Performance Evaluation of Modified Solar Bubble Dryer for Red Pepper (Capsicum)

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ABSTRACT

Red pepper (Capsicum) is a spice type plant having major role in daily dish and plays an important role in the national economy of the country. One of the most serious challenges is getting the vegetable to market and selling before it spoils. The objective of this study was to design and manufacture modified solar bubble dryer to minimize and overcome the post-harvest loss of pepper vegetable crop. The experimental result showed that the efficiency of the dryer and the mass flow rate was found to be 22.6%, 3.53 $x10^{-4}\,kg\,/s$, respectively. It reduces the moisture content of the pepper from about 71% to 13% in 20 hours of operation. It lowers 20% drying time compared to an open-sun dryer. In addition to tis, the drying chamber temperature was higher compared to the ambient temperature by an average of 3 to 5°C.The logarithmic thin layer drying model fits for Red pepper with the respecting value of 0.96552, 0.00533 and 0.05003 values respectively. It will take a minimum of 21 months to return the initial cost of the solar bubble dryer. *Therefore, it is recommended that the modular feature of the solar bubble dryer is an option to dry vegetables to reduce the alarming rate of postharvest losses in countries where drying vegetables is common.*

Keywords: Crop, Pepper, Performance evaluation, Solar bubble dryer, Vegetable,

1. INTRODUCTION

Solar drying, which uses the sun's energy to reduce moisture content in agricultural products, is an efficient and sustainable alternative to traditional drying methods. Solar drying techniques have proven effective for crops with high moisture content, such as red pepper which require careful drying to prevent spoilage and retain nutritional and sensory qualities. The traditional way of open-air drying is widely used due to its low cost, yet it exposes produce to environmental contaminants and leads to significant quality degradation due to fluctuating temperatures and humidity levels. In contrast, solar dryers offer a controlled environment that enhance drying speed, preserve nutrients, and reduce the risk of contamination [1].

Red pepper (Capsicum) is rich in bioactive compounds, including vitamins A and C, capsaicinoids, and carotenoids, which are susceptible to degradation under improper drying conditions. Research highlights the importance of temperature and humidity control to preserve these nutrients effectively. In addition to this, its color and flavor are used as the raw materials for different industries [2]. The antioxidant vitamins have a very important function to protect against oxidative damage and to prevent various diseases like cardiovascular disease and cancer [3].

One of the techniques to overcome post-harvesting loss is to implement a proper drying system. Drying is a means of reducing the weight, which serves to easily transport from place to place, provide longer shelf life, and have a small storage area [4]. However, much of the existing research has primarily explored direct sun drying and conventional solar dryers. Studies specific to modified solar dryers designed for peppers are scarce, highlighting a gap in research on optimal drying methods that can preserve the unique nutritional profile of red pepper.

Drying red pepper in the sun requires a longer time and a large open area. The overall quality of the product may be affected by the availability of sunshine, insects, and fungal infestations. To get the best quality, the product needs to be dried in a shade. Pepper vegetable crop is 71% and 13% wet moisture content [5]. The traditional drying process of red pepper used to take around seven consecutive days, results in undesirable fermentation resulted in the market value of the product [6]. A solar dryer is one way of overcoming the problem of traditional open-sun drying.

The post-harvest loss of fruits and vegetables is estimated to be 30-40% in developing countries [7], and particularly about 20-30% of bell peppers and hot peppers are lost at the post-harvest stage every year [8]. These losses may be quantitatively measured by decreased weight or volume or can be qualitative, such as reduced nutrient value and unwanted changes to taste, color, and texture. The quantitative loss is caused by the reduction in weight due to factors such as spoilage and consumption by pests, as well as qualitative changes due to physical changes in temperature, moisture content, and chemical changes [9].

Inadequate methods of preserving agricultural produce, which may usually be produced in larger quantities during harvest, have remained one of the main problems of farmers. This loss is due to fungi attacks, insects, birds, rodent encroachment, and unpredictable weather effects such as dust, rain, and the wind, which have remained some of the inherent limitations of the traditional open-sun drying method widely being practiced by rural farmers [10]. The open-sun drying also results in physical and structural changes such as unnecessary shrinkage, case hardening, and loss of volatiles and nutrient components [11].

