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Drying of Leaves of Tendu *(Diospyros melonoxylon)* plants using a solar dryer with mirror booster

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Abstract
A laboratory solar dryer with mirror booster was designed and developed for drying Tendu *(Diospyros melonoxylon)* under the climatic condition (Composite Climate Zone) of Malwa region, Indore (Latitude-22.44^{o}N, Longitude-75.5^{o}E) of Madhya Pradesh, India. The Mirror booster solar dryer consist of an integrated collector and drying chamber enclosed. The aluminium drying chamber fitted with one fan operated by a photovoltaic module is placed inside the collector with glazed top, east, west and south wall. The bottom and north wall of the dryer was kept insulated. A door is provided to load and unload material in trays from the north side. The experiment result shows that the drying time reduction of Tendu leaves was nearly 75% in comparison to open sun drying. The maximum and minimum time of drying was found be 18 hours and 12 hours for 15 bundles of tendu leaves.

Keywords: Solar drying; Leaves of Tendu (Diospyros melonoxylon); Moisture content; Mirror booster.

1. Introduction
Tendu leaf Diospyros melanoxylon is the second largest forest product in India after timber and is exclusively used in making local cigarette called Bidi. Annual production of tendu leaves is stable around 300,000 tones as reported by [1]. Madhya Pradesh is the largest tendu producing state. Leaves obtained from a number of trees in India are used for wrapping a cheap type of cigarette, vernacularly known as 'bidi'. Amongst these species, the leaves obtained from *Diospyros melanoxylon*, vernacularly known as 'tendu', 'kendu', 'abnus' or 'bidi' are the most extensively collected both for local consumption and for export. Most of the tendu leaves in India are obtained from natural vegetation. The leaves collected from coppice shoots and root suckers are preferred for cigarette making, because they are generally larger, thinner and relatively more pliable with less prominent veins than those obtained from mature trees.
The collection of Tendu (Diospyros melanoxylon) leaves for bidi cigarette wrappings employs ten million people part-time in the off-peak agricultural season, and earns the state some $40 million in revenue [2]. Tendu leaf collection provides about 90 days employment to 7.5 million people; a further 3 million people are employed in bidi processing industry [3]. Collection and processing of Leaves of Tendu (Diospyros melonoxylon) includes coping, harvesting, plucking, drying, packing and grading. Current study is focused on drying of leaves of tendu. Traditionally tendu leaves are dried in bundle consisting of 50 leaves in each bundle. The leaf bundles are then spread on ground, side by side, with their dorsal sides up. After a period of 3 to 4 days, they are turned upside down. Drying is complete in

about 8 to 10 days. The drying time can be reduced to 18 hours and quality improved with the use of electrically operated or solar air leaf dryers.
India exported 4,675.6 tones of the bidi leaves in 1991-92, valuing Ind. Rs. 183.5 million. In addition to bidi leaves, about 1180 tones of bidi leaves were also exported during 1991-92 [1] reported average wholesale price of Rs. 15000 per tones of bidi leaves. The statistics show the importance of scientific method of drying tendu leaves. The solar dryer earlier was used for drying red chilli as well as amla. But because no data was available for drying of tendu leaves the same dryer is used for drying tendu leaves.

2. Mathematical model

Drying rate is the most important characteristic in drying, which is used for performance estimation of any solar drying system. The drying rate will approximately be proportional to difference in moisture content between the material being dried and the equilibrium moisture content at the drying air state as reported by [4], and can be expressed as

$$\frac{dM}{dt} = -k\left(M - M_e\right) \tag{1}$$

On integration of equation, we get

$$\frac{M - M_e}{M_o - M_e} = c\exp(-kt) \tag{2}$$

$$MR = \frac{M - M_e}{M_o - M_e} \tag{3}$$

$$MR = \frac{M}{M_o} \tag{4}$$

Moisture ratio was simplified from ((M-M_e)/(M_o-M_e)) to (M/M_o) as it has been used by various authors [5, 6]. This is because the relative humidity of the drying air fluctuates continuously during solar drying [7-9]. And also because of the fact that the values of the equilibrium moisture content (M_e) are relatively small, compared to M or M_o [10, 11].

$$MR = c\exp(-kt) \tag{5}$$

$$\log(MR) = -kt + c \tag{6}$$

where M is moisture content, M_o is initial moisture, M_e is equilibrium moisture, MR is moisture ratio, k and c are constants.

