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Development and Performance Evaluation of a Low-Cost Solar Dryer for Drying of Mint Leaves

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Abstract— *The research was conducted to fabricate and develop a portable low cost solar dryer (LCSD) for the drying of mint leaves. The system was designed as a portable system for decentralized applications at various sites to satisfy the drying requirements of small farmers and co-operatives. The cross sectional area of the solar tunnel dryer was dome in shape, with length and width of 1.8 meters and 0.9 meter respectively. It comprises a collector section of 2.16 m^2 and a drying section of 1.36 m^2 and two chimney and three inlet to provide the required air flow rate over the perishable agricultural products to be dried. Transparent polythene cover of size 200 micron UV stabilized was used to close the dryer on top side to maintain the steady state air flow within the dryer. It has been observed that the drying air temperature was easily raised by some 20-25°C above the ambient temperature at air velocity ranges 0-1 m s^{-1}. The efficiency of the solar tunnel dryer was found to be 19-20%.. Time taken by low cost solar drying and open sun drying was 240 and 390 minutes respectively. The color of dried sample was similar to fresh mint leaves and rehydration ratio was better than open sun drying. For low cost solar drying and open sun drying mint leaves sample the moisture diffusivity was 9.28×10^{-9} and 5.42×10^{-9} m^2/s respectively. The process curves were found similar to a conventional dryer showing that this dryer can be successfully utilized for the drying of agricultural products using solar energy.*

Keywords— ***Low-Cost Solar Dryer, Drying Time, Moisture diffusivity, Colour, Rehydration ratio.***

NOMENCLATURE

m = Mass of the product, kg
C_p = Specific heat of product, kJ/kg °c
ΔT = Difference in temperature, °c
Mw = Mass of water to be removed, kg
λ = Latent heat of vaporization of water, kJ/kg
I = Solar radiation, W/m²
A_c = Area of collector, m²
W_1 = mass of product before drying(g)
W_2 = mass of product after drying(g)
M_i = Initial moisture content of product (w.b.%)
M_f = Final moisture content of product (w.b.%)
W_t = Mass of product (kg)
Q_{req} = Total energy required for drying of mint leaves (kJ)
C_{pc}= Specific heat of mint leaves (kJ/kg°C)
T_d = Average drying temperature (°C)
T_a = Average ambient air temperature (°C)
Q_t = Energy required per hour (kJ h^{-1})
T_d = Drying time (h)
A_c = Collector area (m^2)
r = Radius of hemisphere (m)
l = length of dryer (m)
b = Breadth of dryer (m)
DR = drying rate (gram of water evaporated/ gram of dry matter/h)

M = moisture content, kg water per kg dry solids

□□= time, s

R = diffusion path or length, m

Dv = moisture dependent diffusivity, m^2/ s

h = hour

A = constant

B = slope.

M_R = Moisture ratio, dimensionless

M_o = Initial moisture content, g water/g dry matter

M = Moisture content at any time, g water/g dry matter

Me = Equilibrium moisture content, g water / g dry matter

D_e = Effective moisture diffusivity, m^2/s

L = Thickness of mint leaves (0.5 mm)

n = Positive integer

t = Time (s)

Q_a = Quantity of air (m^3)

C_a = Specific heat of air (kJ kg^{-1} $^oC^{-1}$)

ρ_a = Density of air at ambient temperature (kg m^{-3})

T_e = Temperature of moist air at chimney outlet (^{o}C)

T_a = Ambient temperature (^{o}C)

Q_t = Volumetric air flow rate (m^3 s^{-1})

T_d = Drying time (h)

H = Height of chimney (m)

g = Acceleration due to gravity (m s^{-2})

ρ_a = Density of air at ambient temperature (kg m^{-3})

ρ_e = Density of exit air (kg m^{-3})

D_a = Actual draft

Di = Draft produce by chimney

υ = Velocity of exit air (m s^{-1})

K = Constant value for chimney design (0.4)

