Content list available at http://epubs.icar.org.in, www.kiran.nic.in; ISSN: 0970-6429

Indian Journal of Hill Farming

June 2023, Volume 36, Issue 1, Page 75-84

Design, fabrication, and evaluation of a solar-biomass hybrid drying system for drying Pineapple

Gajendra Prasad* • Sudipto Sarkar • Laxmi Narayan Sethi

Department of Agricultural Engineering, Triguna Sen School of Technology, Assam University, Silchar – 788011, Assam, India.

ARTICLE INFO

Article history:
Received: 10 January, 2023
Revision: 20 January, 2023
Accepted: 01 February, 2023

Key words: *Collector, Design, Efficiency, Hybrid dryer, Pineapple, Solar radiation.*

DOI: 10.56678/iahf-2023.36.01.11

ABSTRACT

In India's North-East States, pineapple (*Ananas comosus*) is the most popular fruit. Solar biomass drying systems can be designed to reduce the amount of pineapple wasted, as well as boost the farmers' income. The study aims to design and develop a solar biomass hybrid drying system for fruit and vegetable. The dryer comprises a solar aluminium tubular collector, a biomass heater with a chimney, and a drying chamber with a wind turbine ventilator at the top. The design was based on the study area of Assam University, Silchar (India). The average ambient conditions were 83% relative humidity and temperature 27ºC with maximum solar radiation 1024 wm^{-2}. To dry 30 kg of pineapple slice per batch for 6 hours from 85% initial moisture content to 20% final moisture content on a wet basis10 m^2 collector area was required. The collector efficiency on test day varies from 49% to 71.4 %, while the overall efficiency of the solar biomass hybrid drying system was 11.32% when the drying system was loaded with 8.9 kg of pineapple slices. The dryer was designed to dry 30 kg of pineapple slices per batch. The hourly deviation of the temperature inside the solar collector and the drying chamber is much more elevated than the ambient temperature during the experimental period. The solar collector's average efficiency was 51.67% on the test day. The average drying rate during this period was also observed to be 1.115 kgh^{-1}.

1. Introduction

The main goal of drying is to conserve food by decreasing the amount of water in the food product to a level where microbial growth (bacteria, yeast, and molds) and chemical reactions (enzymatic deterioration) cannot spoil the food during storage. Although drying does not damage enzymes, the moisture in dehydrated food is reduced appreciably to prevent enzymatic deterioration (Bala and Wood, 1994; Arinze *et al.*, 1999;). Drying also has many benefits, such as a decrease in volume, ease of handling and transportation, low possibility of pest and microbial attack during storage, and scope for commercial production of flake and powder products (Majumdar, 1995). Solar or mechanical drying techniques generally remove moisture from agricultural products. The Solar drying process is cheaper, relatively slow, non-uniform, and weather-dependent, which causes a deterioration of the quality of the dehydrated product (Varun *et al.*, 2012; Prakash and Kumar, 2013). These defects are more or less eliminated in mechanical drying, where the material is dried under controlled conditions to yield a desirable quality of the end product in a short period. Most commercial dryers used for agricultural products use hot air, which spreads around the product to remove water (Chua and Chou, 2003; Josef, 2006; Motevali *et al.*, 2011).

The hot air drying process consists of heating of product by convective heat transfer from drying air to the product, evaporation of surface moisture, diffusion of evaporated moisture to the surface of the product, and the transfer of evaporated moisture from the dryer along with exhaust air (Akpinar, 2004; Jasim, 2011). Though mechanical drying is fast, the need for energy adds to the dried product's cost. Furthermore, the crop drying systems that utilize motorized fans and electrical heating are unsuitable in many rural areas due to being inaccessible, unreliable, or for many farmers, too costly (Mekhilefa *et al.*, 2011; Xingxing *et al.*,

*Corresponding author: iitkgp.gajendra@gmail.com

2012). On the other hand, the conventional open sun drying widely used by rural farmers has innate limitations. The product also requires an undesirably long duration to attain this equilibrium moisture content (Borah, 2017; Aremu *et al.*, 2020). Even for the 'most favoured' areas, meteorological data show this is not always feasible. In a hot and humid climate, the deterioration of the product is worse, as both higher temperature and high moisture contents facilitate the growth of bacteria, fungi, insects, and mites in crops (McLean, 1980). The most promising alternative to overcome the drawbacks of conventional open sun drying and the usage of fossil fuels is the development of solar-biomass hybrid dryers.

Among the fruits, pineapple (*Ananas comosus*) is the most popular product grown in the Northeast States of India (Saloni *et al.*, 2017). About 10% of the production is undersized pineapples which are not marketable, and are wasted, which reduces the income of most farmers (Das *et al.*, 2016). With the installation of a solar-biomass hybrid dryer, farmers can dry this pineapple, which otherwise goes to waste, thus adding value to these undersized pineapples, packing them properly, and then selling them in the local market (Borah, 2017). This study attempts to design and fabricate the solar-biomass hybrid drying system and trial and estimate the thermal performance features of the designed hybrid drying system.

2. Design and Fabrication of the Drying System

The drying system consists of three units: a solar air heating collector, a biomass heater with a chimney, and a drying chamber. When the drier is used as a solar dryer, the air will be heated through the solar collector, move through the dormant biomass heater unit and enter the drying chamber to remove the water from the product. In the absence of any solar radiation (night time), the atmospheric air will enter through the solar unit, get heated up in the biomass heater, and then enters the drying chamber. In the hybrid mode, when the solar temperature is insufficient (winter or cloudy weather), the atmospheric air will be first partially heated in the solar collector and partially in the biomass heater to attain the desired air temperature for the drying chamber. The schematic diagram and a photograph of the designed and fabricated unit are shown in Fig.s 1 and 2, respectively.