3. Materials and methods

3.1 Description of the solar dryer with mirror booster

The most of the indirect solar drying system consist of the air collectors coupled to the drying chamber. An effort has been made to design a single chamber unit act as collector cum drying chamber. The collector cum drying unit was a box kept in glass covered enclosure, inside this glass cover an aluminum drying chamber is placed. Inlet air passage facility is provided from bottom of the drying chamber, and outlet air is sucked from the upper part of drying chamber fitted with an air passage unit with fan. The north wall was not receiving any direct solar radiation; therefore the losses will increase from this side during the peak drying hours.
Hence, north wall was made of insulation door to reduce the losses and to make convenient to fix the trays inside the drying chamber. An adjustable mirror is used on the top of the glass cover to enhance radiation in the drying chamber. Solar collector cum drying chamber fitted with a 15W DC fan and 32W

photovoltaic module to run the fan to analyze the effect of different flow rate of air. The detail of the dryer is shown in Figure 1.

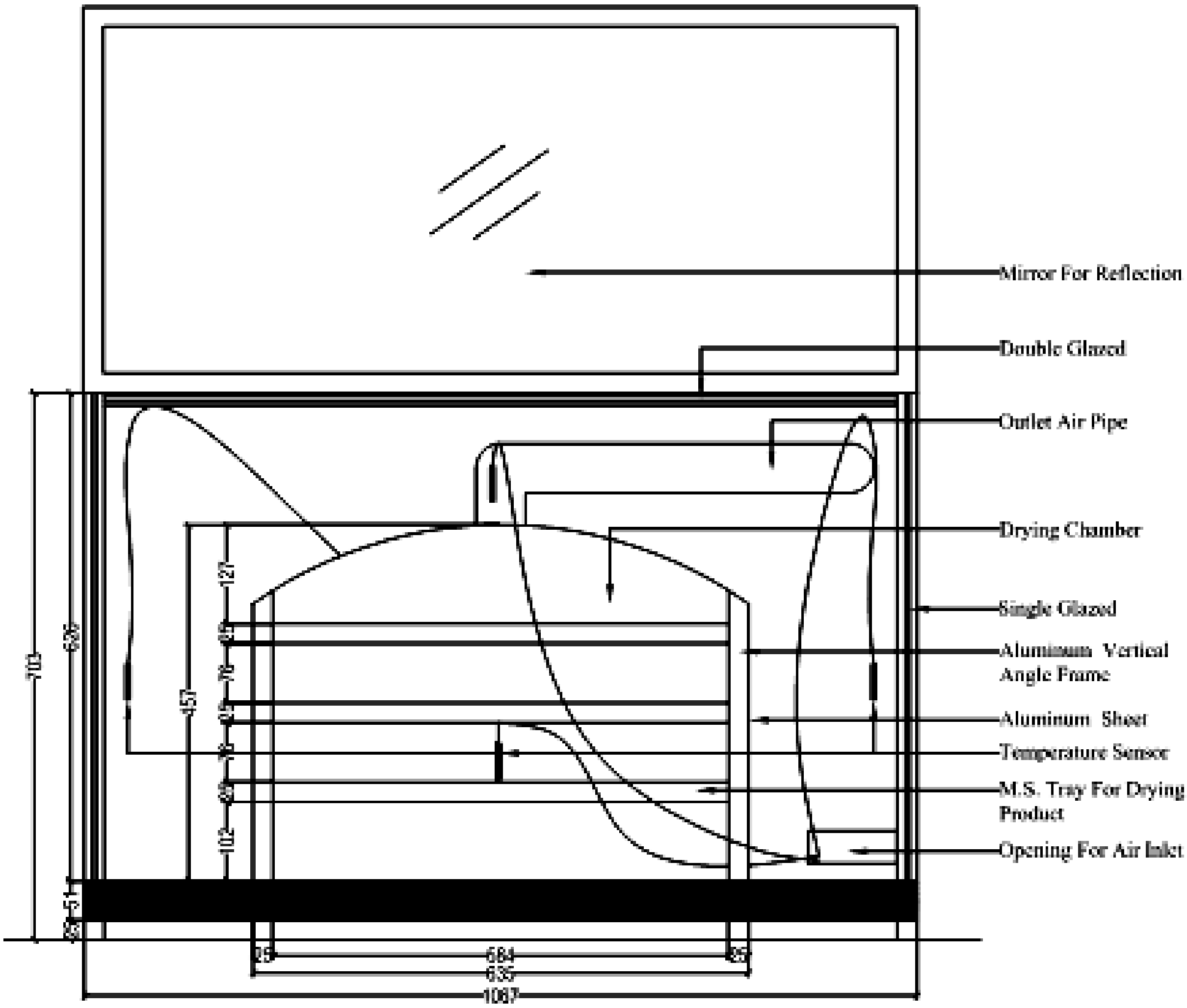

Figure 1. Front view of solar dryer with mirror booster

3.2 Experimental procedure

Experiments were carried out from 14th May to 8th June 2010, first initial moisture content were found out for various samples, generally test for initial moisture content were carried out on the day of experiments. Fresh leaves were taken from the MP Forest Department for the purpose of experiments. The fresh tendu leaves were initially weighed using an electronic balance. The leaves were kept in a hot air oven maintaining a temperature of 135°C [12], and weighed after every three hour interval, till it attained a constant weight. Samples of the leaves were taken out of hot air oven and placed in a decicator before weighing it. Initial moisture content was later calculated and is found between 57.92% (wb) to 29.58% (wb).

Experiments were carried out from 14^{th} to 8^{th} June 2010 for three different mass flow rates i.e. 0.456 m^3/min, 0.285 m^3/min and 0.002 m^3/min (natural convection). Five bundle of tendu leaves which includes 50 leaves each were taken in each tray i.e. 15 bundles in three tray. In total 15 bundles of tendu leaf were loaded to the dryer for each set of experiments. Generally experiment starting