C = Drained weight of rehydrated sample, gm and

D = Weight of dehydrated samples taken for rehydration test, gm

LCSD = Low Cost Solar Dryer

I. INTRODUCTION

Most of the commercial crop dryers use fossil fuel. Firewood and conventional fossil fuels are being used extensively for crop drying in most countries. Apart from this, expensive fuels like diesel and propane are also being used for crop drying. Because of the increase in fuel consumption with a subsequent increase in price of conventional fossil fuels, solar dryers are being studied widely to substitute for the conventional method of crop drying (Pangavhane and Sawhney, 2002). Solar dryers are an appropriate preservation technology for a sustainable world and are being used in both developed and developing countries. For crops that are dried at temperatures higher than 60°C, solar drying could be used as a supplemental system.

The customary technique for processing fruits and vegetables is to dehydrate them in open sunlight. In this process, the rate of dehydration is slow and the quality is adversely affected by dust, insects and unexpected rain. In order to remove these problems, mechanical dryers run by fossil fuel or electricity can be used. However, in the present context when conventional energy resources are fast depleting, it is essential to utilize solar energy more efficiently as well as effectively. However, the cost of these appliances is still high. In order to make it more economical, some experiments were conducted on alternative designs for fabricating solar dryers using low cost materials. UV stabilized sheets as transparent covers for providing a greenhouse effect, available crop residues as insulation and other materials such as bamboo and mild steel (M.S.) sheets were used for fabricating the low-cost solar agricultural dryer.

II. MATERIALS AND METHODS

The low cost solar dryer was designed as a portable solar system for drying of mint leaves at various sites being developed and fabricated in the Department of Renewable Energy Engineering, College of Technology and Engineering, Udaipur.

Development of portable low cost solar dryer (LCSD):

The portable LCSD consists of two parts, solar collector and solar drying unit. The length of solar collector unit and drying unit are 1.8 m and 1.7 m respectively. A 10 cm portion of dryer is fixed in the ground and crop residue at the base as insulation. Solar collector has a base with crop residue as insulator and above crop residue black polythene sheet was used, which acts as a black body to absorb solar radiant energy and transforms incoming sunlight into heat. In the process, the heated air becomes relatively dry and is blown over the required product to be dried, where it takes up moisture. Semi-transparent polythene as a collector with size of 200 micron is used as a greenhouse effect for drying of mint leaves. There are inlet holes of polyvinyl chloride pipe in the base to allow fresh air to enter and upper parts of the box with chimney to leave moist air. The inside of the collector plate was painted with dull black to absorb solar radiation. Air gets heated up by the absorber plate while passing through the collector into the drying chamber. Food

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to be dried is placed on perforated trays within the dryer and warm air from the collector rises up through the food and leaves through the chimney.

Figure 1 shows the front view of low cost solar dryer as length of dryer was 1800 mm and depth of dryer in ground was 100 mm. The orientation of the dryer was maintained in East-West direction in order to achieve maximum solar radiations during the whole day. The tunnel slope was also designed to achieve maximum radiations perpendicular to the surface of the dryer in order to enhance the thermal efficiency of the solar dryer. Different machines and tools are used for the construction of low cost solar dryer like drill machine, grinding machine, welding machine, measuring tape, centre punch, hammer, chisel, right angle etc.

Fig.1 Front view of LCSD (all dimension in mm)

