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Development of Solar Poly House Tunnel Dryer (STD) for Medicinal Plants

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***Abstract*—**There was a scenario present day that drying of fresh fruits and vegetables by indirect solar drying by using mechanical device; hence, an effort was made to develop a small scale solar tunnel dryer (STD). Drying of spinach is carried out to analyze the performance of the dryer and to study its drying characteristics. To evaluate the performance of dryer the independent variables were selected as air flow rate, loading density and shade net while collector efficiency, drying efficiency, overall efficiency and specific energy consumption were selected as responses during performing the experiments. The spinach was dried from initial moisture content 88.21-94.04% (w.b.) to final moisture content 3.50-5.13% (w.b.). The drying time considerably reduced as compared to open sun drying of spinach as sun drying took 15 h for drying. The average collector efficiency, drying efficiency and overall efficiency were in the range 28.73-61.15%, 11.63% to 22.13%, and 7.61-14.66%, respectively.

***Keywords*—**Solar dryer, collector efficiency, drying efficiency, spinach.

I. Introduction

INDIA has a total land area of 328 million hectare. On an average 5 kWh/m^2/day solar energy is falling on this land for over 300 days per annum. In certain areas, brighter sunny days may be more. Even if one per cent of this land is used to harness solar energy for electricity generation at an overall efficiency of 5%, about 246 x 10^{10} kWh/year electricity can be generated [1]. This abundant solar energy can be utilized for drying operation to reduce the operational cost.

Properly designed solar dryers may provide a much-needed appropriate alternative for drying of some of the agricultural products in developing countries [2]. Considerable efforts have been made to design and develop solar dryers for drying of agricultural products [3], [4]. Selection of a solar dryer for drying a particular agricultural product is determined by the drying characteristics of the product, quality requirements and economic considerations [3]. The operational parameters that significantly influence the performance of a dryer are (a) drying air characteristics (such as drying air temperature, humidity and airflow rate); (b) product variables (product throughput, initial and final moisture contents, product size and size distribution); and (c) dimensional variables (width, length, height or diameter of the dryer, number of passes and dryer configuration). Evaluation of the performance of solar dryers should consider these parameters.

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The performance evaluation of the solar dryers con be done on the basis of its physical features (type, size, shape, tray area, loading density etc.), thermal performance, psychrometric parameters and the quality of dried products (sensory, nutritional properties etc.) [3].

Spinach (*Spinacia oleracea* L.) is a flowering plant in the family of *Amaranthaceae* and is locally known as 'Palak'. It is native to central and southwestern Asia. It is one of the most common leafy vegetable of tropical and subtropical region and is grown widely all over the India. It is highly nutritious and available at the cheaper rate in the market as compared to other leafy vegetables. Spinach is widely used in making various food products like vegetable puree, soups, and baked products [5].

The solar tunnel dryer is one of promising option for drying various agricultural and agro-industrial products on large scale. The advantage of solar tunnel dryer is its relatively cheaper cost of construction and operation. Although many solar dryers have been developed, but still no commercial utilization on large scale in worldwide so there is a scope of modification in them with studying the performance and effect of the operating parameters on the performance is the basic need. Therefore, an attempt was made to studying the performance of the solar tunnel dryer using varying operating conditions was studied using spinach vegetable.

II. Material and Methods

A. Solar Dryer

The Solar Tunnel Dryer (STD) used during experimentation as shown schematically in Fig. 1. It consisted of base frame, semi cylindrical drying chamber, solar collector, absorber, air distribution system with chimney and wheels for its mobility.

The overall dimensions of the dryer were 1.54 m × 0.71 m × 0.58 m. (L × W × H).As the length of collector increased there was increase in temperature gradient (ΔT) but as radius of collector increased fall in temperature rise (ΔT). For the optimum ΔT ratio of length to radius of collector was recommended as 4:5 [6]. The radius of collector was selected as 0.33 m and length as 1.54 m. The specifications of the STD are shown in Table I.

