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Comparative Study of Performance of Indirect Mode with PCM and Mixed Mode Solar Dryer for Coriander Leaves

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Abstract

Solar energy can be utilised in many useful ways and solar assisted drying is one of them. In this present study, a natural convection indirect mode solar dryer with phase change material (PCM) and mixed mode solar dryer were designed, fabricated and experimentally investigated. These systems consist of one solar collector and one drying chamber with two trays and in addition PCM cavity was made in collector in indirect mode solar dryer. In this study, thin layer drying characteristics of Coriandrum Sativum L. leaves is studied. 200 grams of Coriander leaves were dried from initial moisture content of 88.02% to 9.68% of final moisture content in 3 hours and 3 hours 15 minute in case of indirect mode with PCM and mixed mode solar dryer respectively during month of February in Gorakhpur (India). The experimental data is validated with fourteen thin layer models available in either empirical or non-empirical form. A statistical analysis software XL-Stat is used to evaluate the values of constants of models through non-linear regression analysis. Among all the models available for thin layer drying characteristics logarithmic, Wang and Singh, Midilli et al., Two term and modified Henderson and pabis (5 models) are best fitted the drying behaviour of Coriander leaves for indirect mode with PCM and Midilli et al. model is best suitable to describe the thin layer characteristics of coriander leaves by mixed mode solar dryer. The thermodynamic behaviour of indirect mode solar dryer is also evaluated. The indirect mode with PCM and mixed mode solar dryer have maximum efficiency of 10.99% and 9.69% whereas overall collector efficiency was 73.19% and 70.79% respectively.

Keywords: Solar Energy**,** Solar Dryer, PCM, Drying Efficiency, Thermal Storage System, Coriander Leaves, Mixed Mode, Indirect Mode.

INTRODUCTION

Since the time when agriculture initiated the process of drying the agricultural products, mainly carried out through solar assisted drying for their safe storage for long period of time. If we concerned about India the main issue is energy supply in some rural areas where a large amount of energy is required to farmer for drying their agricultural products. Therefore, solar dyer is the best suitable option for them for drying of crops without any conventional energy supply which also increases the profit.

NOMENCLATURE

A_c	Cross sectional area of collector inlet (m^2)
a, b,c,n	Drying coefficient
A_t	Total area exposed to radiation (m^2)
C_p	Specific heat (kJ/kg°C)
DR	Drying rate
I	Total solar insolation (W/m^2)
IMSDWP	Indirect mode solar dryer with phase change material
MMSD	Mixed mode solar dryer
h,g,p,T	Drying constants (/h)
L	Latent heat of vaporisation (J/kg)
M	Mass of intake air (kg)
M_e	Equilibrium moisture content
M_i	Initial moisture content on wet basis
MR	Moisture ratio
$MR_{exp,i}$	ith experimental moisture ratio
MR_i	ith moisture ratio
$MR_{pre,i}$	ith predicted moisture ratio
MSE	Mean square error
M_t	Moisture ratio on wet basis at any time
N	Number of observations
PCM	Phase change material
Q	Thermal energy transfer from collector to air
R^2	Correlation coefficient
RMSE	Root mean square error
SSE	Sum of square error
T_i	Inlet air temperature (°C)
T_o	Outlet air temperature (°C)
V	Velocity of air (m/s)
wb	Wet basis
z	No. of constants
H	Efficiency
P	Density of air (kg/m$^{3)}$

But initially the crops were dried in open sun drying which has many disadvantages associated with it, like mixing of dust particle, insects, beasts etc. A number of researches have been performed to increase the performance of solar dryers. By use of solar dryer, reduced transportation cost, product's constant price, improved quality and increased life of crop can be achieved [1]. Mixed mode solar dryer is better in three basic types of solar dryers but use of phase change material in dryers reduces drying time and increases efficiency [2].

Coriander is one of the spices used in Indian cuisines to prepare dishes. It is used in many forms such as green leaves, dried seeds and also coriander powder because all parts of this plant is edible. Around 3 lakh tonnes of coriander is produced in India every year that makes India as the largest producer of coriander in world. India is also the largest exporter and have maximum consumers of coriander. Rajasthan (54%) and Madhya Pradesh (17%) are two largest producing states of India and the other producer states are Gujarat (6.9%), Assam (6.6%), Andhra Pradesh (3.5%), Karnataka (3.3%), Orissa (3.2%) and Tamil Nadu (2%) [3].

Coriander have pleasant, strong, peculiarly aromatic odour and sweetish, slightly bitter flavour because of coriander oil presented in seeds. It has also many nutrients in it such as protein, fat, mineral, fibre, carbohydrates, water, vitamin C, B1 and B2, calcium, phosphorous, iron, carotene, thiamine, riboflavin, sodium, potassium and oxalic acid. It can be stored for 12 months under specific conditions. It has initial moisture content of 88.02% and for safe and durable storage required moisture content should be below 15% [4]. Many researchers monitored drying characteristics of coriander leaves and found that there is no significant change in colour of dried and fresh coriander [5].

Panwar [3] provided drying characteristics of coriander leaves in natural convection indirect mode solar dryer and found the energy efficiency and exergy efficiency varies from 7.18 to 37.93% and 55.35 to 79.39% respectively and also found kinetic model of Midilli et al. for their experimental data. Shalaby et al. [6] experimentally investigated the thermal energy storage medium on drying kinetics of food products and found that use of paraffin wax as a thermal energy storage system provides higher temperature than ambient for minimum 5 hours after sunset and reduces drying time to a marginal value. Sharma et al. [7] performed experimental investigation using principle of natural and forced convection in three different types of solar dryers to select an appropriate design for household, farm and industrial uses. They found that cabinet type natural convection solar dryer was best suitable for household use and for use in farms integrated solar collector type solar dryer was best suitable. Indirect type solar dryer having multiple shelf was suitable for use in industries. Musembi et al. [8] performed experimental investigation for mid-latitude application on an indirect mode natural convection updraft solar dryer. They found that overall dryer efficiency was 17.89% on average solar radiance of 534.95 W/m^2 with drying time of 9 hours 20 minutes for 886.64 grams of apple slices having 86% initial moisture content. An experimental investigation on drying characteristics of banana was done by Hedge et al. [9] They designed and fabricated a solar dryer of mixed mode type having top and bottom flow. It was concluded that bottom flow provides 20°C higher temperature and efficiency of 38.21% under same atmospheric conditions. Phase change material was used in indirect mode solar dryer by Jain et al. [10] to evaluate the performance of dryer for 12 kg of leafy herbs and found that the thermal efficiency of dryer was 28.2% with payback period of 1.5 years. Murthy [11] reviewed different solar dryers on basis of technologies and models for small scale drying applications and they suggested that evaporative capacity should be used for performance evaluation of a solar dryer.

