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Influences of a Novel Cylindrical Solar Dryer on Farmer's Income and its Impact on Environment

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Research Article

Keywords: Cylindrical solar dryer, Maize, Performance Evaluation, Economic Evaluation, Mathematical modelling, Carbon footprint

Posted Date: April 12th, 2022

DOI: https://doi.org/10.21203/rs.3.rs-1477039/v1

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Abstract

Poor grain drying facilities along with the burden of drying cost bound the farmers to market their produce soon after harvest. Thus, this research paper intends to study the influences of a novel cylindrical solar assisted dryer on farmer's income and its impact on environment. The paper also presents design and fabrication of a drying system for maize cobs by the use of non-conventional solar energy. Performance of the solar assisted drying system was also investigated for drying of yellow dent maize cobs. Drying, as a very energy-intensive post-harvest process, consumes a lot of electricity, which is usually provided by conventional energy. Here, solar dryers are the perfect solution in terms of efficiency, uniform drying of agricultural food products, less drying time, increased marketability of agricultural products as well as reducing load on farmer's pocket for drying. With a high internal rate of return of 66 percent, the designed dryer proved to be technically and economically viable. When compared to open sun drying, the solar drying system produced better results in terms of quality and drying time. When compared to other models, the Middili model fits the experimental maize drying data better, with a coefficient of determination R^2= 0.89729. Energy analysis inferred savings of 1352.97 kWh electrical energy and 128.18 liter of diesel fuel plus a reduction of 1.22 t CO_2 per annum can be achieved by using this dryer.

1. Introduction

Solar drying has long been one of the most fundamental, energy-efficient, cost-effective, and environmentally beneficial methods for preserving agricultural products. The potential of the solar drying process to minimize waste, increase shelf-life of products, improving the product quality with all its nutrients intact add on to the pros of being a renewable source. Because drying is necessary for efficient grain storage, this method of food preservation helps to reduce cost of packaging, storage, and transportation by significantly reducing product weight and volume (Vijayavenkataraman, Iniyan, and Goic 2012). Renewable energy sources are the ideal for energy conservation, as they conserve energy while maintaining the product's natural flavour (Sharma et al. 2020). The majority of agricultural items are dried at temperatures between 45 and 60 ^{0}C. For efficient drying of agricultural food products, the best and affordable means is using the energy from the sun which not only provides the temperature in the required range but also does not compromise in the quality of the dried product. Solar energy can be utilised to heat air to the temperature range required for drying agricultural products efficiently and affordably without compromising the end product's quality (Sharma et al. 2020). The average solar radiation accessible in India is 5 kW/m^2/day for 250–300 days per year with around 8–10 hours of sunshine (Rathore et al. 2019a, 2019b). This opens up a lot of possibilities for using solar energy to dry agricultural products.

Maize is one of the most significant cereal crops in the world, ranking third in terms of area and production in India after rice and wheat. The importance of maize lies in its wide variety of uses. Most of the maize crop produced is dried for its utilization all year round as a poultry feed and for human consumption in form of maize flour, maize dalia and other value-added products and only about a quarter of the maize produced is consumed directly (Murdia et al. 2016).

Maize must be dried for 10–15 days after harvesting to lower moisture levels to 13–14 percent. Produce prices will be lower if the moisture content is higher (Bhardwaj, Kumar, and Chauhan 2019). Currently, a substantial portion of maize production in India is sun dried which is accompanied by various problems of drying like much time taking process, uneven drying, deterioration in product quality, exposure to dust and pests, and improper drying practices reduces the quality of grains (Patel, Shah, and Bhargav 2013). Field dried maize cobs still need drying to an ideal moisture content for storage or further processing and it is very difficult to reduce its moisture content after field drying and also requires much energy (Abate et al. 2015). Development of a cylindrical and portable solar dryer is designed to meet these drying requirements and is a step towards improvement in drying practices.

Bola et al. 2013 suggested various parameters for a batch in-bin maize drier on a modest scale with a total costing of 375 USD (Bola. et al. 2013). Abed (2009) designed and developed a maize drying system using solar energy with a V-groove collector and observed high energy gain at an angle tilt of 45^{o} (Abed 2009). Asemu et al. 2020 studied the drying characteristics of maize grain in solar bubble dryer using statistical models (Asemu et al. 2020). He founded that about 24 hours were required to dry maize grains from 29–13% (wb) in thin layer and 39 hours in thick layer at 30 ^{o}C temperature inside the dryer. Using a thin-layer drying model, the results showed better with diffusion approach. Ntwali et al. 2018 assessed the performance of an inflatable solar dryer for maize and found that direct sun drying reduced aflatoxin concentration from 569.6 g kg^{-1} to 345.5 g kg^{-1} while drying with Inflatable solar dryer reduced the same to 299.2 μg kg^{-1} (Ntwali et al. 2021). Sanghi et al. 2018 ran a CFD simulation of maize drying in a solar dryer with natural convection (Sanghi, Ambrose, and Maier 2018). The model simulated the dryer's performance with 32% less moisture removal in overcast weather conditions as compared to simulated fair-weather condition case. Thus, a significant amount of effort has been done for drying of agricultural products but still there is a research gap of studying the influences of solar drying on farmer's income and its impact on environment. The proposed design of solar dryer is an attempt towards this. The novelty of dryer lies in the material used for its fabrication. A polycarbonate sheet of 6 mm thickness was used. The airgap in between the polycarbonate sheet acts as an insulator for heat thereby reducing heat losses from within the dryer. Also, maize drying in this way increases its grind ability so that it can be easily used to make value added items like soups, corn puddings, pop-corn, etc.

