Design and Development of Solar Dryer for Local Seaweeds (Kappaphycus spp.)

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Design and Development of Solar Dryer for Local Seaweeds (*Kappaphycus spp.*)

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Abstract: *This study developed and evaluated a solar dryer for local seaweeds. The drying behavior of seaweeds was examined and fitted with different drying models. The most suitable model is selected based on the quality of fit, which has the highest value of the coefficient of determination (R^2) and the lowest value of root mean square error (RMSE) and mean bias error (MBE). The result shows that the Midili-Kucuk is the best-suited model for predicting and describing the drying behavior of local seaweeds with an R^2, RMSE, and MBE values of 0.999, 0.01, and 0.0001, respectively. A comparative analysis was conducted between the sun-drying and the developed solar dryer regarding their drying rate and drying time. The independent sample t-Test was used to evaluate the significant difference. The analysis of the drying parameters showed that the developed solar dryer is significantly advantageous in terms of drying rate and drying time.*

Keywords: Drying behavior; Drying kinetics; Seaweeds; Solar dryer

1. INTRODUCTION

Seaweed (Eucheuma spp. and Kappaphycus spp.) is one of the significant sources of natural fiber and carrageenan for cosmetics and food processes. As indicated by [1], seaweed as an ingredient in the food industry often requires it to be dried before use (for carrageenan production). In the Philippines, seaweed is among the top aquaculture commodities in this current situation [2]. Additionally, seaweed farming generates income for more than 500,000 people and over 100,000 families living along coastlines and many islands [3]. Seaweed production accounts for over half of aquacultural assets, employing more than 200,000 fishermen and 30,000 traders, making it one of the most profitable agricultural sectors [4]. The post-harvest activity involved in seaweed production is drying. Careful post-harvest treatment is required to maintain the crop's value.

The drying of seaweeds is done mainly through the sun-drying method. The most common method is sun-drying, which spreads the seaweed evenly on the platforms or ground level. It usually takes 2 to 3 days to obtain a moisture content of less than 35%, which is the desired moisture content by buyers [5]. Another method is called the hanging method which the newly harvested seaweeds are hung on a wood or bamboo hanger. However, the current drying methods of seaweed have many disadvantages, such as being weather dependent and exposed to dirt and unwanted materials. Also, a sudden occurrence of rain may hinder the drying process and cause decomposition and damage to seaweeds [6]. Hence, developing an enclosed solar dryer for local seaweeds for village-level operation is highly needed.

Developing a solar dryer for seaweeds is a significant attempt to improve seaweed farmers' drying methods and minimize human labor. It was a village-type dryer that was designed to be simple to construct and can be replicated easily. The enclosure of the solar dryer protects the seaweeds from weather disturbances; thus, the dryer can improve the quality of the dried seaweed.

2. MATERIALS AND METHODS

2.1 Design of Solar Dryer

The design of the solar dryer considered the availability, specification, and selection of appropriate materials to meet the general objectives of the study. The design also considered the dryer capacity to accommodate drying the seaweeds placed inside the chamber. Furthermore, the ergonomic aspect was considered to fit the average Filipino height while standing during the operation.

The designed solar dryer adapted the concept of passive drying, wherein air is naturally heated and circulated by buoyancy force, wind pressure, or a combination of the two [7]. When the solar radiation strikes the dryer's outer surface, the heat energy is delivered to the walls, roof, and space enclosed by the solar dryer. And when the air enters the drying chamber through the side openings, the heat gained is distributed throughout the dryer. As a result of the accumulated heat energy through radiation and convection, the water vapor inside the product evaporates and continues until the sample reaches its moisture equilibrium [8].

The structural design is based mainly on the usual type of greenhouse dryer, which is enclosed with the use of the 200-micron UV-plastic material. For maximum capturing of the free solar radiation, the roof was tilted at an angle of 15 degrees [9]. The roofing has a side lapping of 0.20 m for both sides to avoid the seaweed from being in contact with water when it rained. Figure 1 and 2 shows the various parts and description of the designed solar dryer. The main component of the solar dryer is the drying chamber. The drying chamber has a door-type, open upward and with an installed stick for keeping the door open during loading and unloading of seaweeds. It is elevated 0.65 meters from the ground and is enclosed with a UV-plastic sheet. The drying chamber is enclosed to maximize heat retention, avoid external contamination, and protect from unpredictable weather conditions. The enclosure extended up to one-half of the length of the small post. The chamber also has a 0.15-meter opening on both sides. The drying floor is made of a 1.5cm x 1.5cm mesh fish net, serving as the drying tray of the seaweeds. The fish net was used to cover the drying floor and the sides are adapted to allow the air intake and natural ventilation for proper air circulation inside the drying chamber. Figure 1 below shows the working design of the seaweed's solar dryer.