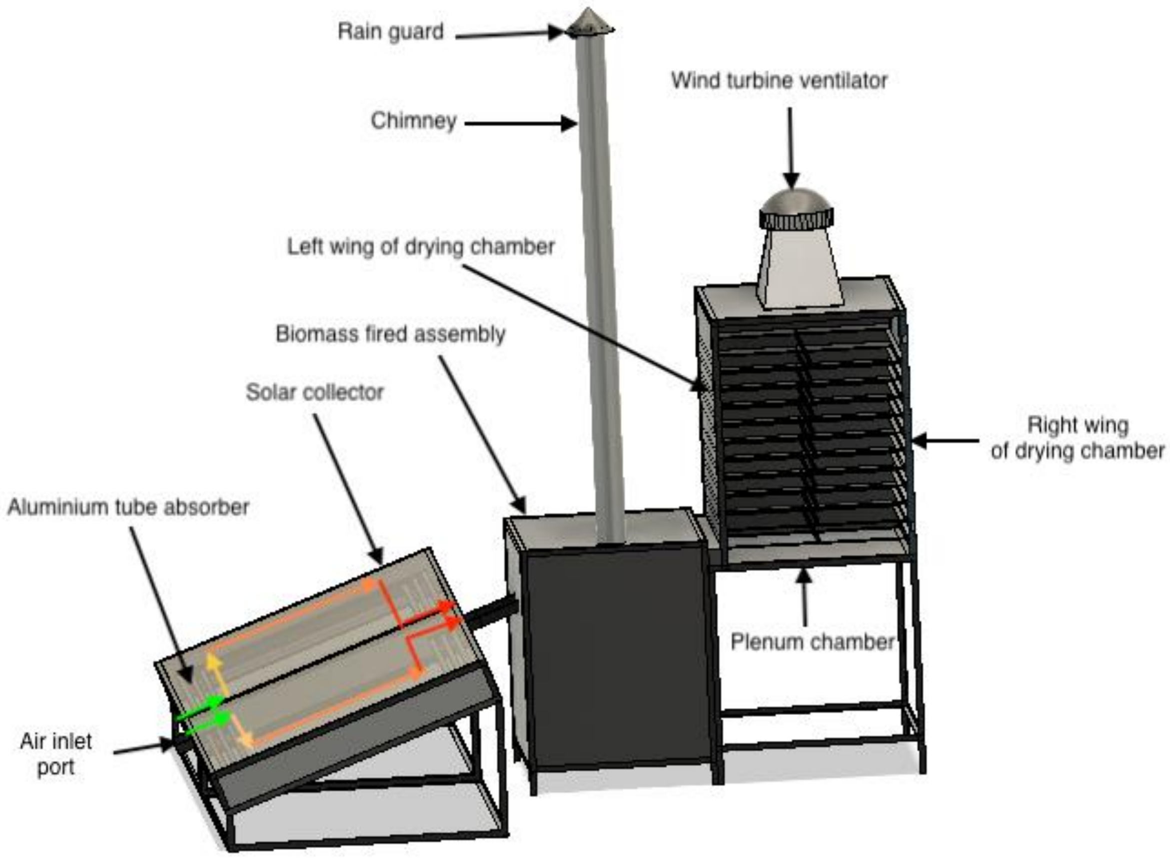

Figure 1. Front view of the designed hybrid drying system

Figure 2. Fabricated hybrid drying system

Design calculations were carried out by using information concerning the type of fruit to be dried, loading density, and amount per batch, along with data relating to the geographical position of the dryer and prevailing climatic conditions during the harvest time. From the climatic data of the study area (Assam University, Silchar), the mean moderate day temperature from July to October was observed to be 27ºC and relative humidity was 83%. Hence, from the psychometric chart, the humidity ratio was found to be 0.018 kg of water vapour per kg of dry air. The maximum permissible drying temperature of pineapple fruit without compromising its quality was assumed to be 60ºC, and the final moisture content of dried fruit was 20% (w.b). The circumstances, assumptions, and interactions summarized in Table 1 have been used to calculate the design parameters.

2.1. The amount of moisture to be removed from pineapple

The mass of water (m_w) to be removed was calculated by using Eq. 1 (Alonge and Hammed, 2007)

$$m_w = m_p \left[\frac{M_i - M_f}{100 - M_f}\right] \qquad \dots (1)$$

The capacity of the dryer is 30 kg, as a loading density of 2.83 kg/m^2 for a pineapple slice of 5 mm thickness was used (Ayala and Topete, 2014). The original and final moisture contents of the pineapple are 85% and 20%, respectively. Hence using equation (1), the weight of moisture evaporated will be 24.37 kg and the weight of the solid product will be 5.625 kg.