The portable cylindrical solar drier was created with smallholder farmers in mind, allowing them to confidently, conveniently, and affordably dry any agricultural product to a long-term storage moisture content regardless of whether circumstances. The dryer prototype is being tested for drying maize cobs on-farm, with the goal of reducing postharvest losses for farmers and thereby boosting their income.

2. Methodological Framework

The dryer prototype is being tested for drying maize cobs on-farm, with the goal of reducing postharvest losses for farmers and thereby boosting their income. The materials used for the fabrication of solar drying system are reasonable and easily obtainable in the local market. The experiment was performed in May month.

2.1 Specifications of the Designed System

The proposed structure comprises of a cylindrical drying bin, a Flat plate collector (FPC), a PV powered DC fan of 1.5 W, a PV panel of 10Wp, an insulated duct and a chimney. A Flat plate collector (FPC) is used for heating of air. The drying chamber is then supplied with hot air via an insulated duct. The drying chamber is made in cylindrical shape to ensure uniform drying of product. The drying chamber is made of a translucent Multiwall polycarbonate sheet (MWPC) which has high heat retention and thermal insulating properties with good solar gain as compared to the material used for dryer construction in the existing solar dryers. The MWPC sheet provides the advantage of itself acting as a solar collector. Further the dryer is fabricated in such a way that only $3/4^{th}$ area is covered by MWPC sheet absorbing solar radiations from south as well as east and west side and $1/4^{th}$ area is insulated to prevent radiation loss from its north side. A PV-powered DC fan is installed at the bottom of the drying chamber to efficiently circulate the incoming hot air at a steady speed within the drying chamber as needed, as well as to eliminate the humidity. Exhaust vent in form of chimney is attached to remove the moist air from the drying bin. The product to be dried is placed in two fixed circular wire mesh trays in the drying chamber. Wheels attached provides portability to the whole system so that it can be easily installed in the farms also.

Using the oven method at 110 ^{o}C for 24 hours, the initial moisture content of maize cobs was assessed (Singh and Gaur 2020). A moisture content of 28 percent (wb) was used as a reference. A solarimeter was used to measure the overall solar irradiance falling on a plane surface (Uncertainty: ±0.5%, Make: M/s. Surya Solar Systems, Ahemedabad). The measurement of all the trays, temperature of ambient air, inlet temperature of dryer and temperature of exit air was done by using dataTaker DT82E (Uncertainty: 0.7 percent, Make-Thermo Fisher Scientific Australia Pvt. Ltd, Australia) with range of temperature -45 ^{o}C to 70 ^{o}C. An electronic balance was used to measure weight (Make- Adair Dutt and Co. Pvt. Ltd.).

Table 1 lists the dryer's design constraints and Fig. 1 depicts the suggested design of a cylindrical shallow bed solar dryer.

Table 1 Considerations used for the design of solar drying system

S. No.	Parameters	Specifications
1.	Drying material	Maize cobs (Zea mays)
1.	Variety	Yellow Dent Maize
1.	Density of product used for drying	671 kg/m^3
1.	Moisture content of product at the time of harvest	28% (wb)
1.	Anticipated moisture content after drying of product	13% (wb)
1.	Average temperature of ambient air (Ta)	27^{o}C
1.	Loading rate (Lr)	50 kgs per batch
1.	Drying temperature (Td)	60^{o}C
1.	Relative humidity (RH)	50%
1.	Wind velocity (Vw)	0.25-0.3 m/s
1.	Collector tilt angle	27^o

The dimensions of the proposed cylindrical dryer are mentioned in Table 2 below.

Table 2 Dimensions of the Cylindrical Solar Dryer

S. No.	Parts of the developed system	Dimensions	Material used for construction
1.	Cylindrical bin	Ht. - 1m Dia. - 1.12m Vol. of cylinder= 0.99 m^3 Total vol. of drying chamber= Vol. of Cylinder + Vol. of Cone = 1.023 m^3	Multiwall Polycarbonate sheet of thickness 6mm. (Covering only $3/4^{th}$ surface area of cylinder)
2.	Insulation for door	Thickness- 0.2m Area- 1m x 0.8m	Inner sheet- G.I Centre- Thermocol Outer sheet- MWPC
3.	Insulation for bottom of drying chamber	Thickness- 0.2m Area- $1m^2$	Inner sheet- Aluminium Centre- Thermocol Outer sheet- G.I
4.	Wire mesh trays	Dia. - 1.12m Depth- 0.18m Perforation size- (20 x 20 m^2)	M.S. 14 gauze
5.	Chimney	Ht. - 0.457 m Dia. - 0.205 m Outlet vent area- 0.785 x $(0.203)^2$ m^2	G.I. sheet
6.	Flat Plate Collector	Ht. - 1.76 m Width- 1.15 m Area- 2.02 m^2	Absorber- Aluminium (0.05 cm thick) Receiver- Glass (0.5 cm thick)
7.	Insulated Connecting Duct	Length- 0.408m Inlet vent area- 0.785 x $(0.075)^2$ m^2	Inner sheet- Aluminium Centre- Thermocol Outer sheet- G.I. sheet

*2.2 **Main Components of the Developed System***

The portable shallow bed solar drying system consists of following the components:

1. FPC solar collector

Flat plate solar collector is used to heat air by using solar energy. The schematic diagram of the flat plate collector is provided in Fig. 2 below.