Different types of solar drying techniques have been tested for red pepper with distinct mechanisms for capturing and utilizing solar energy and degrees of success. Each method has distinct characteristics affecting product quality and drying efficiency.

Sun Drying: Traditional sun drying is widely used, especially in rural and low-resource settings. Although inexpensive, it exposes peppers to environmental contaminants, prolongs drying time, and often results in nutrient losses due to fluctuating temperature and humidity [12]. This method also produces inconsistent moisture levels, leading to higher risks of microbial growth and spoilage [13].

Conventional Solar Dryers: Solar cabinet dryers, among the most common solar dryers, enclose the product in a protected environment, reducing contamination and drying time. However, cabinet dryers often suffer from uneven heat distribution, which results in non-uniform drying and affecting product quality [14]. Noted that temperature control within cabinet dryers is often insufficient for consistent drying of high-moisture produce like peppers.

Hot-Air and Mechanical Drying: Mechanical dryers, which use electric or fuel-powered heat sources are faster and more effective in achieving uniform drying but are costly and energy-intensive. These dryers also risk nutrient degradation, as high temperatures can cause significant losses in bioactive compounds like vitamin C and carotenoids, particularly in sensitive produce like red pepper [15].

Solar Bubble Dryers: The solar bubble dryer is an innovative approach designed to address limitations in traditional solar drying systems by enhancing heat retention and drying uniformity. Using transparent plastic sheeting, the bubble dryer traps solar energy creating a greenhouse effect that maintains stable internal temperatures.

While solar bubble dryers have shown promising results with staple crops, there is limited research on their application for moisture-sensitive, nutrient-rich crops like red pepper. Investigating the performance of modified solar bubble dryers for pepper drying could provide valuable insights into balancing drying efficiency with nutrient retention, therefore meeting both quality and economic demands.

Despite the advances in solar drying methods, there is a lack of comprehensive research specifically focusing on solar bubble dryers for drying red pepper. Most existing studies address general solar drying methods but do not adequately explore how modifications in solar bubble dryers could improve drying rates, nutrient retention, and uniformity for high-moisture crops like peppers. Moreover, there is a need to analyze the economic feasibility and energy efficiency of these modified dryers to assess their potential as a practical solution for small- to medium-scale farmers. The reported research showed that this type of dryer is economically acceptable and environmentally friendly [16].

This study aims to fill these gaps by evaluating the performance of a modified solar bubble dryer for red pepper drying using locally available materials in order to reduce thea post-harvest loss. The research focused on optimizing drying parameters to achieve rapid drying, high nutrient retention, and energy efficiency. By addressing these gaps, the study aimed to advance knowledge on solar drying technologies, contributing to the development of more effective and sustainable drying methods for sensitive, high-value crops of red pepper.

2. MATERIAL AND METHODS

The solar bubble dryer (SBD) used in the study had a drying floor, top cover, fabric mesh tray, DC fan, and solar panel that completely operated independently from fuel or the power grid. The following materials were used for the construction of the solar bubble dryer. The drying chamber was where the drying sample was placed and heated by the hot air that came from the collector. The drying chamber frame was constructed from RHS metal that had a thickness of 1 mm. The total area of the drying chamber was 2000 mm x 620 mm and had a height of 500 mm. The dryer had one tray used to dry the sample having a dimension of 2000mm x 56mm positioned at the center of the dryer. It was made of fabric mashed as shown in Figure 1 to avoid corrosion and contact between the drying sample and the metal frame as well as the plastic cover of the dryer. It had very tiny holes used to transfer solar radiation in order to have a uniform drying and heat-exchanging process between the upper and bottom surfaces of the dryer. This result increase improves both the performance and quality of the pepper. In addition, this solar panel may be used to drive the fan and helps to inflate the plastic top cover. The plastic cover enhanced the quality by preventing impurities like dust, insects, etc. as well as ensuring proportional air movement to achieve the objective of this research. The chimney was used to facilitate the moist air to leave the dryer by enhancing its pressure.