Use of energy storage system in solar dryers increases their efficiency and reduces drying time. Energy storage system are of two types; - 1) Sensible heat storage system, and 2) Latent heat storage system.

A different solar dryers with latent heat storage system were reviewed by Bal et al. [12] for agricultural products. They found that use of energy storage system reduces time gap between energy supply and energy demand. So plays a vital role in energy and time conservation. Khadraoui et al. [13] performed an experimental investigation on indirect type forced convection solar dryer under no load with and without PCM. They found that 4-16°C higher temperature of drying chamber was obtained for full night with use of energy storage system. Also the performance of mixed mode solar dryer with phase change material (paraffin wax in granular form) at base of drying chamber was investigated by Baniasadi et al. [14] and it was concluded that continuous constant drying rate was achieved because of improved performance of solar collector and the thermal efficiency of solar dryer was 11%. There is common procedure for evaluating and comparing the performance of solar dryers. So, Leon et al. [15] suggested some additional parameters along with traditional parameters in their study and also provided methodology and sample evaluation sheet for comparing performance of different solar dryers. An experiment was performed by sebaii et al. [16] on indirect mode natural convection solar dryer for different fruits with and without energy storage system. They provided a different method of reducing drying time by treating the small parts of drying product into boiling water for 60 seconds which includes 0.4% olive oil and 0.3% NaOH in it. They found that drying time for grapes drastically reduced to 8 hours from 60to 72 hours after this chemical treatment. A double pass solar drier was fabricated and investigated by Banout et al. [17] for drying of red chilli (Capsicum annum L.) and compared the performance with cabinet dryer and open sun drying and found that the double pass solar dryer was technically and economically suitable for red chillies.

For agricultural and marine products, drying is very important for their safe storage to a long period of time. Fudholi et al. [1] reviewed solar dryers for agricultural and marine products and suggested that development in solar dryers should be in direction of compact designing of collector, integrated energy storage system, higher efficiency and durable life of system. They also suggested the use of water based solar collector which act as energy storage system in place of air based solar collectors. Sunil et al. [18] performed an experiment to dry fenugreek leaves in indirect mode solar dryer and compare the drying characteristics with open sun drying. They also tested their experimental data to various mathematical models available for thin layer drying and found that Wang and Singh model is the best for explaining fenugreek leaves drying characteristics. A double pass v-corrugated solar collector integrated with indirect mode forced convection solar dryer was investigated experimentally by Sebaii et al. [19] for drying thymus and mint. They found Midilli and page models convenient to explain the thin layer drying characteristics of mint and thymus respectively.

Based on the above literature survey an indirect mode solar dryer with PCM and mixed mode solar dryer were designed and fabricated. The main objective of this present study was the comparative study of thermal performance of solar dryers and also to choose the best suitable mathematical model from fourteen thin layer mathematical models available which describe the drying characteristics of coriander leaves.

EXPERIMENTAL SETUP

An indirect mode natural convection solar dryer with phase change material (IMSDWP) and mixed mode solar dryer without phase change material (MMSD) were designed and fabricated for comparative study of performance. Paraffin wax is used as phase change material in IMSDWP. The experimental set up consists of solar collector and solar dryer with chimney. Solar collector is placed at an inclination of 26.76° which is latitude of location. The solar collector casing was made of plywood of 18 mm thickness. The area of collector of was (0.6×1.2) $m^{2.}$ Absorber plate of collector was black painted aluminium sheet and acrylic sheet was selected for glazing of collector. In case of indirect mode with PCM solar collector was integrated with Phase change material and was placed in the gap between bottom of casing and absorber plate of solar collector in whole surface area of collector. The collector was insulated from back and side through thermocol of 2cm thickness. The solar dryer casing was also made of plywood in case of indirect mode and three sides were made up of acrylic sheet in case of mixed mode solar dryer of dimension 60×30×45 cm^3. Dryer consists of two trays equidistant from each other at 15 cm. The tray were made of stainless steel mesh supported by plywood from all sides and placed on wooden frame in dryer. Back wall of dryer act as door of dryer for easy loading and unloading operation of drying products on trays and trays can also be removed very easily. All the dimensions and materials are same for both dryers (IMSDWP and MMSD) except PCM in collector. A chimney was provide at top of dryer made of plywood casing and inner surface of aluminium for proper ventilation and drying operation. The air entered from bottom of dryer and passed through both trays before leaving through chimney because of that coriander leaves at upper trays have always less temperature and higher moisture content as compared to coriander leaves at lower tray.

Figure 1. Pictorial view of experimental set up during the experiment

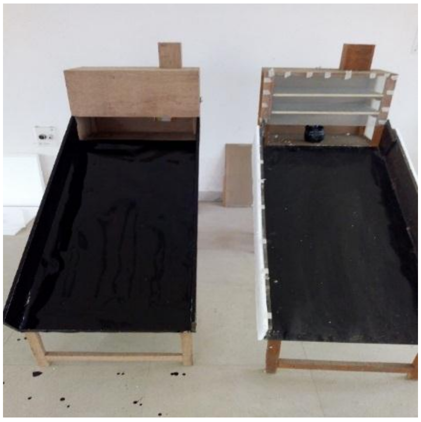

Figure 2. Pictorial front view of IMSDWP (left) and MMSD (right)