2. Drying chamber

The collector is situated alongside the drying chamber, which is where the product is dried. The hot air in the drying bin soaks up moisture from the product and exhausts it to the surrounding area via forced convection. Two trays were placed in this chamber for placing of product for drying. The drying chamber is in cylindrical shape with a diameter of 1.12 m. The height of the bin is 1 m. Three- fourth surface area of the cylinder is covered with UV Polycarbonate sheet of 6mm thickness.

Polygal Multiwall Polycarbonate sheet

It's a translucent sheet made of a special engineered thermoplastic that has excellent mechanical, optical, and thermal qualities. This material's versatility allows it to be used in a variety of engineering applications. A 6mm thickness sheet having weight 1300 g/m^2 is used.

The bin had a circular inlet vent made of insulated G.I. sheet material with a 75 mm diameter for input of hot air from the collector. The drying bin has slight cone-shaped top covering and cylindrical outlet vent for chimney both made of G.I. sheet. An insulated gate is constructed (1m x 0.80m) for loading of wet product and unloading of dried product out from the drying chamber. One- fourth surface area of the cylinder is made insulated with thermocol sheet (north side from front view) and covered on the inner side with G.I. sheet and outer side with polycarbonate sheet to prevent heat loss. H.R. thermal sheet was used to make the gate airtight. The drying chamber's bottom is provided with a small PV operated DC fan of 12V to extract hot air from the flat plate collector at more speed through forced convection mode. This fan can be made off if much heat is not required in the drying chamber and the heat through the transparent polycarbonate walls is sufficient enough to dry the product to the desired level.

2.3 Drying characteristics of maize drying

The drying characteristics of dehusked and silk removed dent maize cobs dried in solar assisted bin type drying system in term of moisture removal (per cent wb), drying rate (g $h^{-1}1g^{-1}$ of bone-dry matter) and moisture ratio were calculated and correlated with the findings of drying under open sun.

2.4 Zero load testing and Complete load testing

The rate of drying of the product and the dryer's drying efficiency determine the thermal evaluation of the proposed system. The drying system's performance was assessed using both zero-load and complete-load testing. The temperature profile was evaluated using a no-load test, which comprised the air temperature inside the drying bin, ambient temperature, air inlet-outlet temperature, and solar insolation.

The evaluation of the solar drying system in fully loaded condition was done by loading the dryer to its maximum designed capacity.

2.5 Data Analysis

For the estimation of solar drying curves, five independent mathematical models were applied. The root mean square error (RMSE) and the coefficient of determination (R^2) were employed for the comparison of models and for the selection of model of best fit using regression analysis. The root mean square error (RMSE) represents the difference between the expected and experimental results. R-square shows how much data is scattered around the fitted regression line. The model with the best fit is considered to have the highest R-square and lowest RMSE values (Kumar and Saha 2021).

2.6 Inferences for techno-economic assessment

1. A solar dryer's life expectancy is estimated to be ten years (n).
2. An 8% discount rate is estimated to be used (i).
3. The cost of repair and maintenance in a year is 3% of the total cost.
4. Labour charge is considered 2.74 USD per day and one labour is needed per day.
5. The dryer may run for 300 days in a year.
6. The system would value 581.90 USD.
7. The total cost of input material is 3.29 USD/kg x 100 batches ie; 328.76 USD per year.
8. Cost of dried maize grains per year: 7.34 USD/ kg x 100 batches ie; 733.55 USD per year.

2.7 CO_2 emission estimation

The use of fossil fuels is a major cause for emission of CO_2 in the atmosphere. Thus, the electricity generated from non-conventional sources is major contributor towards global warming. Energy consumption is a major contributor to carbon footprint. One of the ways by which one can protect our environment is by reducing its carbon footprints. The solution to this biggest problem which our world is facing today is switching to renewable source of energy. Solar energy has the potential to generate power with zero emissions. Equation (1) can be used to calculate CO_2 emission reduction (EY) (Ganesan et al. 2015).

$$E_Y = AES\,(MWh) \times E.F. \tag{1}$$

Where, AES = Annual energy saving for electricity

E.F. = Emission factor for electricity (MWh/year) 0.9

2.8 Energy analysis

One of the important parameters used for analysis of energy in drying is energy consumption (Lawrence et al. 2019). The energy consumption is calculated for the removal of the desired moisture content in the developed solar dryer. This energy consumption is then used for the calculation of energy savings in electrically operated drying system and diesel operated drying system if the conventional energy sources is replaced by non-conventional energy sources.

