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Design, Development and Evaluation of Photovoltaic Integrated Solar Greenhouse Dryer for Paddy

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ABSTRACT

The present study was conducted at College of Agricultural Engineering, Bapatla, Andhra Pradesh, India during the month of January, 2021 to develop photovoltaic power assisted forced circulation solar greenhouse dryer and to evaluate its performance for drying of paddy. A free standing greenhouse structure with arch roof was selected to have high light transmission and low cost of construction. To get adequate and uniform light inside the greenhouse east-west orientation was selected. A frame of solar greenhouse dryer having 4.467 m length, 2.134 m width and 2.591 m height was constructed and was covered with twin wall polycarbonate sheet of 6 mm thickness. Freshly harvested paddy was filled in perforated tray with size 142.5×80×12.5 cm up to 10 cm height the trays were placed in drying chamber consists of three tires and two columns. Forced ventilation was provided with four 40 W DC fans which were powered with two 150 W photovoltaic panels. During drying, the green house and ambient air temperature, relative humidity data was collected at every 1 h interval using data logger, the moisture content of the paddy was determined at every 2 h interval. The paddy was dried till getting 12% (w.b.) final moisture content. The highest greenhouse dryer temperature of 48.1°C was recorded as compared with highest ambient temperature of34.2°C. Moreover, the air flow rate achieved was varied between 75.52–34.25 m^3m^{-1}.In this dryer the paddy was dried from 25.3–12.0% (w.b.) moisture content in 21 h whereas open sun drying took 28 h of drying time.

KEYWORDS: Forced circulation, hybrid greenhouse dryer, paddy drying, photovoltaic

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Data Availability Statement: Legal restrictions are imposed on the public sharing of raw data. However, authors have full right to transfer or share the data in raw form upon request subject to either meeting the conditions of the original consents and the original research study. Further, access of data needs to meet whether the user complies with the ethical and legal obligations as data controllers to allow for secondary use of the data outside of the original study.

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1. INTRODUCTION

The post-harvest losses account for 30–40% of total food production in developing countries whereas in developed nations, the same amount is lost at the retail and consumer levels (Lingayat et al., 2020, Chegere, 2018). Drying of food crops greatly reduces post-harvest losses. Besides extended shelf-life, the main goals of drying are ease of handling, further processing and improving sanitation (Babu et al, 2018, Llavata et al., 2020). Drying also significantly reduces weight, volume, decreases packaging, storage and transport costs, and allows storage of foods at appropriate temperatures (Naseer et al., 2013, Awasthi et al., 2020). Earlier drying was primarily performed in the sun. Currently convective drying is being preferred. In convective drying process, hot air heats the grain and transmits moisture to the atmosphere (Gorjian et al., 2020). To provide heat in conventional process, number of air pollutants emitted into the atmosphere through the combustion of fuels, such as carbon di-oxide (CO_2), sulphur di-oxide (SO_2) and nitrogen di-oxide (NO_2) which leads to the use of acid rain and smog. Such emissions will dramatically change the global environment and lead to global warming (Svejkovsky, 2006, Yildizhan et al., 2021). Sun dryers significantly enhance heat load, reduce humidity from products (Kiburi et al., 2020) and retain product quality (El Hage et al., 2018). Solar drying is a relatively inexpensive process, particularly for medium to small quantity of farm produce. The level of technical advancements in solar drying is different from conventional drying. Solar powered driers are direct, indirect and mixed type dryers in their designs (Kumar et al., 2016, Yahya et al., 2018, Yahya et al., 2017). Comparative studies of these three dryer designs demonstrated that the performance of the mixed-mode forced circulation solar dryer in tropical regions is comparatively effective (Safri et al., 2021).