Figure 1 shows the 3D modeling of the solar bubble dryer. The main part that differs from the existing dryer was the fabric mesh tray, which is located at the center of the dryer. The fabric mesh tray enables uniform energy and air circulation in the drying product. In addition to this, the transparent top cover and the absorber make the dryer generate the energy on both sides. Chimney is the other modified main part of this dryer, which used to pressurize the exit air. It used to improve the moisture removal rate and facilitate the exit air to leave the dryer before it created dew. This helps to reduce the drying time and to improve the quality and the uniform drying process of the product. As a result, it used to increase the efficiency of the dryer. The other modified part of this dryer is the bubble frame or the support of the top plastic cover, which helps to get the bubble shape of the dryer and carry the tray, which lets the drying product lay on it. In addition to this, it has a roller connection, which used to roll it in and out in the dryer. This makes the dryer portable and simpler to operate or handle by anybody.

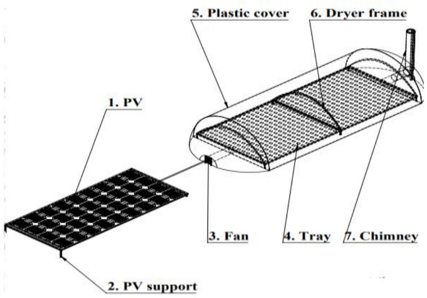

Figure 1 Design of solar bubble dryer developed using solid work.

Figure 2 shows the experimental setup of the dryer. The experimental set-up and the performance evaluation of the SBD dryer were conducted in the winter at AAiT mechanical engineering workshop. Addis Ababa, with a geographical location of latitude 9.2N and longitude 38.7E. The solar collector faced south with an east-west orientation and was tilted at 24.2°.

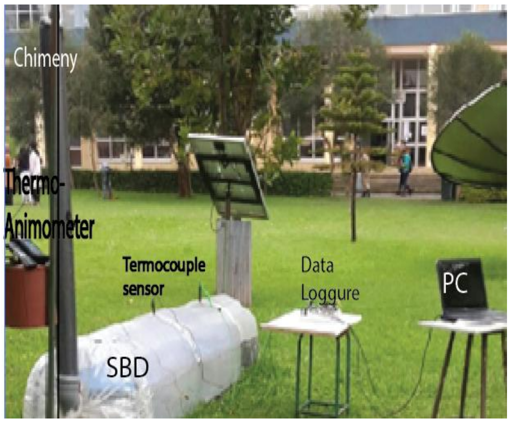

Figure 2 Experimental setup of SBD

Figure 3 shows the solar bubble dryer with respect to the convectional open sun dryers. As it is clearly seen that the pepper vegetable crop is exposed to open air and other impurities, the solar bubble dryer is protected from any type of external factors that cause damage or spoilage to the product. The materials used for the construction of the solar bubble dryer are listed in Table 1.

Figure 3 SBD and open sun drying

Table 1 Materials used for prototype model

No.	Part name	Material	Dimension
1	Collector and dryer cover	Plastic	4mx0.65mx0.5m
2	Dryer and tray support	(rectangular hallow steel) RHS	2mx0.62mx0.5m
3	DC Fan for air circulation	-	-
4	Solar panel	-	-
5	Fabric mesh or mosquito net	Tray	2mx.59m
6	Chimney	PVC	1.5m
7	Wheel for easily movement	Plastic made small wheel	-

2.1. Wet Basis Moisture and Dry Basis Moisture

Moisture content is one of the important parameters that determines the capacity of a solar bubble dryer. A drying product's moisture content is given either based on the total weight of the product to be dried or the amount of solid weight present in the product. It was calculated using the following equation [17].

