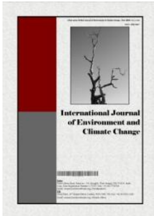

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Design and Development of Solar-biogas Hybrid Dryer for Onion Drying

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Authors' contributions

This work was carried out in collaboration among all authors. Author AKR designed the study, performed the analysis, wrote the protocol and wrote the first draft of the manuscript. Author AKR managed the analyses of the study. Author SJ managed the literature searches. All authors read and approved the final manuscript.

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ABSTRACT

A solar-biogas hybrid dryer was designed, developed and tested for onion drying with a capacity of 8 kg/batch. Solar energy was utilized as primary energy for onion drying in a greenhouse type drying chamber (direct solar) and biogas powered air heater used as a supplementary heat source for continuous operation. The hybrid dryer consists of greenhouse type drying chamber, concentric pipe air heater and biogas burner. The greenhouse type drying chamber has floor area of 1300 mm×900 mm and collector area of 3 m^2. The dryer was operated as a solar dryer during normal sunny day and hybrid mode whenever sunlight is insufficient to maintain desired 60°C inside the drying chamber. The results indicated that the moisture content of onion slices reduced from 80.06% (wb) to 9.88% (wb) in 12 hours in hybrid mode drying. A biogas powered air heater operated for 3 hours in a day with effectiveness of 0.87 and biogas burner efficiency of 47.59%. The dryer was techno-economically feasible with a benefit cost ratio of 1.12 and payback period of 2.1 years.

Keywords: Biogas; design; drying; hybrid; solar.

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NOMENCLATURE

ΔT_{ln}	: Logarithmic mean temperature, °C	Th_{out}	: Temperature of flue gas at outlet
A_0	: Area of injector, m^2	T_i	: Temperature of air at outlet, °C
A_c	: Collector area of dryer, m^2	T_o	: Temperature of air at inlet, °C
A_{ch}	: Area of chimney, m^2	t_p	: Drying thickness, m
A_d	: Drying area, m^2	V_a	: Velocity of exit air
A_p	: Port area, m^2	V_{bg}	: Volume of biogas consumed, m^3/h
C_d	: Coefficient of discharge	V_o	: Velocity of the gas in the orifice
C_{pa}	: Specific heat of air, KJ/Kg °C	V_p	: Volume of product, m^3
C_{pp}	: Specific heat of product, KJ/Kg °C	ϵ	: The effectiveness
C_r	: Capacity ratio	η_{bg}	: Efficiency of burner, %
CV_{bg}	: Calorific value of biogas, MJ/m^3	η_d	: Efficiency of dryer, %
CV_{bg}	: Calorific value of biogas, MJ/m^3	ρ_a	: Density of air, Kg/m^3
D_a	: Actual draft	ρ_e	: Density of air at chimney outlet, kg/m^3
D_c	: Diameter of chimney, m	ρ_i	: Density if air at inlet, kg/m^3
d_o	: Injector orifice diameter, m	ρ_o	: Density of air at outlet, kg/m^3
D_p	: Produced draft	Q_{total}	: Total energy required, KJ
d_t	: Throat diameter	r	: Entrainment ratio
g	: Acceleration due to gravity, m/s^2	s	: gravity of gas, kg/m^3
H	: Height of chimney	T_a	: Temperature of ambient air, °C
I	: Total solar radiation, W/m^2	Tc_{in}	: Temperature of air at inlet
M	: Mass of product	Tc_{out}	:Temperature of air at outlet
m_f	: Final moisture content	t_d	: Drying time, h
m_i	: Initial moisture content	Th_{in}	: Temperature of flue gas at inlet
M_w	: Mass of water to be removed during drying, Kg	T_e	: Temperature of moist air at chimney outlet, °C
m_w	: Mass of water removed per hour, Kg/h	Q_{total}	: Total energy required, KJ
P_{bg}	: Biogas pressure, mbar	r	: Entrainment ratio
q_a	: Amount of moist air removed in 12 h, $m^3\,s^{-1}$	s	: Specific gravity of gas, kg/m^3
Q_{bg}	: Power required for drying from biogas, KJ	T_a	: Temperature of ambient air, °C
Q_{exit}	: Flow rate of exit air at chimney, m^3/h	T_d	: Temperature of drying air, °C
Q_{gas}	: Biogas flow rate, m^3h^{-1}	λ	: Latent heat of vaporization of water, KJ/Kg
Q_{gas}	: Flow of biogas through the orifice, m^3/h		