3. Result And Discussion

3.1 Design procedure

The design was proposed according to steady flow systems with 27 °C ambient temperature (da Silva et al. 2020). Under normal temperature and 101.325 kPa barometric pressure, the original humidity ratio (Hr1) is predicted to be 0.01 kg/kg dry air by using psychometric chart. Asemu et al. 2020 states the most reliable drying temperature (T_2) required for drying of maize as 40 ^{o}C (Asemu et al. 2020).

The designed parameters for dryer fabrication are listed in Table 3 below.

3.2 Thermal performance

The data from the no-load and full-load testing were used to analyse the effectiveness of the drying process using solar drying system.

3.2.1 Temperature variation during No-load testing

The performance of solar dryer under no-load was evaluated to find out the maximal temperature attained inside the dryer. This was useful for predicting effectiveness of solar drying system for drying of agricultural products with respect to drying under open sun. It was evaluated by measuring solar intensity, ambient temperature and temperature at different points inside the drying chamber. During no-load testing, the graphs representing solar radiations and temperature profiles at different locations in the drying system are depicted in Fig. 3. Since there was no load in the drying chamber, the system only served as a collector. The tests were carried out from 09:00 hour to 17:00 hour. It was observed that the input temperature within the drying chamber was increased by an average of 49.85 °C when the drying chamber's walls were heated. The wall is made of polycarbonate sheet and it acted as an excellent absorber of solar radiations. Its north side insulated gate acted as perfect insulator to heat losses from the drying chamber. The hourly collector efficiency with regard to time was used to examine the solar collector's performance. The highest solar radiation at midday was 1116 W/m^2, and the solar intensity increased until 13:00 hours, after which it began to decline. Likewise, the ambient temperature rises during the day and then drops slightly in the evening. Solar radiation values range from 445 to 1116 W/m^2, with a peak at 13:00 local time.

3.2.2 Temperature variation during Full-load performance

The experimental findings for full load performance are represented by graphs shown in Fig. 4. 50 kg maize cobs were fed into the system at full capacity. The drying period was found to be roughly 2 days with 11 hours of sunshine. Drying was conducted till the desired moisture content was achieved.

Based on the results obtained during the experiment, temperature above 45 ^{o}C was recorded. The rate of weight loss on the first day was higher than on the second day of drying. During times of maximum sun exposure, a rapid rate of weight loss can be observed. Because of the rise in inlet temperature of air, the rate of heat transfer between the drying air and the maize kernels became greater thereby increasing the drying rate of maize. The graph showed that the rate of drying increased as the moisture content increased. The drying rate decreased as the moisture content lowered. The variation in weight of maize cobs in the solar dryer on each day is given in Table 4.

Table 4 Variation in weight of maize cobs in solar dryer on each day

Drying day	Mass of product at start of the day, kg	Mass of product at end of the day, kg	Mass of water evaporated, Kg	Average Solar Radiation, W/m^2	Daily drying Efficiency (%)
1	50	43.93	6.07 (8 h)	767	29.88
2	43.93	41.98	1.95 (3 h)	795	24.69
			8.02		

3.3 Variation in moisture content

The moisture ratio of maize cobs varies in the dryer and during drying in the open sun as shown in Figure 2. The moisture content of the maize cob dropped from 28.61 percent (wb) to 12.99 percent (wb) after 11 hours of drying in the solar dryer which is the required level of moisture content for safe storage of maize. Open sun drying of maize cobs, on the other hand, took 37 hours to achieve the same moisture content, resulting in a net time savings of 70.27 percent for solar drying versus open sun drying.

3.4 Difference in drying rate

The variation in content of moisture in a specific interval of time was used to assess the drying rate of dent maize cobs. The water evaporation is measured in grammes per hour (Agrawal and Sarviya 2016). The average rate of drying of dent maize cobs in solar assisted dryer was found to be 0.0209 g/h-g of bone-dry matter as compared to 0.0068 g/h-g of bone-dry matter in open sun drying.

3.5 Variation of moisture ratio

The average moisture ratio obtained for the solar assisted dried maize cobs is 0.419 while the average moisture ratio obtained for the open sun-dried maize cobs is 0.367. The graph of moisture ratio with drying time shows moisture ratio decreases with rise in drying time. The results obtained were similar with the results obtained by (Asemu et al. 2020). An overview of testing of solar drying system is presented in the Table 5.

The graphs representing the disparity of moisture content, drying rate and moisture ratio with drying time are plotted for product in both solar drying and drying under open sun and are given in Fig. 5 below.

Table 5 An overview of testing of solar dryer

Initial M.C. (wb)	Final M.C. (wb)	Ambient Temp. (˚C)	Average Dryer Temp. (˚C)	Drying time (h)	Collector Efficiency (%)	Effectiveness factor c
28	12.64	31.0	54.6	11	60.77	3.07

3.6 Data Analysis

Regression analysis was carried out (Table 6) using Excel 2019 software for estimating the drying curves between moisture ratios and drying time. The results were found similar with the results obtained from (Coradi et al. 2015),(Mukwangole and Simate 2017) for drying kinetics of maize cobs. Middili model was found model of best fit with highest R-square (Coefficient of determination) values than other models and lowest value of Root Mean Square error (RMSE).

