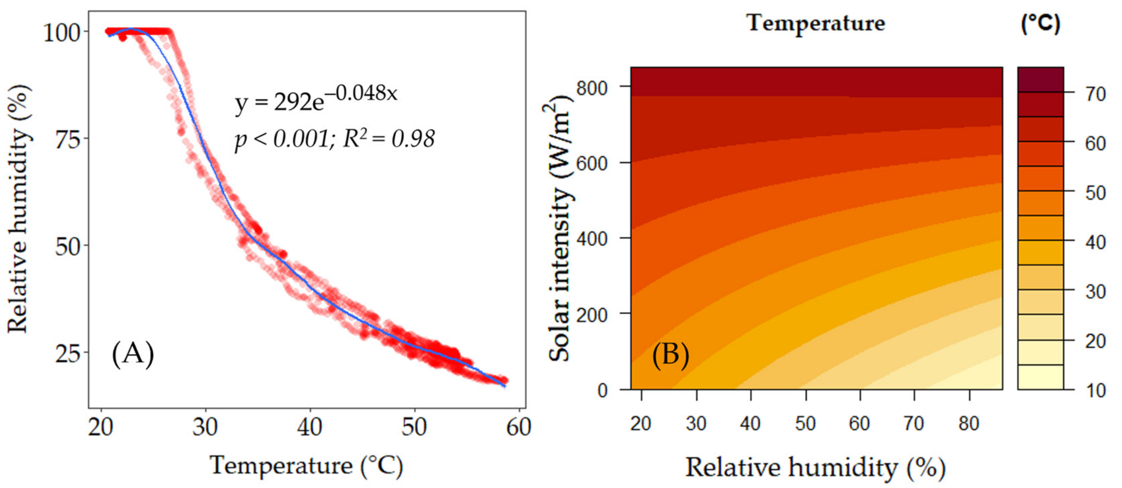

Figure 9. Relationship between relative humidity and temperature recorded in the solar dryer (**A**) and the best model of temperature as a function of relative humidity and solar radiation (**B**).

3.5. Relationship between Solar Radiation, Relative Humidity, and Temperature inside the Drying Chamber

Correlations among all climatic parameters measured both in the ambient condition and inside the drying chamber were detected (Table 1). In all cases, relative humidity had a strong and inverse relationship with solar radiation and temperature, both of which had a strong and positive relationship. Afterwards, several models were run to create functions of the temperature inside the drying chamber with respect to relative humidity inside the drying chamber and solar radiation and then evaluated using AIC to determine the best model (Table 2). In the test, the best model was $z = 59.40 - 0.44x + 0.02y - 0.001xy$ and, according to the graph (Figure 9B), lower relative humidity, but higher solar radiation, may lead to an increase in the temperature inside the solar dryer.

Table 2. Determination of the best model for temperature as a function of relative humidity and solar radiation, evaluated using AIC.

Formulas	K	AICc	Delta_AICc	ModelLik	AICcWt	LL
$z = 59.40 - 0.44x + 0.02y - 0.001xy$	5	4293.78	0.00	1	1	−2141.86
$z = 06.92 - 0.50x + 0.01y$	4	4753.89	460.11	0	0	−2372.93
$z = 48.80 + 129.76x^2 - 103.31y^2$	4	6858.86	2565.08	0	0	−3425.41

Note: "x", "y", and "z" refer to relative humidity, solar radiation, and temperature, respectively. These formulas were based on the data inside the solar dryer.

3.6. Comparison of Dried Fish Weight and Moisture

The initial weight of fish prepared for drying was compared between traditional drying and the use of a solar dryer. A significant difference was not detected ($p = 0.853$; Table 3), meaning that the average weight of prepared fish was the same in both cases. The final weight of dried fish between traditional sun-drying and the use of a solar dryer was significantly different ($p = 0.036$). The fish in the solar dryer lost more weight during the same time frame, resulting in higher moisture losses.

Table 3. Comparison of the weight and moisture of dried fish measured initially before drying and at the final stage after drying.

