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Design, Fabrication and Performance Analysis of a Mixed Mode Solar Dryer for Black Soldier Fly Larvae

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Abstract
The use of black soldier fly (BSF) for organic waste conversion and as an alternative source of animal feeds is sustainable and gaining momentum. The flies are easy to rear and the larvae is a rich source of crude protein, fatty acids, amino acids and vitamins that are important components in poultry, pig and fish feed. Prior to processing, the larvae must be dried up. This research is focused on the design, fabrication and performance analysis of a mixed mode solar dryer for black soldier fly (BSF) larvae. The mixed mode solar dyer constitutes two main parts: solar collector, and drying chamber with three trays was fabricate for the purpose and used. A sample containing 750g of BSF larvae were immobilized and dried to a constant mass of 302 g on the dryer. The maximum drying temperature attained during the drying process was 61°C, which corresponds to the highest intensity of solar radiation (833W/m^2) recorded at the experiment site 12.00 noon. The highest efficiency of the solar collector was 57.58% at 12.00 pm while the lowest collector efficiency was 33.9 % at 9:00 am.
Keywords: *solar dryer, Black soldier fly, performance, Efficiency*

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I. Introduction

Solar drying is one of the most popular and simplest methods of drying matter used by man since ancient times. Solar energy is freely available all year round in the tropical region and its significance is further emphasized by the high prices of fossils fuels and their negative impact on the environment (Prakash and Anil, 2014). In most developing countries, notably Kenya, farming is predominantly small scale, rainfed and provides the means of livelihood for most of the rural population. The farmers mostly use open sun drying to preserve agricultural products such as fruits, vegetables, grains and spices.

Open drying however, has a number of drawbacks such as exposure of the agricultural products being dried to rain, dust particles, fungi and wind. The products may also suffer interference from insects, birds, rodents and other animals as well as humans leading to contamination. Besides, the process of drying the product takes time, is difficult to control and is uneven hence degrading the product quality (Misha, S. et al, 2013). The use of solar dryers thus alleviates the challenges associated with open sun drying with a minimal additional cost.

Purohit, *et al.* (2006), compared the use of solar driers and open sun drying and established that drying agricultural produce is economical for cash crops and the use of solar dryer systems is justifiable. However, drying highly perishable products needs low-cost systems. Today, local materials can be used to develop inexpensive solar dryers.

Solar dryers are classified as direct, mixed mode, indirect or forced circulation type. In this study, a mixed mode solar dryer was designed, fabricated and analyzed on its efficiency for drying black soldier fly (BSF) larvae. The advantages of a mixed mode solar dryer compared to direct and open sun drying include good product quality and significant reduction of the duration of the drying process. Moreover, the main drying parameters - temperature and relative humidity are controlled and hence the drying process is uniform. As a result, the dried products can be preserved for an extended period and the weight of the product is significantly reduced hence making it easier to transport.

The black soldier fly (*Hermetia illucens)* is a non-pest insect of the *Stratiomyidae* family. At the adult stage, the fly is black, wasp like and about 20mm long. The black soldier fly (BSF) is known for its remarkable organic waste conversion abilities. The larvae have a dull and whitish colour and can reach up to 27mm in length, 6mm in width and weigh up to 220mg in their last larval stage. It has a voracious appetite for organic waste, a rapid growth rate and a nutrient-rich larvae that has been rapidly adopted as a sustainable feedstock for animal feeds and biodiesel (Wang *et al.*, 2019; Finke, 2013). The flies are easy to rear and the larvae is a rich source of crude protein, fatty acids, amino acids, vitamins that are important components in poultry, pig and fish feed. (Diclaro II *et al.*, 2009; Liu, *et al.,* 2019). The duo qualities of being rapacious feeders and being able to convert large amounts of organic waste normally found on farms and anywhere where people congregate makes the black soldier fly larvae an object of great interest to a wide variety of researchers.