1. INTRODUCTION

Onion is one of the main crops under Allium family, cultivated mainly in the tropical countries since long time. Onion is one amongst the important vegetable crops grown in India. Globally, the country occupies the second position after China in onion production with a share of around 14%. In India, during the year 2017-18, the total area under onion cultivation was around 1285.00 thousand hectares with a production of 23262.31 thousand tones [1]. Onion is perishable because of its high moisture content (about 82%). Besides imparting a characteristic taste and flavour to food, it additionally has vital therapeutic values. Onion contains Vitamin B complex, a trace of water-soluble vitamins and additionally traces of iron and Ca [2].

The quality, appearance, colour, flavour and texture, deteriorates because of spoilage caused by microbes, enzymes, vinegar flies etc. The presence of moisture and oxygen lead to the growth and multiplication of microbes which degrade the harvested onions. The bruises, caused throughout mechanical harvesting and handling, accelerate the process and cause internal contamination of onions [3]. Therefore, harvested onions should be marketed, processed or preserved as early as possible. To overcome these problems, drying is a prerequisite process for proper storage of onion. Drying enhances shelf life, reduces weight and volume of foods substantially. In addition, it minimizes packaging, storage and transportation costs. Onions are generally dried from an initial moisture content of about 80-85% (wb) to 7% (wb) or less for efficient storage and processing [4]. Drying permits transformation of raw onions into powder form which further can be used in various products such as ketchup, chutney, sauce, puree, dry soup mix. Dried onions are considered as a potential product in world trade and India rank first in the world to produce dehydrated onions. Of the total 60,000-70,000 tons of dehydrated onions produced annually in India, nearly 85% is exported to European countries [5]. Domestically based wholesale consumers account for the consumption of the rest 15% of the total produce [6].

The commercial scale drying of products done by most of the enterprises use cabinet tray dryers powered by electricity or liquefied petroleum gas (LPG) burners. In some cases, the drying begins with the open-sun drying and further continues with mechanical tray dryer which needs additional cost for heating [7]. As India receives abundant solar radiation (about 5000 trillion kWh/year), the country has tremendous potentials for solar drying of fruits and vegetables. On the other side there is ample potential of biogas energy considering the livestock population of 512.06 million. The total current biogas potential in India is estimated at 60,443 million m^3 (raw biogas) which is equivalent to 26 million tonne LPG per year (www.mnre.gov.in, 2018). The fluctuation in available solar energy and the need for continuation in drying process during periods of non-sunshine hours are serious problems. The integration of solar energy with other renewable technology like biogas is the need of agro industry for better performance and sustainable development [8].

2. METHODOLOGY

2.1 Experimental Assumptions

To carry out design calculation and size of the solar-biogas hybrid dryer, the assumptions and conditions were made as summarized in Table 1.

2.2 Design of Biogas Burner

The design calculations for biogas burner were carried out as per Demissie, et al. 2016.
Throat diameter by Prigs formula,

$$d_t = \left(\frac{r}{\sqrt{s}} + 1\right) \times d_0 = 3.8 \cong 4 \text{ mm}$$

$$d_0 = \sqrt{\frac{Q_b}{0.036 C_d}} \times \sqrt[4]{\frac{S}{P}} = 1 \text{ mm}$$

$$Q_b = \frac{Q_{air}}{CV_{bg}} = 0.63 \text{ m}^3$$

$$Q_{mix.} = \frac{Q_{b \times (1+r)}}{3600} = 5.65 \times 10^{-5} \text{ m}^3/\text{s}$$

$Q_{air} = m \times C_p \times (T_d - T_a) = 14073.045$ KJ at raise the temperature from 30 to 60°C.

$$L_m = 15 \times d_t$$

$$A_p = \frac{Q_{mix}}{\eta_{bg}}$$

$$d_p = \sqrt{\frac{4 \times A_p}{\pi}} = 15.6 \text{ mm}$$

2.3 Design of Air Heater

The air heater was developed on the basis of working principle of parallel flow heat exchanger as per Cengel, [9].