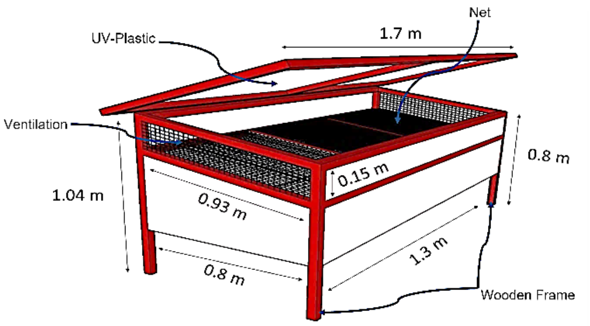

Fig. 1. Working Design of Seaweeds Solar Dryer

2.2 Experimental Set-up and Procedure

There were two series of drying experiments done in this study. The solar dryer was placed in an open field with no obstruction from the sun. All drying experiments conform to the thin layer drying, where samples are dry as one layer. The drying process starts at 8:00 AM and ends until the seaweed reaches the bone-dry weight. The temperature and relative humidity inside the dryer and the weight of the seaweeds were measured every thirty minutes. The first drying experiment was for the drying kinetics of seaweeds under the solar dryer. The second experiment is the comparative analysis between the developed solar dryer and the sun drying in terms of drying time and drying rate. The sun-drying process was spreading the seaweed on a wood platform with a fish net and letting the direct sunlight remove the moisture content on the sample. The drying kinetics experiment used one (1) kg of seaweed samples. And for the comparative analysis experiment, 0.5 kg of seaweed samples were used with three replications made for the drying experiment. The sample's initial moisture content wet basis was determined using the oven-drying method. The initial moisture content of the samples was 91.2 %.

2.3 Data Gathered

The following data were gathered during the experiment.

1. The temperature (inside and outside) and relative humidity in the solar dryer and the sun-drying method.
2. The moisture content of seaweeds, %
3. Drying time, hr

The following data were calculated using the measured data in the experiment.

4. The moisture ratio
5. The drying rate, kg/min

2.3.1 Determination of Moisture Content of Seaweed

The determination of the initial moisture content of the raw seaweeds sample and the final moisture content (wet basis) of the dried seaweeds sample was done through the oven-drying method. The samples were placed in the oven at a constant temperature of 80˚C to attain their bone-dry weight. The sample's moisture content was then calculated by two methods based on either a wet or dry basis using the following equation.

$$MC_{wb} = \frac{W_o - W_f}{W_o} x100 \quad (1)$$

Where:

MC_{wb} = Moisture content wet basis, %
W_o = weight of the sample before drying, g
W_f = weight of the sample after drying, g

$$MC_{db} = \frac{W_o - W_f}{W_f} x100 \quad (2)$$

Where:
MC_{db} = Moisture content dry basis, %

2.3.2 Determination of Drying Rate

The drying rate DR is calculated using MC at two successive times divided by the change in time (dt) and is shown as,

$$DR = \frac{dMC}{dt} = \frac{MC_{t+dt} - MC_t}{dt} \quad (3)$$

Where:

MC_{t+dt} = moisture content at t_1
MC_t = moisture content at t_2
dt = change in time ($t_1 - t_2$)

2.3.3 Mathematical Modelling

The drying kinetics of the seaweed dried under the solar dryer can be determined using the selected drying model (Table 1).

Table 1. Selected Drying Kinetic Models [10]

No	Model Name	Model
1	Newton	$MR = \exp(-kt)$
2	Page	$MR = \exp(-kt^n)$
3	Modified Page	$MR = \exp(-(kt)^n)$
4	Henderson and Pabis	$MR = a \exp(-kt)$
5	Midilli–Kucuk	$MR = a \exp(-kt^n) + bt$

The Moisture Ratio (MR) can be calculated as follow:

$$MR = \frac{MC_{db} - M_e}{M_o - M_e} \quad (4)$$

Where:

MC_{db}= moisture content dry basis
M_e= equilibrium moisture content
M_o= initial moisture content