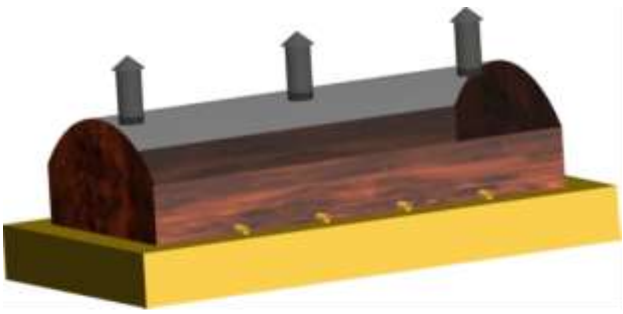

Fig.2 Schematic diagram of low cost solar dryer

Table 1: Design Specification of LCSD

Sr. No.	Components/ Particulars	Dimension
1.	Product dried	Mint leaves
2.	Length of dryer	180 cm
3.	Breadth of dryer	90 cm
4.	Dryer depth in ground	10 cm
5.	Chimney height from ground	90 cm
6.	Spacing between Chimney	88 cm
7.	Diameter of inlet	7 cm
8.	Diameter of chimney	10 cm
9.	Total number of chimney	2
10.	Total number of inlet	3
11.	Height of tray	24 cm
12.	Length of tray	170 cm
13.	Breadth of tray	80 cm
14.	Chimney height	15 cm

Performance evaluation of solar tunnel dryer:

The overall drying efficiency is defined as the ratio of energy output of the dryer to the total energy input. Thus, overall efficiency of the system is given as (Schirmer *et al*., 1996)

Drying efficiency (per cent) = $\frac{m\,Cp\Delta T + Mw \times \lambda}{I \times Ac \times t} \times 100$

The initial moisture content of mint leaves was determined by digital moisture analyser or oven drying method (Ranganna, 2000).

Moisture content (w.b.) = $\frac{W_1 - W_2}{W_1} \times 100$

Mass of water to be removed during drying (M_w) is

$$M_w = \frac{M_i - M_f}{100 - M_f} \times W_t$$

Total energy required for drying product is

$$Q_{req} = [W_t \times C_{pc} \times (T_d - T_a) + (M_w \times \lambda)]$$

Energy required per hour is

$$Q_t = \frac{Q_{req}}{T_d}$$

Collector Area (A_c)

It has been observed that about 68% of the area of hemispherical- shaped solar tunnel dyer towards south side is able to receive sunlight while remaining 32% of area towards north side is shaded from sun (Rathore and Panwar, 2011). The area required to collect the energy for drying will be calculate by using given formula.

$$A_c = 0.68(\Pi rl + lb)$$

Dry matter recovery is defined as the ratio of final weight of dried product to the initial weight of product and was calculated by using following formula: (Rameshbhai, 2016)

Dry matter recovery (%) = $\frac{\text{Weight of dried sample} \times 100}{\text{Weight of fresh sample}}$

Drying rate (DR) = $\frac{\text{Amount of moisture removed (db) in grams}}{\text{Time required (hr.)} \times \text{Amount of dry matter in grams}}$

$$\text{Moisture ratio (MR)} = \frac{M}{M_0}$$

Moisture Diffusivity During Drying

Fick's second law has been adopted for evaluation of moisture transport mechanism of the falling rate regions and is mathematically expressed by classical mass balance equation (Crank, 1975) as:

$$\frac{\partial M}{\partial \theta} = \frac{\partial}{\partial R}\left(D_v \frac{\partial M}{\partial R}\right)$$

A general form of above equation could be written in semi- logarithmic form, as follows:

$$\ln (M_R) = A - Bt$$

A plot of ln (M_R) versus drying period gives a straight line with a slope B as:

$$\text{Slope} = \left(\frac{\pi^2 D_e}{L^2}\right)$$

The effective moisture diffusivity was determined by substituting values of slope B and thickness L

Design of Chimney

Quantity of air will be need to absorb M_w kg of water

$$Q_a = \frac{M_w \times \lambda}{C_a \times \rho_a (T_e - T_a)}$$

Volumetric air flow rate required for drying will be calculated by using given formula.

$$Q_t = \frac{Q_a}{T_d}$$

Draft produce by chimney (Di) will be given by following formula.

$$D_i = H\, g\, (\rho_a - \rho_e)$$

Actual draft (D_a) produce by chimney will be

$$D_a = 0.40 \times D_i$$

Velocity of exit air will be given by following formula.