TABLE I
SPECIFICATIONS OF SOLAR TUNNEL DRYER

Name of the Part		Specifications
Dryer	Name of the dryer	Solar Tunnel Dryer
	Type of the dryer	Batch type, forced Convection, Portable
	Dimensions of the dryer	1.54 x 0.71x 0.58 m (L x W x H)
	Ground clearance	0.10 m
	Total weight	60 kg
	Price of the dryer	Rs. 6200
Drying chamber	Capacity	2 kg
	Shape	Hemispherical in shape
	Dimensions of the chamber	1.5 x 0.67x 0.58 m (L x W x H)
	Mesh No. of the screen	2 openings / inch
	Area of the tray	1 m^2
Air Distribution system	Size of the inlet	Φ=½”
	No. of ports	24 opening of Φ=6 mm
	Size of duct	12” x 6”, round end, Φ= 4”
	Chimney for draft	Φ=4” PVC pipe
	Fan	12 V Dc Fan

TABLE II
VALUES OF INDEPENDENT VARIABLES IN CODED AND ACTUAL FORM

Independent variables	Code	Coded level		
		-1	0	+1
Air flow rate, m/s	X_1	1.2	1.7	2.2
Loading density, kg/m^2	X_2	1	1.5	2
Shade net type, %	X_3	0	25	50

B. Experimental Design

On the basis of literature search, the variables, namely air flow rate, loading density and different shade nets were selected as processing parameters for dehydration of spinach. The range of variables was selected on the basis of earlier research work [7], [8]. The three levels of each variable were taken. The coded and actual values are given in Table II. Response Surface Methodology was used as it helped to reduce the number of experiments without affecting the accuracy of results and to decide interactive effects of variables on the responses [9]. Incomplete Composite Block design (Box & Behnken) was used to design the experiments with three variables, each examined at three levels.

C. Experimental Procedure

1. Sample Preparation

Fresh and matured spinach was procured from a local market of Pantnagar and thoroughly cleaned before manual trimming. The roots and stem were removed from spinach leaves followed by cleaning in cold water to remove soil and dust particles if any attached to it.

Washed spinach were weighed using digital balance for various loading densities of 1, 1.5, 2 kg/m^2 and placed in a perforated tray of size of 0.22×0.23 m^2 giving a sample size of 50.6, 75.9, 101.2 g respectively.

Prior to drying, the samples were blanched in boiling distilled water containing 0.5% of sodium metabisulphite for 3 min with the sample to solution ratio of 1:5. Treated sample were placed over a perforated tray to drain surface water and after that loaded into the tray.

2. Drying in Solar Tunnel Dryer

Samples of treated spinach were spread uniformly in a single layer on tray of STD. Temperature of the drying air varied during the experiment as per ambient air conditions. For each of the experiment the dryer was loaded to its full capacity. Weight loss of the sample was measured with electronic balance and recorded with an interval of 5 min for first 30 min of observation. The time interval was increased to 10 min, 20 min and 30 min in later stages of drying. The initial moisture content of spinach was determined by air oven method [10]. The drying of spinach leaves, to bring the moisture at safe level of 4 to 6% (d.b.) took 6 to 9 h. When the desired moisture content was not achieved within 1 day experiment then spinach sample was kept in closed condition and the drying was continued on following day.

During the drying operation the temperature (ambient air, inside the STD and at exhaust), relative humidity (ambient and inside the STD), solar radiation and air velocity were recorded from 10.00 am to 4.00 pm on each day of experiment. Weight loss of the food product was recorded at an interval of 5 min for first half hour. The interval subsequently increased as 10 min, 20 min and 30 min towards the end of experiment.

Fig. 1 Experimental set-up of spinach drying in solar tunnel dryer (STD)

3. Performance Analysis of Solar Tunnel Dryer System

a. Collector Efficiency

Collector efficiency is defined as the ratio of energy output of the collector to energy input to the collector. Solar energy input on the collector is computed as [11]

$$I_{AC} = 10^{-3} A_c S_r T \quad (1)$$

where, I_{AC} - Input to the collector, kJ, A_c - Area of solar Collector, m^2, S_r - Solar radiations W/m^2, T - Time, s

The output of the collector in terms of energy is the amount of heat generated inside the dryer.