$$MC(w.b)\% = \frac{M_w - M_d}{M_w} x100 \quad (1)$$

Where, M_w −weight of wet material

M_d- Weight of dry material

It is the other way of determining the amount of water present in the dried pepper vegetable crop. Even though it is not commonly applicable in most areas, it was found to be significant while calculating dry base-related calculations [18]. It can be easily determined using equation 2, once the percentage moisture content of the pepper is determined.

$$MC(d.b)\% = \frac{M_w - M_d}{M_d} x100 \quad (2)$$

2.2. Water to be Evaporated from the Drying Product

In the process of removing the moisture found in the pepper at the outer surface, it starts to evaporate, and the moisture content of the dried product found in the center dissipates and gets closer to the outer surface. This dehydration process depends on the porosity and surface area of the drying product. In addition to this, it will also be affected by the weather condition of the area where the pepper vegetable crop is being dried [18]. The amount of water content that could be removed was calculated using equation 3.

$$M_r = \frac{M_p(M_i - M_f)}{(100 - M_f)} \quad (3)$$

Where, M_P - the mass of the sample (kg)

M_i - primary vapor (% wb).

M_f - final vapor (% wb)

2.3. Moisture Removal Rate and the Amount of Air Required

The moisture removal rate is the amount of evaporated moisture over time that takes to completely remove the amount of moisture from the drying product [19].

$$DR = \frac{M_r}{t_d} \quad (4)$$

Where, M_r - the amount of moisture removed, (kg)

t_d - the time taken to dry the drying product, (hr)

The amount of air needed to evaporate the water content from the sample weight of the drying product can be determined using the equation explained by [20].

$$V_A = \frac{M_r(R_a - T_a)}{C_{pa}P_a(T_0 - T_f)} \quad (5)$$

Where, T_f= the final temperature at the end of the drying chamber

$$T_f = T_a + 0.25(T_c - T_a) \quad (5.1)$$

2.4. Heat Required to Remove Vapor Content

The amount of heat required to remove the moisture content from the drying product was evaluated using Eq. (6) [21]. It depends on the amount of water removed from the drying product and the dehydration rate of the pepper vegetable crop [21].

$$Q_{load}=M_r L_v \quad (6)$$

Where, M_r- the dehydration rate of the pepper (kg)

L_v- the latent heat of water from the surfaces of pepper vegetable crop, 2320 kJ/kg

Q_{load}_ amount of heat required to remove the moisture

2.5. The Amount of Mass Removed and Air Velocity

The amount of moisture removed from the drying product determines the duration to dry a particular amount of drying sample [22].

$$\dot{m}_a=\dot{\upsilon}_a \rho_a \quad (7)$$

Where $\dot{\upsilon}_a$-Volume flow rate of air

ρ_a-Density of air

$\dot{m}_a$- Amount of moisture removed from the drying product

The speed of exit air velocity is evaluated as the rate of discharge per the drying area of the dryer.

$$V=\frac{Q}{A} \quad (8)$$

Where, A- Area

Q- Discharge

V -speed of exit air velocity

2.6. Performance of collector, dryer and capacity of the dryer

The collector performance is expressed as the ratio of the amount of energy migrated from the collector to total solar incidence over the specified time [23].

$$\eta_c = \frac{v\rho\Delta T C_p}{I_c A_c \tau} x100 \quad (9)$$

It is the ratio of the amount of heat required to dry the drying product per the product of solar radiation, collector area, and time taken to dry the product. It is the main criteria to evaluate the performance of the given dryer [24].

Drying Efficiency,

$$\eta_d=\frac{M_w L}{I_c A_c t\tau} x100 \quad (10)$$

The capacity of the dryer can be determined once the volume of the drying product is determined. The volume of pepper vegetable crop may be obtained from equations given in [25] as:

$$\nu_y=W_T L_T Y_l \quad (11)$$

The total volume of the drying product on the tray may evaluated as;

$$\nu_T=n\nu_y=nW_T L_T Y_l \quad (12)$$

Where n- Number of tray

The relation between the bulk density and the total volume may be evaluated as follows:

$$W_w=\rho_b \nu_T \quad (13)$$

Where Y_l - Thickness of the pepper vegetable crop (m)