The moisture ratio is simplified as follows due to relative humidity variations in the dryer [11].

$$MR = \frac{MC_{db}}{M_o} \quad (5)$$

The statistical measures value like the coefficient of determination (R^2), mean bias error (MBE), and root mean square error (RMSE) were used to determine the quality of the drying model. The highest R^2 values and the values of the lowest MBE and RMSE were selected to estimate that the drying curve is the best [12]. The R^2, MBE, and the RMSE were calculated using the equations 6, 7, and 8, respectively.

$$R^2 = 1 - \frac{\sum_{i=1}^{N} (MR_{pre,i} - MR_i)^2}{\sum_{i=1}^{N} (MR_{exp,i} - MR_i)^2} \quad (6)$$

Where:

R^2 = Coefficient of determination
$MR_{pre,i}$ = predicted moisture ratio
$MR_{exp,i}$ = experimental moisture ratio
N = number of observations

$$MBE = \frac{1}{N} \sum_{i=1}^{N} (MR_{pre,i} - MR_{exp,i})^2 \quad (7)$$

Where:

MBE =Mean bias error

$$RMSE = \left[\frac{1}{N} \sum_{i=1}^{N} (MR_{pre,i} - MR_{exp,i})^2\right]^{\frac{1}{2}} \quad (8)$$

Where:

$RMSE$ = Root mean square error

2.4 Statistical Analysis

To analyze the data gathered during the first experiment, the non-linear regression techniques were used to obtain the different constants and coefficients in each selected model, using the SOLVER tool in Microsoft Excel based on the General Reduced Gradient (GRG) iteration method. The gathered data in the second experiment were analyzed statistically using a t-test for independent sample analysis in SPSS.

2.5 Financial Analysis

Financial analysis was conducted to evaluate the new technology's financial impact. The financial analysis estimates the profitability of using the machine from an investor's perspective. The project costs are compared to the expected revenue over the machine's lifespan. The following indicators discussed below are the medium for measuring the financial and economic impact of the technology. The financial analysis can also determine whether the newly developed solar dryer should be sold [13].

2.5.1 Net Present Value (NPV)

The Net Present Value (NPV) of a product is calculated from the present values of the net cash flows. It can be expressed mathematically by equation 9 below.

$$NPV = -C_o + \frac{C_1}{1+r} + \frac{C_2}{(1+r)^2} + \cdots + \frac{C_n}{(1+r)^T} \quad (9)$$

Where:

C_o = initial investment
C = cash Flow
r = interest rate
T = time

2.5.2 Internal Rate of Return (IRR)

The Internal Rate of Return (IRR) is the interest rate at which the NPV of costs throughout the product's life span equals the NPV of benefits. The IRR can be calculated using equation 10.

$$NPV = \sum_{t=0}^{T} \frac{C_t}{(1+\text{IRR})^t} - C_o \quad (10)$$

Where:

C_t = net cash inflow during the period t
IRR = the internal rate of return
t = the number of time periods

2.5.3 Benefit-Cost Ratio (BCR)

The Benefit-Cost Ratio (BCR) is a method for calculating the project's net benefits concerning its net cost. It can be expressed mathematically, as shown below.

$$\text{BCR} = \frac{\text{PV of benefit expected from the product}}{\text{PV of the Cost of the Product}} \quad (11)$$

2.5.4 Payback Period (PBP)

A product's Payback Period (PBP) is when a project's total cash flow becomes positive. It determines how fast you can recover the investment. It can be calculated using equation 12 below.

$$PBP = \frac{\text{Investment Cost}}{\text{Annual Cash Inflows}} \quad (12)$$

3. Results and Discussion

3.1 Working Principle of Solar Dryer

The solar dryer is associated with two types of heat transfer: radiation and convection. The developed solar dryer adopted the idea of a greenhouse effect where the solar energy is trapped inside by the aid of the UV-plastic sheet, thus increasing the drying temperature inside the drying chamber. The opening gaps in the drying floor allow the air to enter the chamber and circulate freely to distribute the heat energy into the raw seaweeds and exit in an open area. Figure 2 below shows the actual prototype of the solar dryer. A roof side lapping is more extended, about 10 cm compared to the working drawing, to fully protect the seaweeds from unpredictable rain.