Solar drying in closed structures by forced convection is an ideal way to reduce losses after harvest and poor quality of dried product attributed with traditional open-sun drying methods (Jain and Tiwari, 2003). The greenhouse solar dryer mostly falls under the category of direct sun drying, while it occasionally uses a mixed mode system. The solar greenhouse dryer absorbs solar heat and retains it for use in the night and cloudy days (Yadav and Bhagoria, 2013). A solar greenhouse reduces the user of hydrocarbons for heating (Anonymous, 2009). Passive solar greenhouses are indeed good alternatives for small farmers, because they provide an economical way to extend the growing season for farmers. Active greenhouses use supplemental energy in order to transfer heated solar air through food material for faster drying in a greenhouse dryer (Svejkovsky, 2006). For areas without electrical power connections, solar photovoltaic power dryers tend to be attractive (Mekhilefa et al., 2011, Xingxing et al., 2012, Anonymous, 2009). In remote areas where grid energy is not enough for paddy drying, the integrated photovoltaic greenhouse dryer is one of the best alternatives. The hybrid greenhouse drier integrates the greenhouse and PV modules that provide DC electrical power to run a fan in forced mode. Various designs were developed by the researchers for drying of different agricultural commodities which are mainly designed for drying of fruits and vegetables (Prakash and Kumar, 2014, Sangamithra et al., 2014). The development of suitable design for dying large quantity of wet paddy is essential to minimize drying time and maximize drying capacity. In view of these factors, an attempt was made to design and develop a hybrid solar greenhouse dryer for drying of fresh harvested paddy and to evaluate its performance.

2. MATERIALS AND METHODS

Hybrid greenhouse dryer has been designed with following theoretical considerations, fabricatedat College of Agricultural Engineering, Bapatla, Andhra Pradesh, India and evaluated its performance for drying of paddy during the month of January, 2021.

2.1. Theoretical design of hybrid greenhouse dryer

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

Table 1: Design conditions and assumptions

Sl. No.	Particulars	Conditioner Assumptions
1.	Location	Bapatla
2.	Product	Paddy
3.	Loading rate (M) in each batch, kg	1000
4.	Initial moisture content (mi), %	22
5.	Final moisture content (mf), %	12
6.	Ambient air temperature (Ta), °C	30
7.	Dryer air temperature (Tg), °C	50
8.	Drying period (td), h	16
9.	Incident solar radiation (I), kWh m^{-2}	5.21
10.	Thickness of poly carbonate sheet, mm	6
11.	Specific heat of bone-dry paddy (Cd), kJ kg^{-1} °C (Khanali et al., 2012)	2.358
12.	Latent heat of vaporization(λ), kJ kg^{-1} (Norman, 1987)	2447
13.	Dryer efficiency, %	40

2.2. Quantity of moisture removed from the product

Henderson and Perry (1980) suggested a model to determine the quantity of water removed to dry the product from initial moisture content to safe storage moisture content.

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

$M_w=(m_i-m_f/100-m_f)\times W$ ….1

Where,

m_i=Initial moisture content, %

m_f=Final moisture content, %

W=Mass of product, kg

Mass of water removed h^{-1}, m_w, kg h^{-1}

$m_w=(M_w/t_d)$ ….2

M_w=Mass of water to be removed during drying, kg

m_w=Mass of water to be removed h^{-1}, kg h^{-1}

t_d=Assumed time of drying, h

Total energy required (Q), kJ (Sangamithra et al., 2014, Seveda, 2012)

$Q=MdCd(Td-Ta)+M_wC_P(T_d-T_a)+(M_w\lambda)$ …3

Specific heat (Cd) of bone dry paddy was calculated using equation suggested by Khanali et al. (2012).

$C_d=0.085\ M^2+29.693\ M+3.819\ T-(0.008T)M+1163.54$ …4

Specific heat of water at average greenhouse air temperature was calculated using the equation suggested by Heldman and Lund (2006).

$C_P=4.1762-9.0864\times10^{-5}\ T+5.4731\times10^{-6}\ T^2$ …5

Where

W=Mass of product, kg

Md =Weight of dried paddy, kg

C_p=Specific heat of water, kJ kg^{-1} $^{o}C^{-1}$

T_d=Dryer temperature, °C

T_a=Ambient temperature, °C

λ =Latent heat of vaporization, kJ kg^{-1}

(C_d), kJ kg^{-1} °C

T=Average temperature, °C

Energy required h^{-1} (Q_t), kJ h^{-1}

$Q_t=Q/t_d$ …….6

The size of the greenhouse dryer was arrived as per the following calculation:

It has been observed that about 68% of the area of hemispherical-shaped solar greenhouse dryer toward south is able to receive sunlight whereas remaining 32% of the area toward north is shaded from the sun. Global solar radiation (I) for Bapatla region is 521 W m^{-2}. The area of dryer was calculated as below (Rathore and Panwar, 2011, Seveda, 2012)

$Area=(Q_t/IX\eta X0.68)$ ….7

Where,

I=Incident solar radiation, kJ h^{-1} m^{-2}

η =Dryer efficiency, Decimal

32% of north wall of the greenhouse dryer should be protected (Rathore and Panwar, 2011, Seveda, 2012)

2.3. Design of fans

Maximum air flow rate for paddy drying is 48 cmm t^{-1} of paddy (Brooker et al., 1974). Hence, 4 DC exhaust fans of fans with 15 cmm air flow rate were selected.