The graph plotted between moisture ratio obtained from the experiment and Middili's model predicted moisture ratio shows the accuracy of the model with the experimental data and is presented in Fig. 6.

3.7 Techno Economics of Solar dryer

The techno economics were conducted based on assumptions formed in Section 2.6 and as described by (Selvanayaki and Sampathkumar 2017). The system's net present value came out to be 1802.00 USD. Along with benefit cost ratio of 1.71 and payback period of 4.07, the greater the internal rate of return percentage ie; 66 percent indicated a good economical return of investment. Thus, it is evident that the proposed dryer is both technically and commercially viable.

3.8 CO_2 emission estimation

Estimation and reduction of CO_2 emissions is a very important step towards protection of our environment. The carbon footprint can be reduced by using renewable sources of energy in place of non-renewable fossil fuels and solar energy has great potential to generate power with zero emissions.

Considering quantity of one batch of product and 300 operating days of solar dryer, the total number of batches per annum can be estimated as 150. Substituting the value of annual energy electricity savings in eq. (1), it can be inferred that a total of 1.22 t CO_2 per annum can be reduced by using the developed dryer.

3.9 Energy analysis

Table 7 displays the findings of the energy study.

Conclusion

The accessible energy from the sun can be employed to obtain sufficient air temperature required for drying with the help of solar drying technology at almost nil fuel charges saving lots of money and quality of food products. The experiment conducted on a cylindrical and portable solar drying system revealed that the system is compatible for effectively drying of maize cobs from a moisture content of 28 % (wb) to a moisture content of 13% (wb) in 11 sunshine hours. The special feature of this solar dryer is the use of a Multiwall polycarbonate sheet in the drying chamber which provides several advantages as compared to the other drying materials such as high thermal conductivity, high solar gain etc.

The developed dryer's technoeconomic metrics reveal that it is both technically and economically feasible, with a high internal rate of return (66%) indicating a favourable return on investment. There was a significant saving of 70.20 % of drying time in solar assisted dryer than in open sun drying along with an effectiveness factor of 3.07. The developed unit for drying of maize cobs can effectively save a significant amount of 1352.97 kWh electrical units and 128.18-liter diesel fuel annually along with a total of 1.22 t CO_2 emission reduction per year. Thus, by using solar dryer farmers can also contribute in protecting the environment by reducing its carbon footprint. Thus, it is proposed to use this dryer on community scale for the benefit of both farmers and environment.

Declarations

Ethics Approval

Not applicable

Consent to Participate

Not applicable

Consent to Publish

Consented

Author Contributions

All authors contributed to the study conception and design. KS, SK, NLP: Material preparation, data collection and critical review; MRP: energy related calculations and statistical analysis. All the authors read and approved the final manuscript.

Fundings

The authors declare that no funds, grants, or other support were received during the preparation of this manuscript.

Competing Interest

The authors have no relevant financial or non-financial interests to disclose.

Availability of data and materials

All the relevant data is provided in the paper only.

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Tables

Table 3, 6 and 7 are available in the Supplemental Files section.