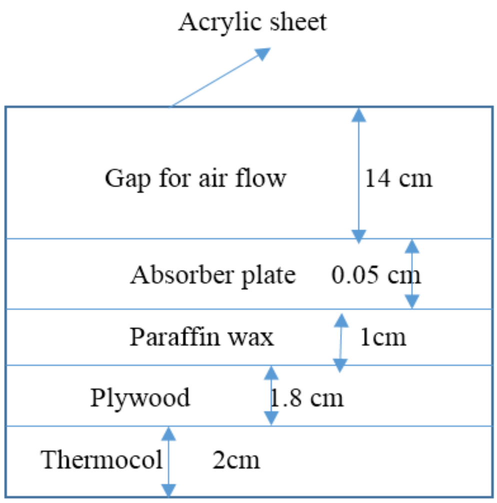

Figure 3. Cross sectional view of IMSDWP collector

INSTRUMENT AND MEASUREMENT

The experiment was performed in month of February, 2018 at Madan Mohan Malaviya University of Technology, Gorakhpur (26.7347° N, 83.3362° E) U.P. (India). Total solar insolation was measured by solar power meter at angle of inclination of solar collector. Inlet air velocity, outlet air velocity, ambient temperature, ambient humidity and dryer humidity were measured with the help of anemometer (BTH 401). The temperature of acrylic sheet, absorber plate were measured by infrared temperature sensor (FLUKE 59 Max). The temperature of both trays, dryer temperature, PCM temperature and chimney temperature were measured with the help of thermocouple (AUTONICS thermocouple K (CA)) having digital display of temperature reading. For measuring the weight of product placed on trays, a weighing machine (AIWA digital scale) having maximum capacity of 30kg was used.

MATERIALS AND METHODS

For this present study, fresh coriander leaves were procured from the nearest market of MMMUT, Gorakhpur. The spoiled leaves and unwanted materials such as grass and soil particles were removed from coriander leaves and it was washed from fresh water. Extra water particle after washing were removed by use of cotton cloth. Equal amount of 100 gram of coriander leaves with stem were placed on each tray and kept inside the dryer. Coriander leaves have initial moisture content of 88.02% and for it's safe storage to a long period of time final moisture content should be less than 15% [4]. Before proceeding for experiment, experimental set up with no load was run for 30 minutes so that it can achieve steady state condition.

In this experiment, ambient temperature, ambient humidity, inlet and outlet air velocity, acrylic sheet temperature, absorber temperature, dryer cabin temperature, trays temperature, dryer humidity and amount of total solar radiation were measured at interval of 1 hour. The mass of each tray was also measured at 1 hour interval until the moisture content of coriander leaves reaches below 15%.

Table 1. Thin layer mathematical models applied to solar drying curve

S.NO.	DRYING CURVE MODEL	MATHEMATICAL EQUCATION	
1	Newton	MR = exp(-ht)	[20]
2	Page	MR = exp(-ht^n)	[21]
3	Modified page	MR = exp[(-ht)^n]	[22]
4	Henderson and pabis	MR = a exp(-ht)	[23]
5	Logarithmic	MR = a exp(-ht)+c	[24]
6	Wang and Singh	MR = a+bt+ct^2	[25]
7	Verma et .al	MR = a exp (-ht)+(1-a) exp(-gt)	[26]
8	Midilli et al.	MR= a exp (-ht^n) + bt	[27]
9	Two term	MR= a exp(ht)+bexp(-gt)	[28]
10	Modified Henderson and pabis	MR= a exp(-pt)+b exp(-gt)+c exp(-ht)	[29]
11	Diffused approach	MR= a exp(-ht)+(1-a)exp(-hbt)	[30]
12	Two term exponential	MR= a exp(-ht)+(1-a)exp(-hat)	[31]
13	Modified page II	MR= exp (-c(t/L^2)^n)	[32]
14	Simplified Fick's diffusion equation	MR= a exp (-c(t/L^2))	[32]

Mathematical modelling of thin layer drying curve

Moisture ratio can be estimated from the drying experiments by following equation

$$MR=\frac{Mt-Me}{Mi-Me}$$

The moisture ratio was converted to M_t/M_i instead of $(M_t - M_e)/(M_i - M_e)$ due to fluctuation in relative humidity value [33]. Hence, moisture ratio was calculated as

$$MR=\frac{M_t}{M_i}$$

The drying rate (DR) of the processing crops was calculated as [34];

$$DR=\frac{M_t-M_{t+dt}}{dt}$$

CORRELATION COEFFICIENT (R^2):

The correlation coefficient, R^2, help to estimate the linear relation between measured and estimated values, which can be calculated from the equation given below [35]

$$R^2=\frac{\sum_{i=1}^{N}(MR_i-MR_{Pre,i})\times\sum_{i=1}^{N}(MR_i-MR_{exp,i})}{\sqrt{[\sum_{i=1}^{N}(MR_i-MR_{pre,i})^2]}\times\sqrt{[\sum_{i=1}^{N}(MR_i-MR_{exp,i})^2]}}$$

SUM OF SQUARES ERROR (SSE):

The SSE can be calculated as

$$SSE=\frac{\sum_{i}^{N}(MR_{exp,i}-MR_{pre,i})^2}{N-z}$$

The lower are the values of SSE, the better is the goodness of fit.

MEAN SQUARE ERROR (MSE)

The mean square error is given as

$$MSE=\frac{\sum_{i=1}^{N}(MR_{pre,i}-MR_{exp,i})^2}{N}$$

The MSE measures the average of the squares of the errors. The error is the amount by which the value implied by the estimator differs from the quantity to be estimated. The ideal value of MSE is zero [28].

ROOT MEAN SQUARE ERROR (RMSE)

The RMSE may be computed from the following equation

$$RMSE=\sqrt{\frac{\sum_{i=1}^{N}(MR_{pre,i}-MR_{exp,i})^2}{N}}$$

Information on Short-term performance can be achieved. In ideal case RMSE is zero otherwise it is always positive. This is error because of randomness and provides a measure of square deviations [29].

For thin layer drying characteristics mathematical models have suitable equation which helps to draw the curve between the moisture ratio and drying time. The best mathematical model is that which gives maximum value of correlation coefficient (R^2) and minimum value of all the errors such as SSE, MSE, and RMSE among all the models tested.