time is 9:00 AM to 5:00 which is 8 hrs duration in each day. Sample bundle were kept with initial weight in each tray and weight is checked after every two hrs in order to access the weight loss with an electronic balance. After each day of experiment i.e. after 5:00 PM the bundles of solar dryer were kept in a room at ambient condition. These control samples were again loaded next morning at 9:00 AM in the dryer. This will continue till specified moisture level is achieved i.e. 7%- 8.5% in case of tendu leaves. The solar dryer is fitted with Pt-100 type sensor (upto 300°C range ±0.01°C) which was used to measure the temperature of product in tray at specified location at every wall i.e. east,west south as well as outlet temperature of drying chamber were measured. Pt-100 sensor were used connected to data logger (Model 2700, Keithley Instruments, Cleveland, Ohio, USA: accuracy ±0.1µV) which is attached to a computer (Pentium- Core Duo Processor P41-0006) which continuously measures temperature of tray, wall and outlet of drying chamber after every 30 second interval. These temperatures are recorded by data logger and can be retrieved by computer. A pyranometer (Model CMP-3, Kipp and Zonen BV, Rontgenweg, Holland: accuracy 7.69 µv/w/m^2) was used to measure the solar radiation at the position of the dryer and PV module. Relative humidity and temperature of the ambient air were measured with a digital humidity/temperature meter (accuracy±2.5% and ±0.01ºC). Velocity of drying air was measured with a vane type anemometer (Model AV6, 100 mm Hg, Air Flow Instruments, England: Range: 0-30m/s, accuracy ±.01 m/s) at the outlet of the dryer. The relative humidity is measured is measured at two location at the inlet i.e. atmospheric as well as outlet of the drying chamber is measured at half hrs interval during drying of tendu leaves. After completion of drying, the dried tendu leaf bundles was collected, cooled in a shade to the ambient temperature and then sealed it in the plastic bag for storage.

4. Result and discussions

4.1 Performance of dryer

The variation in solar radiation, ambient temperature, collector temperature, tray temperature, outlet temperature of drying chamber, relative humidity at inlet and outlet of drying chamber, wind velocity and mass flow rate in the drying chamber affect the performance of drying. These parameters are measured as shown in figure for a typical day Figure 2.