Fig. 2. Actual Prototype of Seaweeds Solar Dryer

3.2 Drying Kinetics

Drying using the developed solar dryer takes 8 hours to bone-dry the seaweeds from initial moisture of 90.3%. Figure 3 shows the temperature and relative humidity plot inside the solar dryer, ranging from 37˚C to 48˚C and 45 % to 70%, respectively. It can be observed in the figure that there is a variation in values of temperature and relative humidity. This event is merely due to the conditions outside that vary at a particular time. It can also be observed that when the temperature rises, the relative humidity falls, causing the air to become drier. When the temperature drops, the air becomes wet, causing the relative humidity to increase.

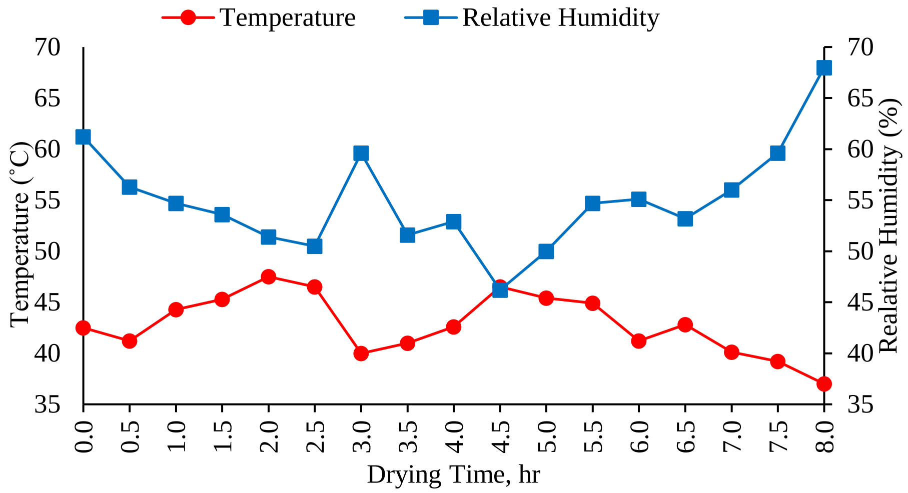

Fig 3. Recorded Temperature and Relative Humidity

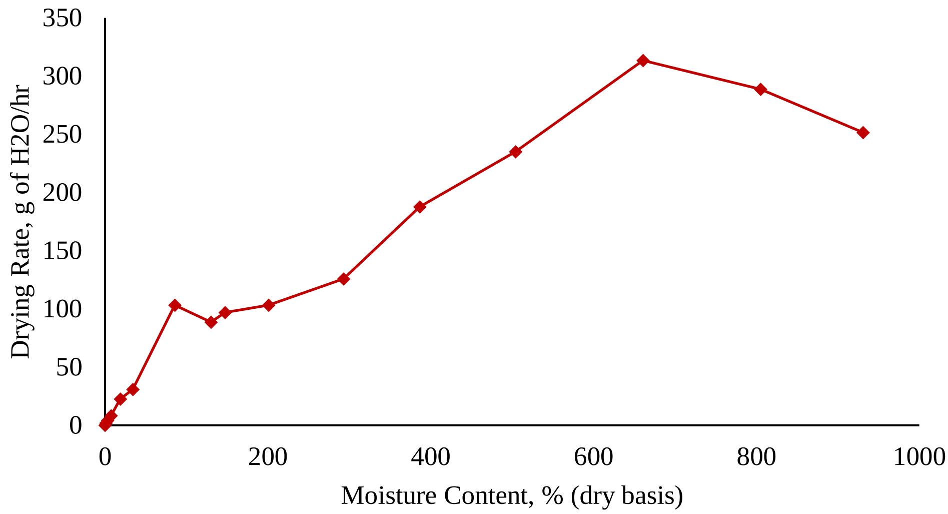

Fig. 4. Variation of drying rate with moisture content

The drying rate was calculated and plotted. The drying curve presenting the drying rate versus the moisture content in dry basis is presented below (Fig. 4)

The drying curve of the seaweeds dried under the developed solar dryer follows the standard drying curve wherein the constant rate and falling rate period are present; however, the constant rate period is not significantly visible in the graph. The drying curve mainly shows the falling rate period. The constant period can be observed in the graph in a short period from the first sampling time to the third sampling (8:00 am to 9:30 am). After the third sampling time, the temperature increases, which follows the drying rate decrease (falling rate period). This result is mere because internal moisture is being removed during the falling rate period, and it takes enough time to remove the said moisture entirely; hence, the drying rate also decreases.