$$\upsilon = \sqrt{\frac{2D_a}{\rho_e}}$$

There are 2 chimneys, then air exist by each chimney (Q_c) will be given by following equation.

$$Q_c = \frac{Q_t}{2}$$

Area of each chimney (A)

$$A = \frac{Q_c}{\upsilon \times K}$$

Color

Color is one of the most important qualities of acceptance for products in market. It reflects sensation to the human eye and color is important for consumers as a mean of identification. The colorimeter used in the present investigation was Hunter Lab Colorimeter (Model CFLX/DIFF, CFLX-45). The 3-dimensional scale L*, a* and b* were used in a Hunter Lab Colorimeter for color measurement. The L* is the lightness coefficient, runs from top to bottom, ranging from 0 (black) to 100 (white) on a vertical axis. The positive a* value is red and negative a* value is green on a horizontal axis. A second horizontal axis is b*, that represent positive b* value is yellow and negative b* value is blue.

Rehydration Characteristics

During rehydration, the per centage of increase in original weight of dried sample mainly depends upon the porosity of dried sample (Lewicki, 1998). The rehydration characteristics are used as quality index of dried product. Further, it also indicates the physico-chemical changes occurred in sample as influenced by processing conditions, pre-treatment and composition of biological materials.

$$\text{Rehydration Ratio (RR)} = \frac{C}{D}$$

III. RESULTS AND DISCUSSION

Calculation of Design Consideration of Drying System

The average initial moisture content of fresh mint leaves determined by digital moisture analyser was found as 81.25 percent (w.b.).

The final moisture content of mint leaves in low cost solar dryer was found to be average 10.35 per cent (w.b.). Mass of water to be removed during drying was calculated by following equation

$$M_w = \frac{81.25 - 10.35}{100 - 10.35} \times \frac{2.3}{1}$$

$$= 1.82 \text{ kg}$$

The total energy required for drying mint leaves in LCSD will be calculated by using given formula:

$$Q_{req} = [2.3 \times 3.58 \times (60.09 - 39.95) + (1.82 \times 2257)]$$

$$= 4273.57 \text{ kJ}$$

Energy required per hour will be calculate by following formula.

$$Q_{t1} = \frac{4273.57}{4}$$

$= 1068.39 \text{ kJ h}^{-1}$

$A_c = 0.68(3.14\times0.45\times1.8 + 1.8\times0.35)$

$= 2.16 \text{ m}^2$

The intial weight of product for drying was taken 2.3 kg for open sun drying and LCSD. After drying the final weight of dried product for open sun drying and LCSD system was 0.48 kg and dry matter recovery was 21% for both cases.

Drying efficiency (per cent) for low cost dryer = $\frac{4273.57\times1000}{4\times3600\times690\times2.16}\times100$

$= 19.91$

Design Calculation of Chimney for LCSD

Quantity of air will be need to absorb M_w kg of water

$$Q_a = \frac{1.6\times2257}{1.005\times1.184(51-39)}$$

$= 252.90 \text{ m}^3$

Volumetric air flow rate required for drying will be calculated by using given formula.

$$Q_t = \frac{252.90}{4\times60\times60}$$

$= 0.02 \text{ m}^3 \text{ s}^{-1}$

Draft produce by chimney (Di) will be given by following formula.

$D_i = 0.3\times9.81\times(1.1206 - 1.0539)$

$= 0.1963 \text{ kg/m}^2$

Actual draft (D_a) produce by chimney will be

$D_a = 0.40 \times 0.1963$

$= 0.07852 \text{ kg/m}^2$

Velocity of exit air will be given by following formula.

$$\upsilon = \sqrt{\frac{2\times0.07852}{1.0539}}$$

$= 0.3860 \text{ m/s}$

There are 2 chimneys, then air exist by each chimney (Q_c) will be given by following equation.