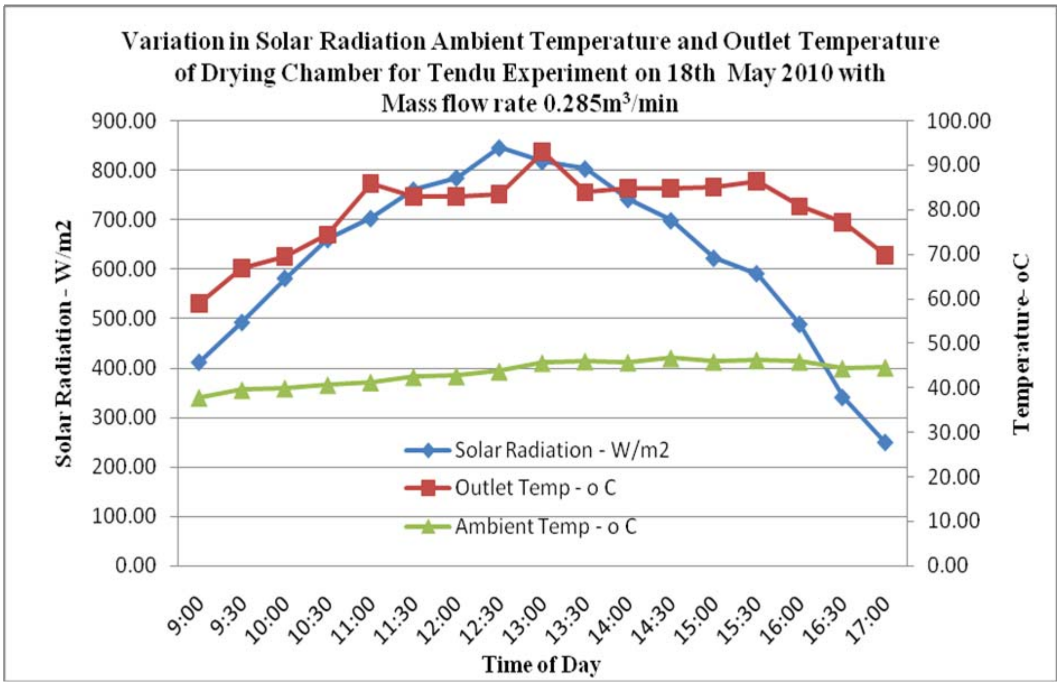

Figure 2. Variations of solar radiation, ambient temperature and drying air temperature at the outlet of the drying chamber with time on 18th May 2010 during solar drying of Tendu leaf with mass flow rate of 0.285 m^3/min

Various parameters that affect the drying rate during the experimental period i.e. from 14th to 8th June 2010 were measured. It was observed that the solar radiation and ambient temperature varied from 1072 W/m^2 to 107 W/m^2 and 46.7ºC to 31.2ºC. The collector temperature was found to vary between 87.44ºC to 52.52ºC. Maximum and minimum tray temperatures were measured and were found to vary between 71.64ºC to 41.35ºC, the average tray temperature was found to be 62.67ºC during the conduction of the experiment.

The maximum, minimum and average outlet temperatures of the drying chamber were measured and found to be 95.33ºC, 46.4ºC and 78.85ºC. Relative humidity at inlet and outlet of drying chamber varied from 50% to 8%, and 62% to 8%. Atmospheric wind velocity measured was found to be between 4.6 m/s to 0.4m/s and mass flow rate in the drying chamber was 0.002 m^3/min (without fan) i.e. with natural convection, 0.285 m^3/min and 0.456 m^3/min. The average rise in air temperature at the outlet of the drying chamber above ambient air temperature during solar drying of tendu leaves was found to be 36.50°C during the experiment period i.e. from 14th to 8th June 2010. It was observed that rise in temperature above ambient temperature affected the drying process. It was further found that rise in temperature above ambient was 42.44°C for experiment with mass flow rate of 0.002m^3/min and it required 12 hrs to dry the product compared to the experiment conducted with mass flow rate of 0.456 m^3/min which recorded a rise in temperature of 34.92 °C which required 18 hrs for drying the product.

4.2 Drying of Tendu Leaves

Traditionally tendu leaves are dried in bundles consisting of 50 leaves each. The leaf bundles are then spread on the ground, side by side, with their dorsal sides facing upwards. After a period of 3 to 4 days, they are turned upside down. Drying is completed in about 8 to 10 days or 64 to 80 hrs. The drying time can be reduced and quality can be improved by using solar air dryers. Leaves of tendu were dried in the solar dryer during the experimental period, each tray was loaded with five bundles (each bundle contains 50 leaves) of tendu leaves in each tray i.e. top, bottom, and centre tray. Three different mass flow rates were considered during the drying period i.e. 0.456 m^3/min, 0.285 m^3/min and 0.002 m^3/min (natural convection) and then compared with the conventional way of drying tendu leaves in terms of drying time i.e. moisture content, colour, physical appearance etc. The change of moisture content and moisture ratio with drying time for a typical experimental run for solar drying at various mass flow rates were plotted as shown in Figures 3 and 4.