$$O_{AC} = (m\, C_P \Delta t) + m_a\,(H_2 - H_1) \quad (2)$$

where; O_{AC} -Output of the collector, kJ, m_a - Mass of the material, kg, C_p - Specific heat of material, kJ/kg/^{0}C (3.954 kJ/kg/ ^{0}C), m_a - mass flow rate of air, kg/s, H_2 - Enthalpy of air at exhaust conditions, kJ/kg, H_1 - Enthalpy of air at ambient conditions, kJ/kg.

$$\eta_c = \frac{O_{AC}}{I_{AC}} \quad (3)$$

where, η_c - Collector efficiency, %.

b. Drying Efficiency

The drying efficiency is defined as the ratio of energy output of the drying section to energy input to the drying section. The output of the dryer in terms of energy is amount of heat required to remove moisture from material, considering sensible heating of the sample is very small in comparison with latent heat.

$$O_d = m_r\, L_v \quad (4)$$

where, O_d - Output of the dryer, kJ, m_r - Moisture removed, kg, L_v - latent heat of vaporization of moisture, kJ/kg. Thus, efficiency of the dryer is

$$\eta_d = \frac{O_d}{I_{AC}} \quad (5)$$

where, η_d - Drying efficiency, %

c. Overall Efficiency of Dryer

The energy consumed by the fan is calculated as-

$$E_{fan} = 10^{-3} P_{fan}\, t \quad (6)$$

where, E_{fan} - Energy consumed by the fan, KJ, P_{fan} - Power of the fan, W,t - Time, s

The overall efficiency of dryer is defined as the ratio of energy output of the dryer to total energy input. Thus, overall efficiency of the system is,

$$\eta_o = \frac{m_r L_v}{I_{AC} + E_{fan}} \quad (7)$$

where, η_o - Overall efficiency of dryer, %

d. Specific Heat Energy Consumption

The Specific energy consumption of the dryer is calculated using [12]:

$$Q_s = \frac{O_d \eta_d}{m_r L_v} \quad (8)$$

where, Q_s- Specific heat energy consumption, kJ/kg

4. Development of Second Order Models

A complete second order model was fitted to the data and adequacy of the model was tested considering R^2 (coefficient of multiple determination) and fisher's F-test. The models were then used to interpret the effect of various parameters on the response. The experimental data were then analyzed employing multiple regression technique to develop response functions and variable parameters optimized for best outputs.

TABLE III
EXPERIMENTAL DATA FOR TECHNICAL PARAMETERS

Expt. No.	Energy Input (kJ), Q	Energy Output (kJ), Y_1	Energy Output (kJ), Y_2	Efficiency (%) Collector*	Drying**	Overall***	Specific Energy Consumption (kJ/kg)
1	24697.08	10395	3640.349	42.09	14.74	7.94	**3296.17**
2	24305.55	10455.77	3349.304	43.01	13.78	8.51	2818.19
3	27676.39	11341.79	5659.821	40.98	20.45	14.59	3127.88
4	27957.8	16398.32	5731.344	58.65	20.50	**14.66**	3115.99
5	28214.74	8106.09	3484.521	**28.73**	12.35	11.05	2289.98
6	25841.08	10525.07	4046.713	40.73	15.66	11.82	2754.64
7	35029.84	12651.37	4273.640	36.11	12.2	8.98	3030.78
8	31677.35	16104.76	4099.049	50.84	12.94	9.61	2493.71
9	16432.09	6394.926	2369.507	38.91	14.42	12.42	**2220.89**
10	37623.74	16934.44	5805.342	45.01	15.43	11.13	2688.01
11	26942.27	13157.23	3133.385	48.83	**11.63**	**7.61**	2907.53
12	27290.97	13301.61	5807.519	48.74	21.28	15.22	3105.53
13	25810.5	11323.06	4186.462	43.87	16.22	11.99	3012.82
14	22898.48	8170.177	3908.770	35.68	17.07	13.22	3071.89
15	23595.9	11559.63	5221.771	48.99	**22.13**	12.6	2817.68
16	24427.9	11239.27	5010.162	46.01	20.51	12.74	3284.92
17	23430.72	14425.79	4208.157	**61.15**	17.96	13.02	2730.64

Y_1- Total heat gained by the air, Y_2 – Based on evaporation of water $*= \frac{Y_1}{Q}$, $**= \frac{Y_2}{Q}$, $***= \frac{Y_1}{(Q+E_{fan})}$