RESULT AND DISCUSSION

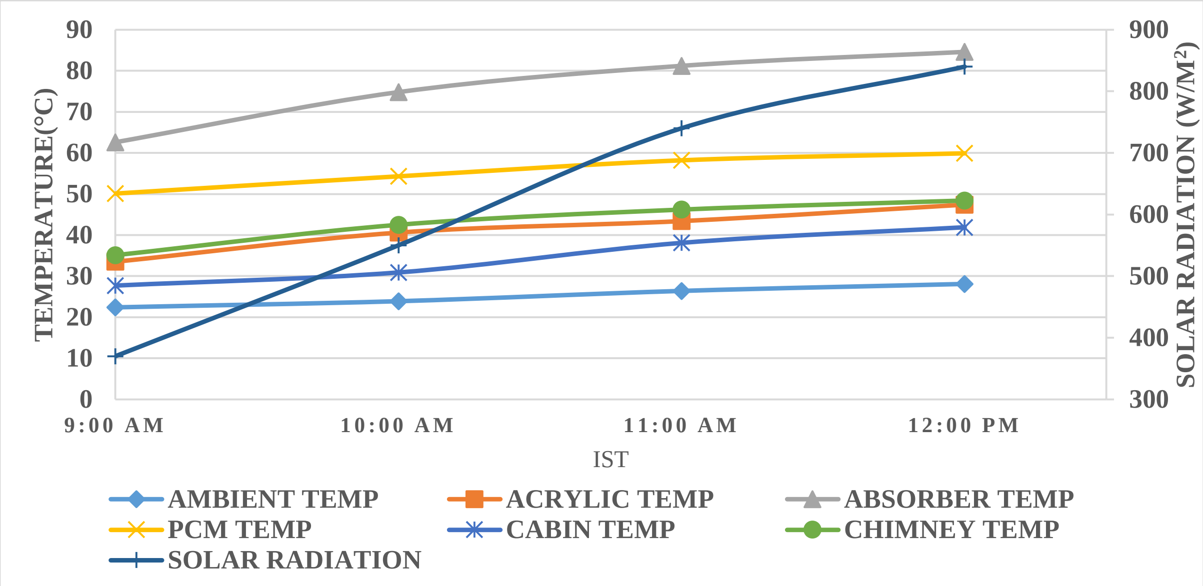

Figure 4. Measured temperature at different points of indirect mode solar dryer with phase change material

During the experiment on indirect mode solar dryer with PCM, measured temperatures on hourly basis is shown in figure 4. The measured solar radiation, ambient temperature, acrylic temperature, absorber temperature, drying chamber temperature and chimney temperature are shown. It is clear that solar intensity during the drying was in range of 370-855 W/m^2. The ambient temperature and humidity were in range of 22.4-28.1°C and 27.8-21.1% RH respectively. The ambient temperature increases with increase in solar radiation and reaches to maximum value of 28.1°C during the experiment for maximum solar radiation of 840 W/m^2 at 12:00 noon. The phase change material reached to maximum temperature of 59.9°C during the experiment.

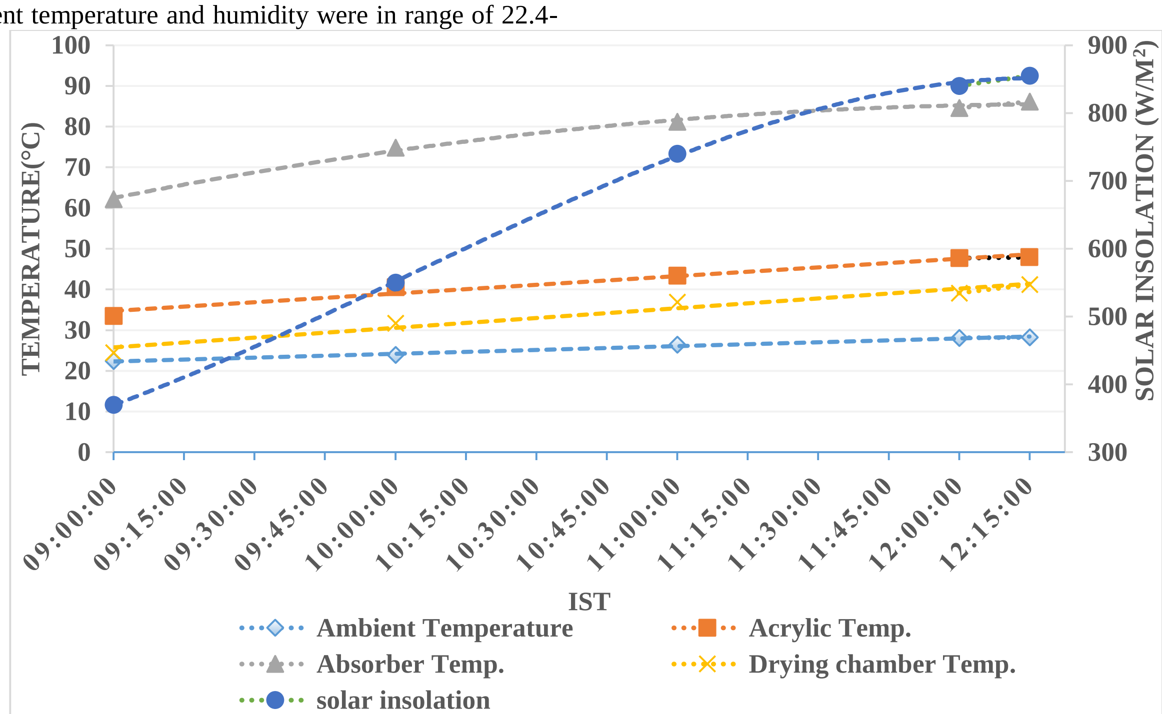

Figure 5. Measured temperature at different point of mixed mode solar dryer

Figure 5 shows the solar radiation and temperature variation for mixed mode solar dryer during the experiment at different positions of dryer on hourly basis. It is shown that there was only a small change in value of drying chamber temperature of mixed mode solar dryer as it was slightly lower than IMSDWP. The maximum temperature attained by drying chamber was 40.6°C. All the other parameter such as solar radiation, ambient temperature, wind velocity were same as in case of IMSDWP because both setup were placed side by side and readings were taken at same time.