$$Q_c = \frac{0.02}{2}$$

$= 0.01 \text{ m}^3\text{/s}$

Area of each chimney (A)

$$A = \frac{0.01}{0.3860\times0.4}$$

$= 0.0648 \text{ m}^2$

Temperature and Solar Radiation Variations in LCSD during No Load Testing

It was observed that the maximum temperature obtained inside the LCSD was 69^0C at 13:00 h, while minimum was 41^0C at 10:30 h. Maximum ambient temperature was 41^0C at 12:40 h, while the minimum ambient temperature was 35^0C at 16:20 h. It was observed that there is an increment of 28^0C temperature inside the LCSD. It was also observed that the maximum and minimum ambient solar insolation in this month was 1071 W/m^2 at 12:40 hrs and 658 W/m^2 at 16:30 hrs respectively. The trend of result for temperature and solar insolation during no load for LCSD was plotted on graph as shown in Fig. 3

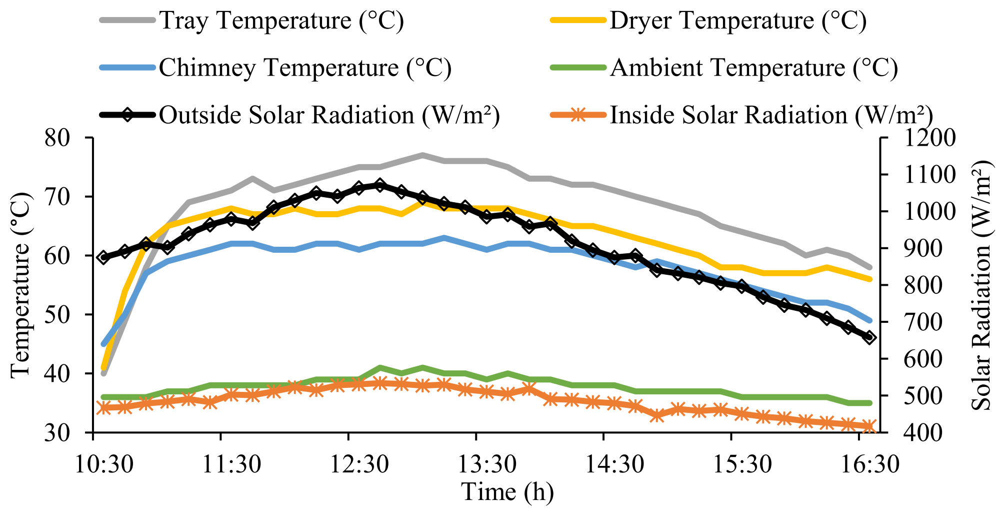

Fig. 3 No Load Performance Curve of LCSD

Temperature and Solar Radiation Variations for Open Sun Drying and LCSD Under Full Load Testing

It was observed that the maximum ambient temperature obtained was 41^0C at 13:30 h, while minimum was 35^0C at 10:00 h in the month of April 2019. The maximum temperature obtained by LCSD was 64^0C at 12:15 h. It was observed that there is an increment of 23^0C temperature inside the LCSD as compared to ambient temperature. It was also observed that the maximum and minimum solar radiation in the month of April was 1059 W/m^2 at 13:15 h and 789 W/m^2 at 16:30 h respectively. Time taken in open sun drying was 6.5 h and in LCSD was 4 h. The trend of result for temperature and solar radiation during full load testing in open sun drying and LCSD was plotted on graph as shown in Fig.5 and Fig. 6 respectively. Fig. 4 showing drying of mint leaves.

