Chapter-5

Performance Studies of Solar Withering of Fresh Tea Leaves (*Camellia assamica*)

Tea-leaf withering is a low temperature partial drying process, and also an energy intensive operation. The moisture level in the tea leaves reduces from (75-80) % to nearly (55-60) % during withering when the air temperature and relative humidity are maintained appropriately. About 30% of the total price of made tea is due to the energy costs. The specific energy consumed by withering is around 6.48 MJ/kg out of the total specific energy consumed in the overall tea manufacturing process [26,192]. The energy utility may be prevented to some extent by using certain energy effective and environmentally sound alternatives. Most of the tea processing industries at present depend on natural gas, coal, tea drying oil for the tea withering process. Intervention of solar thermal energy in the tea-leaf withering process is a substitute to the general withering process. This will help in the decline in the emanation of greenhouse gases and also the preservation of fossil fuels [26,155].

In a bid to restrain the utilization of conventional energy resources, it is seen that solar thermal energy has been broadly used to dry agricultural products. Ample literature regarding solar drying of various products have been already discussed in the literature review chapter. A few studies on black tea drying by usage of renewable energy have been done previously. Nevertheless, no experimental work has been conducted on the freshly plucked tea-leaf (*Camellia assamica)* withering process with the involvement of solar thermal energy in the local climatic conditions of North-east India as reflected from the already available literature. In the North-eastern part of India, the tea processing industries generally carry out the tea-leaf withering at air temperatures between 25 °C to 35 °C. This heating of air is associated with combustion of fossil fuels [26,153,155]. The generic low temperature tea-leaf drying operation may be conducted by introducing an energy efficient solar air heater in the process. Such partial interventions of solar thermal energy in the form of SAH to wither tea leaves will save the limited fossil fuel consumption in addition to reduction of greenhouse gas emissions. Thus, the chapter illustrates an attempt to perform the tea-leaf withering process in a newly developed laboratory-scaled solar thermal based tea withering trough. The withering properties along with the performance of the set-up like specific energy consumption and activation energy are studied.

Moreover, an economic analysis for the arrangement has been carried out to check its commercial viability.

5.1 Materials and methods

5.1.1 Scoping design estimations for the bed area of the tea-leaf withering trough

The bed area dimension of the proposed withering trough was designed by the following procedure [22]-

(i) Water evaporation rate, W_{ev} (kg/s):

$$W_{ev} = S(X_i - X_o) \quad (5.1)$$

where, S is the mass flow rate, X_i and X_o are the initial and final moisture contents in kg/kg respectively with their assumed values of 0.75 kg/kg and 0.60 kg/kg.

(ii) Gas mass flow rate, G (kg/s):

$$G = W_{ev} / (Y_o - Y_i) \quad (5.2)$$

(iii) Y_0 was obtained from psychrometric chart for scoping design calculations in kg/kg by assuming the value for Yi as 0.005 kg/kg and that for T_{ai} as 35 °C, where Y_0 and Yi are the outlet and inlet air humidity respectively in kg/kg and T_{ai} is the inlet air temperature in °C. The value for Y_0 was 0.007 kg/kg.

(iv) Approximate air density at inlet condition and atmospheric pressure, ρ_a (kg/m^3):

$$\rho_a = 353 p_a / [(273 + T_{ai}) \times 101.4] \quad (5.3)$$

where, p_a is the atmospheric pressure in kPa.

(v) Bed area, A_b (m^2):

$$A_b = G / \rho_a u \quad (5.4)$$

where, u is the air velocity (= 0.1 m/s).

The leaf bed area for the withering trough was computed to be 0.18 m^2. Hence, the dimension of the bed would be (0.2 × 0.9) m^2.