W_T- tray width (m)

L_T-tray length, (m)

M_p - the mass of the drying product (kg)

ρ_b- the bulk density of pepper vegetable, $402.1(\text{kg/m}^3$ [25]

$$L_d \cong L_T \quad (14)$$

2.7. Sizing of the Power of Fan and Determine the Capacity of the Solar Panel

The international standard of the conducive thermal comfort range for blowers found between 50 and 100cm. It can be related to that as $100\text{cm}=0.0491747\text{m}^3/\text{s}$ [26].

Fan horse power =
(Air flow×pressure)/(6320× efficency of fan) [24].

The efficiency of the fan ranged in between 70 and 85%. For this study, an axial fan that has the maximum efficiency was taken for adequate air circulation and optimum heat transfer rate in the drying chamber.

The capacity of a solar panel is based on the size of the panel. Panel generation factor and the size of the module determine the maximum watt that can be produced. In addition to this, the weather condition is also one of the determinant factors for the given solar panel. This study considered a 20-watt axial DC fan that runs for 8 hours per day to supply sufficient air for the drying product. Based on this, the daily energy consumption can be evaluated as [27].

$$\text{Daily energy consumption} = \text{power x time} \quad (16)$$

For PV Module Sizing a factor of 2.5 is reasonable [28].

$$\text{Total PV module needed}=\frac{\text{Total dayily energy consumption}}{\text{PV corection factor}} \quad (17)$$

$$\text{No. of PV module} = \frac{\text{Total PV Module needed}}{\text{Standard PV Module}} \quad (18)$$

2.8. Design of chimney

The chimney helped to pressurize the exit air to live the drying chamber before it created dew. This ensures the proportional drying rate of the drying product throughout the dryer.

$$M_e=M_r+M_a \quad (19)$$

Where M_e- mass of exit air (kg)

The density of air that enters the dryer may be evaluated as;

$$\rho_i=\rho_o\times\frac{T_o}{T_a} \quad (20)$$

Were, ρ_i – Air density (kg/m^3)

ρ_o - Density of air at 0°C (kg/m^3)

T_a- Ambient air temperature (°C)

T_0- Exit temperature (°C)

The height of the chimney was assumed to be 2 m, and the upward draft was calculated based on the equation as follows:

$$D_P=(\rho_i-\rho_e)\times H\times g \quad (21)$$

Were,D_P-Produced draft (kg/ms^2)

ρ_i - Density of inlet air (kg/m^3)

ρ_e - Density of exit air (kg/m^3)

g- Gravity (m/s^2)

The actual draft is the ratio of the product draft per the exit velocity of the air. It may be evaluated as follows:

$$V_eD_a=0.75\times D_P \quad (22)$$

D_a- Actual draft (kg/ms^2)

The exit air velocity has to be evaluated as the ratio of the square root of two times the actual draft per the exit density, as illustrated in Eq. (24).

$$V=\sqrt{\frac{2D_a}{\rho_e}} \quad (23)$$

Where V- exit air velocity (m/s)

The rate of exit air may be evaluated as the ratio of the rate of air required per number of chimneys found in the given dryer;

$$Q_c=\frac{Q_a}{n} \quad (24)$$

Where, Q_a – rate of expected air needed (m^3/s)

n- Number of chimney (assumed to be 1)

Since exit air is discharged using n chimneys, once the number of chimneys is specified, the rate of exit air can be evaluated using the Eq. (25).

$$\dot{\upsilon}_{ch}=\frac{Q_a}{n} \quad (25)$$

Where $\dot{\upsilon}_{ch}$ - volume flow rate (m^3/s)

Therefore, the area of the chimney may be evaluated based on the amount of air interring in to the dryer and its speed in the dryer.

$$a_{ch}=\frac{Q_a}{V} \quad (26)$$

Where a_{ch} - Diameter of chimney (m)