The moisture ratio was also calculated and plotted versus drying time, as shown in Figure 5. The moisture ratio decreases along with time, as observed in the figure. However, the moisture ratio from 3.5 hours to 4 hours is slightly steady, indicating small moisture removal. This also shows the beginning of removing internal moisture from the material, as indicated by [14] in their study of drying bamboo at varying temperatures.

3.3 Model Fitting

The non-linear regression technique using the SOLVER tool in Microsoft Excel based on the General Reduced Gradient (GRG) iteration method was used to obtain each model's different constants and coefficients. The different constants and coefficients are shown in Table 2. After the different constants and coefficients were determined, the predicted moisture ratio from the various models was calculated using their respective MR equations, as presented in Table 1. The experimental moisture ratio was plotted and fitted with the predicted moisture ratio from different drying models, as shown in Figure 6.

The best fit model was selected based on the calculated value of their R^2, MBE, and RMSE. The calculation revealed that among all the models, the Midili-Kucuk model obtained the highest R^2 value of 0.9988 and the lowest MBE and RMSE values of 0.0001 and 0.01, respectively, as presented in Table 2.

3.4 Comparative Evaluation Analysis

The drying performance of the developed solar dryer in terms of the drying rate and the drying time was evaluated by comparing it to sun drying. The temperature, weight, and relative humidity were recorded at 30-minute intervals. The temperature and relative humidity range were 31˚C-49˚C and 42%-83%, respectively. Table 3 below presents the summary of the result of the comparative evaluation. It can be seen in the table that the lowest drying time is 3.5 hours, and the highest drying rate is 0.12686 kg/hr, both at replication 3 under the developed solar dryer.

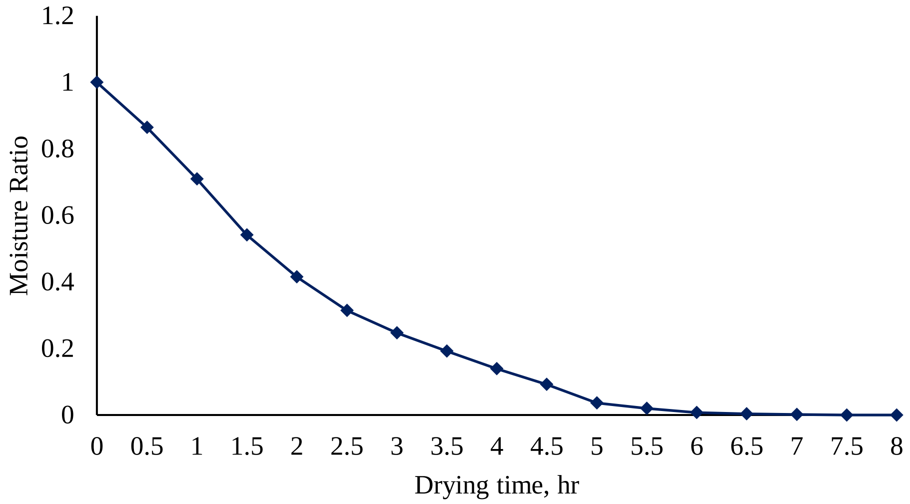

Fig 5. Experimental MR versus Drying Time

Table 2. Calculated drying constants and statistical measures value

Model	Drying constant	Drying coefficient	R^2	MBE	RMSE
Newton	k= 0.00793		0.992	0.0009	0.03
Page	k=0.001539	n=1.4934	0.999	0.0001	0.01
Modified Page	k=0.005	n=1	0.981	0.259	0.51
Henderson and Pabis	k= 0.00843	a= 1.0722	0.989	0.0026	0.05
Midilli-Kucuk	k= 0.0015	a= 0.9973 n= 1.33 b=0	0.999	0.0001	0.01