Air properties at $\frac{60+30}{2}$ = 45°C were considered for further calculations,

$$Re = \frac{V \times D}{\vartheta} = 3541.97$$

Nusselt number for forced convection parallel flow condition

$$Nu = 0.3 + \frac{0.62 \times Re^{\frac{1}{2}} \times Pr^{\frac{1}{3}}}{[1+\left(\frac{0.4}{Pr}\right)^{\frac{2}{3}}]^{\frac{1}{4}}} + [1+\left(\frac{Re}{28\ 2000}\right)^{\frac{5}{8}}]^{\frac{4}{5}}$$

$$h = \frac{k \times Nu}{D} = 37.74 \text{ W/m}^2\text{K}$$

Length of air heater calculated by considering the diameter of inner cylinder 25 mm

$$L = \frac{Q}{hAD\Delta Tln} = 1.06 \text{ m}$$

The performance of air heater was evaluated for air velocity of 2.0, 2.5 and 3.0 m/s in terms of its effectiveness as given by Weis, [10].

From energy balance the mass flow rate of cold fluid (air)

$$m_c = \frac{m_h \times C_{ph} \times (T_{hin} - T_{hout})}{C_{pc}\,(T_{cout} - T_{cin})}$$

$$C_h = m_h \times Cp_h$$

$$C_c = m_c \times C_{pc}$$

$$C_r = \frac{C_h}{C_c}$$

$$\epsilon = \frac{Q_{act.}}{Q_{max}}$$

$Q_{act.} = m_c \times C_{pc} \times (Tc_{out} - Tc_{in})$

$Q_{max.} = C_h \times (Th_{in} - Tc_{in})$

2.4 Design of Drying Chamber

The design of drying chamber was done as per Rathore, et al. [11].

The mass of water to be removed during drying, M_w in kg

It was calculated by using following formula

$$M_w = \frac{m_i - m_f}{100 - m_f}$$

$$Q_{total} = M \times C_p (T_d - T_a) + (M_w \times \lambda) = 15043.42 \text{ KJ}$$

$$A_c = \frac{Q_{total}}{I \times \eta} = 3.03 \text{ m}^2$$

$$Q_a = \frac{M_w \times \lambda}{C_a \times \rho_a (T_e - T_a)} = 31.83 \text{ m}^3$$

$$V = \frac{\text{mass of onion to be dried}}{\text{density of onion}} = 0.01358 \text{ m}^3$$

$$A_d = \frac{V}{T_d} = 4.56 \text{ m}^2$$

Six trays were used with thickness of onion slices about 3 mm, therefore area of one tray = 4.56/6 = 0.76 m^2. Hence a tray of 700 mm width and 1100 mm length was selected.

Design of chimney

$$Q_a = \frac{m_w \times \lambda}{C_{pa} \times \rho_a \times (T_e - T_a)}$$

$$q_a = \frac{Q_a}{12 \times 60 \times 60}$$

$$D_p = H \times g \times (\rho_i - \rho_e)$$

Considering height of chimney about 450 mm

$$D_a = 0.40 \times D_p$$

$$V_{exit} = \sqrt{\frac{2D_a}{\rho_e}}$$

$$A_c = \frac{Q_{exit}}{V}$$

$$D_c = \sqrt{\frac{4A_c}{\pi}} = 156 \text{ mm}$$

For fabrication convenience diameter of chimney was taken as 200 mm.

2.5 Construction of Hybrid Dryer

A small-scale 8 kg capacity solar- biogas hybrid dryer was constructed at workshop of Department of Renewable Energy Engineering, CTAE, Udaipur. The physical structure of the experimental dryer set-up is shown in Plate 1. The hybrid dryer consists of a drying chamber, air heater and biogas burner. The constructional material consists of UV stabilized polythene sheet, mild steel angle for frame, aluminum sheet for floor, aluminum trays, thermocol insulation etc. The main frame of drying chamber was made of 3 mm thick mild steel angles and these angles joined by arc welding at each corner. The main horizontal section of the drying chamber having 1300 mm x 900 mm cross sectional area was made from 3 mm thick mild steel angle. The height of drying chamber was kept about 1300 mm. This inclined top side and south facing side of the dryer were covered with 200 micron UV stabilized polythene sheet both acts as a solar collector. This sheet was selected to be the transparent cover of the drying chamber, because it has high transmittance (0.8) in short wave solar radiation and low infrared transmittance (about 0.2), thus creating a good greenhouse effect in the drying chamber. All the sides of dryer were covered with UV stabilized polythene sheet and, thermocol sheet insulation of thickness 20 mm was provided to the north and west side walls of the dryer from the inner side to minimize the heat losses. An arrangement was made to place the trays inside the drying chamber such as 6 numbers of trays were placed with full loading capacity. The mild steel angles of 3 mm thickness were welded along the length of the drying chamber at fixed distance so that trays could be easily supported inside drying chamber. The rectangular trays were made of aluminum angles of size 30 mm×30 mm with 3 mm thickness and a wire mesh was fastened with aluminum angles and each tray was provided with a handle as it made easy to place or remove the tray during loading and unloading.