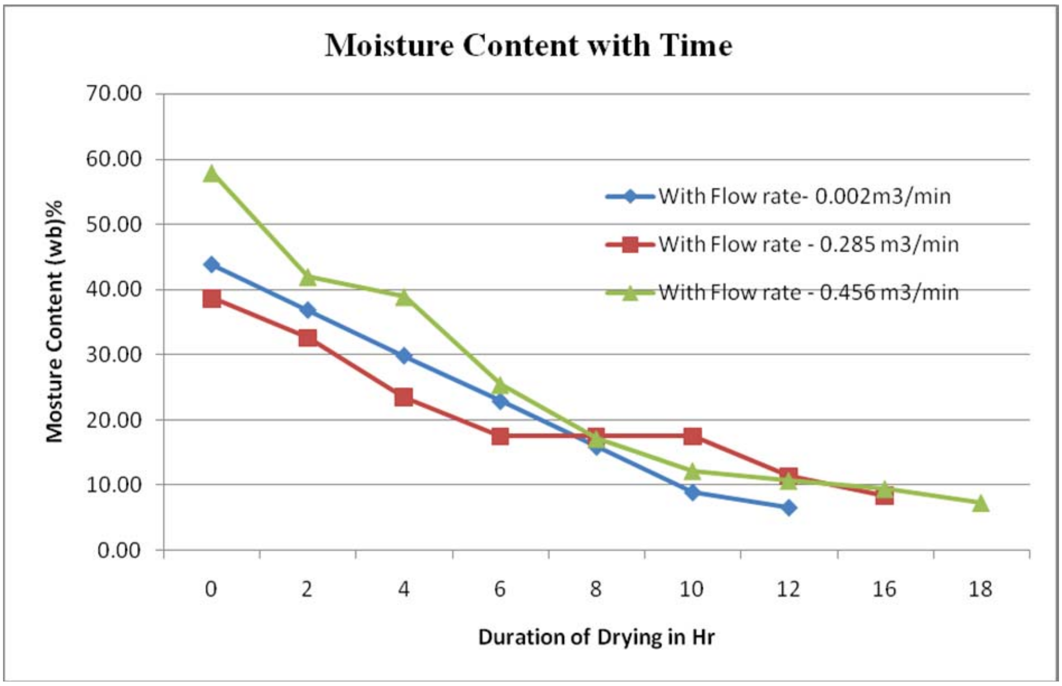

Figure 3. Variation of Moisture Content with Duration of drying for Tendu Leaf for different mass flow rates

Initial drying rate for drying experiments with mass flow rate of 0.456 m^3/min was high as the initial moisture content in the leaves of tendu was high i.e. 57.92%(wb), whereas it was 38.68%(wb) and 43.80%(wb) for experiments with mass flow rate of 0.285 m^3/min and 0.002 m^3/min. This depicts that rate of moisture removal will be more in case of leaves with higher moisture content than in case of lesser moisture content. Mass flow rate has lesser effect for product with low moisture content. As the moisture content is less in the product the air inside the drying chamber is less moist than the product with high moisture content.