2.4. Construction of hybrid greenhouse dryer

The site for construction of hybrid greenhouse dryer was selected in the premises of College of Agricultural Engineering, Bapatla, Andhra Pradesh, India. To get adequate and uniform light inside the greenhouse east-west orientation was selected. Afree standing greenhouse structure with arch roof was selected to have high light transmission and low cost of construction. A width-to-length ratio of 1:2 of floor area is ideal for solar greenhouses for optimum heat gain (Edward, 1979). Single standing greenhouse dryer with 4.467 m length, 2.134 m width and 2.591 m central height with arch roof has been designed for construction (Figure 1).

A 4.467×2.334 m^2 rectangular area was selected orienting the longer dimension in east-west direction for construction of pit for foundation. A pit has been excavated up to 20 cm depth; periphery of the pit was lined with one layer of brick wall. The foundation pipes were placed in straight vertical position at marked points and filled with gravel and sand. Surface of the foundation was covered with black stones and coated with white paint to get better light condition inside the greenhouse. Foundation pipes, side frames, middle frame, roof and doors of the greenhouse structure were constructed with 50.8×25.4 mm MS pipe and 19×30.2 mm MS angles. The pre-fabricated greenhouse frame assembly was placed on the foundation pipes and fixed with the help of bolts and nuts. Pre-fabricated roof structure was placed on the top and bolted to the bottom greenhouse structural assembly. Two doors of 1.920×0.850 m size were used as side doors which are attached to front side corner post of the greenhouse with hinge joint, which are used only while loading and unloading of trays in to the green house dryer. Central door of 1.920×0.400 m size was fixed to the central front column by hinge joint, which was used to walk the person to monitor the drying process (Figure 2).

Inlet for fresh air was provided at the front door (west side) bottom of the greenhouse near to the foundation level. The