TABLE IV
REGRESSION ANALYSIS OF TECHNICAL PARAMETERS

	Collector efficiency		Drying efficiency		Overall efficiency of dryer		Specific heat energy consumption	
	Coeff.	P (%)	Coeff.	P (%)	Coeff.	P (%)	Coeff.	P (%)
Constant	47.14	31.74	18.77	4.35	12.71	0.57	2983.59	6.06
X_1	5.66	6.12*	0.392	62.08	0.25	51.62	-70.28	36.69
X_2	2.56	34.63	2.88	0.67***	2.39	0.04***	99.33	21.5
X_3	3.89	16.97	0.02	97.59	-0.62	13.78	198.00	2.99**
X_1X_2	4.18	28.25	0.25	82.07	-0.12	81.95	116.52	29.54
X_1X_3	0.68	85.49	-0.64	56.81	-0.03	94.9	-250.43	4.54**
X_2X_3	-1.54	67.99	2.16	8.40*	2.22	0.39***	-67.28	53.47
X_1^2	-3.61	33.69	-1.90	11.10	-1.25	4.41**	8.876	93.21
X_2^2	2.65	47.33	0.49	64.97	-0.02	95.59	97.09	36.59
X_3^2	-4.42	24.74	-3.58	1.10**	-1.08	7.18*	-350.19	1.02**
R^2	65.17		83.34		91.28		81.36	
F-value P (%)	1.45(31.74)		3.89(4.35)**		8.14(0.57)***		3.39(6.06)*	
LOF	Ns		Ns		S		Ns	

X_1, X_2 and X_3 are coded variables for air flow rate, m/s, Loading Density kg/m^2 and Shade net (%), respectively. ***, **,* Significant at 1, 5 and 10% level of significance respectively, s: significant, Ns: Non significant

III. RESULTS AND DISCUSSION

The performance of a solar tunnel dryer was analyzed based on the collector efficiency, drying efficiency, overall efficiency of dryer and specific heat energy consumption. The average values of each parameter for experimental conditions are given in Table III. The regression analysis was used to develop a full second order model for collector efficiency, drying efficiency, overall efficiency of dryer and specific heat energy consumption. The response surface methodology was used to analyze the effect of variables. The obtained results are described in following text.

A. Effect of Variables on Collector Efficiency

The Collector efficiency is one of the parameter used to know the energy available for drying. From Table III the maximum and minimum collector efficiency was observed as 61.15% and 28.73%, respectively. The air flow rate, loading density and shade net conditions for maximum and minimum were reported as 1.7 m/s, 1.5 kg/m^2, 25% and 1.2 m/s, 1 kg/m^2, 25%, respectively. The average collector efficiency was calculated for each day and used in RSM analysis.

Table IV shows that the coefficient of determination (R^2) for the regression model for collector efficiency was 65.17%, which implied that the model accounted for 65.17% variability in data. Lack of fit is insignificant but model is considered inadequate as it had a low R^2 and F-value (1.45). Further analysis has not been done because the model was insignificant.

B. Effect of Variables on Drying Efficiency

The drying efficiency was calculated to know how efficiently heat energy is utilized for removal of moisture from the spinach samples. The drying efficiency was calculated at different time intervals during the experiments. The variation of drying efficiency of solar tunnel dryer with time of the day during experimental run is shown in Fig. 2. It was observed from Fig. 2 that drying efficiency continuously decreasing along with drying time as the rate of moisture removal is decreased.

The maximum drying efficiency was observed as 22.13% at 1.7 m/s air flow rate, 1.5 kg/m^2 loading density and 25% shade net. The minimum drying efficiency was 11.63% corresponds to 1.7 m/s air flow rate, 1 kg/m^2 loading density, 50% shade net (Table III).