Fish for Drying	Drying Stage	Traditional Drying	Solar Dryer	Grand Mean	Difference	Pr (>|t|)
Weight (kg)	Initial	1.05 ± 0.09	1.03 ± 0.05	1.04 ± 0.07	0.02	0.853 ^{ns}
	Final	0.58 ± 0.03	0.48 ± 0.02		0.10	0.036 *
Moisture (%)	Initial	80.2%	82.1%	81.1%	−1.9	0.065 ^{ns}
	Final	49%	45%		10	0.045 *

Note: Asterisk (*) means significant difference at $\alpha < 0.05$, while "^{ns}" means non-significance. Grand mean is applied between the two drying techniques when significance is not detected.

3.7. Dried Fish Quality

The quality of fish products dried in traditional sun-drying and a solar dryer was compared with the Cambodian dried fish standard (Table 4). The result shows water properties in both drying methods abided by the standard (<0.78). Meanwhile, the sugar content was also in compliance with the standard. Ash was lower in dried fish experimented with the use of a solar dryer, while protein content in both drying techniques was similar to the standard. In the analysis of biological properties, *E. coli* was not detected in dried fish experimented upon with both drying techniques but Salmonella was found in fish dried in a traditional way.

Table 4. Comparison of dried fish quality using traditional drying and solar dryer with the standard values.

Parameters	Dried Fish Quality		Standard
	Traditional Drying	Solar Dryer	
Moisture (%)	49 **	45 ^{ns}	<45
Water (Aw)	0.75 **	0.70 *	<0.78
Salt (% WB)	6.7 ***	6.6 **	<10
Sugar (% WB)	8.1 ^{ns}	7.2 ^{ns}	<8
Ash (% WB)	11.1 *	9.0 ^{ns}	<9
Protein (% WB)	49.2 *	48.1 **	40–45
E. coli	ND	ND	-
Salmonella	*Salmonella* spp.	ND	-

Note: Dried fish samples were compared with the given national standard values using a one-sample *t*-test. Asterisks "*", "**", and "***" mean significant differences at <0.05, <0.01, and <0.001. Meanwhile, abbreviations "Aw", "WB", "^{ns}", and "ND" refer to water activity, wet basis, non-significance, and "not detected," respectively.

4. Discussion

Solar radiation was observed to change according to the time in 2024. Its pattern is fixed, being flat during the evening and at nighttime, but it has a concave parabolic shape, going from 7:00 to 18:00. Peak solar radiation is observed to be from 11:00 to 13:00. NASA reported that peak average solar radiation at 1361 W/m^2 [55], while the peak varies from 1330 to 1400 W/m^2, depending on the position of the Sun closest to the Earth [56]. However, only about 1000 W/m^2 (70%) can reach the Earth due to atmospheric absorption and reflection [57]. Peak solar radiation measured in the study was roughly 889 W/m^2 (90%) of the solar radiation available on Earth, and this is because Cambodia is close to the equator. With such substantial solar energy sources for use [58], the use of the solar dryer can benefit fish drying. Many studies found similarities with this research in terms of changes in solar radiation over time [59–61]. However, peak solar radiation varies by country and weather. Because this research was carried out in Cambodia in the early dry season, the peak solar radiation was estimated to be almost 900 W/m^2, while a study by Ennisioui et al. [59] in Tanzania found it to be 1140 W/m^2. In the USA, it was only 500 W/m^2, and this might be related to the season of the experiment [60]. In a study by Shrestha et al. [62], the peak solar dryer radiation was around 700 W/m^2 in Bangladesh. However, another study by Wazad et al. [61] in the same found that peak solar radiation reached almost 1000 W/m^2. Different maximum solar radiation values were observed in those studies because they depend upon geographical location, time of the day, season, local landscape, and local weather [63].