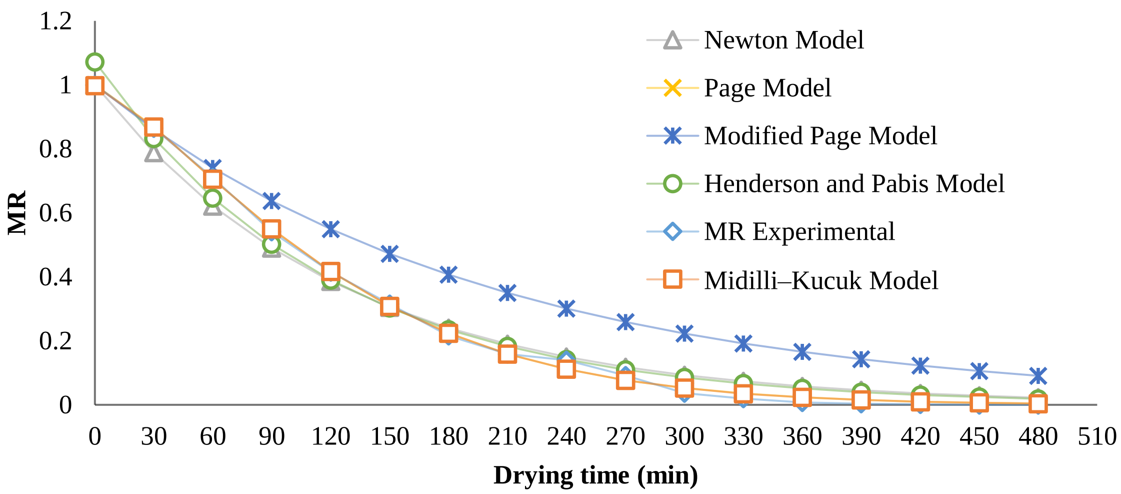

Fig 6. Predicted MR from different models versus experimental MR

The independent sample t-test with a 0.05 level of significance was used to determine if the mean of all measured data were statistically different, as presented in Table 4. The analysis revealed that the developed solar dryer was statistically different in drying time and drying rate, having a value of 4.17 hours and 0.10806, respectively, compared to sun-drying. This implies that drying using the designed solar dryer will shorten the drying time and increase the drying rate compared to the sun-drying. The fast-drying event was due to the accumulation of hot air inside the drying chamber, resulting in high moisture removal of the seaweed [15].

3.5 Financial Analysis

A summary of the financial analysis calculation is presented in Table 5. The developed solar dryer has a maximum drying capacity of 0.11 kg/hr, and the dried seaweed price per kilogram was based on the market value. It was assumed that the dryer has an estimated life span of one (1) year. A BCR value of 3.05, which is greater than 2, is the acceptable BCR for a developed technology. For every one (1) peso of investment to the developed technology will result in a 3.05 peso of profit for the seaweed farmers. Under a constant price and production cost assumptions, a relatively high NPV of income can be generated from the newly developed solar dryer having a value of ₱2,948.00 at a 10% discount rate. It is also estimated that the investment cost can be recovered at approximately four (4) months with a rate of return value of 205.35%.

Table 3. Summary Performance Between Solar Dryer and Sun-Drying

Replication	**Drying Rate (kg/hr)**		**Drying Time (hr)**	
	Solar Dryer	Sun-Drying	Solar Dryer	Sun-Drying
1	0.09778	0.07782	4.5	5.5
2	0.09956	0.08000	4.5	5.5
3	0.12686	0.08461	3.5	5.2

Table 4. Independent Sample t-Test between Solar Dryer and Sun-Drying

Types of Dryers	N	Drying Time (hr)	Drying Rate (kg/hr)
Solar Dryer	3	4.17^{a}	0.10806^{a}
Sun-Drying	3	5.40^{b}	0.08081^{b}

Note: Means with a different letter is significant with each other at a 5% level of significance

Table 5. Summary of the financial analysis of solar dryer

Item	**Value**
Drying Capacity	0.11 kg/hr or 0.88 kg/day (8 hr/day)
Investment Cost	Php 1,660.00
Drying Capacity per year	84.48 kg/year
Dried Seaweed Price	Php 60.00
Discount rate	10%
Estimated Life Span	One (1) year
NPV	Php 2,948.00
IRR	205.35%
BCR	3.05
PBP	0.33

4. CONCLUSIONS

Based on the results of the evaluation, the designed solar dryer is capable of drying guso. The most suitable model to describe the drying behavior of seaweed inside the solar dryer was the Midilli-Kucuk model, with 99.88% accuracy. There is an absence of a constant rate of the drying rate of seaweed dried under the designed solar dryer because of variations in temperature and relative humidity values inside the drying chamber. The drying performance of the developed solar dryer is significantly different compared to the sun-drying method in terms of drying time and drying rate. The solar dryer is effective in drying the guso at a short drying time at a faster drying rate. The financial analysis shows that the developed solar dryer is profitable and can provide a positive financial impact on the investor.

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