Problem Statement

Black Soldier fly (BSF) has proved an essential component in the manufacture of livestock feeds and biodiesel. The high population growth rate currently being witnessed in Africa comes with both positive and negative effects. Some of the negative effects include constraints on key resources such as food and water, degradation of the environment and increased consumption that leads to an increasing level of greenhouse gas emissions that result in climate change. Consequently, the demand for interventions such as BSF larvae that can sustainably convert some of the increased levels of waste into useful byproducts is on the rise; their importance cannot be overemphasized. In most setups where BSF rearing is practised, open sun drying predominates; this is mainly because it is cheap. However, open sun drying is a slow process and its use is not suitable to meet the increased demand. Besides, it exposes the food products to insects, dust, mold, ultra violet rays and other sources of contamination (Phadke et al, 2015). These shortcomings result in a slow production process that yields a low-quality product. To address the aforementioned shortcomings, it is therefore necessary to innovate low-cost intervention measures that not only prevent external contamination, but also shorten drying time and produce a uniformly dried product. This study provides an intervention through the design, fabrication and performance analysis of a low-cost mixed mode solar dryer with the object of evaluating its ability to overcome the challenges identified.

II. Materials And Methods

Data Collection

Fresh black soldier larvae weighing 750g were immobilized and placed in a tray in the fabricated mixed mode solar dryer. As drying progressed, the ambient temperature and the temperature at solar collector inlet and outlet were recorded between 9.00 am and 06.00 p.m. in three-hour intervals. The total incident solar radiation. The air velocity was measured using a hand-held weather meter of model HP-866B-WM over the same period and at similar intervals.

Experimental Set up

Cheap and locally available materials were used to develop the mixed mode solar dryer. The main parts of the dryer include the solar collector and a drying chamber fitted with drying trays with transparent roof.

The solar collector was constructed with a 2 mm thick galvanized plate with the surface facing the sun painted black. The collector assembly was insulated with a 5 mm thick layer of wool with thermal conductivity of 0.04 $Wm^{-2}K^{-1}$ and covered with a 4 mm thick transparent glass sheet. A fine wire mesh was fitted at the inlet to prevent the ingress of insects and other small creatures.

The drying chamber was also constructed with wood and fitted with has a door to allow insertion/ withdrawal of drying trays. It was provided with an air outlet above the trays level and covered with a slanted 3 mm glass pane. The drying chamber's volume was 0.28 m^3.

The design parameters of the dryer are illustrated in Figure 1 and Figure 2.

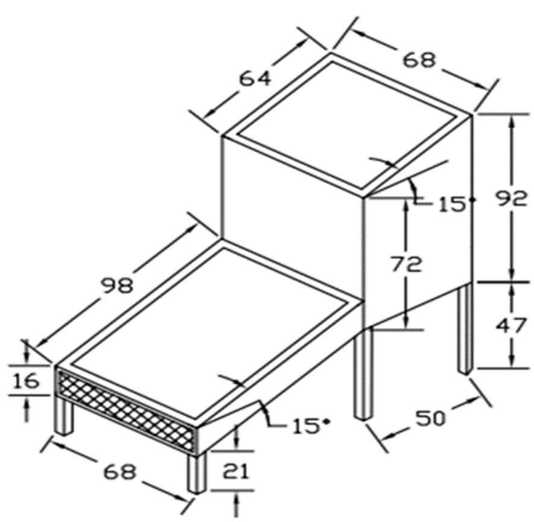

Figure 1: Design features of the mixed mode solar dryer design. All dimensions in cm

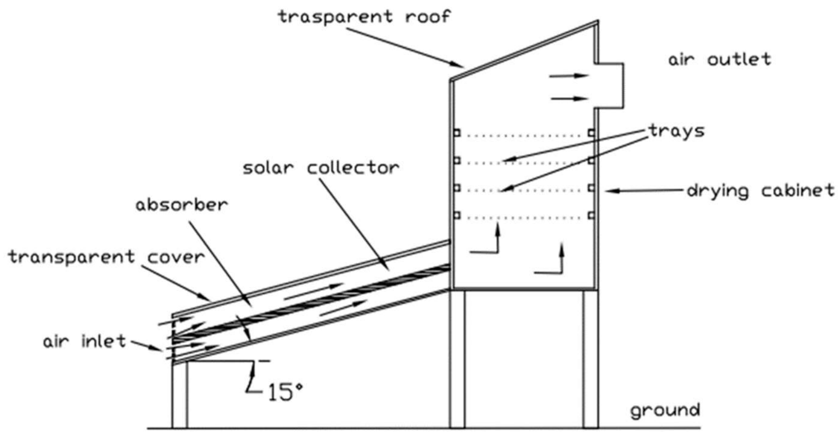

Figure 2: A sectional view illustrating various parts of the mixed mode solar dryer

Data Analysis

Moisture content was determined by subtracting the weight of dried larvae from the weight recorded before loading the drying cabinet and applying Equation 20. The effective collector area exposed to solar insolation was computed and the dryer efficiency determined from Equation 21. The air mass flow rate was determined by multiplying the velocity by cross-sectional area of the collector exit opening and air density. The efficiency of the solar collector was determined using Equation 17.