A centrifugal blower having 19.07 m^3/h capacities was operated at 2150 rpm to supply air. Air supplied by the blower was heated to required temperature in a double pipe concentric cylindrical heating chamber made of 1.5 mm thick M.S. material. A single jet type biogas burner was used to heat the air. Temperature of air at which it was meant to be heated controlled by manually, controlling the inlet air flow and adjusting the biogas flow to the burner. The dry bulb temperature of the air in the drying chamber was measured by a digital temperature indicator (accuracy= 0.1°C) with the help temperature sensor was installed at a distance of 20 mm above the drying product kept in each of the sample holding tray in the drying chamber. An insulated door with lock was provided on the front side of the drying chamber for loading and unloading the product holding trays. The bottom side of the drying chamber was sealed with G.I. sheet and insulation of thermocol sheet was provided over the G.I. sheet from inner side of the chamber. The inlet of drying chamber and outlet of air heater were connected through

Table 1. Assumptions made for design of solar-biogas hybrid dryer

S. no.	Particulars	Specifications
1	Product	Onion slices
2	Capacity	8 kg
3	Initial moisture content (m_i)	80%
4	Final moisture content (m_f)	10%
5	Specific heat of product, Onion	3.7 kJ/kg °C
6	Ambient temperature	30°C
7	Drying efficiency	25%
8	Drying temperature	60°C
9	Drying time	12 hours

Plate 1. Developed solar-biogas hybrid greenhouse dryer

Table 2. Technical specifications of solar-biogas hybrid greenhouse dryer

S. no.	Component	Specifications in mm
1	Drying chamber	1300×900×1850
2	Trays (6 trays)	110×70
3	Air heater	L=100, ϕ=45
4	Injector diameter	1.0
5	Throat diameter	4.0
6	Mixing tube length	60
7	Burner port diameter	20
8	Number of burner ports	1 No.
9	Electric blower	150W, Centrifugal
10	Biogas Plant used	Deenbandhu, 2 m^3

25 mm diameter G.I. pipe. A gate valve (V_1) was provided for regulating the flow rate of the air to the drying chamber. Ball valves (V_2) and (V_3) were provided for disconnecting the drying chamber from the air circuit when required. Air flow rate was measured with the help of anemometer.

3. RESULTS AND DISCUSSION

The performance of solar-biogas hybrid greenhouse dryer was assessed on the basis of performance of biogas burner, air heater and drying of onion at no load and full load test. The performance of the developed hybrid dryer was evaluated for onion drying in full load test by loading drying chamber with onion slices of 3±1 mm thickness and total mass of 8 kg. During full load test dryer was operated continuously for 12h in a day. The test was conducted during summer season in the month of May, 2018 from 8:00 hours to 20:00 hours in a day. The blower was run at three different air velocities viz. 2.0, 2.5 and 3.0 m/s and biogas burner were operated to achieve the desired 60ºC temperature whenever the solar radiation was insufficient. Different observations of variations in the temperature inside drying chamber at different locations were recorded with 1 hour time interval.

3.1 Biogas Burner

The biogas consumption rate of biogas burner calculated by volume method was found to be 352 l/h. It was observed that the water boiled at 92ºC from its initial temperature of 29.9ºC and total biogas consumption was about 95 litres. The overall efficiency of developed biogas burner evaluated through water boiling test (WBT) was found to be 47.59% as shown in Fig.1.

3.2 Air Heater

It was observed that air heated at a velocity of 2.5 m/s raised required 59.9ºC inside the drying chamber. On the other hand, air heated at a velocity of 2.0 m/s raised temperature inside the drying chamber to 62.02ºC which was higher than required drying temperature and air heated at a velocity of 3.0 m/s raised temperature inside the drying chamber to 55.17ºC which was lower than the required drying temperature. The highest value of effectiveness of air heater was found to be 0.88 at air velocity of 2.0 m/s. Similarly, the effectiveness of air heater was found 0.87 and 0.85 at air velocities of 2.5 and 3.0 m/s respectively, as shown in Fig. 2.