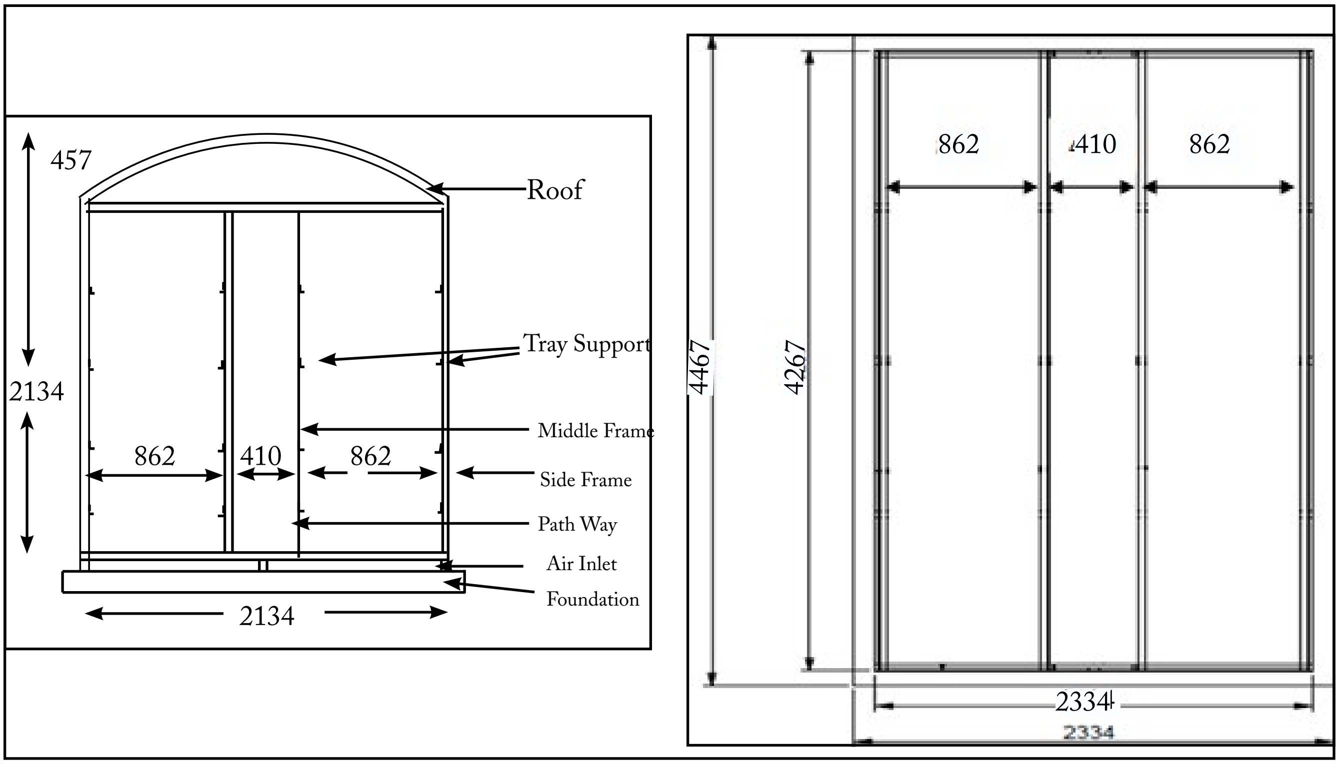

Figure 1 : Schematic diagram of designed Hybrid

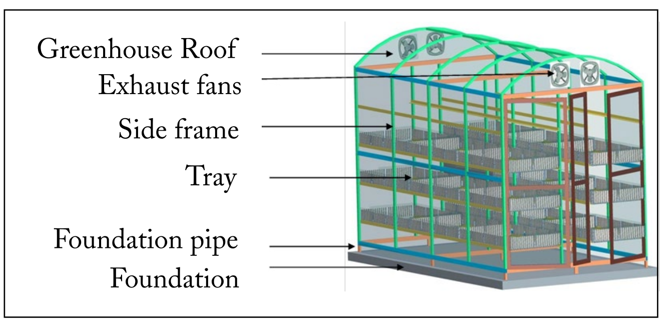

Figure 2: Structural details of designed hybrid greenhouse dryer

structural details of greenhouse dryer are shown in the Figure 2. Clear twin wall polycarbonate sheet with 6 mm thick was used to insulate the greenhouse dryer structure. The polycarbonate sheet has good light transmittance about 82%. Twin wall channels trap air between two walls. This gives up to 50% energy savings over single-wall coverings, reduces heating costs. Polycarbonate panels were fixed to the greenhouse dryer frames with the help of aluminum profiles and self tapping screws.

The drying chamber of the solar greenhouse dryer is divided into multiple tires. The trays were used for holding the paddy inside the drying chamber of the designed greenhouse dryer. Each tray is having 1.425 m length, 0.80 m width and 0.15 m height. Tray frame was fitted with good quality stainless steel woven mesh having 11 openings in a linear inch (can it be written in mm) with 0.8 mm diameter, 2.83 mm aperture, open area 61% and weight 2.24 kg m^{-2} was used. The trays were made convenient to remove or place in the greenhouse frame (Figure 3). The thermocol sheet was of 1m height was fixed at north bottom side of the greenhouse to insulate

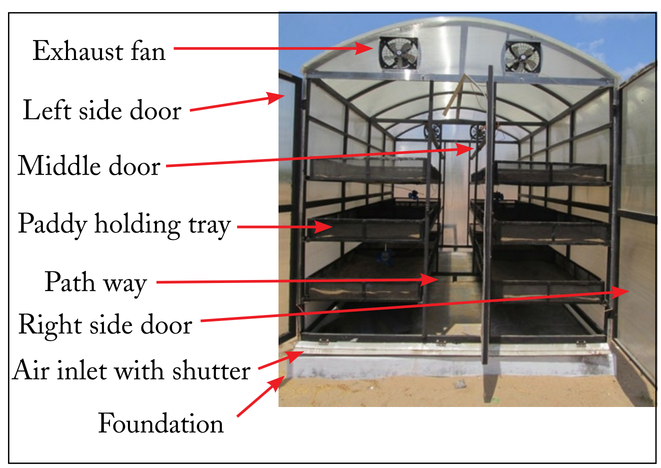

Figure 3: Side elevation of fabricated hybrid greenhouse dryer

north wall. Forced air ventilation includes fans on one end of the greenhouse and air inlets, or shutters, at the opposite end. Air flow is obtained with fan that forces air to move through the grain mass, absorb moisture from the grain, and carry that moisture away from the grain mass. 22.86