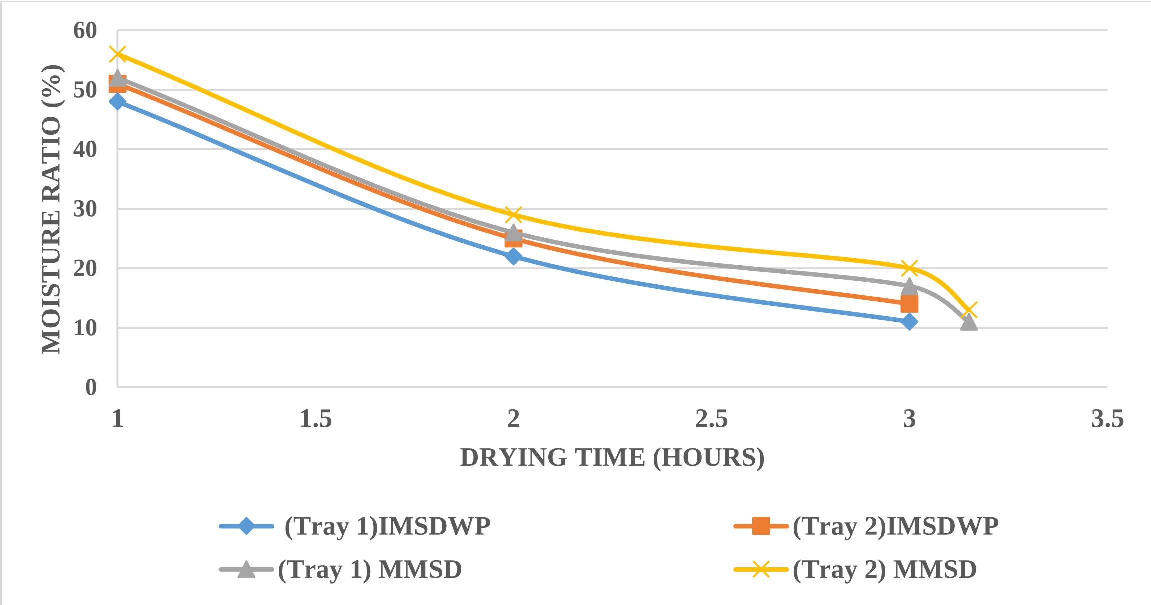

Figure 6. Variation of moisture ratio with drying time for both dryers

Figure 6 shows the variation of moisture ratio with drying time for all trays of both dryers. It is also clear that MMSD takes more time than IMSDWP to reach same moisture ratio. Initially, reduction in moisture ratio was more because of presence of moisture on outer surface of coriander leaves which was easily removed during process and as experiment proceeded the rate of moisture removal decreases. It is also clear that lower trays (Tray 1) in both dryers shows more reduction in moisture content in respect of corresponding upper trays (Tray 2). It is due to the process of flow of air from lower tray to upper tray and finally to atmosphere through chimney. As air got in contact with lower tray it absorbs some moisture so capacity of absorbing moisture of air was reduced. From the initial moisture content of 88.02% coriander leaves were dried in both the dryers to 9.68% moisture content for its procurement to longer duration of time.

Figure 7 shows the variation of moisture content with time for both dryers. It is clear that moisture content of coriander leaves decrease continuously but initially rate of reduction is more than rate of reduction in moisture content after some time of drying. As it can be seen that initially moisture content of coriander leaves was same for both dryers but as time goes the rate of reduction of moisture content in IMSDWP is more than MMSD because of higher temperature of drying chamber of IMSDWP than MMSD. For reaching to same final moisture content, MMSD takes 15 minutes more time than IMSDWP.