3.3 Drying of Onion

3.3.1 Drying at 2.0 m/s

The maximum temperature of 73.3ºC was recorded in afternoon at 13:00 hours. An average 62.02ºC temperature was maintained inside dryer throughout 12 h drying period. The onion was dried from initial moisture content of 80.06% (wb) to final moisture content of 10.90% (wb) in 12 h with average solar radiations availability of 553.54 W/m^2 and total biogas consumption of 660 litres. Drying rate was 0.6975 g of water evaporated/g of dm for initial first hour and it was reduced to 0.00221 g of water evaporated/g of dm after 12 h of drying as shown in Fig. 3.

3.3.2 Drying at 2.5 m/s

The maximum temperature of 71.2ºC was recorded in afternoon at 13:00 hours. An average 59.92ºC temperature was maintained inside dryer throughout 12 hour drying period. The onion was dried from initial moisture content of 80.06% (wb) to final moisture content of 9.88% (wb) in 12h with average solar radiations availability of 552 W/m^2 and total biogas consumption of 684 litres. Drying rate was 0.7063 g of water evaporated/g of dm for initial first hour and it was reduced to 0.00221 g of water evaporated/g of dm after 12 h of drying as shown in Fig. 4.

3.3.3 Drying at 3.0 m/s

The maximum temperature of 67.7ºC was recorded in afternoon at 13:00 hours. An average 55.36ºC temperature was maintained inside dryer throughout 12 h drying period. The onion was dried from initial moisture content of 80.06% (wb) to final moisture content of 11.31% (wb) in 12 h with average solar radiations availability of 553.54 W/m^2 and total biogas consumption of 749 litres. Drying rate was 0.6922 g of water evaporated/g of dm for initial first hour and it was reduced to 0.00221 g of water evaporated/g of dm after 12 h of drying as shown in Fig. 5.

The results obtained during drying indicated that moisture removal rate was higher for initial four hours as the temperature inside the drying chamber increased rapidly. After that drying rate decreased with loosing free water and becomes near to more or less horizontal line in falling rate period which indicates that drying rate decreases rapidly and remains nearly constant for last four hours. Drying rate was higher for the initial four hours and it was decreased rapidly with reduction in moisture content and gradually becomes near to constant rate for last four hours. It was revealed that highest moisture reduction found in onion dried at 59.92ºC with air velocity of 2.5 m/s followed by onion dried at 62.02 and 55.36ºC with air velocity of 2.0 and 3.0 m/s respectively. The final moisture content of onion dried at 59.92ºC was determined to be 9.88% (wb) in 12h whereas it was found to be 10.90 and 11.31% (wb) for onion dried at 62.02 and 55.36ºC respectively, similar results quoted by Kassem, et al. [12] Similarly highest drying rate was observed for onion dried at 2.5 m/s followed by 2.0 and 3.0 m/s. The drying efficiency of the hybrid dryer was determined on the basis of actual energy absorbed to remove the moisture from the onion and total heat supplied during drying. The drying efficiency of the hybrid dryer found 22.2%, similar result found by Kothari, et al. [13].

3.4 Economic Analysis

The economic feasibility of hybrid dryer was assessed on the basis of Net Present Worth, Benefit Cost ratio, Payback Period and Internal Rate of Return etc. The considerations taken into account while assessing the economics are, operating life of dryer -10 years, repair and maintenance cost - 5% of total cost, operating period-300 days in year and discount rate-10%. The capital cost of hybrid dryer was INR 35,000/- and total production cost around INR 88,348/. Net present worth (NPW) of developed drying system after 10 years has found to be Rs. 67,319.3/- and internal rate of return (IRR) has found to be 63.4. The benefit cost ratio has found to be 1.12 with payback period of 2.1 years.