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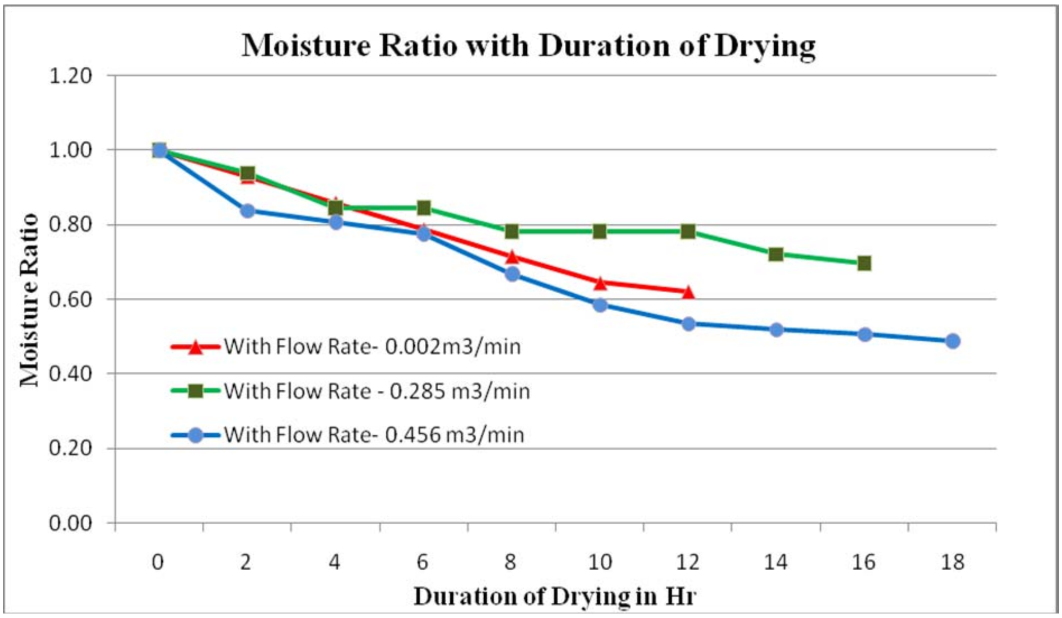

Figure 4. Variation of Moisture Ratio with Duration of drying for Tendu Leaf for different mass flow rates

This can be seen in Figure 3 wherein the performance of experiments with mass flow rate of 0.002 m^3/min i.e. natural convection was better than experiments with higher mass flow rate i.e. forced convection. This depicts that heat was not carried away by the air and retention time of drying air is more in case of natural convection and hence the drying time taken is comparatively less. Tendu leaves dried in solar dryer takes 75% less time than in case of conventional drying. It takes 12 to 18 hrs to dry the product to the desired level. Drying time taken is 12 hrs, 16 hrs and 18 hrs for mass flow rates of 0.002 m^3/min, 0.285 m^3/min and 0.456 m^3/min, which proves that low mass flow rates are suitable for drying products with less moisture content like tendu leaves.

4.3 Evolution of drying constants for drying of tendu leaf

The variation of moisture ratios with time for each mass flow rate was used for calculation of constant c and k of the model **log*(MR)* = -*kt* +c** using the linear regression (Table 1). This has been done earlier using non-linear regression by [13], and using exponential model by [14]. Curve was drawn between Log of MR and time in hour and is shown in Figures 5 to 7. Following empirical relation was developed for all the mass flow rates.

For experiment tendu leaves using solar dryer with flow rate 0.002 m^3/min(Natural Convection)
Log(MR) = - k t + c **(R^2 = 0.99)**
Values of c = -0.00462 k = 0.01850

For experiment tendu leaves using solar dryer with flow rate 0.285 m^3 / min
Log(MR) = - k t + c **(R^2 = 0.96)**
Values of c = 0.02656 k = 0.00808

For experiment tendu leaves using solar dryer with flow rate 0.456 m^3 / min
Log(MR) = - k t + c **(R^2 = 0.97)**
Values of c = 0.04006 k = 0.01655

The coefficient of determination (R^2) between the experimental and calculated moisture ratios was also obtained**.** The *c* and *k* values thus obtained along with their (R^2) values are tabulated below. The value of COD ranged from 0.99 to 0.96 indicating that the model fitted reasonably well with the experimental data for each mass flow rate i.e. 0.456 m^3/min, 0.285 m^3/min and 0.002 m^3/min (Natural Convection) for drying of tendu leaves.

Table 1. Estimated values of drying rate constants for solar drying of Tendu Leaves

S.No	Mass Flow rate (m^3/min)	Model	Constants		
			k	c	R^2
1	0.002 m^3/min	$\log(MR) = -kt + c$	0.01850	-0.00462	0.99
2	0.285 m^3/min	$\log(MR) = -kt + c$	0.00808	0.02656	0.96
3	0.456 m^3/min	$\log(MR) = -kt + c$	0.01655	0.04006	0.97