5.1.2 Experimental studies

The experiments in the newly developed tea-leaf withering trough were conducted in the Department of Mechanical Engineering, Tezpur University (26°65'28" N, 92°79'26" E). The experiments on the SAH were conducted according to the ANSI/ASHRAE Standard 93-2003 for evaluating the thermal enactment of solar collectors [14]. Fresh tea leaves were collected from a nearby tea garden and kept under refrigeration in an airtight container to preserve the moisture content. The tea leaves were divided into equal weights and mounted on three sample trays. The sample trays were then placed inside the withering trough on top of a perforated tray loaded with tea leaves. The weights of the sample trays were taken in a digital weighing balance after every hour till the desired moisture level was attained. The withering air temperature was not allowed to surpass 32 °C. The relative humidity within the trough was maintained in the range of (75-85) %. The withering trough was coupled with an SAH to carry out the withering process of fresh tea leaves. A corrugated absorber plate having an exposed area of 1.41 m^2 was used in the SAH [226]. The angle of tilt was kept around 27° to conduct the experiments. Fig. 5.1 shows the schematic diagram of the experimental set-up. Fig. 5.2(a) and 5.2(b) show the schematic of the corrugated absorber plate and the corrugated plate SAH respectively. The complete experimental set-up is shown in Fig. 5.3. Table 5.1 lists the dimensions of the set-up. The temperature and RH were recorded using thermo-hygrometers during the experiments. Withering air velocities were measured using an anemometer while a pyranometer was used for measuring the solar radiations. The initial moisture level of the fresh tea leaves (78% w.b.) was determined by oven-drying the leaves in a hot-air oven at 103 °C for 6 h [74]. The moisture levels were measured in wet basis during the experiments. Table 5.2 lists the technical specifications of the instruments used in the experiments. Fig. 5.4 comprises of all the instruments used in the experiments.