Fig. 4 Drying of mint leaves in LCSD

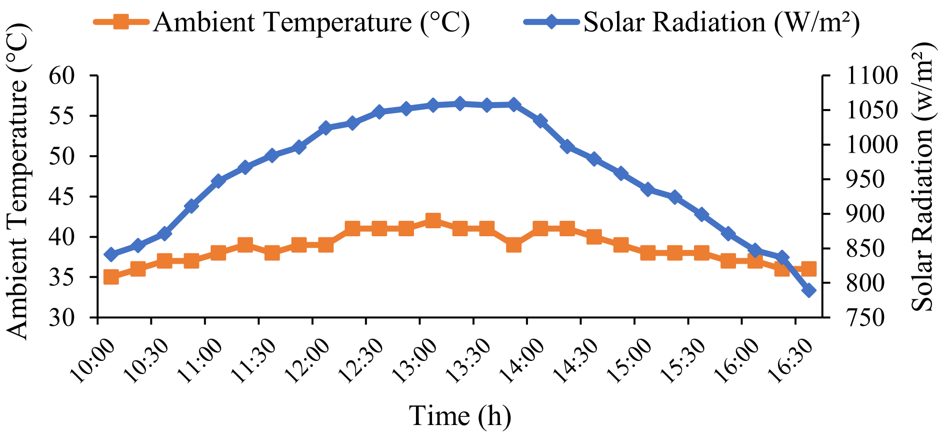

Fig.5 Variation of Temperature and Solar Radiation Under Open Sun Drying

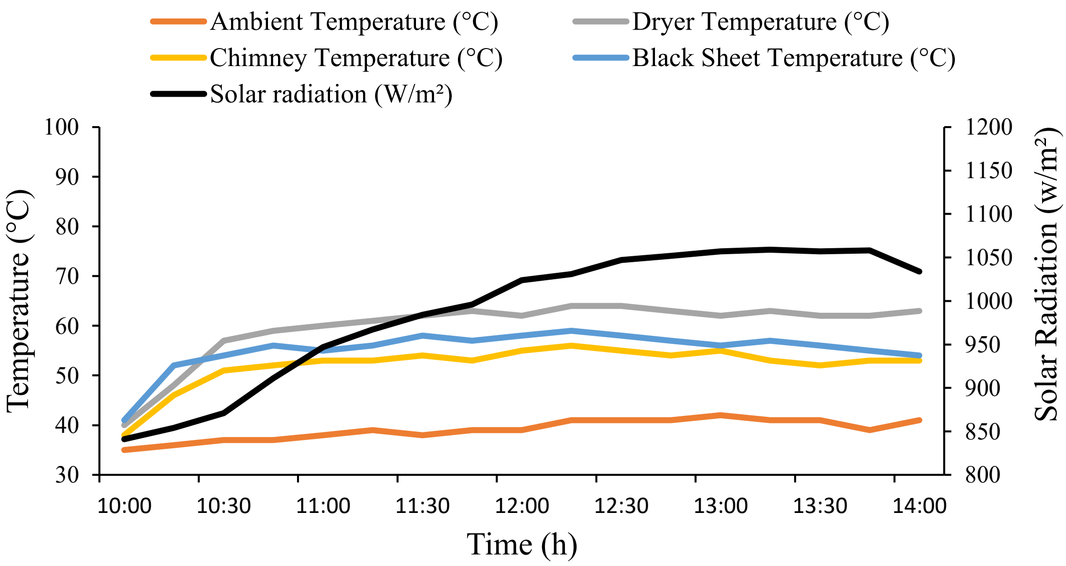

Fig.6 Variation of Temperature and Solar Radiation Under LCSD

Performance Evaluation of Drying Process

Variations in Moisture Content of Mint Leaves with Respect to Time

The moisture content (d.b.) during full load testing of open sun drying and LCSD is presented in Fig. 7 and Fig. 8 within 390 minutes 240 minutes respectively. The mint leaves were dried from moisture content of 432.76 to 10.20 per cent (d.b.) in open sun drying and from moisture content 457.57 per cent (d.b.) to final moisture content 11.54 per cent (d.b.) in LCSD. Time taken in open sun drying is approximately double the time taken in low cost solar drying.