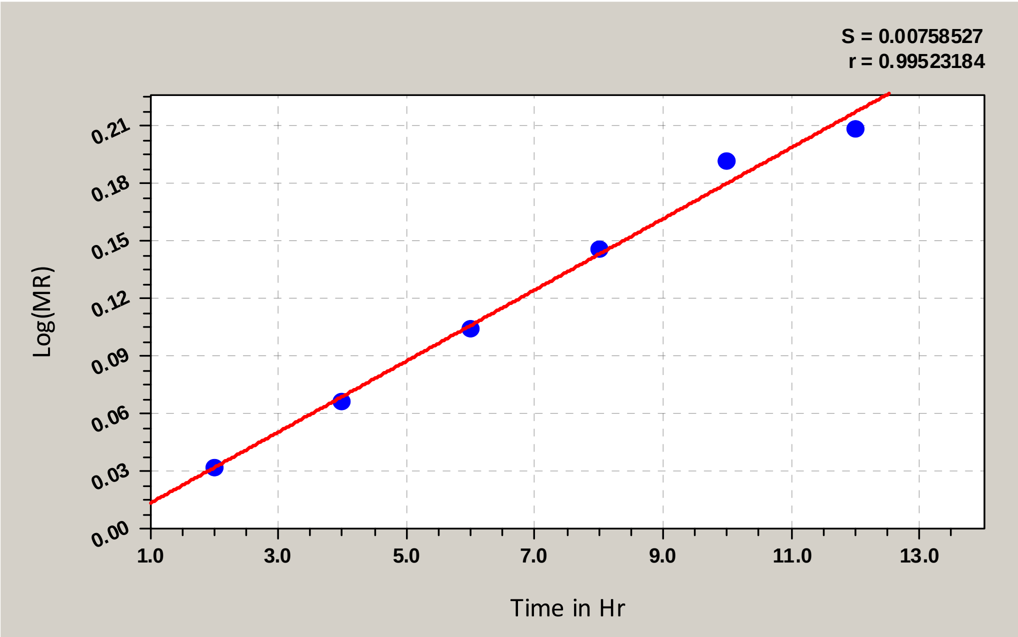

Figure 5. Log (MR) as a function of time for experiments of tendu leaves with mass flow rate of 0.002 m^3/min (Natural Convection) using solar dryer

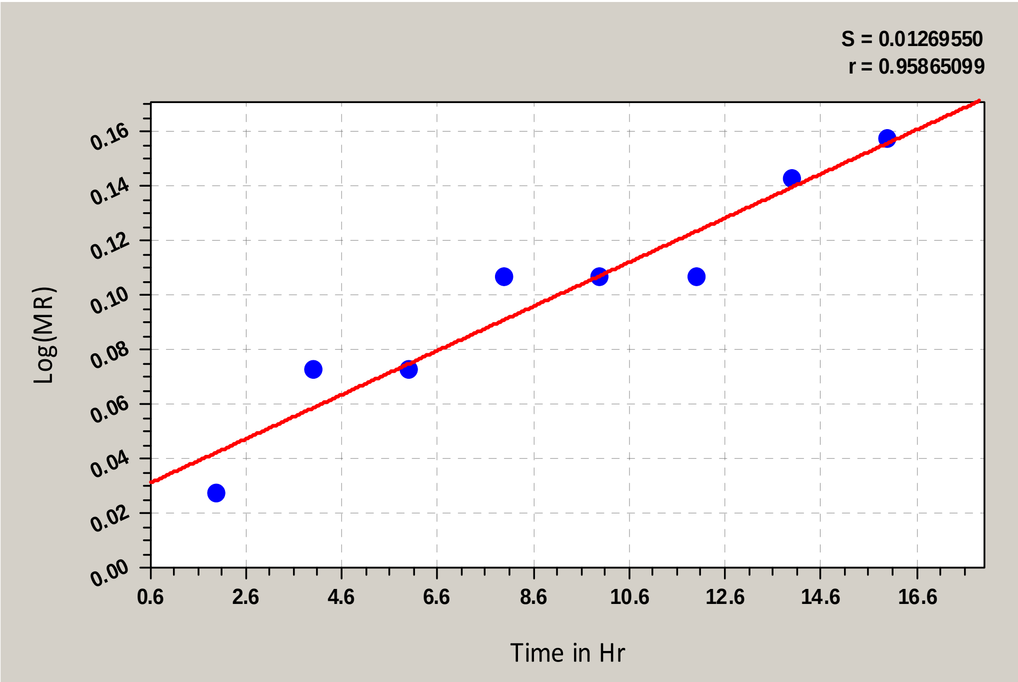

Figure 6. Log (MR) as a function of time for experiments of tendu leaves with mass flow rate of 0.285 m^3/min using solar dryer