Table 1. Design conditions and assumptions

Items	Conditions and assumptions
Location	Assam University, Silchar (Latitude 24.6897ºN and Longitude 92.7512ºE)
Fruit	Pine apple (*Ananas comosus*)
Drying period	July to October
Drying per batch (kg/batch)	30
Initial moisture content, M_i (%) w.b	85
Final moisture content, M_f (%) w.b	20
Ambient air temperature, t_{am} (^{o}C)	27
Ambient relative humidity, RH_{am} (%)	83
Maximum allowable temperature, t_{max} (^{o}C)	60
Drying time (sunshine hours) t_d (h)	6
Incident solar radiation, I_h (W/m^2)	1024
Collector efficiency, η_c (%)	40
Thickness of pineapple slice (mm)	5
Distance between two adjacent trays, (cm)	12

2.1. *Final relative humidity or equilibrium relative humidity*

ERH (%) was calculated by using the sorption isotherms equation given in Eq. 2, Eq. 3, and Eq. 4 (Ogheneruona and Yusuf, 2011):

$$M=\frac{M_f}{(100-M_f)} \quad \ldots (2)$$

$$a_w=1-\exp[-\exp(0.914+0.5639\ \ln M)\ ] \quad \ldots (3)$$

$$ERH=100\ a_w \quad \ldots (4)$$

The final moisture content of the pineapple is considered to be 20% (w.b). By using equation (2), moisture content on a dry basis will be 25%. Now using equations (3) and (4) the water activity and equilibrium relative humidity obtain are 0.6806 and 68.06% respectively.

2.2. *The amount of air needed for drying*

Taking ambient air temperature of 27ºC (dry bulb) and relative humidity of 83%, the psychometric chart gives a humidity ratio of 0.018 kg water per kg dry air. The humidity ratio remains constant when air is heated to an optimum drying temperature of 60ºC (dry bulb). While drying the pineapple slice inside the dryer, the air absorbs water until its relative humidity equals ERH 68% (calculated). The psychometric chart shows the humidity ratio to be 0.028 kg water per kg dry air. The change in humidity ratio is, therefore: 0.028 - 0.018 = 0.01 and the corresponding dry bulb temperature is 37ºC.

From the gas law equation

$$PV=M_ART \quad \ldots (5)$$

For a humidity ratio increase of 0.01 kg water/kg dry air, each kg of water will require 1/0.01 = 100 kg dry air. For this calculation, the absolute temperature is 37+273 = 310 K, and the air volume required to remove 1 kg of water at 310 K is 89.052 m^3. Hence 24.375 kg of water will require 2170.642 m^3 of air for efficient drying.

2.3. *The volume flow rate of air V_a (m^3/h)*

The amount of air to pass through the drying unit from the starting of drying till the final drying is achieved is calculated from Eq. 6 (Alonge and Hammed, 2007)

$$V_a=\frac{W_a}{t_d} \quad \ldots (6)$$

Assuming a total drying time of 6 h per batch, the quantity of air needed is calculated to be 2170.642 m^3, and accordingly, the calculated value of the volume flow rate of air is 361.77 m^3/h (0.1005 m^3/s).

2.4. *The air mass flow rate, m_a, (kg/h)*

The air mass flow rate was calculated by using Eq. 7.

$$m_a=\rho_a\times V_a \quad \ldots (7)$$

Assuming the density of drying air as 1.2 kg/m^3 and the volumetric air flow rate was calculated as 361.77 m^3/h. By using Eq. 7 mass flow rate of air is calculated as 434.124 kg/h (0.1206 kg/s).

2.5. *The amount of heat required to remove the water*

The amount of heat required to remove the water would be calculated from Eq. 8.

$$E=m_a\left(h_f-h_i\right)t_d \quad \ldots (8)$$

The psychometric chart's final and initial enthalpy of drying and ambient air is determined as 107 kJ/kg of dry air and 73 kJ per kg of dry air, respectively. The mass flow rate was calculated as 434.124 kg/h and the drying time as six hours. According to Eq. 8 total heat required to remove the water is calculated as 88.561 MJ.

2.6. *Average drying rate*

The average drying rate, M_{dr} will be determined from the amount of water to be removed by the solar air heater and the drying period by Eq.9 (Chakravarty, 2000)

$$M_{dr}=\frac{m_w}{t_d} \quad \ldots (9)$$

The drying rate is distinct as the mass of water removed per hour. In this work, 24.375 kg of water is evaporated in 6 hours. Hence average drying rate is obtained as 4.0625 kg/h.

2.7. *Design of the Solar collector*

As far as the design of the solar collector is concerned, the two parameters, viz. daily sunshine hours and daily solar radiation are essential to finding out the total drying time and energy received by the collector per day. Apart from this, the amount of air needed to remove a certain amount of water from a given quantity of pineapple slices is also essential. The size of the collector will be estimated as a function of the drying area needed per kilogram of pineapple fruit. The target drying air temperature is restricted by the maximum temperature to which the fruit can be exposed without altering its Physio-chemical attributes.

2.7.1. *Length of aluminium tube absorber inside the solar collector*

The cross-sectional length and width of the rectangular aluminium tube absorber were selected as 0.063 m and 0.0381 m, respectively. It was assumed that the average temperature inside the collector box was 80ºC and that the temperature of hot air out from the aluminium tube was 70ºC. The aluminium tube's overall heat transfer coefficient (U) is 25 $Wm^{-2}k^{-1}$. The density and specific heat of air are 1.2 kgm^{-3} and 1005 $Jkg^{-1}K^{-1}$, respectively. The air velocity inside the aluminium tube was calculated by dividing the volumetric air flow rate by the number and cross-sectional area of the tube.

Rate of heat transfer through the tube $q = U \times A_s \times \Delta T_{l.m}$

$$q=U\times2(l+b)\times L\times\Delta T_{l.m} \quad \dots (10)$$

Rate of heat received by air inside the tube $E_a = m_a \times C_{pa} \times \Delta T$

$$E_a=A_x\times v_a\times \rho_a\times C_{pa}\times\Delta T \quad \dots (11)$$

From Eq. (10) and (11), the length of the tube is given as

$$L=\frac{A_x\times v_a\times\rho_a\times C_{pa}\times\Delta T}{U\times2(l+b)\times\Delta T_{l.m}} \quad \dots (12)$$

Using the value of variables in Eq. (12) and the assumption made above, the length of each tube was found to be 6.75 m.