Figures

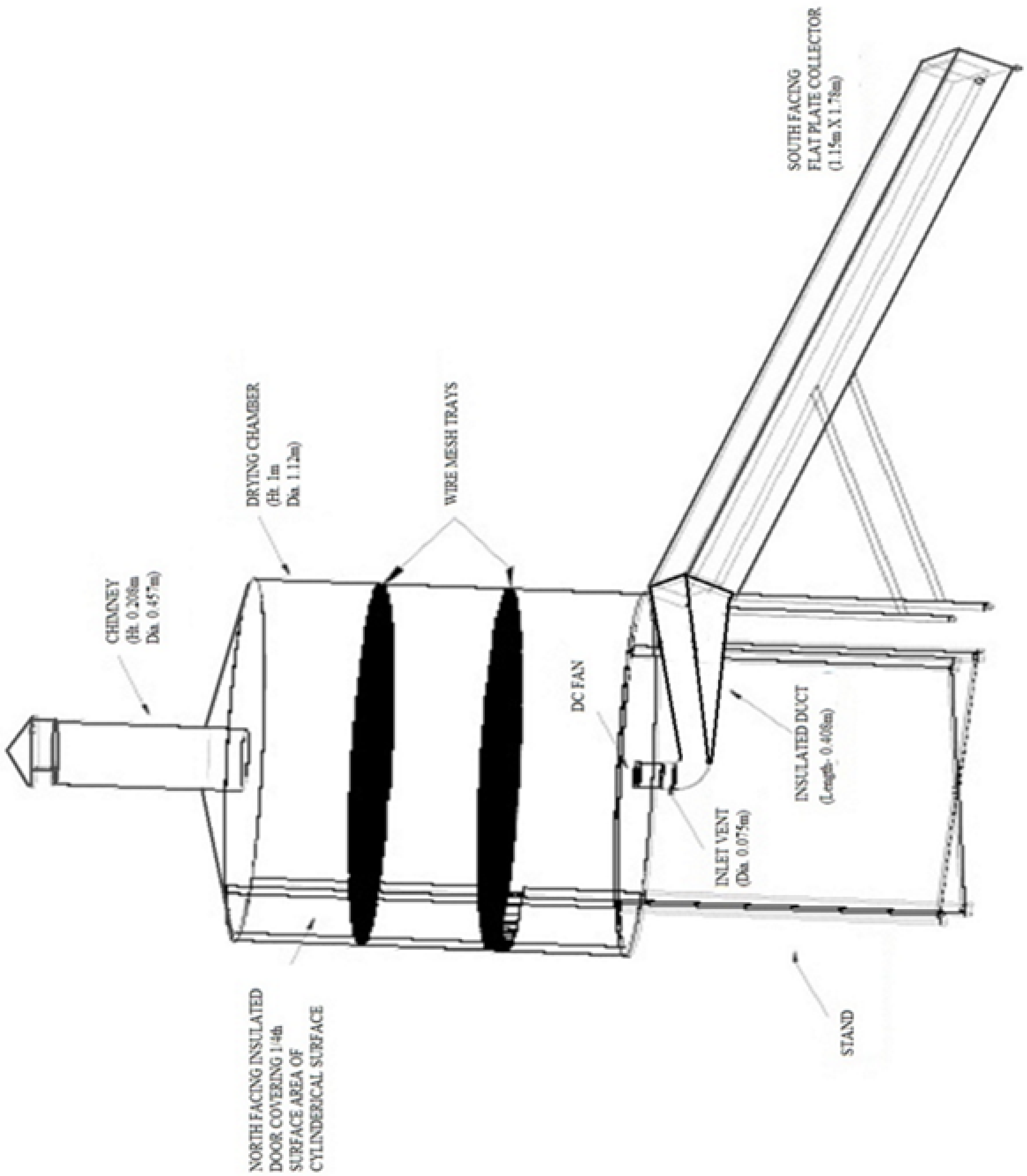


Figure 1

Proposed design of the Novel cylindrical Solar Drying system

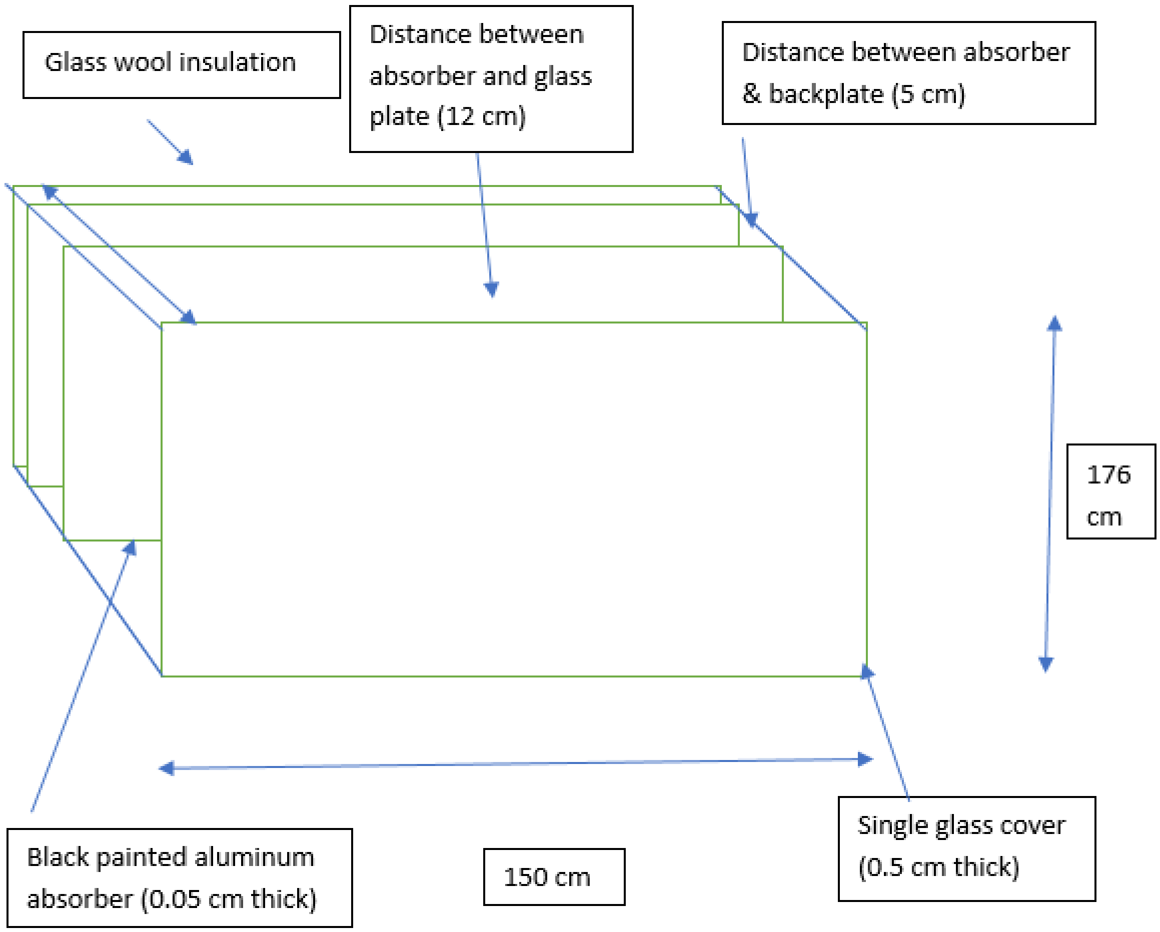


Figure 2

Schematic diagram of the used Flat Plate solar collector of Area 2.02 m^2