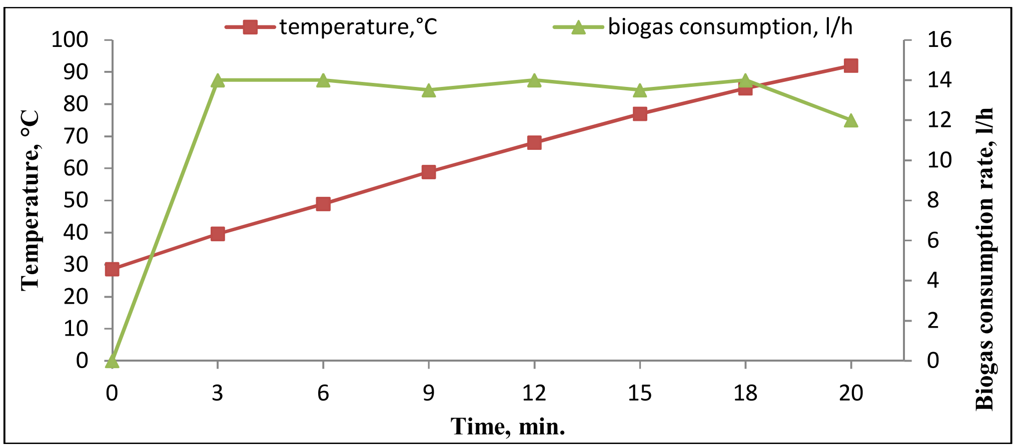

Fig. 1. Variation of temperature and biogas consumption rate (l/h) with respect to time (min.) during water boiling test

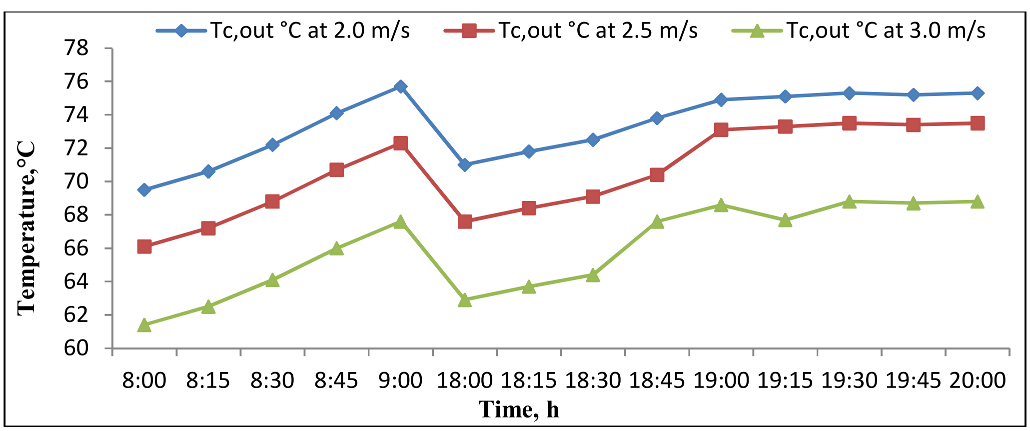

Fig. 2. Variation of air temperature (°C) for different air velocities (m/s) with respect to time (h) at outlet of air heater

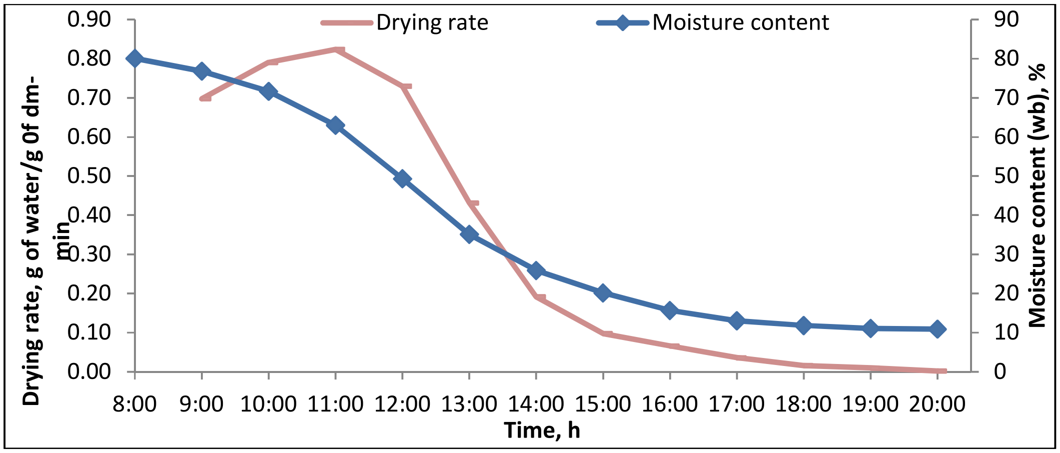

Fig. 3. Variation of moisture content (wb) % and drying rate with respect to time (h) during full load test at 2 m/s