The effect of processing variables can be well explained by the regression coefficients of the factors of the model as shown in Table IV. The model showed insignificant lack of fit and high coefficient of determination of 83.34% with F-value of 3.89 (P-value 4.35 %). The developed model was significant and can be written as

$$\boldsymbol{Drying\ Efficiency} = 18.77 + 0.39X_1 - 2.8X_2 + 0.023X_3 - 0.25X_1X_2 - 0.64X_1X_3 - 2.16X_2X_3 - 1.90{X_1}^2 + 0.49{X_2}^2 - 3.5{X_3}^2 \ldots (9)$$

Table V shows that drying efficiency was significantly affected by loading density (P<0.01) at linear level and shade net (P<0.05) at quadratic level. There was interaction between loading density and shade net that affected drying efficiency.

The total effect of variables at linear, interactive and quadratic levels is given in Table IV. The total effect of variables on drying efficiency was significant at linear and quadratic level at 5% level of significance. There was no interaction effect on average drying efficiency.

Table VI showed the total effect individual variable on average drying efficiency. It was observed from table that the loading density had significant effect on average drying efficiency at 5 % level of significance. The drying efficiency was not affected by air flow rate and shade net.

Contour plots for drying efficiency are shown in Fig. 2 (A_1)-(A_3). Fig. 2 (A_1) shows that there was no effect of loading density while increased air flow rate increases drying efficiency. Figs. 2 (A_2), (A3) show that there was effect of shade net on drying efficiency compared to that of air flow rate and loading density when loading density and air flow rate at centre point, respectively.

C. Effect of Variables on Overall Efficiency of Dryer

The overall efficiency will take into account total energy input. In Solar Tunnel Dryer (STD), the total energy input to dryer was the solar energy input and energy added by fan. The overall drying efficiencies are always less than the drying efficiency. The maximum and minimum overall efficiency was observed as 14.66% and 7.61% at 1.2 m/s air flow rate, 2 kg/m^2 loading density, 25% shade net and 2.2 m/s air flow rate, 2 kg/m^2 loading density, 25% shade net, respectively (Table III).

From Table IV, the model showed significant lack of fit with high coefficient of determination of 91.28% with F-value of 8.14 (P-value 0.57%). The model is found adequate. The developed model can be written as

$$\boldsymbol{Overall\ Efficiency} = 12.71 + 0.25X_1 + 2.39X_2 - 0.62X_3 - 0.125X_1X_2 - 0.035X_1X_3 + 2.225X_2X_3 - 1.259X_1^2 + 0.029X_2^2 - 1.08X_3^2 \quad (10)$$

Table IV shows that air velocity and shade net did not have any effect at linear level but significant at quadratic level on overall efficiency.

Interaction between load density and shade net was significant at 1% level of significance.

Table VII shows the ANOVA for overall efficiency. It can be found that the total effect of variables- air flow rate, loading density and shade net on overall efficiency was significant at linear and interactive level at 1% and 5% level of significance, respectively. However, that at quadratic level it was insignificant.

TABLE V
ANOVA FOR DRYING EFFICIENCY

Source	DF	SS	MS	F-value
Regression	9	161.22	17.91	3.89**
Linear	3	67.88	22.63	4.91**
Quadratic	3	70.42	23.47	5.10**
Interactive	3	20.56	6.86	1.49
Error	7	32.22	4.60	
Total	16	193.44		

***, ** Significant at 1% and 5% level of significance, resp.

TABLE VI
TOTAL EFFECT OF INDIVIDUAL VARIABLES ON DRYING EFFICIENCY

Source	DF	SS	MS	F-value
Regression	9	161.22	17.91	3.89**
Air flow rate	4	18.44	4.61	1.00
L. Density	4	86.60	21.65	4.71**
Shade Net	4	74.40	18.60	4.04
Error	7	32.22	4.60	
Total	16	193.44	12.09	