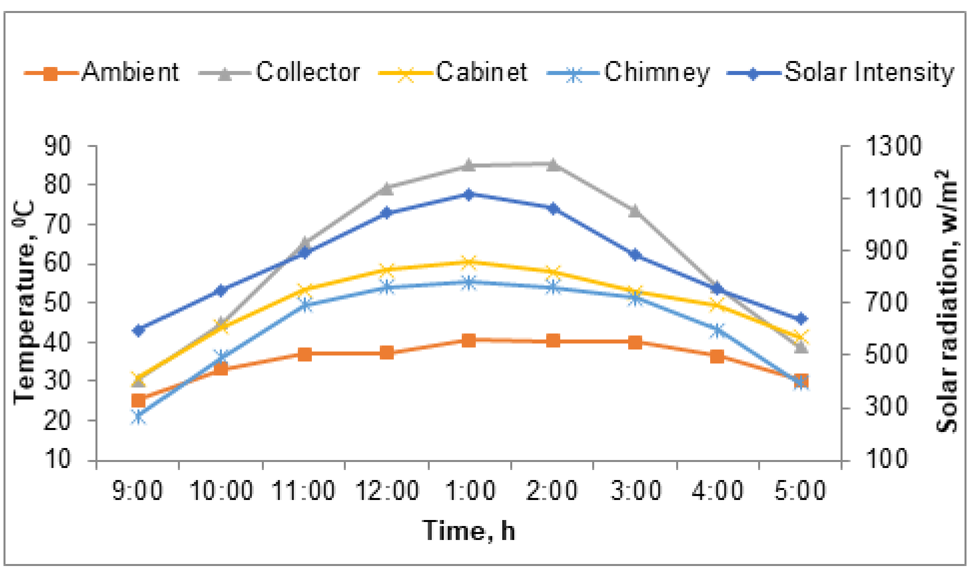


Figure 3

Variation of temperature during No-load Testing of Solar dryer

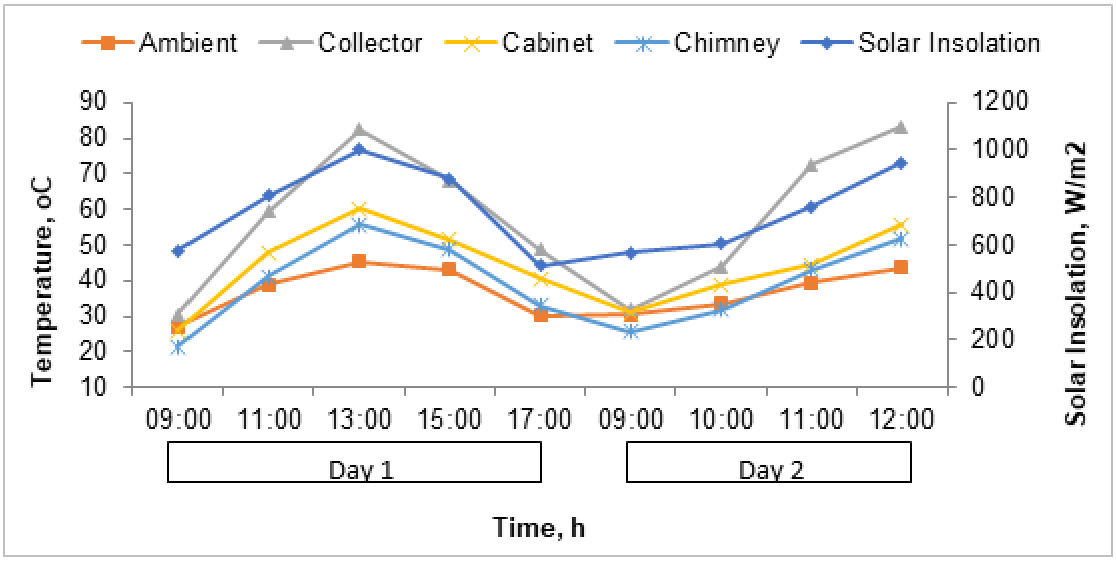
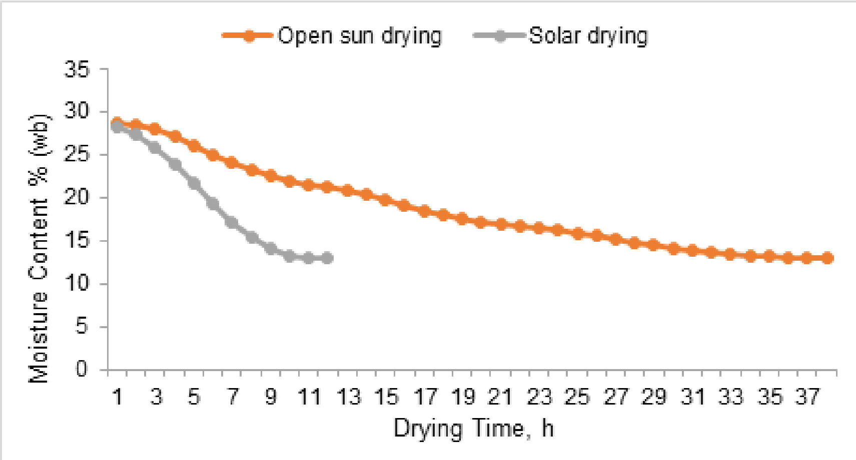
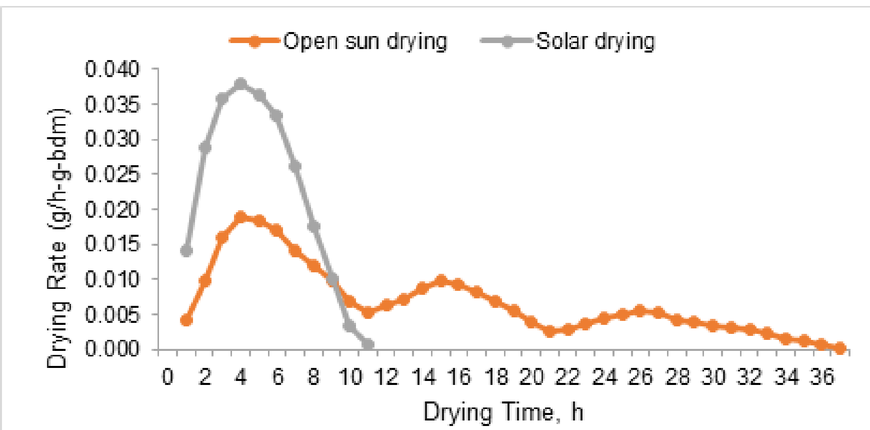