cm diameter, 1200 rpm, 40 W powered DC power operated exhaust fans were used to achieve the desired ventilation rates. Two 150 W power capacity solar photovoltaic panels with 18.5 V rated voltage and 8.10 A rated current was used to drive the DC Exhaust fans (Figure 4). The photovoltaic solar collector is always tilted and oriented in such a way that it receives maximum solar radiation during the desired season of use.

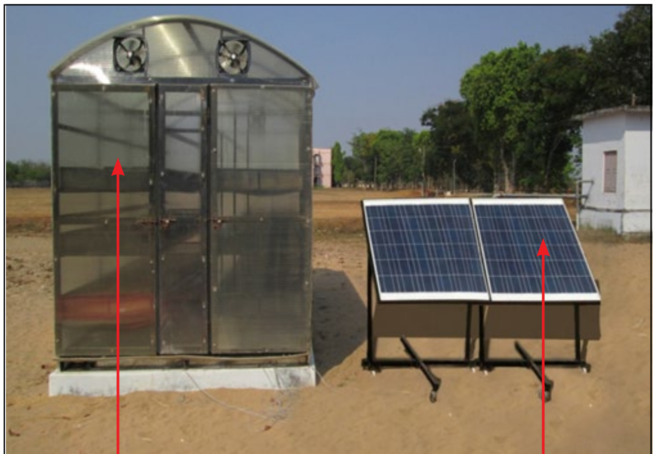

Figure 4: Solar hybrid greenhouse dryer connected to photovoltaic panels

2.5. Drying of paddy

The drying experiments were conducted during 9 AM to the 5 PM. The freshly harvested paddy was filled in the trays up to 10 cm (write in mm everywhere) thickness then the trays were placed inside the greenhouse dryer. During drying, the green house and ambient air temperature, relative humidity was measured using thermocouple and hygrometer respectively. Data was collected at every 1 h interval using data logger.

The temperature and humidity were measured using datalogger (Process precision instruments (PPI), India) and air velocity was measured with Lutran 4201 anemometer. The moisture content of the paddy was Determined (Anonymous, 1985) at every 2 h interval.

3. RESULTS AND DISCUSSION

3.1. Performance evaluation of hybrid greenhouse dryer

The freshly harvested paddy was loaded to the greenhouse dryer at early morningafter measuringinitial moisture content. Drying was started at 9.00 AM and was stopped at 5.00 PM, intermittent paddy mixing was done after every of drying.

3.2. Variation of moisture content during drying

It was observed from the Figure 5 that the paddy was dried from initial moisture content of 25.3% w.b. to final moisture content of 12% (w.b.). It was found that the moisture content decreased with drying time. It was reached to 12.0% after 21 h of drying in the developed structure whereas in the open air, it reached to 12.00% after 27 h of drying. Figure 5 shows that, the moisture content of paddy was reduced from 25.3–20.17% (w.b.) in the first day of drying. During second day, the paddy was dried from 20–14.8% M. C. (w.b.). At the end of drying period the moisture content of paddy was achieved as 12% (w.b.). It was also noticed that about 5.17% of moisture was removed on the first day of drying whereas 5.37% of moisture was removed on second day and 2.8% on third day of drying.