2.7.2. The tilt angle of the solar collector

The tilt angle (β) of the solar collector at a latitude (ϕ) of the collector is obtained using (Gutti *et.al.*, 2012). The latitude value of the site (Assam University, Silchar) where the dryer was designed was 24.6897º N.

$$\beta = 10^o + \text{latitude } (\phi)$$

$$\beta = 34.6897^o$$

2.7.3. The total area of the solar collector

From the total valuable heat energy needed to eliminate moisture and the net energy received by the collector, the collector area (A_c) of the solar drying system in m^2 can be calculated from Eq. 13 (Alonge and Hammed, 2007).

$$A_c I\eta_c=E=m_a\left(h_f-h_i\right)t_d \quad \dots (13)$$

And the area of collector may be calculated from Eq. (14

$$A_c=\frac{E}{\eta_c I} \quad \dots (14)$$

During the drying period, the average global radiation on a horizontal surface was found to be 1024 wm^{-2}. The collector efficiency was assumed to be 40% (Sodha *et al.*, 1987). The total helpful energy received by the drying air is calculated as 88.561 ×103 kJ; hence using Eq. 15 collector area is found to be 10 m^2.

A solar collector was fabricated to harness maximum solar intensity for achieving higher temperatures. Two sets of tubular-type solar collectors have been used for this purpose. Each collector is sheltered in a rectangular box made of a mild steel sheet of 2 mm thickness with a dimension of (2.5m × 2m × 0.1m). The absorber plate consists of a transparent glass cover at the top, a black painted metal sheet (absorber) at the bottom, and all the sides covered with the same iron sheet to form a closed box-like structure. Inside the box, a bundle of three thin wall aluminium tube absorbers, each having a length of 6.75 m with a black painted surface, has been installed to heat the incoming atmospheric air. A common input manifold connects all three aluminium tubes from the bottom side to draw ambient air, while a separate exhaust manifold at the collector's top end sends hot air out the top. The exit manifold of the solar heating unit is connected with the air heating chamber of the biomass-fired assembly.

2.8. Biomass fired assembly

The amount of biomass needed to be burned in the biomass fire assembly was determined using the following equation (Olaniyan and Adeoye, 2014)

$$m_b=\frac{E}{C_b} \quad \dots (15)$$

The average calorific value of rice husk is 13603.85 $kJkg^{-1}$. The energy requirement of the dryer is 14.76×10^3 kJh^{-1}. The feeding rate of the husk will be 1.085 kgh_{-1}. Assuming 30% bio-waste fire assembly efficiency, the husk's feeding rate is 3.617 kgh^{-1}.

The biomass-fired assembly consists of three main parts: a combustion chamber, an air heating chamber, and a chimney. The horizontal cylindrical part of the biomass-fired assembly in the middle acts as a combustion chamber. The combustion chamber has a length of 1500 mm and a diameter of 500 mm and was fabricated from a 1.45 mm thick mild steel sheet. The cylinder was constructed to rest on three pairs of supports made from 51 mm angle iron to maintain a gap of 500 mm from the bottommost aimed at air circulation for heating. The combustion chamber is designed to have a horizontal grate for properly burning of biomass. A duct on the exhaust side would generate the required draught for the complete burning and discharge of the flue gases. According to the design calculations, a duct of 3481 mm in height and 200 mm in diameter is fabricated from a mild steel sheet to fit the combustion chamber. A traditional rain guard is provided over the chimney, and the exit end of the air heating chamber of the biomass-fired assembly is connected with the plenum chamber of the drying unit.

2.9. Drying unit

The drying unit comprises a plenum chamber, a drying chamber, removable drying trays, an air inlet, and an exit port. The drying chamber includes a mild steel angle iron frame and is covered with a mild steel sheet of 2 mm. The drying chamber comprises two sections divided into left-wing and right-wing modules. Each wing of the module consists of eleven levels of wire mesh trays of 25 mm square perforation with two trays on each level. The trays are positioned at a vertical distance of 12 cm apart. The practical dimension of each tray is 750 mm × 650 mm. To ensure easy hot air flow through the drying trays, the thought of a wind turbine ventilator is envisaged to be positioned over the freeboard. The neckband of the turbine ventilator is chosen to be 500 mm in diameter. With minimum ambient airflow, the wind turbine was anticipated to generate a draft within the chamber, creating an air flow from inlet to outlet. The ambient air, after getting heated in the solar collector and then in the biomass-fired assembly, would pass through the trays and remove the moisture from the product placed in the trays before being sucked out to the atmosphere by the wind turbine at the top.

3. Experimentation

The experiments to evaluate the designed and fabricated hybrid dryer were conducted in natural convection solar dryer mode under no load conditions and natural convection solar-biomass hybrid dryer mode under loaded conditions. The drying temperature was measured hourly at the bottom and top of the drying chamber using electronic thermostat. A electronic thermostat also measured the ambient temperature, collector outlet temperature, biomass assembly outlet temperature, and drying chamber outlet temperature. A solarimeter was used to reckon solar radiation and the relative humidity in the ambience and drying chamber was measured using a hygro-thermometer. The initial and final weights of the pineapple and the amount of biomass burnt are measured using a digital weight balance. The airflow rate was measured by using a hot wire anemometer.