The Drying Mechanism

During the product drying process, heat is essential in the evaporation of moisture from the product while continuously flowing air carries away the evaporated moisture. As the process takes place, two mechanisms are involved. First, individual water molecules migrate from the interior of the product to the surface. Secondly, the water molecules on the surface of the food product evaporates to the surroundings. This process is enhanced by factors such as product porosity and the active surface area. Other factors include low relative humidity, high wind speeds and high temperature among others (Bukola & Ayoola, 2008). When drying food products like the BSF larvae, meat, yam and fish among others, overheating should be avoided as it interferes with the product texture and quality.

Solar Collector

The solar collector converts light received from the sun into heat. The geometry of a solar collector is described in terms of gross surface area, aperture area, and absorber area. Also known as collector area, the gross surface area refers to the product of the external dimensions of the collector. According to the German Solar Energy Society, (G.S.E.S) (2010), it determines, among other elements, the area needed for mounting. The aperture area refers to the area of entry of solar radiation into the solar collector. Also known as the effective collector area, the absorber area refers to the actual area of the absorber panel. A transparent outer cover is fitted on the outer surface of the solar dryer to transmit shortwave radiation into the dryer and prevent them from exiting the dryer. The space between the outer box and the inner box will be lined with foam material to minimize heat loss (Rhushi, *et al.,* 2010).

A glazed flat-plate collector was used in this study (Figure 3). Glazing will be done by lining the upper surface with a transparent cover (glass). Glazing is done to minimize heat loss from through radiation and convection, to shield the absorber plate from the surrounding environment and to transfer incident solar radiation to the collector's absorber plate while minimizing losses (G.S.E.S., 2010). Other materials essential properties of glazing material are transmission, absorption and reflection. For maximum efficiency in solar radiation transmission, glazing materials are required to have minimum absorption and reflection while transmission should be at the highest possible value (Quaschning, 2005). Plastics and glass are the common materials used for glazing applications. Glass is the most commonly used material for glazing solar collectors (Kabeel & El-Agouz, 2010). It has been chosen as the glazing material in this design because it has the capacity to transmit upto 90% of the incident shortwave radiation while ensuring that any long wave radiation transmitted by the absorber plate cannot be transmitted outwards (Prasad *et al.*, 2010). The optimum thickness of glass recommended for use as cover for solar collectors is 0.33 cm (Garg & Prakash, 2006).

Absorber

The absorber is a 2 mm thick aluminum metal sheet occupying the central area between the back plate and the glass cover. Its purpose is to enhance the ability of the solar collector to give a high thermal yield. To perform this role, it is provided with minimal thermal emissivity and high light absorption ability which is achieved through a dark coating on its surface. The absorber mainly absorbs and partially reflects the solar radiation that hits its surface. The absorption process creates heat which is then transferred to the heat transfer medium channels through conduction. The heat transfer medium (air) absorbs this heat and transfers it to the product hence creating a drying effect.

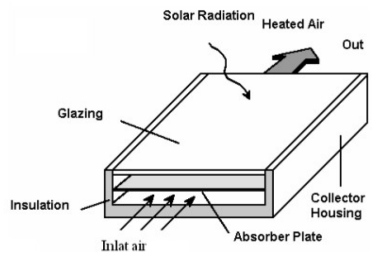

Figure 3: Typical solar collector for heating air (Gatea, 2011)

The Drying Cabinet

Many factors were considered when designing a drying cabinet. They include size and quantity of product to be dried, velocity of air to dry the product, required relative humidity and temperature of the air passing over the product (Gatea, 2011).

The drying cabinet constitutes three drying trays, arranged vertically with a vertical spacing of 25 cm between two successive trays. Each tray dimension (0.62 x 0.62 x 0.08 m) was fabricated and stacked vertically for placing the BSF larvae to be dried. The trays were fitted with a thin aluminum wire mesh to support the flies. The sides of the drying chamber was lined with 0.005 m thick foam material to minimize heat loss.

III. Design Calculations

The performance evaluation of the mixed mode drier was analysed using equations in the subsections below.