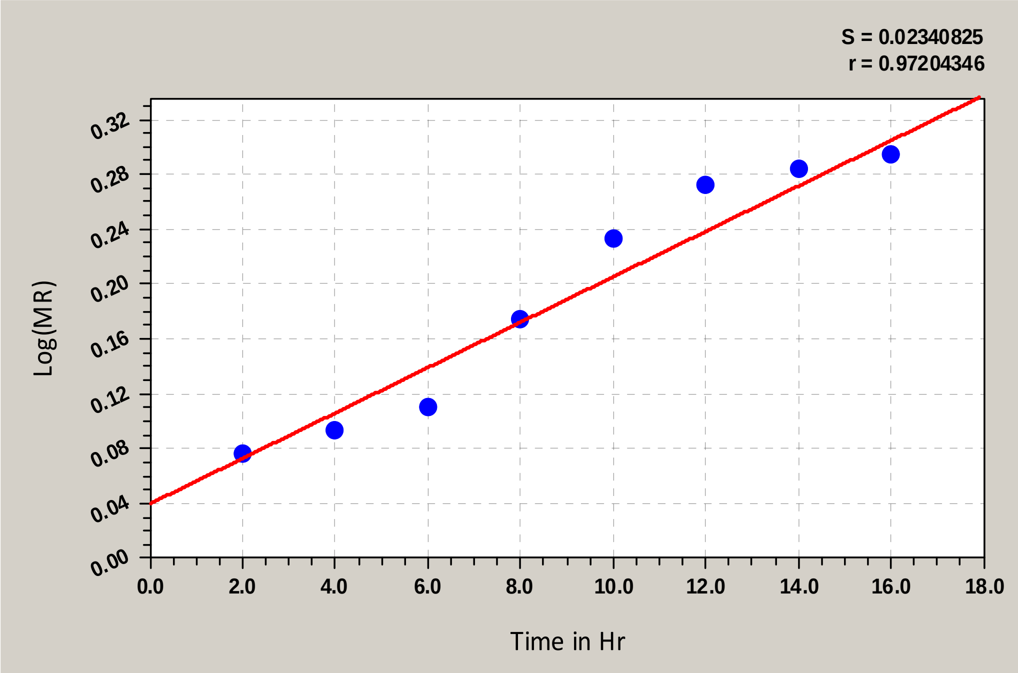

Figure 7. Log (MR) as a function of time for experiments of tendu leaves with mass flow rate of 0.456 m^3/min using solar dryer

4.4 Quality of dried Tendu Leaves

Traditionally moisture content in tendu leaf without prominent vein and its colour reflects the quality of tendu leaves as these characteristics attracts the consumer and is convenient for making beedies. As the quality parameters were not standardized, hence it was decided to standardize at least one quality parameter i.e. moisture content. For standardization of moisture content, rolled beedies available in the market were purchased and test for moisture content was carried out. After the test it was found that leaf of the rolled beedies had moisture level of 6-9% (wb). Leaves dried using solar dryer with mirror booster had attained the required moisture level. Hence we can say that solar dried tendu leaves were found to be technically acceptable.

5. Conclusion

The solar dryer with mirror booster achieved considerable reduction of 75% in drying time when compared to that of conventional sun drying. Drying time taken was 12 hrs, 16 hrs and 18 hrs for mass flow rates of 0.002 m^3/min, 0.285 m^3/min and 0.456 m^3/min. On the basis of present design the vertical as well as horizontal dimensions may be increased for modular or continuous type commercial dryers. By a large it can be concluded that this direr can be beneficial for rural area of Madhya Pradesh or any other interior location anywhere in the world.

Nomenclature

M	Moisture content on the wet basis, (%)
Mo	Initial Moisture content on the wet basis, (%)
Me	Equillibrium Moisture content on the wet basis, (%)
MR	Moisture ratio (Dimensionless)
DR	Drying Rate (g of water / g of dry solid. min)
k	Drying Rate Constant
c	Constant
RH	Relative Humidity (%)
G	Solar radiation received by a horizontal surface, W/m2
$\dot{m}$	Air flow rate, m3 / min
wb	Wet basis (%)
db	Dry basis (%)

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