4. Results and Discussion

4.1. Analysis of temperature profile inside the dryer

The results were obtained by running the dryer from 9 A.M to 4 P.M in August in solar mode. The hourly variation of the temperatures in the drying chamber and solar collector compared to ambient temperature is shown in Fig. 3. The ambient air temperature at the inlet of the solar collector varies from 31 to 40ºC. The solar radiation varies from 97 W/m^2 to 743 W/m^{2}on the test day. The peak solar radiation was observed at 14:00 hrs. The collector outlet temperature ranges from 36 to 70ºC, and the drying chamber temperature ranges from 36 to 52ºC. Suddenly drop in the intensity of solar radiation was observed from 14:15 hrs due to a cloudy sky resulting sudden drop in collector outlet temperature, drying chamber temperature, and ambient temperature, which was observed at 15:00 hrs.

4.2. Variation of relative humidity

The variation of the relative humidity of the ambient air and the air inside the drying chamber is shown in Fig. 4. It was observed that the variation of relative humidity of ambient air during the test period was 48 to 73%, while the solar drying chamber varies from 32 to 62%. Many authors suggest that the drying process is improved by heated air at very low humidity.

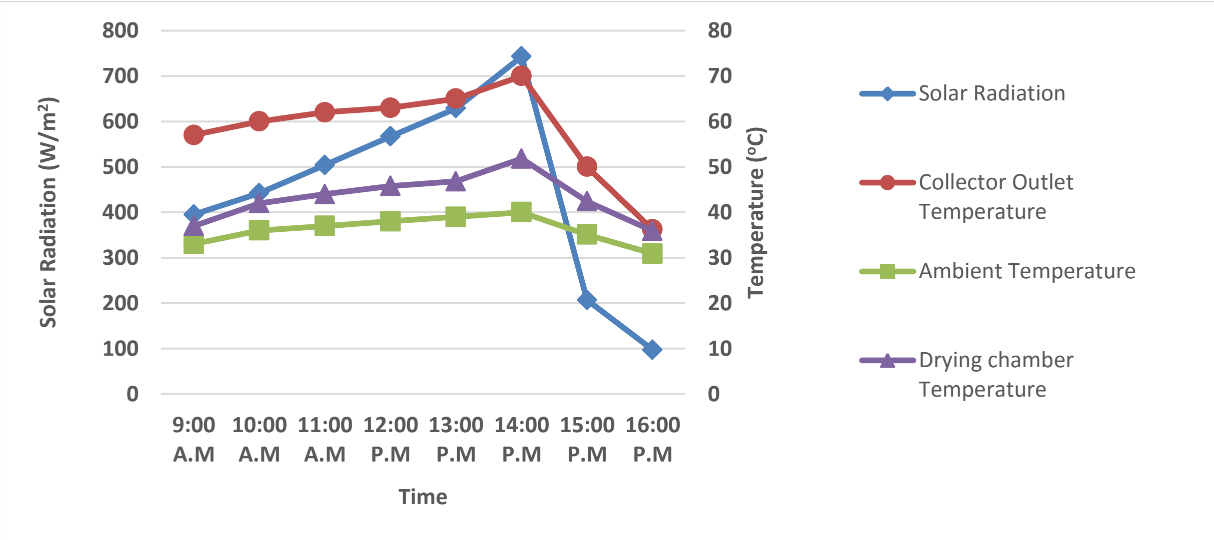

Figure 3. Variation of ambient temperature, collector temperatures and drying chamber temperature with solar radiation

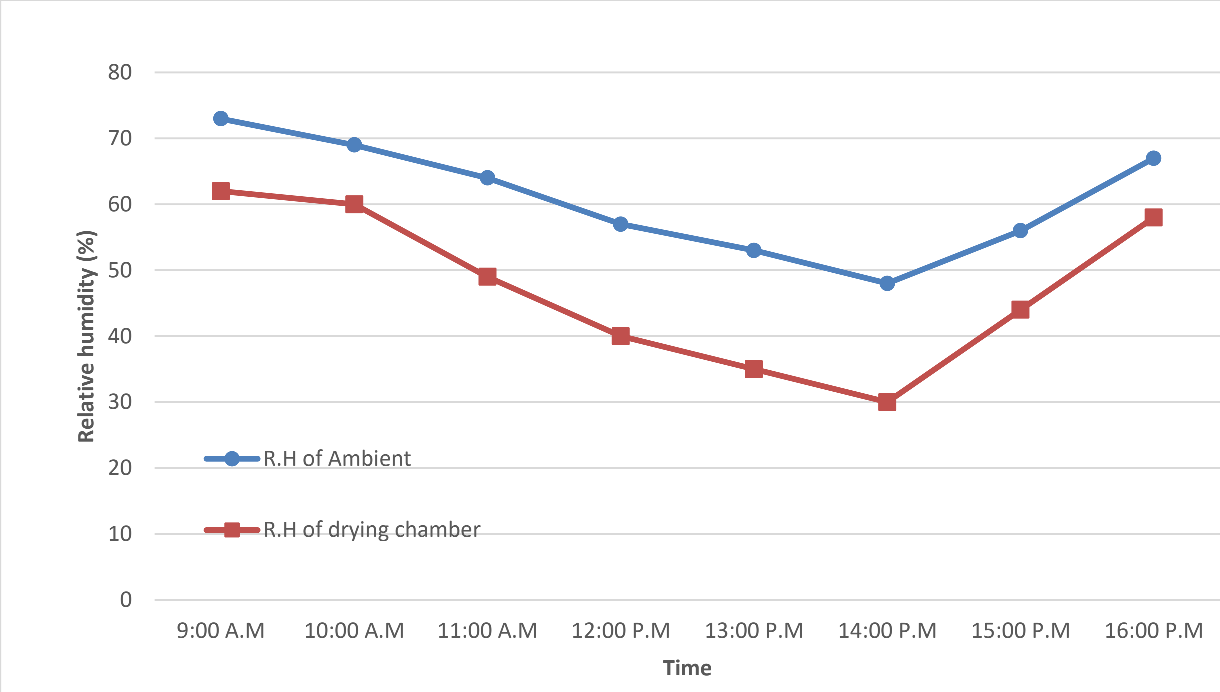

Figure 4. Variation of relative humidity of ambient air and air inside the drying chamber.