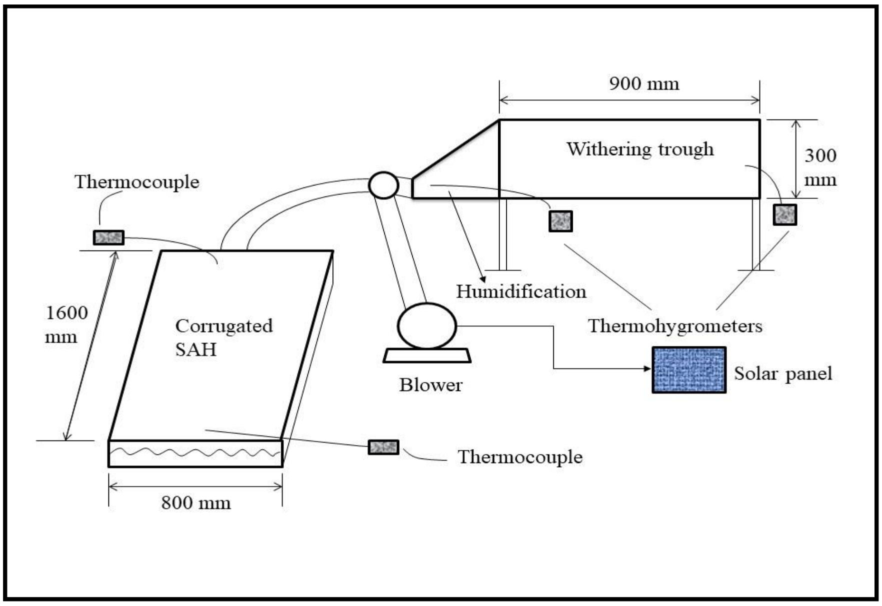


Fig. 5.1. Schematic diagram of the experimental set-up

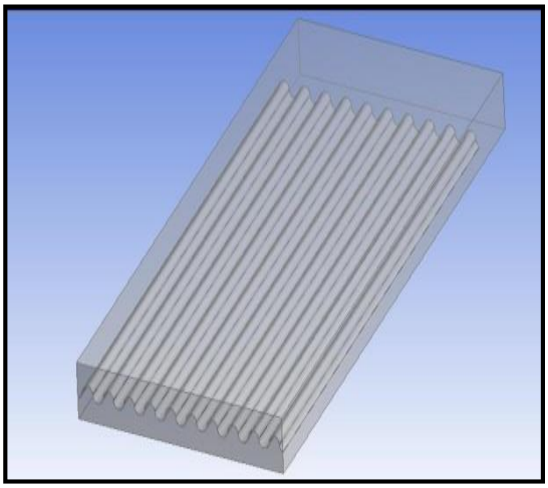


Fig. 5.2(a). Schematic of Corrugated plate

Fig. 5.2(b). Corrugated SAH

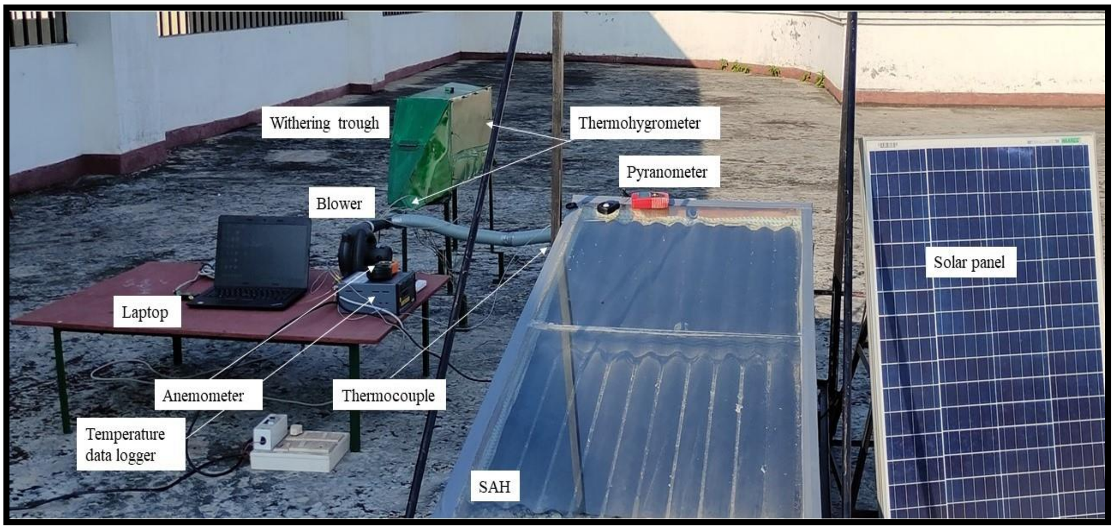


Fig. 5.3. The complete experimental set-up

Table-5.1. Dimensions/specifications of the set-up

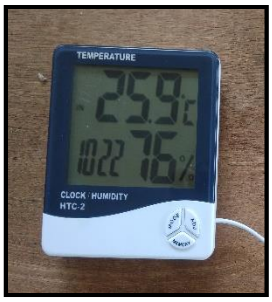
Item	**Dimensions/Specifications**
Enclosure wooden box	1810 mm×810 mm×150 mm
Glass cover	1810 mm×810 mm×4 mm
Absorber plate	1600 mm×800 mm×1 mm
Withering chamber	GI sheet with thickness 2.0 mm, size 900 mm×200 mm×300 mm
Number of perforated trays	1 with size 900 mm×200 mm
Number of sample trays	3
Dimension of each tray	200 mm×150 mm

Table-5.2. Technical specifications of the instruments used

Instruments	**Make**	**Model**	**Range**	**Accuracy**
Pyranometer	Amprobe	Solar-100	0-1999 W/m^2	± 1 W/m^2
Thermo-hygrometer	HTC	HTC-2	-10 ºC to 60 ºC, 10%-99%	±0.1 ºC, ±1%
Thermocouple	TESTO	830-T1	-30 ºC to 400 ºC	±0.1 ºC
Temperature data logger	Libratherm Instruments	Datalog-16	Input- K-type T/C	±0.1 ºC
Anemometer	HTC	AVM 06	0-30 m/s	± 0.01 m/s
Air Blower	Black & Decker	KTX5000	4 speeds up to 3.5 m^3/min	
Hot-air oven	Reico			

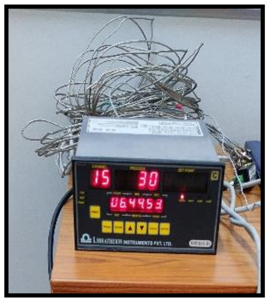
Digital balance	A&D Company Limited	HT-120	0-120 g	±0.01 g
Solar panel	Generic		Peak power output 100 W, Voltage 18 DC, Short circuit current 5.5 A	