Angle of declination (δ)

The angle of declination refers to the angle between the direction of the rays of the sun and an equatorial plane. The angle of declination is given by Equation 1.

$$\delta = 23.45^0 \, sin[360^0(284+n)/365] \quad (1)$$

Where n is the day in a year. It varies from n = 1 (1st January) to n = 365 (31st December) (Forson *et al.*, 2007).

It is positive between December 21 and June 21) when the sun is directly overhead north of the equator and negative between June 21 and December 21 when the sun is directly overhead south of the equator. On June 21st, δ has a maximum value of $+23.45\,^o$ while on December 21st, it has a minimum value of -23.45^o. Peak radiation is received when declination angle is maximum.

On June 21st $n = 172$. Therefore;

$$\delta = 23.45^0 \sin\left[\frac{360^0(284+172)}{365}\right] = 23.45^0 \sin[449.75^o] = 23.45^0$$

Solar hour angle

It refers to the angle that depicts the sun's position relative to solar noon at a given time anywhere on earth. When the sun is directly overhead it is called a local solar noon and the hour angle is zero. The hour angle is negative before noon and positive in the afternoons. In every 4 minutes, the hour angle changes by one degree.

Solar Altitude angle, θ

It refers to the angle between the rays of the sun and a horizontal plane. At sunrise and sunset, the solar altitude angle is zero and 90^o when the sun is directly overhead. It is obtained from Equation 2.

$$sin\,\theta = sin\,L\,sin\,\delta + cos\,L\,cos\,\delta\,cos\,\omega \quad (2)$$

where, θ = solar altitude angle, L = latitude and ω = Solar hour angle

To compute solar altitude angle for Meru, Kenya (Latitude 0.046389^0) on 21st June at 12 noon; $\omega = 0$; $L = 0.046389^0$; $\delta = 23.45^0$.

$$\sin\theta = sin\ 0.046389^o \sin 23.45^0 + \cos 0.046389^o \cos 23.45^0\, cos\ 0^o$$

$\sin\theta = 0.917729593$

Therefore, $\theta = 66.60^o$

Optimum Collector Slope, β

This refers to the inclination of the collector that will result in absorption of maximum amount of solar radiation. For maximum yield, the collector should be positioned perpendicular to the sun's rays. To achieve this, the solar collectors are required to face the equator. Thus, solar collectors in the northern hemisphere should face south while solar collectors in the southern hemisphere should face North. However, the optimum angle of inclination varies from one season to another, as the position of the sun is higher in the summer compared to the winter.

In general terms, the optimum angle of tilt is equal to the latitude of the site. This ensures uniform thermal power production throughout the year. On sites located along the equator, for example in Meru, Latitude 0.046389^0, the altitude angle is extremely small. Such small angles of collector inclination hinder the thermosyphon effect. As a result, a minimum angle of collector inclination has been set at 15^o. Based on available technical literature, the optimum collector tilt angle has been set at local latitude plus or minus 15^o for winter and summer season respectively. The optimum collector slope angle is determined using Equation 3.

Thus, $\beta = L \pm 15^o$ (3)

where β = Optimum collector slope.

L = latitude of the site (Stanciu & Stanciu, 2014)

Thus, $\beta = 0.046389^0 + 15^o = 15.046389^o \approx 15^o$

Thus, an angle of 15^o was used as the optimum inclination angle of the solar collector in this study.

Energy Balance on Collector

The energy balance on a collector is given by equating heat lost by the heat absorber to the amount of heat gained as shown in Equation 4.

$I_c A_c = Q_A + Q_V + Q_K + Q_R + Q_P$ (4)

Where:

I_C = total amount of radiation incident on the heat absorber of the collector (Wm^{-2});

A_c = area of the solar collector (m^2); Q_A = rate of absorption of useful heat energy by air (W); Q_V = rate heat loss through convection (W); Q_K = rate of heat loss through conduction (W); Q_R = rate of re-radiation of heat from the collector (absorber) (W); Q_R =rate of heat loss from the absorber through reflection (W);

Replacing Q_V, Q_K and Q_R by a single term, Q_L , yields

$I_c A_c = Q_A + Q_L + Q_P$ (5)

But,

$I_c A_c = \tau I_{CT} A_c$ and, (6)

$Q_P = \sigma \tau I_{CT} A_c$ (7)

where,

σ = reflection coefficient of the collector absorber;

τ = transmittance of the glazing on the top surface;

I_{CT} = total amount of solar radiation striking the top surface.