4.3. Performance of solar collector

4.3.1. No load condition:

The system's temperatures were measured when the solar dryer was worked with no load. The steady-state efficiency of the solar collector using the Hottel-Whillier-Bliss equation (Forson *et al.,* 2007), given as

$$\eta_c = \frac{m_a C_{pa}(T_o - T_i)}{A_c I} \quad \ldots (16)$$

The average solar radiation on test day was 448 w/m^2, while the average ambient temperature and collector outlet temperature were 36°C and 58°C, respectively. The mass flow rate of air was observed to be 0.0987 kg/s. The collector efficiency on test day varies from 49% to 71.4 %, with an average value of 51.67 %. The hourly variation of collector efficiency is illustrated in Fig. 5.

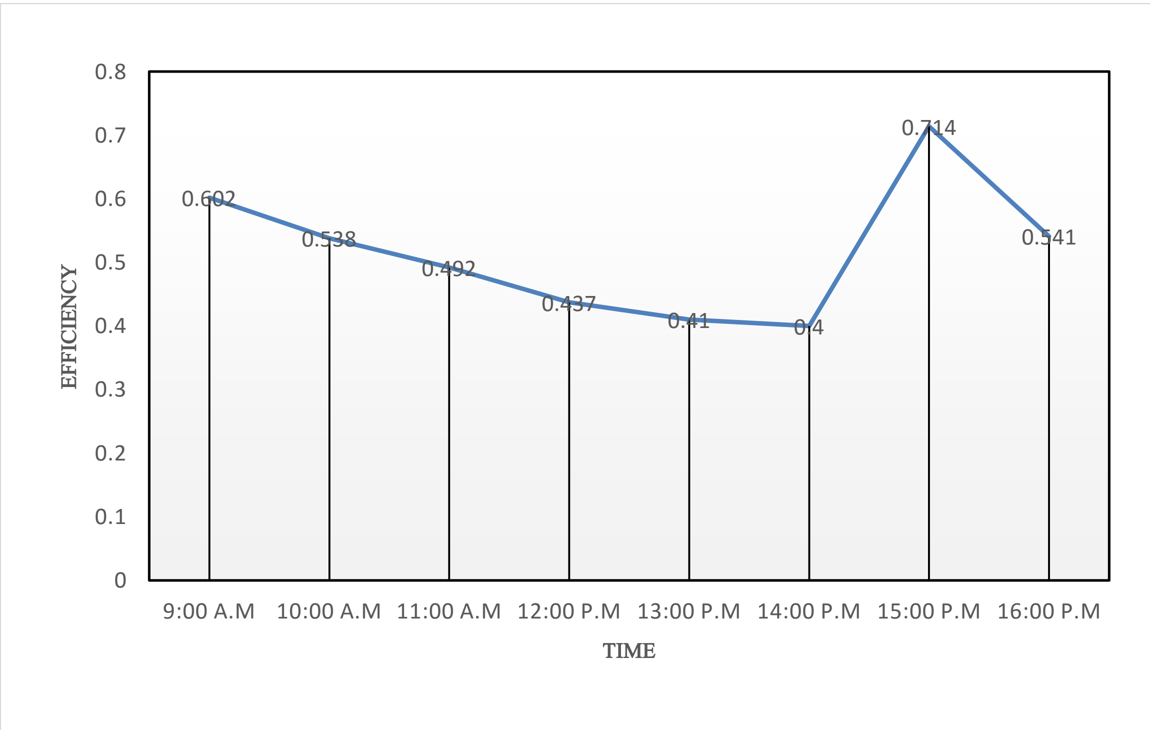

Figure 5. Hourly variation of efficiency of solar collector

4.3.2. Loaded condition:

The dryer was loaded with 8.9 kg of pineapple slices on four trays, left and right wings of the drying chamber. The intensity of solar radiation was not continued during the test period due to the suddenly cloudy sky in July-August. Thus experiment was conducted by combining solar collector and biomass fire assembly in hybrid mode to maintain the drying chamber inlet temperature at 65 ± 2ºC. The experimental results were tabulated, and the system's performance was analysed using the drying curve, as shown in Fig. 6. The initial moisture content of fresh pineapple slices was 85% at the time of loading at the drying tray. The pineapple slice was dried up to 19.09% moisture content in 6.5 hours at 65 ± 2ºC, as shown in the drying rate curve (Fig. 6.). During this process, 7.25 kg of water was removed. The average drying rate, the amount of water removed from the pineapple slice over the drying time, is calculated from Eq. (9) as 1.115 kg/hour.

4.3.3. Overall thermal efficiencies of the dryer

The overall thermal efficiency of the solar-biomass hybrid dryer can be defined as the ratio of energy used to remove the water from the product to the energy supplied to the dryer. The overall efficiency of natural convection solar biomass hybrid dryer is calculated by the following expression (Saravanan *et al.,* 2014).

$$\eta_o = \frac{m_w h_{fg}}{IAt + m_b C_b} \qquad \ldots (17)$$

The solar collection area taken in calculating efficiency is the sloping front face of the collector, i.e., 10 m^2. The average solar radiation during the experimental period was observed to be 395 w/m^2. The latent heat of vaporisation is a function of temperature and has been calculated as 2346.4 kJ/kg using the steam table. Approximately 4.25 kg of rice husk was burnt during the experimental period. The overall thermal efficiency of the solar-biomass hybrid dryer during the experimental period was 11.32%.