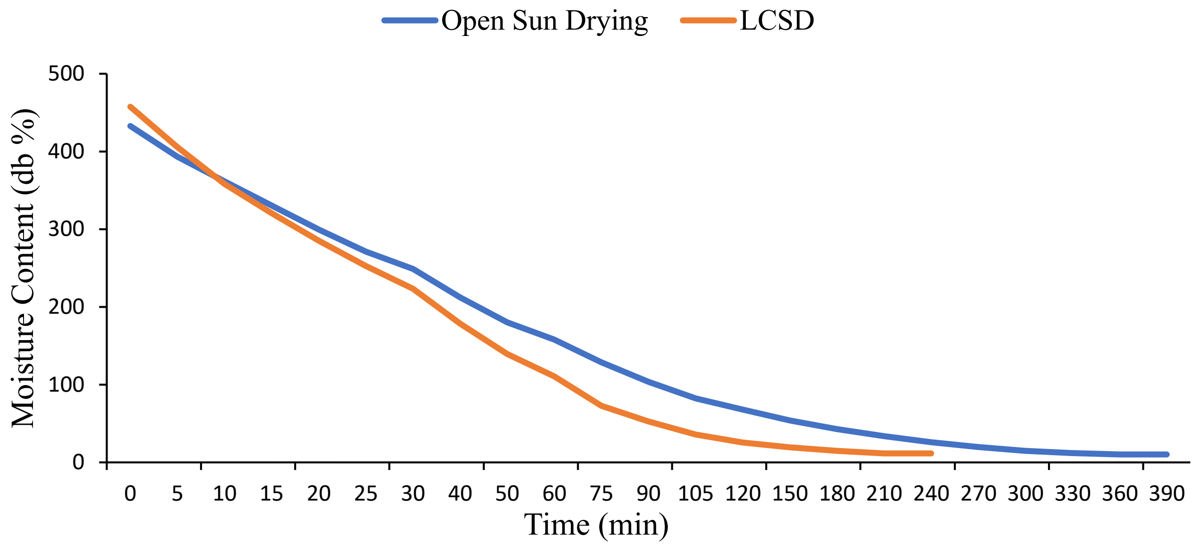

Fig.7 Moisture Content Variation

Moisture Diffusivity of Mint Leaves

Diffusion is the process by which matter is transported from one part to another of a system as a result of random molecular motions (Crank 1975). The ln (MR) was plotted with drying time in order to find out moisture diffusivity for mint leaves. The variation in ln (MR) with drying time of mint leaves have been presented in Fig. 8 and Fig 9 for LCSD and open sun drying. For LCSD and open sun drying mint leaves sample the moisture diffusivity is 9.28×10^{-9} and 5.42×10^{-9} m^2/s respectively.

Quality Analysis of Dried Mint Leaves

Rehydration Characteristics

Ten gram of dried mint samples were taken for the experiment. 200 ml of distilled water in glass beakers was taken and the beakers were kept in a water bath, maintained at 80ºC. Dehydrated samples of each were placed in beakers for 10 min. After 10 min the excess water was drained off through filter paper. The drained samples were weighed. The weight of sample before and after rehydration ratio was measured. The rehydration ratio of mint leaves in open sun drying and low cost solar dryer was 5 and 4.39 respectively. It can also be observed that the rehydration ratio (RR) gradually decreased with increase in air temperature.

Effect of Drying Temperature on Colour of Dehydrated Mint Leaves

Color values were measured using a Hunter lab Colorimeter at room temperature 29-32°C. It can be observed that the L^* value for dried mint leaves in open sun drying and low cost solar drying was 30.47 and 33.58 respectively. Fig. 10 shows Hunter Lab Colorimeter used for colour measurement. The a^* value for dried mint leaves in open sun drying and low cost solar drying was -3.84 and -4.91 respectively. The b* value for dried mint leaves in open sun drying and low cost drying was 10.87 and 12.25 respectively.