Using solar dryers can produce higher temperatures inside when compared to traditional drying. This study found that the temperature inside the solar dryer, used for drying giant snakehead, was high during the daytime, about 1.7 times higher than traditional sun-drying. Its highest temperature could reach almost 60 °C, while the ambient temperature ranged from 30 to 36.8 °C. Many studies also found that high temperatures could be obtained using solar dryers to dry fish or agricultural products. Heilporn et al. [25] experimented with drying 50 kg of tilapia for each of the five different mobile solar dryers in comparison with traditional sun-drying. The result indicated the temperature inside those solar dryers was around 60 °C, while fish were protected from dust, rain, or bugs. Meanwhile, in traditional drying, fish were exposed to those contaminants. Other research also shows that the use of solar dryers was superior to traditional drying, including a research study on catfish by Olokor and Omojowo [64], who developed two solar dryers. The temperature was almost 50 °C, while the dried fish quality could also be maintained. According to a study by Ennissioui et al. [59], who developed an indirect solar dryer, the maximum temperature obtained was about 58 °C, which was almost similar to that of the solar dryer tested in this research. A solar dryer with thermal energy storage (TES) could retain a temperature of 50–60 °C for seven hours from 11:00 to 18:00, while the ambient temperature was around 30 °C during that same period [65]. The reason that the temperatures were the highest during those hours was because the Sun was right above the experimental location [66].

Excluding the period of 8:00–17:00, the temperatures outside and inside the solar dryer in this study were not different and had the same trend. This was similar to many research studies on the application of solar dryers for drying fish or products [67–69]. In this study, relative the humidity measured inside the solar dryer dropped from about 100% to about 20% in three hours and remained constant for another 5 h before going up at sunset, while the lowest ambient relative humidity was observed to be around 50% before going up again after sunset. It is clear that during peak hours, the relative humidity measured inside the solar dryer was half the ambient humidity due to hotter air inside the drying chamber. Many studies indicate that relative humidity inside solar dryers drops faster and is much lower than ambient humidity during the daytime. A solar dryer developed by Ennissioui et al. [59] to dry banana slices had a relative humidity of 10% (WB) from 11:00 to 18:30, while ambient relative humidity was not less than 30% (WB). The reason why there was a faster drop in relative humidity inside the drying chamber was due to an increasing temperature that heats up the air inside. Hot air absorbs more liquid, thus reducing relative humidity. The lower the relative humidity, the faster the drying [70]. Temperatures inside the solar dryer became higher than the ambient temperature during the daytime due to solar radiation that heats up the air [71]. The result of this study was similar to the research by Seveda and Jhajharia [72] and Susuk et al. [73], who found that when solar radiation increased, so did the temperature in solar dryers. However, the temperatures obtained using the solar dryers in their research were lower than in this study. The duration for drying apples and apricots was saved 1.5–2 times using solar dryers when compared to traditional sun-drying [74].

In this study, it is clear that temperatures measured both inside and outside the solar dryer had a strong and positive relationship with solar radiation, while relative humidity in both cases had an inverse relationship with solar radiation. Shrestha et al. [62], who studied the relationship between relative humidity, air temperature, and solar radiation, also found the same results, meaning that the higher the solar radiation, the higher the temperature and the lower the relative humidity. When solar radiation is emitted to the Earth, whose atmosphere acts as a fluid, the air becomes warmer, resulting in an increase in temperature [75]. Warmer air also has the ability to absorb more water than cooler air, which reduces ambient relative humidity faster [75,76].