5. Conclusions

The solar biomass hybrid dryer was designed and fabricated to dry 30 kg pineapple slices per batch, increasing the rural farmer's income by saving energy and post-harvest losses as well as value addition of pineapple fruit. During the testing period, the hourly fluctuation of the temperature inside the solar collector and the drying chamber is significantly higher than the surrounding air temperature. At 14.00 hrs, when the maximum ambient temperature for the day was 40ºC, the solar collector temperature was 70ºC, and the drying chamber temperature was 51.8ºC, corresponding to 743 w/m^2 of solar radiation. Significant changes in the relative humidity of the drying chamber and ambient air occurred, and it was concluded that heated air at a relatively low temperature accelerated the drying process. On test day, the collector efficiency ranges from 49% to 71.4%, with an average of 51.67%. When the system was loaded with 8.9 kg of pineapple slices during the testing period, the solar- biomass hybrid dryer's overall thermal efficiency was 11.32%.

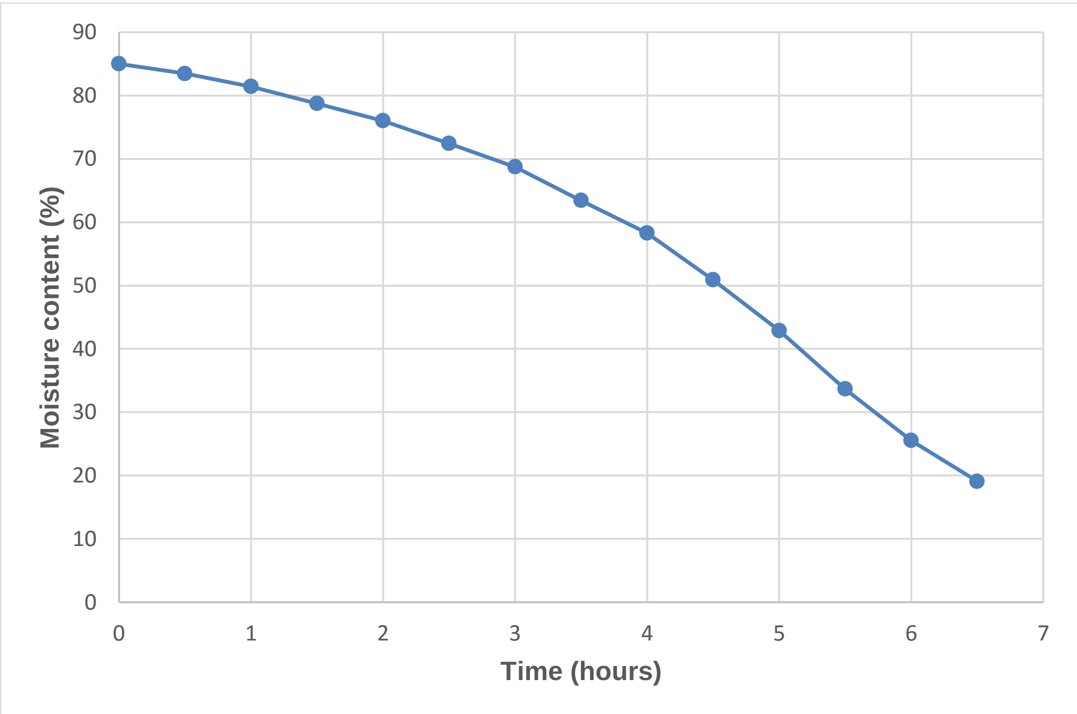

Figure 6. Variation of moisture content with time at 65 ± 2ºC temperature.

6. Conflict of Interest

The authors declare that they have no conflict of interest within themselves and others, including the funding agency and the agency where the research was carried out.

7. References

Akpinar, E. K. (2004). Energy and exergy analyses of drying of red pepper slices in convective type dryer. *Int. J. Heat Mass Transfer*, 31: 1165 – 1176.

Alonge, A. F., and Hammed, R. O. (2007). A Direct Passive Solar Dryer for Tropical Crops. *African Crop Science Conference Proceedings*, 8: 1643 -1646.

Aremu, O. A., Odepidan, K. O., Adejuwon, S. O., and Ajala, A. L. (2020). Design, Fabrication and Performance Evaluation of Hybrid Solar Dryer. *International Journal of Research and Innovation in Applied Science,* 5(3): 159 – 164.

Arinze, E. A., Schoenau, G. J., and Sokhansanj, S. (1999). Design and experimental evaluation of a solar dryer for commercial high-quality hay production. *Renew Energy*, 16: 639-642.

Ayala, D. G., and Topete, A. C. (2014). Pineapple drying using a new solar hybrid dryer. *Energy Procedia*, 57: 1642 – 1650.

Bala, B. K., and Woods, J. L. (1994). Simulation of the indirect natural convection solar drying of rough rice. *Sol Energy,* 53(3): 259-266.

Borah, A., Sethi, L. N., Sarkar, S., and Hazarika, K. (2017). Effect of drying on texture and colour characteristics of ginger and turmeric in a solar biomass integrated dryer. *Journal of Food Process Engineering,* 40:1-6.

Chakraverty, A. (2000). *Post-Harvest Technology of Cereals, Pulses, and Oilseeds*. 3rd ed. New Delhi: Oxford and IBH Publishing Co. Pvt. Ltd.