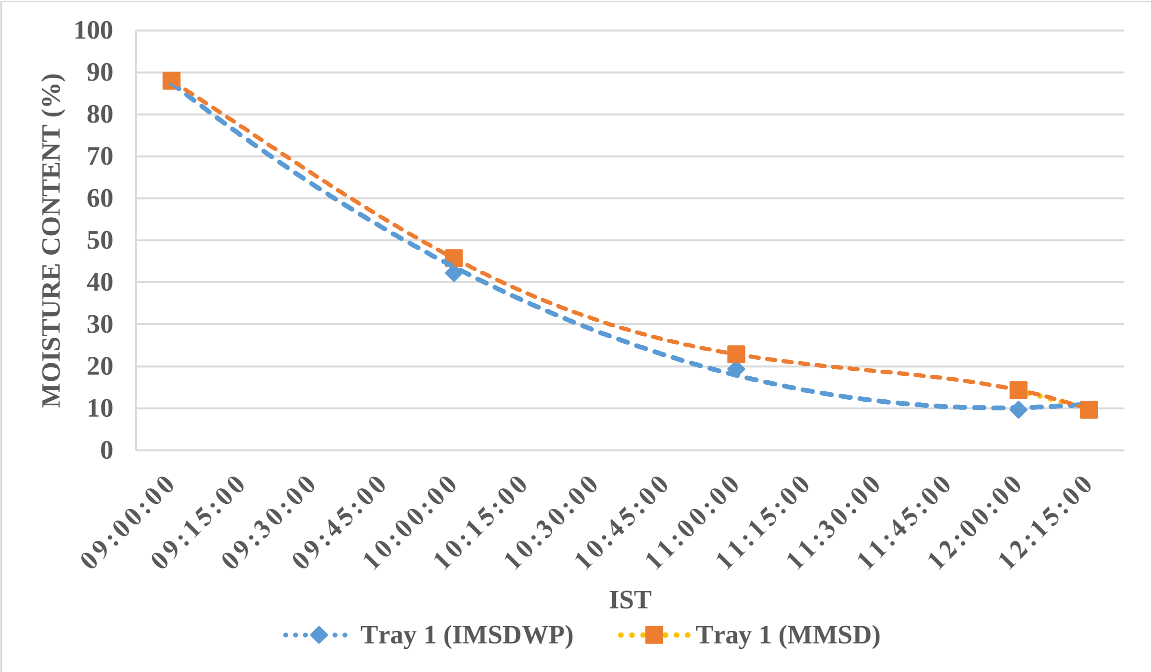

Figure 7. Variation of moisture content with time for both dryers

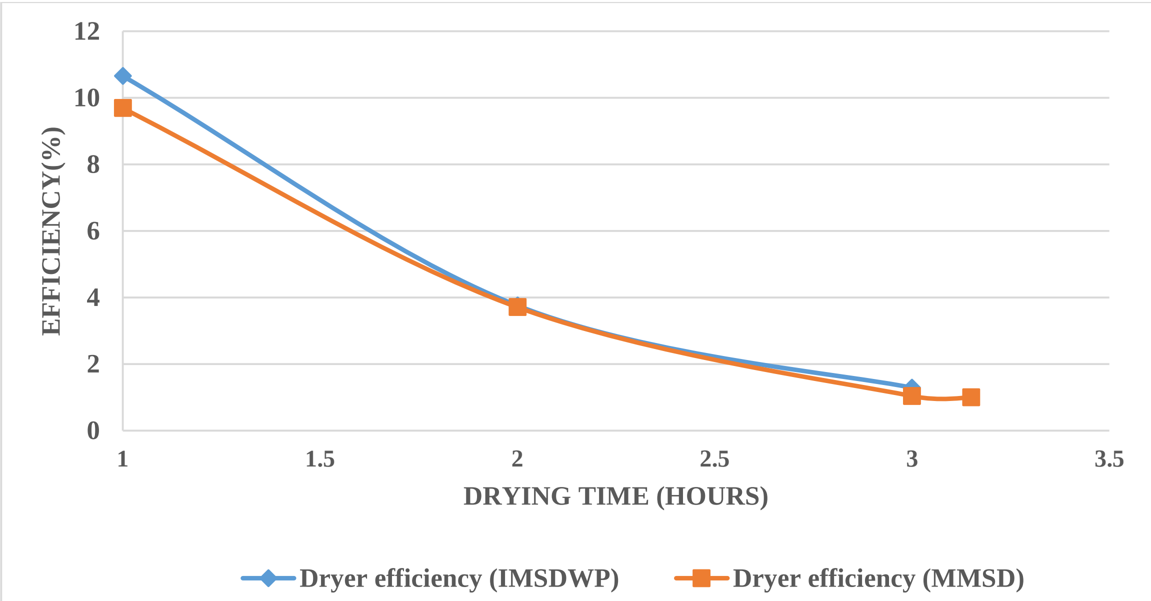

Figure 8. Comparative graph of dryer efficiency of IMSDWP and MMSD.

Figure 8 shows the comparison between dryer efficiency of IMSDWP and MMSD with drying time. Initially dryer efficiency of IMSDWP is more than MMSD because of higher temperature drying chamber caused by phase change material. After one hour both type of dryers have equal dryer efficiency and after that again IMSDWP shows higher efficiency than MMSD. This is because of fluctuation in solar radiation. Initially dryer efficiency is more and it is reduced continuously because the moisture content of product (coriander leaves) is decreasing continuously and after some time it is almost constant as shown by MMSD after three hours of drying time. During first hour of drying IMSDWP and MMSD shows maximum efficiency of 10.66% and 9.69% respectively.

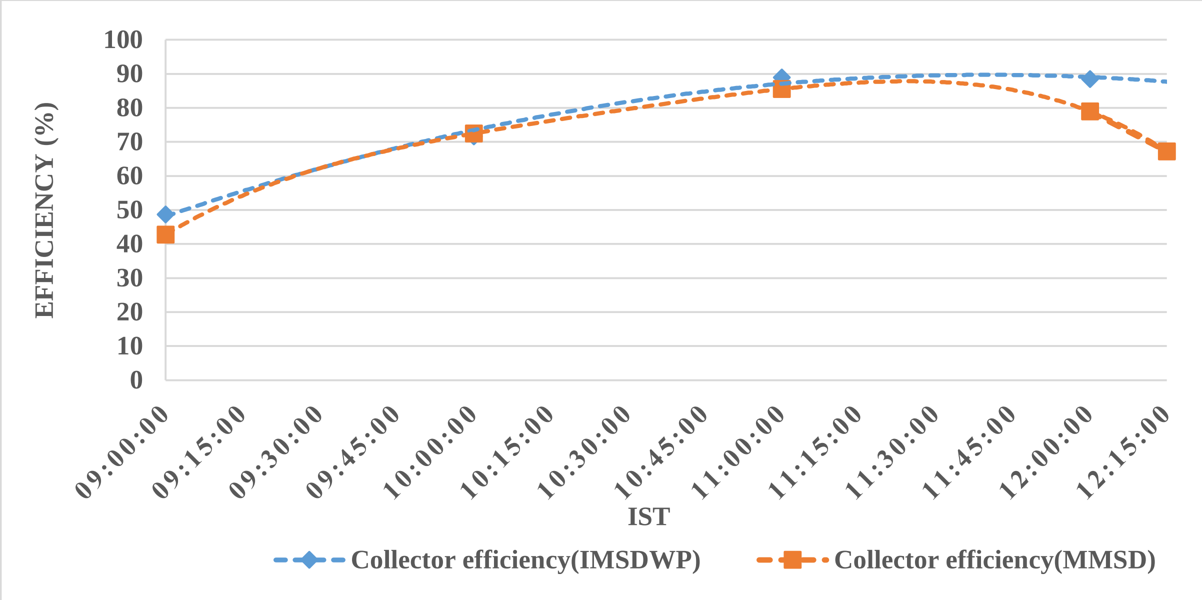

Figure 9. Comparative graph between collector efficiency of IMSDWP and MMSD

Fig.9 shows the comparative graph between collector efficiency of both type of solar dryers. It can be seen that IMSDWP shows higher collector efficiency than MMSD collector efficiency. Collector efficiency is dependent on humidity, air velocity and solar radiation. IMSDWP shows higher efficiency because PCM (paraffin wax) contributes some of its heat to collector. Collector efficiency increase with increase in solar radiation. The maximum collector efficiency attend by IMSDWP and MMSD were 88.98% and 85.56% at 11:00 AM respectively. The overall collector efficiencies of mixed mode solar dryer and indirect mode solar dryer were 70.79% and 73.19% respectively.