In this study, the weight and moisture of dried fish in the solar dryer and traditional drying were compared in two periods: right before and after drying. Both initial weight and moisture were not different, but after 8 h of drying, the moisture of the fish dried in the solar dryer dropped from about 100% to 45% (WB), while the fish dried in traditional sun-drying had a moisture content of 49% (WB) during the same period. Many studies also suggest that using solar dryers of all kinds could potentially lower the moisture of agricultural products faster than traditional sun-drying. For example, mola carplet was dried in three different ways, via traditional drying, a tunnel solar dryer, and a rotary solar dryer; among them, using the tunnel solar dryer could lower fish moisture to about 14–19%, while traditional sun-drying had a moisture content of about 26.5%. This moisture was much lower than the experiment in this study, but their experimental duration was not mentioned. A solar dryer used to dry Bombay ducks could potentially reduce its moisture from 90% to 15% in 9 h, while it took 20 h for traditional sun-drying [27]. The moisture of dried mackerel fish was also compared between traditional drying and solar dryers fabricated by Chavan et al. [77]. The finding showed that the initial and final moisture was 73% and 17%, respectively. Traditional sun-drying took 44 h, while the use of the solar dryer took only 24 h, which saved about half of the time needed for drying. For longer use and consumption safety, the moisture content of dried fish for commercial purposes should be in the range of 18–25% because it can be prevented from being attacked by mold [78]. Bacterial activities are also stopped at a moisture content below 25% [79]. Moisture content below 15% makes dried fish brittle and hard to eat [80]. In contrast, the moisture content of dried fish found in this study was in the range of 45–49%, measured directly after the drying was finished. These percentages exceed the recommended moisture for the prevention of mold growth. However, this range is quite common for fish processors in Cambodia because they normally dry fish for 1–2 days, and then start sales directly and continue to hang them dry at the same time [28]. Several studies also found that dried fish sold at the market by fish processors had moisture content in the range of 36.1–52.0% [81]. Rasul et al. [82] mentioned that dried fish with a moisture content of 25–40% had a unique taste and flavor, while it is also rich in protein.

A comparison between traditional sun-drying and the use of solar dryers was used to analyze fish quality, based on the Cambodian dried fish standards. It was found that the parameters of water activities, 0.75 in the traditional drying method and 0.70 in the solar dryer method, were compliant with the standard. This result was also aligned with the findings of [83] and Fasuan et al. [84], who stated that water activity below 0.75 was safer and more capable of controlling pathogenic bacteria and fungi.

Moreover, although *E. coli* was not detected in this study, Salmonella was found, which could pose risks to human health. Nevertheless, bacteria were not detected in fish dried in the solar dryer. Many studies indicated that sun-dried fish are not safe to eat because of being contaminated with harmful bacteria. Hasan et al. [85], whose research was on rotary and tunnel solar dryers, also mentioned that sun-dried fish were contaminated with bacteria, while Maqsood et al. [86] also found *E. coli* on sun-dried fish. Majumar et al. [87] found both *E. coli* and Salmonella in sun-dried fish.

5. Conclusions

This study compared the performance of a locally made solar dryer in comparison with traditional drying, considered a control. Climatic parameters were collected using a self-developed sensor, while fish weight and moisture losses were detected using a portable moisture meter. It can be seen that solar radiation available in Cambodia is so high because this country is near the equator and the experimental period was in the early dry season. Moreover, the temperatures created inside the solar dryer were much higher than those of traditional sun-drying, while reducing relative humidity faster. This means that fish being dried in the solar dryer tend to dry faster when compared to traditional drying. In the study, the initial weight of the fish prepared for drying in both methods was similar but at the final stage, the weight was lost faster with the use of a solar dryer, thus leading to lower fish moisture. In terms of quality, traditionally dried fish were infected with Salmonella, which can affect human health when it is eaten. More importantly, equations related to the operation of solar dryers in terms of relative humidity, temperature, and solar radiation were created for better prediction and application.

This study found that the use of the solar dryer was more effective when compared with traditional sun-drying within the same drying period, which was 8 h. Lower final moisture content in the solar-dried fish means that the actual time to arrive at the same moisture content was shorter for the solar dryer. Despite that, the difference was not much. Thus, future studies should focus on modifications to the ventilation systems to ensure much faster drying to remove moisture from the solar dryer, which can lead to time saving. A hybrid drying system should also be considered in future studies to maintain high temperatures even at nighttime. In this study, the presence of Salmonella could be detected, but without knowing its amount, so it was hard to check if it met the standard. Thus, identifying and counting bacteria are also important for future studies to ensure food safety.

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