The diameter of the chimney was evaluated based on the area of the chimney and determined as follows:

$$d_{ch}=\sqrt{\frac{4\times a_{ch}}{\pi}} \quad (27)$$

Where d_{ch} - Diameter of chimney (m)

2.9. Sensor positioning of the dryer

The primary goal of this research was to address the problem of traditional ways of drying and improve the efficiency of the existing solar bubble dryer. Sensor position is one of the technical parameters to determine and analyze the distribution of the temperature, which originated from the collector of the dryer. Thermocouples were located in three different place a (inlet), b (middle), and c (outlet) as shown in Figure 4. Each thermocouple was connected with the data logger. Moreover, the data logger receives and transfers the data to the PC for further analysis.

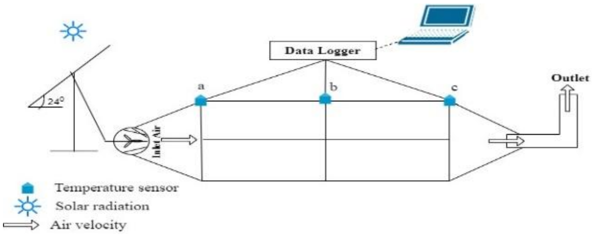

Figure 4 Sensor positioning and layout of SBD experimental set up

Figure 4 shows the positioning of the sensors Red dots represent the instrument used to measure the temperature integrated with the instrument called National Instrument NI cDAQ-9172.

3. RESULTS AND DISCUSSION

3.1. Moisture Removal Rate of SBD

Figure 5 shows the moisture removed from the sample which was measured in two ways: by using a device called a moisture meter, and by using an analytical balancing machine or analytical weighting scale. Moisture content of pepper was measured in both open-sun and solar bubble dryer methods in order to understand the difference between them by recording the result on the data spread sheet every 30-minute interval. The moisture content of the pepper did not build up every next day since it was packed in zipped plastic bag, which did not let it lose or gain moisture overnight. Moreover, zipped plastic was stored in a desiccator. As it is clearly seen in Fig.5, the final moisture contents of the sample pepper dried in the solar bubble dryer and the traditional type dryer were 13.6% and 17.7%, respectively, with a weight of 7,2233 g and 10.6163, respectively.

Figure 5 Final moisture content of pepper vegetable crop on both SBD and OSD

3.2. Drying performance

Figure 6 shows that drying performance were observed to be lower in the winter season than in the summer season due to the effects of rain, cold, and foggy weather, as well as low temperatures. [29]explained that the drying rate of the dryer gets higher when the drying air temperature provided by the solar collector gets high. This is due to the intensive heat and mass transfer followed by a high rate of water evaporation.

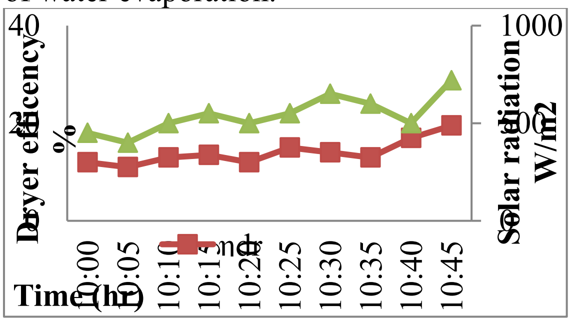

Figure 6 Dryer efficiency vs. solar radiation variation

Drying of red pepper in solar drying reduced the moisture content from approximately 71% to approximately 13% in 20 h. At the average solar radiation of 356.3 W/m2 and mass flow rate of 3.53 $x10^{-4}$ kg /s, and the collector and drying system efficiencies were 15% and 22.6%, respectively. Even though the initial moisture content of the pepper vegetable crop and rice are too different, this dryer efficiency is much more efficient and faster than what it was reported in [30].

3.3. Moisture Distribution

The moisture distribution of the pepper vegetable crop was faster than that of the open-air dryer. The weight loss was recorded every half-hour interval in order to realize the reduction weight of the drying sample. As it is known, if the drying process takes more than one day, the drying product may gain moisture content in the dormant time [31]. However, this problem was resolved using the equipment called a dissector that helps to contain the moisture or weight of the sample until the next experiment. This equipment resolves the re-watering phenomena of the pepper vegetable crop and helps accurately conduct the experimental process of the drying product.