(a) Pyranometer



(b)Thermo-hygrometer

(c) Thermocouple



(d) Temperature data logger

(e) Anemometer

(f) Blower

(g) Digital balance

(h) Hot air oven

Fig. 5.4. Instruments used in the experiments

5.1.3 Working principle of the solar powered tea withering system

The green tea leaves were withered in a laboratory-scaled tea withering trough based on solar thermal energy. The experimentation of the SAH for low temperature green tea-leaf drying was performed as per the ANSI/ASHRAE Standard 93-2003 [14]. For this purpose, the withering trough was coupled with a corrugated plate SAH. The pitch of the corrugated plate is 75 mm and taken according to IS 277 for galvanized steel sheets (plain and corrugated) specification [226]. The artificial roughness created because of the corrugation would enhance the local turbulence and the heat transfer to the flowing air over it, thus contributing to its better efficiency. The air had entered the SAH from the inlet, got warmed up and passed to the outlet. Green tea leaf withering, being a low temperature drying process, the hot air coming out from the SAH was sent to the withering chamber after it had attained the required temperature in the mixing chamber by introduction of ambient air with a variable speed blower. The air entered the inlet of the withering trough and passed to the tea leaves laid on three sample trays over a perforated tray uniformly. The continuous flow of air made the tea leaves flabby by reducing the moisture in them gradually. The moisture loss was determined by weighing the samples after every hour. The experiment was continued till the leaves had reached an anticipated moisture content. The maximum withering temperature was maintained around 308 K with a relative humidity range of (75-85) % in the trough.

5.1.4 Energy analysis

From the conservation of mass for drying medium,

$$\sum \dot{m}_{ai} = \sum \dot{m}_{ao} = \sum \dot{m}_{air} \tag{5.5}$$

where, $\dot{m}_{ai}$ and $\dot{m}_{ao}$ are the mass flow rates of air at inlet and outlet of the SAH (kg/s).

Amount of useful heat gained by the solar air heater is given by,

$$Q_u = \dot{m}_{air}\, C_p (T_o - T_i) \tag{5.6}$$

The thermal efficiency of the air heater ($\eta_{SAH_{avg}}$) is given by [106]-

$$\eta_{SAH_{avg}} = \frac{\dot{m}_{air}\, C_p (T_o - T_i)}{\alpha \tau I_S A_S} \tag{5.7}$$

where, $\dot{m}_{air}$ is the mass flow rate of air (kg/s), C_p is the heat capacity (kJ/kg K), T_i and T_o are the inlet and outlet temperatures, I_S, A_S, α and τ are the solar insolation (W/m^2), area of the collector plate (m^2), absorptivity and transmissivity respectively.

The amount of energy input (E_T) to the withering chamber is calculated as,

$$E_T = [XA_S I_S \alpha\tau + E_b]\times t \tag{5.8}$$

where, X is the fraction of energy taken from air heater, E_b is the power consumption of the blower (kW) and t is the withering time duration (h).

The specific energy consumed (SE in MJ/kg) by the withering trough is,

$$SE = \frac{E_T}{M_w} \tag{5.9}$$

where, M_w is the mass of water removed from the leaves (kg).

The overall efficiency (η_{over}) of the withering trough is estimated as [106],

$$\eta_{over} = \frac{M_w \times h_{fg}}{E_T} \tag{5.10}$$

where, M_w is the mass of water removed from the leaves (kg), h_{fg} is the latent heat of evaporation (kJ/kg) and E_T is the amount of energy input to the withering chamber (MJ/kg).

5.1.5 Analysis of the withering data

The moisture content of the tea leaves at any time ($M_{(t)}$) is estimated by,

$$M_{(t)} = M_{(0)} - M_{L(t)} \tag{5.11}$$

where, $M_{(0)}$ and $M_{L(t)}$ are the initial moisture content and moisture loss of the leaves at any instant *(t)* respectively.