Chua, K. J., and Chou, S. K. (2003). Low-cost drying methods for developing countries. *Trends Food Sci. Technol,* 14(12): 519-528.

Das, B., Das, K. K., and Roy, T. N. (2016). Study on marketing system and value addition of pineapple fruit (*Ananus comosus*) in West Bengal. *Agriculture Economics Research Review*, 29(2): 279 – 285.

Forson, F. K., Nazha, M. A. A., Akuffo, F. O., and Rajakaruna, H. (2007). Design of Mixed mode Natural Convection Solar Crop Dryers: Application of principles and rules of thumb. *Renew. Energ.,* 32**:** 2306–2319.

Gutti, B., Kiman, S., and Mustafa B. G. (2012). Design and Construction of Forced/Natural Convection Solar Vegetable Dryer with Heat Storage. *ARPN Journal of Engineering and Applied Sciences*, 7(10): 1313 – 1317.

Josef, B. (2006). *Handbook of fruits and fruit processing*, Blackwell Publishing, USA.

Majumdar, A. S. (1995). *Handbook of industrial drying.* second ed. New York: Marcel Dekker.

McLean, K. A. (1980). *Drying and storage of combinable crops*. Farming Press Ltd., Ipswich, U. K.,

Mekhilefa, S., Saidurb, R., and Safari, A. (2011). A review on solar energy use in industries. *Renewable and Sustainable Energy Reviews,* 15: 1777–1790.

Motevali, A., Minaei, S., and Khoshtagaza, M. H. (2011). Evaluation of energy consumption in different drying methods. *Energy Conversion and Management*, 52(2): 1192-1199.

Ogheneruona, D. E., and Yusuf, M. O. L. (2011). Design and Fabrication of a Direct Natural Convection Solar Dryer for Tapioca. *Leonardo Electronic Journal of Practices and Technologies*, 10 (18): 95-104.

Olaniyan, A. M., and Adeoye, O. A. (2014). Conceptual Design of a Charcoal-fired Dryer. *Proceedings of International Conference of Agricultural Engineering*. Zurich, 06-10.07, 2014.

Prakash, O., and Kumar, A. (2013). Historical review and recent trends in solar drying systems. *International Journal of Green Energy*, 10: 690-738.

Saloni, S., Sindhu, Chauhan, K, and Tiwari, S. (2017). Pineapple production and processing in north-eastern India. *Journal of Pharmacognosy and Phytochemistry*, 665 -672.

Saravanan, D., Wilson, V. H. and Kumarasamy, S. (2014). Design and Thermal Performance of the Solar Biomass Hybrid Dryer for Cashew Drying. *Facta Universitatis Series Mechanical Engineering*, 10(3): 277-288.

Sodha, M. S., Bansal, N. K., Kumar, A., Bansal, P. K., and Malik, M. A. (1987). *Solar Crop Drying. CPR Press,* Boca Raton, Florida, USA.

Varun, Sunil, Sharma, A., and Sharma, N. (2012). Construction and performance analysis of an indirect solar dryer integrated with solar air heater. International conference on modelling, optimization and computing. Procedia Engineering. 38: 3260-3269.

Xingxing, Z., Xudong, Z., Stefan, S., Jihuan, X., and Xiaotong, Y. (2012). Review of R&D progress and practical application of the solar photovoltaic/thermal (PV/T) technologies. *Renewable and Sustainable Energy Reviews*, 16: 599-617.

List of Nomenclature

Parameters	Meaning
β	Tilt angle of solar collector
ϕ	Latitude of the site
ρ_a	Density of air (kgm^{-3})
η_c	Collector efficiency
η_o	Overall efficiency of dryer
$\Delta T_{l.m}$	Log mean temperature difference (ºC)
A_c	Surface area of collector (m^2)
A_s	Surface area of aluminium tube (m^2)
a_w	Water activity
A_x	Cross-sectional area of aluminium tube (m^2)
B	Cross-sectional width of aluminium tube (m)
C_b	Calorific value of biomass ($kJkg^{-1}$)
C_{pa}	Specific hat of air ($Jkg^{-1}k^{-1}$)
E	Total heat energy require (kJ)
ERH	Equilibrium relative humidity (%)
H_f	Final enthalpy of drying air ($kJkg^{-1}$ dry air)
h_{fg}	Latent heat of vaporization ($kJkg^{-1}$)
H_i	Initial enthalpy of ambient air ($kJkg^{-1}$ dry air)
L	Cross-sectional length of aluminium tube (m)
M	Moisture content on dry basis ($kg_w kg_s^{-1}$)
M_A	Mass of air, (kg)
m_a	Mass flow rate of air (kgh^{-1})
m_b	Mass of biomass (kg)
M_{dr}	Average drying rate (kgh^{-1})
M_f	Final moisture content (% w.b)
M_i	Initial moisture content (% w.b)
M_p	Mass of product (kg)
m_w	Mass of water evaporated (kg)
P	Atmospheric pressure (kP_a)
R	Gas constant ($kP_a m^3 kg^{-1} K^{-1}$)
T	Absolute temperature, (ºK)
T	Total time in (s)
T_c	Air temperature inside the collector (ºC)
t_d	Total drying time (h)
T_i	Inlet air temperature (ºC)
T_o	Outlet air temperature (ºC)
U	Overall heat transfer co-efficient ($Wm^{-2}K^{-1}$)
V	Volume of air, (m^3)
V_a	Volume flow rate of air (m^3h^{-1})
v_a	Velocity of air inside aluminium tube (ms^{-1})
W_a	Quantity of air required (m^3)