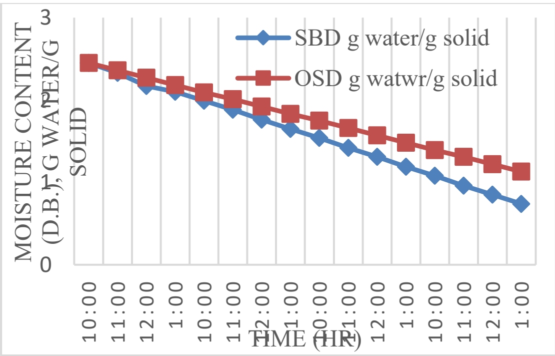

Figure 7 Moisture content (dry basis) with time of pepper vegetable crop for SBD & OSD

3.4. Drying Kinetics Models

The most used type of drying kinetics model was implemented in this study to determine the best one for drying pepper vegetable crops under a solar bubble dryer. This study was based on the maximum result and minimum value to determine the best type of drying kinetics for the drying product. Among them, the logarithmic model satisfied the requirement to be selected as the tine layer model for the drying process, and related results were reported in [32].

Table 2 Drying kinetics models of pepper vegetable crop

Model no	Model constant	x^2	R^2	RMSE
1	k=0.05837	0.00837	0.88904	0.09149
2	a=0.94208, k=0.05531	0.00824	0.89229	0.09076
3	**a=0.98796, k=0.04359, c=0.08125**	**0.00533**	**0.96552**	**0.05003**
4	a=0.47104, k_0=0.0552972, b=0.47104, k_1=0.0553017	0.00847	0.89229	0.09203
5	k=0.00688, n=1.164944	0.00817	0.90123	0.07028
6	a=0.01023, b=0.00025	0.00824	0.90032	0.08973

3.5. Payback Period

Payback period is one of the simplest methods to find out the period by which the investment on the project recovered from the net cash inflows, i.e., gross cash inflow less the cash outflows. In short, it was defined as the period required to recover the original investment cost. The payback period starts with a preconceived notion that the management wants to recover the cost of investment within a specific period. It is found that it may take a minimum of 21 months to return the initial cost of the solar bubble dryer. It is seen that the solar bubble dryer is feasible technically and economical when it is compared to a related dryer, which was reported in [33].

4. CONCLUSION

Proper drying of pepper vegetable crops has been one of the major problems in Ethiopia. The performance evaluation of the SBD dryer was conducted in the CoTBE mechanical engineering workshop in the winter season. The evaluated output indicated that the pepper vegetable crop moisture reduced from about 71 to 13% in 20 hours of operation. The temperature distribution and moisture removal rate were uniform in all locations of the SBD dryer during drying time. The total drying time of the dryer was 20 hours, saving 20% of the drying time of the pepper vegetable crop when it was compared with open sundries. The drying rate as well as the dryer and the collector efficiency were found to be 3.53 $x10^{-4}$ kg /s, 22.6%, 15%, respectively. The logarithmic thin layer drying model fits better for pepper vegetable crops than other models based on the value of R^2, x^2andRMSE. The analysis showed 0.96552, 0.00533, and 0.05003 values, respectively. It will take a minimum of 21 months to return the initial cost of the solar bubble dryer. It was economical and feasible when compared to similar dryers. Moreover, the technical performance and the experimental observation resulted in the finding that the pepper vegetable crop sample used to dry in the dryer has better quality, quantity, and proportional drying profile than open-sun drying. Therefore, it was concluded that the modified solar bubble dryer can be one of the options for drying pepper vegetable crops. It is recommended that this dryer is an option to dry vegetables to reduce the alarming postharvest losses in the country.

CONFLICT OF INTEREST

The authors declare that they don't have any conflict of interest.

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