Figure 4

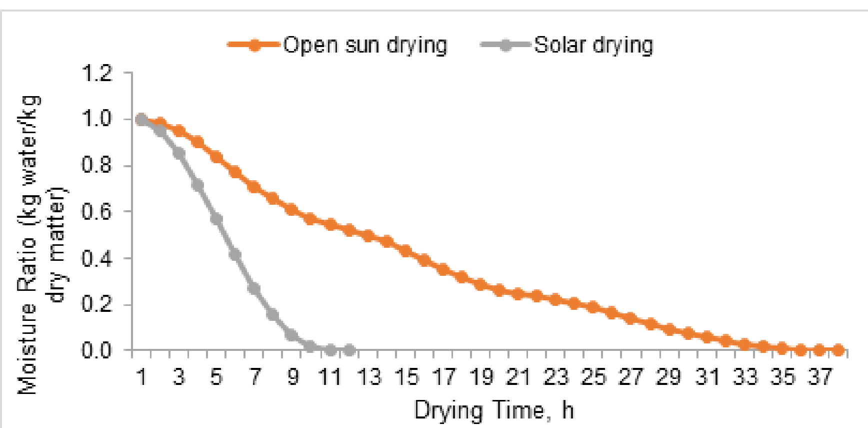
Variation of Temperature during full load test in solar dryer



(a)



(b)



(c)

Figure 5

(a, b, c) Variations of moisture contents, drying rate, drying time and moisture ratio in solar drying system and drying under open sun

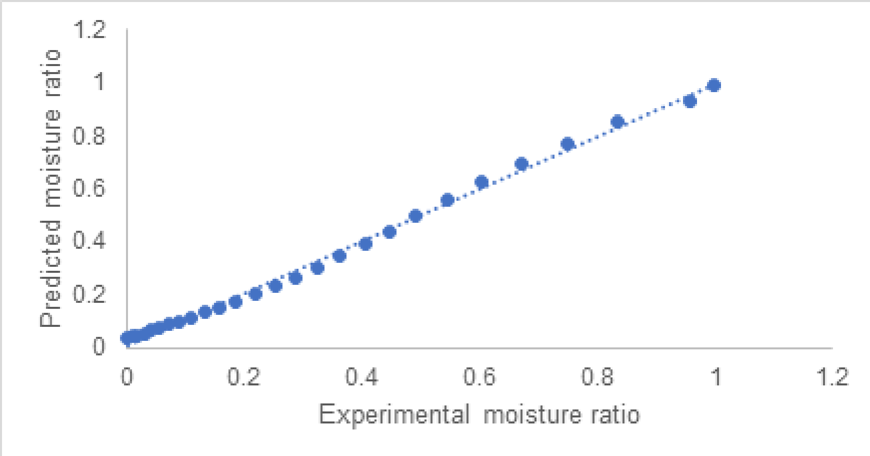


Figure 6

Moisture ratio projected by Middili's model as a function of experimental moisture ratio

Supplementary Files

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- Table367.docx