Substituting equations (6) and (7) in (5) yields

$\tau I_{CT} A_c = Q_A + Q_L + \sigma \tau I_{CT} A_c$, or $Q_A = \tau I_{CT} A_c (1 - \sigma) - Q_L$. (8)

For an absorber of a solar collector, $(1 - \sigma) = \varepsilon$, (9)

Where ε = solar absorptance. Replacing equation 9 in equation 8 yields equation 10 given below.

$Q_A = (\tau\varepsilon) I_{CT} A_c - Q_L$. (10)

According to Bukola and Ayoola (2008), heat energy loss term, Q_L, can be written as shown in equation 11 below.

$Q_L = \propto_C A_c (T_C - T_K)$ (11)

where,

$\propto_C$= the overall heat transfer coefficient of the solar collector's absorber ($Wm^{-2}K^{-1}$); T_C = the absorber temperature (K); T_K = temperature of ambient air (K).

Substituting equation (11) in equation (10) yields equation 12 shown below.

$Q_A = (\tau\varepsilon) I_{CT} A_c - \propto_C A_c (T_C - T_K)$ (12)

For a unit area of the collector, the energy gained, q_A, is given by equation 13 below.

$q_A = (\tau\varepsilon) I_{CT} - \propto_C (T_C - T_K)$ (13)

If heated air leaves collector area at collector temperature, then heat absorbed by the air, Q_G is expressed as shown equation in 14 below:

$Q_G = \dot{m}_K C_{PK} (T_C - T_K)$ (14)

Where:

$\dot{m}_K$ = air mass flow rate out of the solar dryer (kgs^{-1});

C_{PK} =Specific heat capacity at constant pressure for air (kJ/kgK) (Stanciu & Stanciu, 2014)

Heat Removal Factor, F_R

The heat removal factor, F_R is obtained using equation 15. It refers to the ratio of actual heat transfer, Q_G, to the maximum heat transfer, Q_A (Rosli *et al*., 2014; Lupu et al, 2018). These are represented by Q_G and Q_A respectively. Therefore,

Heat removal factor, $F_R = \frac{Q_G}{Q_A}$

$F_R = \frac{\dot{m}_K C_{PK}(T_C - T_K).}{(\tau\varepsilon)I_{CT}A_C - \propto_C A_c(T_C - T_K).}$

(15)

Rearranging equation 15 above yields equation 16, which governs actual heat transfer.

$\dot{m}_K C_{PK}(T_C - T_K) = F_R A_c[(\tau\varepsilon)I_{CT} - \propto_C (T_C - T_K)]$ or

$Q_G = F_R A_c[(\tau\varepsilon)I_{CT} - \propto_C (T_C - T_K)]$ (16)

Thermal Efficiency of the Collector

Thermal efficiency of a collector is the ratio of useful thermal energy out to the thermal energy available expressed as a percentage (Lupu *et al.*, 2018). It is obtained using equation 17.

$$Collector\ efficiency, \eta_c = \frac{\text{thermal energy out of collector}}{\text{solar radiation incident on the surface of the collector}} \times 100\%$$

$$\eta_c = \frac{Q_G}{A_c I_{cT}} \times 100\%$$

$\eta_c = \frac{\dot{m}_K C_{PK}(T_C - T_K)}{A_c I_{cT}} \times 100\%$ (Ramadhani et al., 2014) (17)

Energy Balance for the Product drying process and Dryer Efficiency

Energy Balance

Equation 18 is used to analyze energy balance during the water evaporation process. It is used to estimate the total quantity of thermal energy required to dry a specific quantity of products (Bukola & Ayoola, 2008).

$m_l L_v = m_k C_p(T_{k1} - T_{k2}),$ (18)

Where,

$m_l =$ mass of water evaporated from the product (kg); $m_k =$ mass of drying air; $L_v =$ Latent heat of vaporization of water (Jkg^{-1}); $C_p =$ Specific heat capacity at constant pressure (kJ/(kgK)); $T_{k1} =$ Initial temperature of the drying air (K); $T_{k2} =$ Final temperature of the drying air (K);

The mass of water evaporated or moisture loss is obtained from equation 19 as given below:

$m_l = m_i - m_f$ *(g)* (19)

Where:

$m_i =$ mass of food product before drying (kg); $m_f =$ mass of dry product (kg);

Moisture Content (MC) is obtained using equation 20.

$MC\ (\%) = \left(\frac{m_i - m_f}{m_f} \times 100\right)$

(20)

Dryer Efficiency

Dryer efficiency is given by equation 21.