Moisture loss of the leaves is determined by,

$$M_{L(t)} = \frac{m_i - m_f}{m_i} \tag{5.12}$$

where, m_i and m_f are the initial and final masses of the tea leaves (g) respectively.

The relative humidity does not remain constant during the experiment. Hence, the moisture ratio (MR) is defined by neglecting the equilibrium moisture content as [127]-

$$MR = \frac{M_{(t)}}{M_{(0)}} \tag{5.13}$$

The goodness of fit was determined by the parameters of R^2, adjusted R^2 and *RMSE*. The R^2, *RMSE* and adjusted R^2 are calculated by the following relations [79]-

$$R^2 = 1 - \frac{S_r}{S_t} \tag{5.14}$$

where, S_r and S_t are residual sum square and total sum square respectively.

$$RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(MR_{ei} - MR_{pi})^2} \tag{5.15}$$

where, MR_{ei} and MR_{pi} are the experimental and predicted *MR*s, respectively.

$$R^2{}_{ad} = 1 - \frac{MS_r}{MS_t} \tag{5.16}$$

where, MS_r and MS_t are residual mean square error and total sum square error respectively.

5.1.6 Activation energy and effective diffusivity

The drying attributes of biological products may be explained by the Fick's diffusion equation. The solution to this equation for regularly shaped bodies as given by [37]-

$$MR = \frac{8}{\pi^2}\sum_{0}^{\infty}\frac{1}{(2n+1)^2}\exp\left(-\frac{(2n+1)^2\pi^2 D_e t}{4t_0{}^2}\right) \tag{5.17}$$

where, D_e is the effective diffusivity (m^2/s) and t_0 is the half thickness of leaf (m).

The simplified logarithmic form of Eq. (5.17) is as follows-

$$\ln MR = \ln\frac{8}{\pi^2} - \frac{\pi^2 D_e t}{4t_0{}^2} \tag{5.18}$$

Diffusivities can be determined from the plot of '*ln MR* versus *t*'. The slope of Eq. (5.18) is-

$$Slope = -\frac{\pi^2 D_e}{4t_0{}^2} \tag{5.19}$$

An Arrhenius type of relationship is obtained from the plot of '$\ln D_e$ versus *1/T*' with *T* in K. It is given by-

$$D_e = D_0 \exp\left(-\frac{E_a}{RT}\right) \tag{5.20}$$

where, D_0 is the diffusivity constant, and E_a is the activation energy (kJ/mol).

5.1.7 Economic analysis

An economic analysis of the solar thermal based tea-withering trough was carried out by applying the life cycle savings and payback period techniques [167].

The cost of fresh tea leaves against one kg of withered leaves (C_w) is given by,

$$C_w = C_{ft} \times \frac{m_{ft}}{m_{wt}} \tag{5.21}$$

where, C_{ft} is the cost of fresh tea leaves per kg (Rs/kg); m_{ft} and m_{wt} are the masses of fresh and withered tea leaves per batch respectively.

The cost of withering 1 kg of tea leaves in the trough (C_{ws}) is calculated by,

$$C_{ws} = C_w + C_s \tag{5.22}$$

where, C_s is the cost of solar withering.

The solar withering cost is determined from the annualized cost of the trough (C_{ann}),

$$C_{ann} = C_{acc} + C_{mc} - V + C_{rfc} + C_{ec} \tag{5.23}$$

where, C_{acc} is the annualized capital cost, C_{mc} is the maintenance cost, V is the annual salvage value, C_{rfc} is the running fuel cost, and C_{ec} is the running electrical cost. For the present case, the running fuel cost is zero since it is a solar thermal based withering chamber. The maintenance cost is assumed 10% of the annualized capital cost.

Annualized capital cost is calculated by,

$$C_{acc} = C_c \times \frac{x \times (1+x)^n}{(1+x)^n - 1} \tag{5.24}$$

where, C_c is the capital cost of the chamber, x is the rate of interest on the investment and n is the lifespan of the chamber.