Table 2. Statistical results of mathematical modelling of thin layer drying curves for coriander leaves (IMSDWP)

Model no.	**Model constant**	**R^2**	**SSE**	**MSE**	**RMSE**
1.	h= -0.94882	0.78705	2336.511	1168.2555	34.179
2.	h= -3.87604, n= -0.37077	0.98834	8.68663	8.68663	2.94731
3.	h= -583676.2232, n= -583676.22324	65535.00	2750.00	2750.00	52.4404
4.	a=101.90655, h=0.75496	0.99939	0.44892	0.44892	0.67001
5.	**a= 106.52121,h= 0.86020, c=2.933**	**1.0000**	**0.0000**	_____	_____
6.	**a=89.0000,b= -48.5000, c=7.50**	**1.0000**	**0.0000**	_____	_____
7.	a=102.18630,h=0.75779,g=2339.620	0.99442	0.44098	_____	_____
8.	**a=101.32583,h=0.76477,n=1.0709 b=0.83902**	**1.0000**	**0.0000**	_____	_____
9.	**a=1.144,h=0.221,b=107.275,g=0.834**	**1.0000**	**0.0000**	_____	_____
10.	**a=85.785,p=0.685,b=41.963,g=3.229,c=72.820, L=3.160**	**1.0000**	**0.0000**	_____	_____
11.	a=27.001,h=0.000,b= -396967.796	0.975	722.069	_____	_____
12.	a=102.186,h= 0.758	0.999	0.441	0.441	0.664
13.	c= -3.999,L= -0.959,n= -0.371	0.988	8.687	_____	_____
14.	a=102.186,c=13.391,L=4.204	0.999	0.441	_____	_____

Table 3. Statistical results of mathematical modelling of thin layer drying curves for coriander leaves (MMSD)

Model no.	Model constant	R^2	SSE	MSE	RMSE
1.	h= -0.9234146	0.83294	2889.8723	963.29079	31.036926
2.	h= -3.958525,n= -0.328817	0.97457	25.30933	12.65466	3.557340
3.	h=2.618034,n= -0.352713	0.83295	2889.8723	1444.93619	38.012316
4.	a=98.829672,h=0.648848	0.98710	12.71136	6.35568	2.521048
5.	a=102.433892,h=0.753048,c=3.697394	0.98773	12.034455	12.03445	3.4690712
6.	a=89.294455,b= -43.714973,c=6.220678	0.98555	14.17118	14.17118	3.764463
7.	a=98.923944,h=0.647864,g=976.61455	0.98708	12.68937	12.68937	3.562215
8.	**a=501.4184,h=2.2324,n=0.334,b= -1.849**	**0.98855**	**11.23092**	________	________
9.	a=35.945,h= -0.420,b=73.604,g=0.954	0.988	11.864	________	________
10.	a=54.785,p=0.486,b=31.884,g=1.107,c=28.551,L=1.305	0.988	11.770	________	________
11.	a=26.510,h=0.000,b= -402428.66	0.975	981.094	981.094	31.322
12.	a=98.924,h= 0.648	0.987	12.689	6.345	2.519
13.	c=2401.125,L=2401.125,n=2401.125	65535.000	3582.000	3582.0000	59.850
14.	a=98.924,c=3.076,L=2.179	0.987	12.689	12.689	3.562

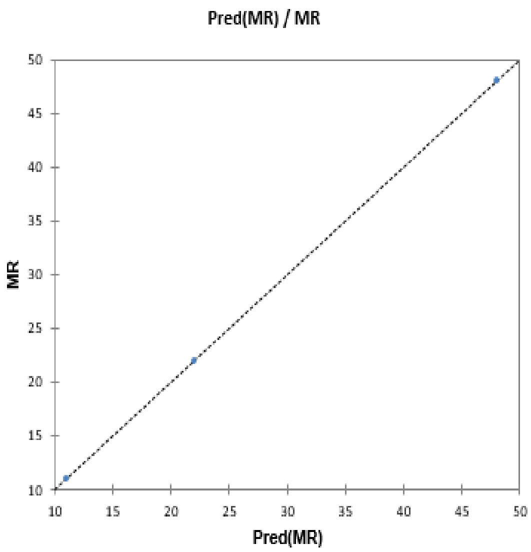

Figure 10. Comparison between experimental and predicted moisture ratio for IMSDWP

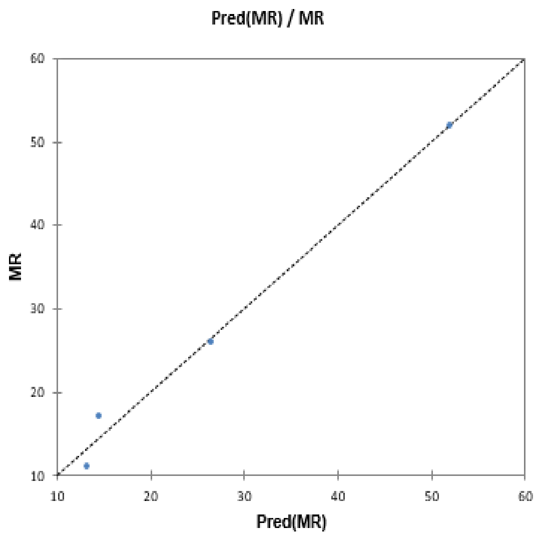

Figure 11. Comparison between experimental and predicted moisture ratio for MMSD

For IMSDWP, based on values of R^2, SSE, MSE and RMSE, five models (Logarithmic, Wang and Singh, Midilli et al., Two term and modified Henderson and pabis) are selected for drying of coriander leaves. All these models have maximum value of R^2 =1 and minimum value of SSE=0. Figure 10 shows the graph between experimental moisture ratio and predicted moisture ratio for all the selected mathematical models. It can be seen that values of experimental moisture ratio values lie on the straight line representing predicted moisture ratio.

Figure 11 shows the graph between experimental moisture ratio and predicted moisture ratio for MMSD. Midilli et al. model is selected as best suitable model to describe drying characteristics of coriander leaves because it provides maximum value of R^2 and minimum value SSE among all the fourteen mathematical models tested of the experiment. Selected model gives value of R^2=0.9885 and SSE=11.23092.

It can also be seen that values of experimental moisture ratio are closest to the straight line representing the predicted moisture ratio.

CONCLUSION

In drying of agricultural products, large amount of energy and lower temperature are required, hence solar energy is considered to be the best source of energy for this purpose. In this present study, based on the results obtained for drying of coriander leaves in IMSDWP and MMSD, it was found that IMSDWP was better in all aspect than MMSD. IMSD have higher efficiency and takes 15 minute less than MMSD to dry the coriander leaves to same moisture content level. It was also found that logarithmic, Wang and Singh, Midilli et al., Two term and modified Henderson and pabis (5 models) are convenient to describe the thin layer drying characteristics of coriander leaves by IMSDWP and Midilli et al. model is best suitable to describe the thin layer characteristics of coriander leaves by MMSD.

REFERENCES

[1] K. S. M. R. M. A. M. S. A. Fudholi, "Review of solar dryers for agricultural and marine products," *Renewable and sustainable energy reviews,* vol. 14, pp. 1-30, 2010.