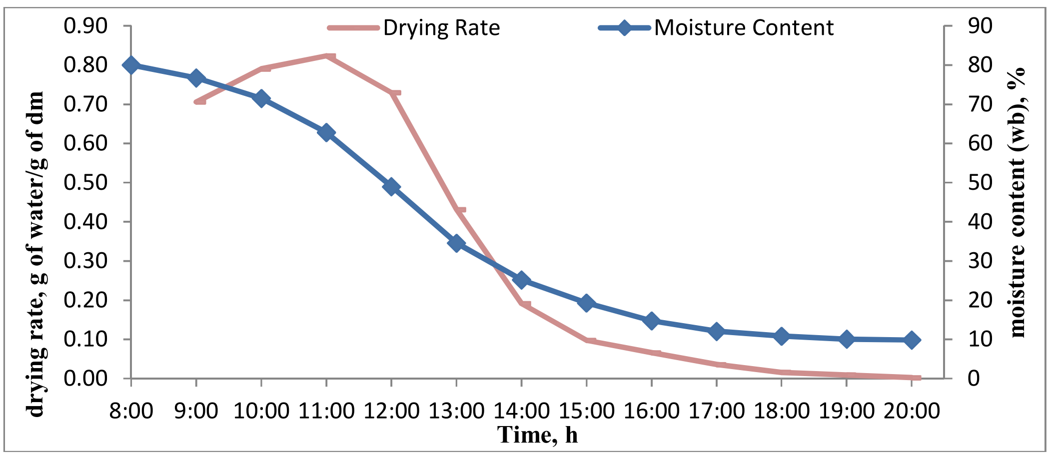

Fig. 4. Variation of moisture content (wb) % and drying rate with respect to time (h) during full load test at 2.5 m/s

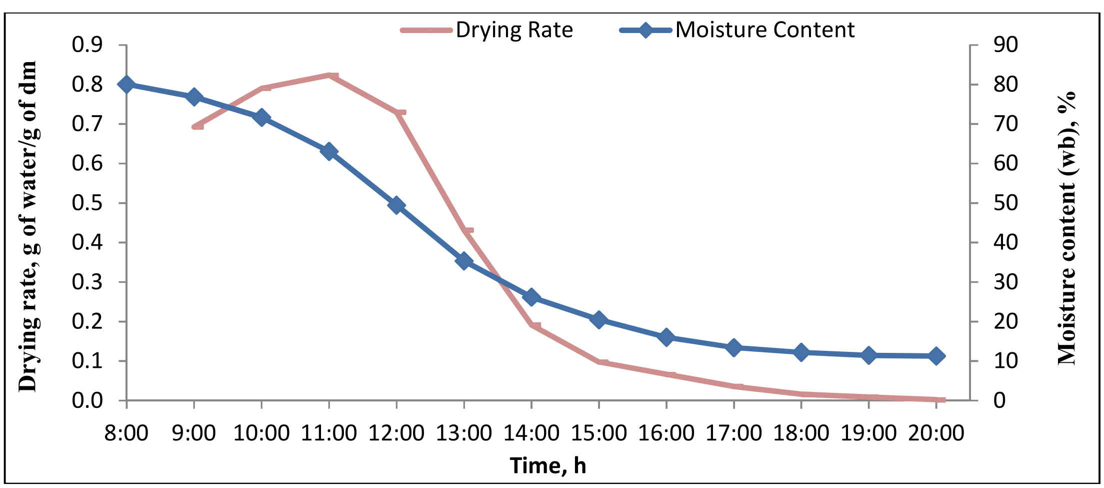

Fig. 5. Variation of moisture content (wb) % and drying rate with respect to time (h) during full load test at 3.0 m/s

4. CONCLUSION

Drying of high moisture content agro-products helps to increase shelf life of product with superior quality. The hybrid solar drying system integrated with biogas powered heating system yields increased throughput capacity of dryer by continuous drying with uniform drying condition and reduced drying time. An effective use of both solar and biogas energy for drying of fresh onion from 80 to 9.88% can be achieved with continuous drying operation. The economic feasibility in terms of benefit cost ratio has found 1.12 with payback period of 2.1 years. The hybrid dryer can be a better option for existing solar only drying systems. Further it can helps in reduction of use of conventional fuels and benefits in terms of clean environment which leads to sustainable development.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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