***, ** Significant at 1% and 5% level of significance, resp.

TABLE VII
ANOVA FOR OVERALL EFFICIENCY OF DRYER

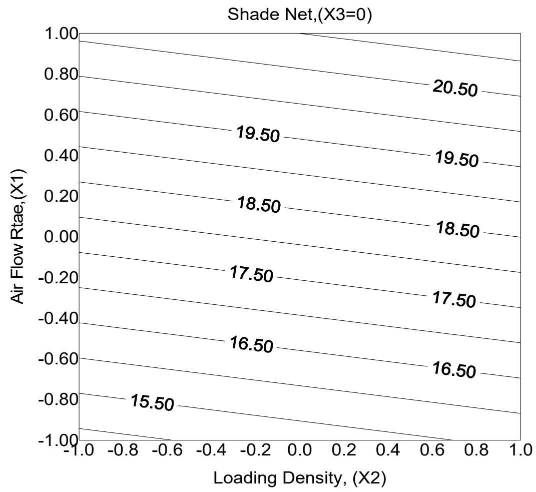
Source	DF	SS	MS	F-value
Regression	9	81.63	9.07	8.14***
Linear	3	49.34	16.45	14.77***
Quadratic	3	11.68	3.89	3.50
Interactive	3	19.86	6.62	5.95**
Error	7	7.79	1.11	
Total	16	89.43		

***, ** Significant at 1% and 5% level of significance, resp.

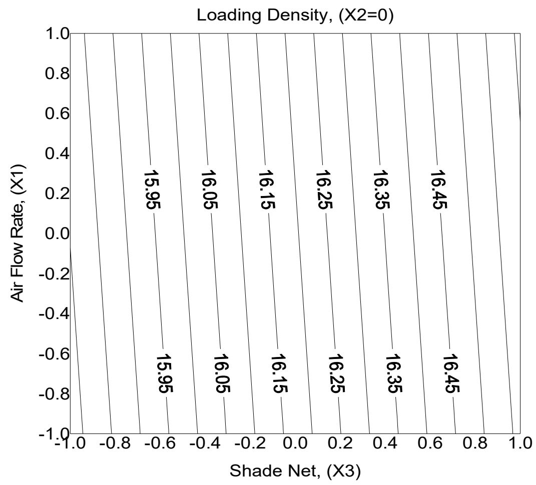
TABLE VIII
TOTAL EFFECT OF VARIABLES ON OVERALL EFFICIENCY

Source	DF	SS	MS	F-value
Regression	9	81.63	9.07	8.14***
Air flow rate	4	7.27	1.82	1.64
L. Density	4	65.57	16.39	14.77***
Shade Net	4	27.93	6.98	6.29**
Error	7	7.79		
Total	16	89.43		

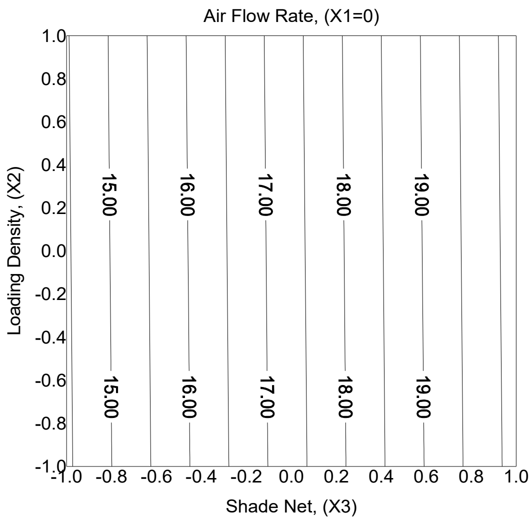
***, ** Significant at 1% and 5% level of significance, resp.



(A1)



(A2)

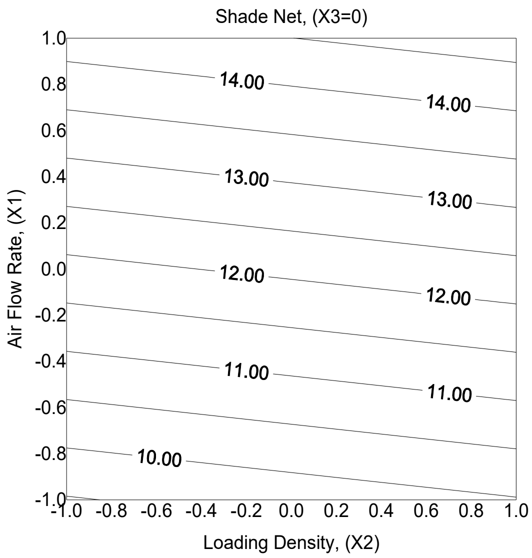


(A3)