$\eta_d = \frac{m_i L_v}{I_{CT} A t}$ (21)

where $L_v =$ Latent heat of vaporization of water (Jkg^{-1}); $I_{CT} =$ total amount of solar radiation striking the top surface; $m_i =$ mass of food product before drying (kg); $t =$ time of drying; $A =$ effective collector area facing the sun (Gatea, 2011).

IV. Results And Discussion

Performance of the Solar Dryer

Various factors such as dryer design factors, solar dryer inlet temperature and solar radiation determined the performance of the solar dryer. Notably, the highest drying temperature of 61°C was obtained when the intensity of solar radiation was maximum (833W/m^2) at 12.00 noon (Figure 3).

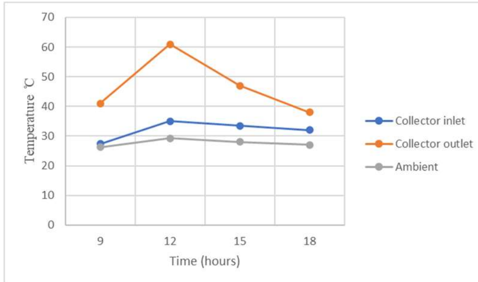

Figure 4: Variation of drying air temperatures and ambient temperature

Moisture Content Variation

The moisture content of BSF larvae was obtained using equation 20 as 60%. The moisture content was reduced from 60% to 49% over 8 hours. The BSF larvae were completely dried after 24 hours (3 days).

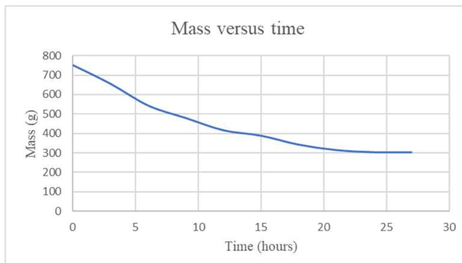

Figure 3: Variation of moisture content

Efficiency of Solar Collector

The solar collector efficiency is a function of radiation intensity and temperature gradient between the collector inlet and the collector outlet, $(T_{co} - T_{ci})$ as shown in Equation 17. The highest solar collector efficiency was obtained as 57.58% at 1200 noon (Figure 6). This figure corresponds to the highest solar radiation incident on the collector (Figure 7). The lowest collector efficiency was 32.56 % at 6:00 pm. These values correspond to the values published in Muhammad *et al.* (2018) Wilma *et al.* (2015) and Bolaji & Olalusi (2008), where the efficiency of a mixed mode solar dryer was said to range between 34% - 57.5%.

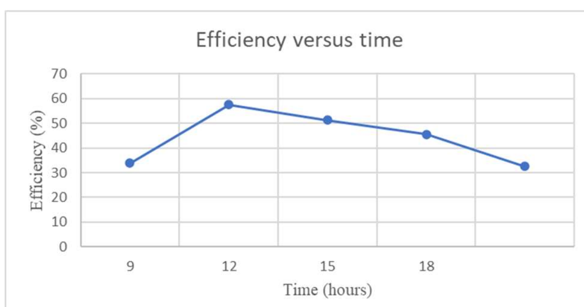

Figure 4: Variation of solar collector efficiency

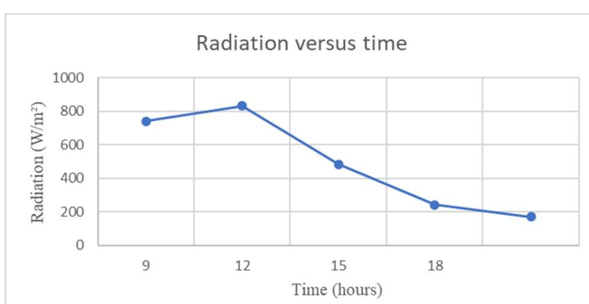

Figure 7: Variation of incident solar radiation

V. Conclusion

The objective off this study was to innovate and analyse a low-cost mixed solar drier for black soldier fly larvae. The following conclusions were drawn from the study:

i. The maximum drying temperature attained during the drying process was 61ºC which is much higher than could be attained with sun drying.
ii. The drying time is dependent on climatic factors such as wind speed, intensity of solar radiation, ambient temperature and relative humidity. Uniform drying of the larvae free from contamination was achieved faster in three days.
iii. The highest efficiency of the solar collector was 57.58% at 12.00 noon while the lowest collector efficiency was 33.9 % at 9:00 am.

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