[2] D. S. Prashant Mall, "Advance technologies and experimental investigations in solar dryers: A review," *Indian jouranal of scietific reserarch,* vol. 17, no. 2, pp. 145-150, 2017.

[3] NL Pawar, "Experimental Investigation on Energy and Exergy analysis of Coriander Leaves Drying in Natural Convection Solar dryer," *Applied solar enegy,* vol. 50, pp. 133-137, 2014.

[4] H. Panda, Fruits, vegetables, corn and oilseeds processing handbook, 2010.

[5] A. Sarimeseli, "Microwave drying characterstics of coriander leaves," *Energy conversion and management,* vol. 52, pp. 1449-1453, 2012.

[6] M. B. S.M. Shalaby, "Experimental investigation of a novel indirect solar dryer implementing PCM as energy storage medium," *Energy conversion and management,* vol. 83, pp. 1-8, 2014.

[7] A. c. g. s. Vinod kumar sharma, "Experimental investigation of solar dryers suitable for fruoit and vegetable drying," *Renewable enegy,* vol. 6, no. 4, pp. 413-424, 1995.

[8] K. S. K. N. Y. Maundu Nicholas Musembia, "Design and Analysis of Solar Dryer for Mid-Latitude Region," *Energy procedia,* vol. 100, p. 98 – 110, 2016.

[9] V. s. h. k. r. P. A. H. a. K. B. n. Vinay narayan hegde, "Design, fabrication and performance evalutionof solar dryer for banana," *Energy, Sustainability and Society,* 2015.

[10] P. T. Dilip Jain, "Performance of indirect through pass natural convective solar crop dryer with phase change thermal energy storage," *Renewable energy,* vol. 80, pp. 244-250, 2015.

[11] M. R. Murthy, "A review of new technologies, models and experimental investigations of solar driers," *Renewable and Sustainable energy reviews,* vol. 13, pp. 835-844, 2009.

[12] S. S. S. N. ,. V. M. Lalit M. Bal, "Review of solar dryers with latent heat storage systems for agricultural products," *Renewable and sustainable energy reviews,* vol. 15, pp. 876-880, 2011.

[13] S. B. S. K. A. F. A. G. Aymen El Khadraoui, "Thermal behavior of indirect solar dryer: Nocturnal usage of solar air," *journal of cleaner production,* vol. 148, pp. 37-78, 2017.

[14] S. R. O. B. Ehsan Baniasadi, "Experimental Investigation of the Performance of a Mixed-mode Solar Dryer with Thermal Energy Storage," 2017.

[15] K. S. B. S. Leon MA, "A comprehensive procedure for performance evaluation of solar food dryers," *Renewable & Sustainable Energy Reviews ,* vol. 6, pp. 367-93, 2002.

[16] S. A.-E. M. R. H. E.-G. A.A. El-Sebaii, "Experimental investigation of an indirect type natural convection solar dryer," *Energy conversion and management,* vol. 43, pp. 2251-2266, 2002.

[17] P. J. B. Z. V. J.Banout, "Design and performance evaluation of a Double-pass solar drier for drying of red chilli (Capsicum annum L.)," *Solar Energy,* Vols. 506-15, p. 85, 2011.

[18] V. a. N. S. Sunil, "Experimental investigation of the performance of an indirect mode natural convection solar dryerfor drying fenugreek leaves," vol. 118, pp. 523-531, 2014.

[19] S. A.A.El-Sebaii, "Experimental investigation of an indirect-mode forced convection solar dryer for drying thymus and mint," *Energy Conversion and Management,* vol. 74, pp. 109-116, 2013.

[20] L. WK, "The drying of solid materials," *Indian Journal of Enginering,* vol. 5, pp. 427-433, 1921.

[21] P. GE, "Factors influencing the maximum rates of air drying shelled corn in thin layers," *Unpublished master thesis, Purdue University, Lafayette, IN, USA;,* 1949.

[22] R. I. P. R. White GM, "Fully exposed drying of popcorn," *Trans Am Society of Agricultural Engineering,* vol. 24,

pp. 466-468, 1981.

[23] C. MS, "Evaluation of selected mathematical models for describing thinlayer drying of in-shell pecans," *Trans Am Soc Agric Eng ,* vol. 27, p. 610–615, 1984.

[24] D. A. C. F. Yagcioglu A, " Drying characteristics of laure leaves under different conditions. In: Bas Cetincelik A," *Proceedings of the seventh international congress on agricultural mechanization and energy,26–27 May, Adana, Turkey. Faculty of Agriculture, Cukurova University,* 1999.

[25] S. R. Wang CY, "A single layer drying equation for rough rice," *American Society of Agricultural Engineers, Paper no.3001.,* 1978.

[26] B. R. E. J. W. F. Verma LR, "Effects of drying air parameters on rice drying models," *Trans Am Soc Agric Eng,* vol. 28, pp. 296-301, 1958.

[27] K. H. Y. Z. Midilli A, " A new model for single layer drying," *Dry Technol,* vol. 20, pp. 1503-1513, 2002.

[28] H. SM, "Progress in developing the thin layer drying equation," *Trans Am Soc Agric Eng,* vol. 17, pp. 1167-1168, 1974.

[29] K. VT, "Determination of water content of dried fruits by drying kinetics," *Journal of Food Engineering,* vol. 39, pp. 337-344, 1999.

[30] K. AS, " Comparative studies on thin layer drying models for wheat," *13th international congress on agricultural engineering, Morocco,* pp. 2-6, february 1998.

[31] B. J. H. M. Sharaf-Elden YI, " A model for ear corn drying," *Trans Am Soc Agric Eng,* vol. 5, pp. 1261-1265, 1980.

[32] M. P. Diamante LM, "Mathematical modeling of hot air drying of sweet potato slices," *International Journal of Food Science Technology ,* vol. 26, pp. 91-99, 1991.

[33] G. T. Sumit Tiwari, "Energy and exergy analysis of a mixed-mode greenhouse-type solar 1 dryer, integrated with partially covered N-PVT air collector," *solar energy,* 2017.

[34] S. sukhatme, A Book on solar energy.

[35] R. F. Benon Bena, "Natural convection solar dryer with biomass back-up heater," *solar energy,* vol. 2, pp. 75-83, 2002.