Table 2: Moisture Diffusivity Values for Dried Mint Leaves

Sample	Regression equation	Moisture diffusivity (m^2/s)	R^2
Open sun drying	y = -0.0101x - 0.4676	5.42×10^{-9}	0.9696
Low cost solar drying	y = -0.0173x - 0.2511	9.28×10^{-9}	0.9433

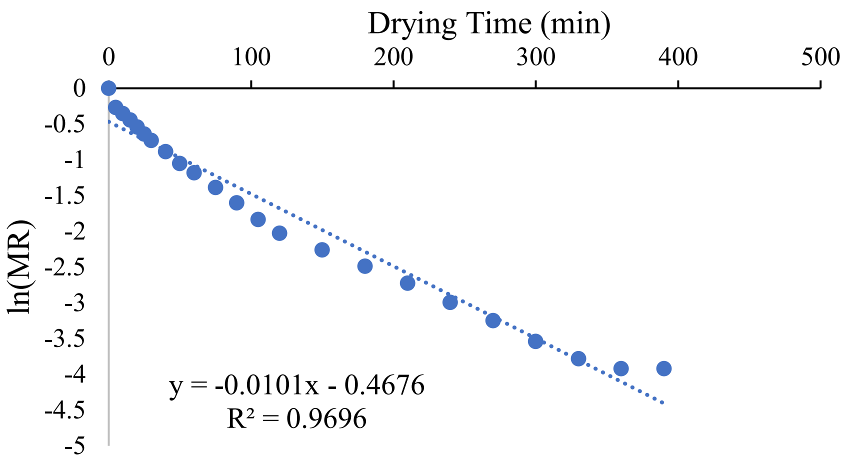

Fig.8 ln MR verses Drying Time in Open Sun Drying

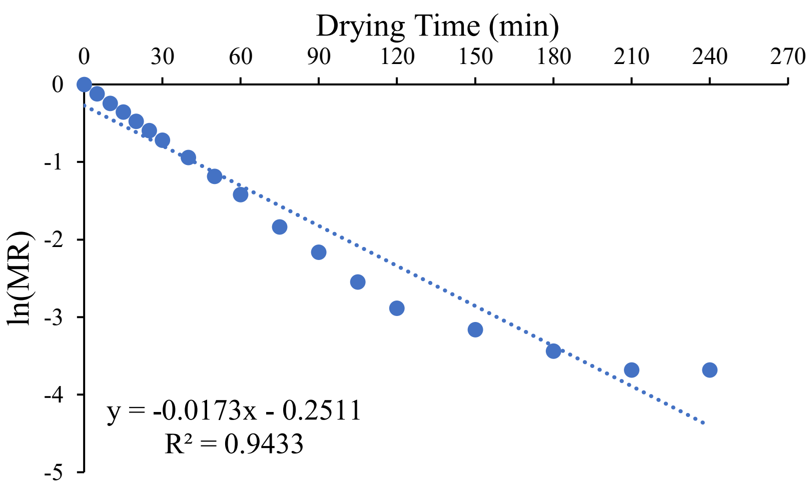

Fig.9 ln MR verses Drying Time in LCSD

Fig. 10 Colour Measurement of Mint Leaves Sample

IV. CONCLUSION

This dryer is simple in construction and it can be constructed using locally available materials by the local craft man. The LCSD dried products are protected from dirt, insects and climatic conditions due to its perfect sealing. The air leaving the dryer was found to have still greater potential for drying more products. However, this should also be considered for other products, as this dryer is designed for multi-products use. The solar based renewable technology is free from operating cost and can play a vital role in promoting the field of post-harvest technology using solar energy. In the experimental trials, the drying time was found to reduce by about 40% of time required in open sun drying. The cost of this device has been evaluated to be Rs. 4400. For low cost solar drying and open sun drying of mint leaves sample, the moisture diffusivity was found to be $9.28\times10^{-9}$and 5.42×10^{-9} m^2/s respectively. The rehydration ratio of mint leaves in open sun drying and low cost solar dryer was 5 and 4.39 respectively. Further, this technology can contribute in clean development mechanism and thus organization effectiveness and higher productivity (Jain 2007) and along with long-term benefits in terms of fuel and environment saving can be obtained.

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