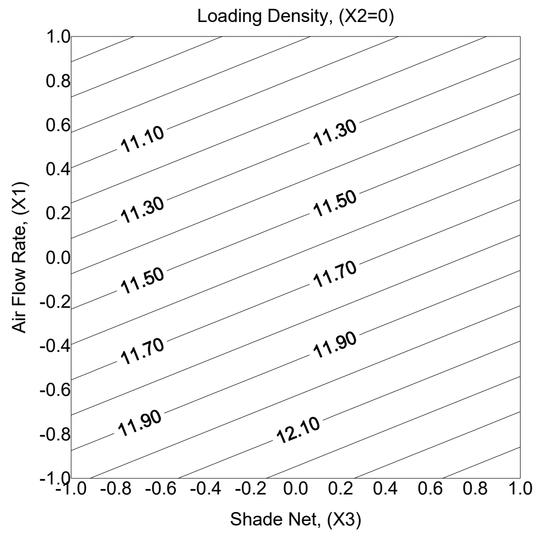
Fig. 2 Effect of operating parameters on the Drying Efficiency

Total effect of individual parameter on overall efficiency is reported in Table VIII. The total effect of air flow rate is insignificant. However, the loading density and shade net had significant effect at 1 and 5% level respectively.

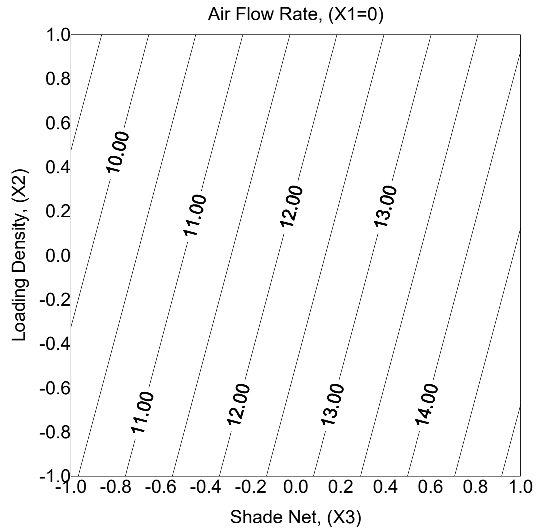
Figs. 3 (A_1)-(A_3) showed the contour plots for overall efficiency of dryer when shade net, loading density and air flow rate at centre point, respectively. Fig. 3 (A_1) showed that overall efficiency of dryer was not affected by loading density and very less affected by air flow rate. From Figs. 3 (A_2) and (A3), it was observed that overall efficiency of dryer was more for higher percentage of shade net but minimum the air flow rate and loading density, respectively. The effect of air flow rate was less than that of loading density.



(A_1)



(A_2)



(A_3)

Fig. 3 Effect of operating parameters on the Overall drying Efficiency

D.Effect of Variables on Specific Heat Energy Consumption

The specific heat energy consumption is the amount of heat energy utilized to remove one kilogram moisture from material. The specific heat energy consumption was ranged from 2220.89 kJ/kg to 3296.17 kJ/kg. The maximum value for specific heat energy consumption was observed for the processing conditions of air flow rate, loading density and shade net as 1.2 m/s, 1 kg/m^2 and25% respectively, while the corresponding process conditions for a minimum were 1.7m/s, 1 kg/m^2, 0% and also at 1.7 m/s, 2 kg/m^2 and 0% respectively.

The effect of processing variable on specific heat energy consumption is shown in Table IV. The second order model has a coefficient of determination of 81.36 % which implies that the model could account for 81.36% data. Lack of fit was not significant. Thus, the model was inadequate to predict the specific heat energy consumptions and therefore further analysis was not done.

IV. Conclusions

The temperature rise in solar tunnel dryer was 15-17^{0}C higher than ambient air temperature. Total drying time was in range of 380 min (6.3 h) to 600 min (10.0 h). Sun drying took 15 h for drying of spinach. The full second order model was found adequate in describing drying efficiency and overall efficiency while inadequate for collector efficiency and specific energy consumption due to lower values of R^2 and F. The drying efficiency of the dried spinach in STD varied from 11.63% to 22.13%. The drying efficiency was mostly affected by loading density. It increased with increase in loading density. The overall efficiency was increased with increased air flow rate and loading density.

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