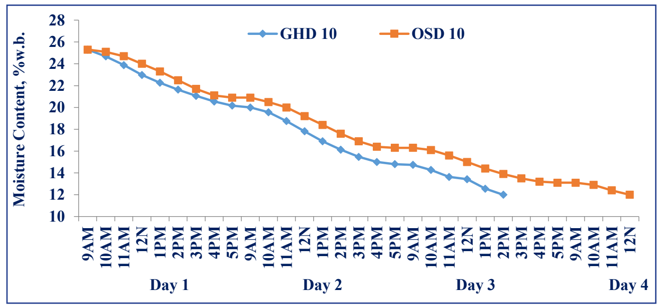

Figure 5: Comparison of moisture reduction with respect to grain bed thickness during drying

The variation in moisture content of paddy at different positions in the drying chamber indicated that the trend of reduction in moisture content of paddy in upper trays were little faster than the middle and bottom trays. The difference is due to the higher product temperature in upper trays. Statistical analysis shows that there was no significant difference of paddy moisture content in the different positions inside the solar greenhouse dryer. However, there was a significant difference between the moisture content of solar dried and sun dried paddy at significance level of 5%.

3.3. Variation of temperature, relative humidity and air flow rate during drying

Variation of greenhouse temperature (GT), ambient air temperature (Ta), and solar radiation intensity (I) is shown in Figure 6. The highest greenhouse dryer temperature recorded was 48.1°C and the lowest temperature was 34.2°C. During this period, the highest ambient temperature recorded was 39°C and the lowest was 30°C. The airflow rate increased sharply in the early part of the day then became fairly constant and dropped sharply in the afternoon. The trend is shown in the Figure 6. The Figure 6 shows the pattern of changes in airflow rate followed the pattern of the changes in solar radiation. Since the airflow is regulated by three fans powered by a PV module, the maximum air flow rate (Q) obtained was 75.52 $m^3 m^{-1}$, whereas minimum air flow rate was 34.25 $m^3 m^{-1}$.

The relative humidity of the greenhouse dryer (HG) varied

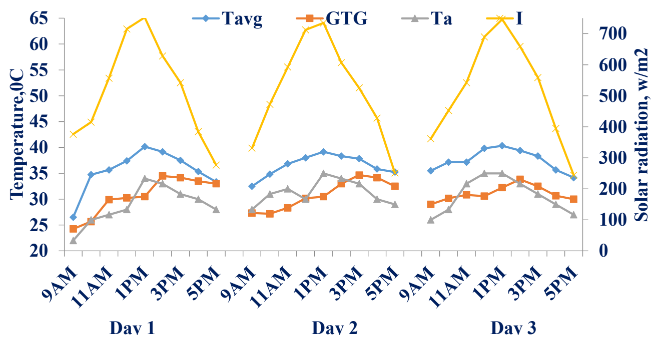

Figure 6: Comparison of greenhouse air, ambient and grain temperature and solar radiation during drying

between 37.8–20.7% and 32.8–21.7% during the first and second days of drying respectively. Whereas the ambient relative humidity (Ha) varied between 49–31% and 46–33% during the first and second days of drying respectively. During third day, the relative humidity of the dryer varied between 34.3% and 23.7%, whereas the ambient relative humidity varied between 47% and 34% as shown in Figure 7. During the experimental period, the relative humidity of the dryer was less than that of ambient relative humidity due to high temperature prevailing inside the dryer. It is due to the greenhouse effect.

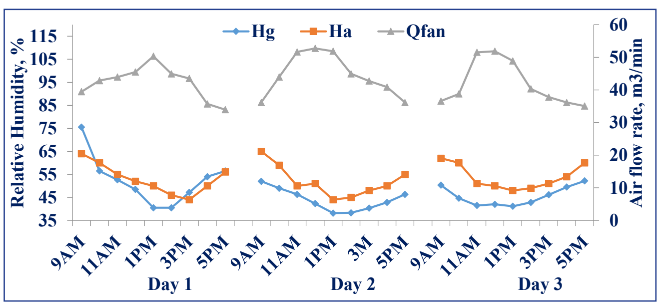

Figure 7: Comparison of relative humidity and airflow rate in during drying in January, 2018

4. CONCLUSION

A photovoltaic power assisted forced circulation solar greenhouse dryer having 4.467×2.134×2.591 m size was developed and evaluate its performance for drying of paddy. The highest greenhouse dryer temperature of 48.1°C was recorded and the air flow rate achieved was varied between 75.52–34.25 $m^3 m^{-1}$. In this dryer the paddy was dried from the initial moisture content of 25.3 (w.b) to final moisture content of 12.0% (w.b.) moisture content in 21 h whereas open sun drying took 28 h of drying time.

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