The yearly salvage value is determined by,

$$V = SV \times \frac{x}{(1+x)^n - 1} \tag{5.25}$$

where, SV is the salvage value (assumed as 10% of C_c).

The running electrical cost of the chamber is estimated by,

$$C_{ec} = t_h \times E_b \times C_{elc} \tag{5.26}$$

where, t_h is the annual running hours of the blower, C_{elc} is the electricity cost per unit and E_b is the power consumption of the blower. The electricity is considered as zero as the blower operates with the help of a solar panel.

The cost of solar withering (C_s) per kg of withered tea leaves is given by,

$$C_s = \frac{C_{ann} \times t_d}{m_{wt} \times t_s} \tag{5.27}$$

where, t_s is the number of available solar withering trough operating days (assumed to be 6 months in this case) per year and t_d is the withering time (days) required per batch.

Savings per day (R_d) is defined by,

$$R_d = \frac{\left(C_{pw} - C_{ws}\right) \times m_{wt}}{t_d} \tag{5.28}$$

where, C_{pw} is the cost of withered tea in the market. The value of C_{pw} is taken as 25% of made tea.

Annual savings (R_n) in the nth year is estimated as follows,

$$R_n = R_d \times t_s \times (1+i)^{n-1} \tag{5.29}$$

where, i is the inflation rate (%).

Payback period of the solar thermal based tea withering trough (P) is calculated as,

$$P = \frac{\ln\left[1 - \frac{C_c}{R_1}(x-i)\right]}{\ln\left[\frac{1+i}{1+x}\right]} \tag{5.30}$$

where, R_1 is the savings in the first year of operation.

5.2 Results and discussion

5.2.1 Performance studies of the solar air heater

The performance of the SAH mainly depends on the solar radiation incident on it, the geometry of the absorber plate, absorber material and insulations used in the air heater. Fig. 5.5 shows the average outlet temperature variations of the corrugated SAH as well as the solar radiation incident on the SAH for October and November' 2019.

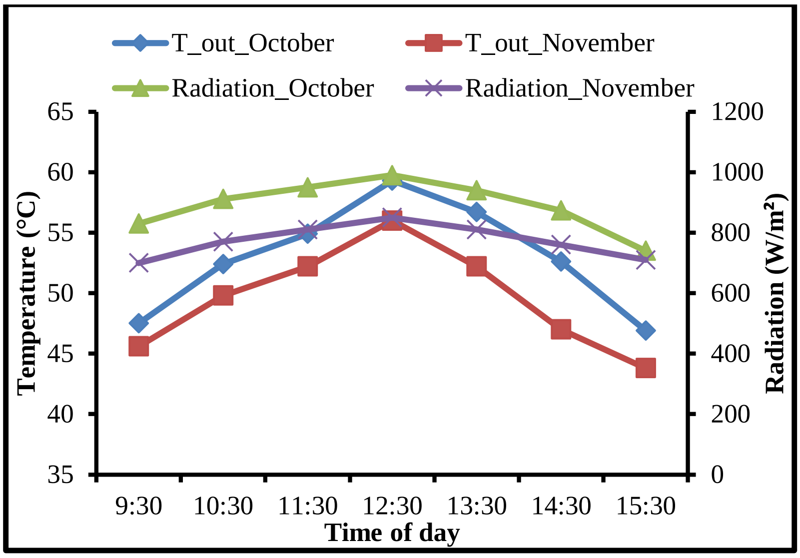


Fig. 5.5. Outlet temperature variations and solar radiation intensity with time of the day

The maximum outlet temperature of the air heater in October was recorded as 59.31 °C with a solar radiation intensity of 990 W/m^2. In the month of November, the maximum outlet temperature was 56.21 °C at 850 W/m^2. It is noted from Fig. 5.6 that the average useful heat gains during October and November were 657.7 W and 627.1 W respectively. Fig. 5.7 shows that the average thermal efficiencies of the SAH during October and November were evaluated as 63.15% and 56.06% at the average solar radiations of 891 W/m^2 and 772 W/m^2 respectively. The results obtained were comparable with those of Lakshmi et al. (2019) where an individual air heater showed an efficiency of 56.31% [106].

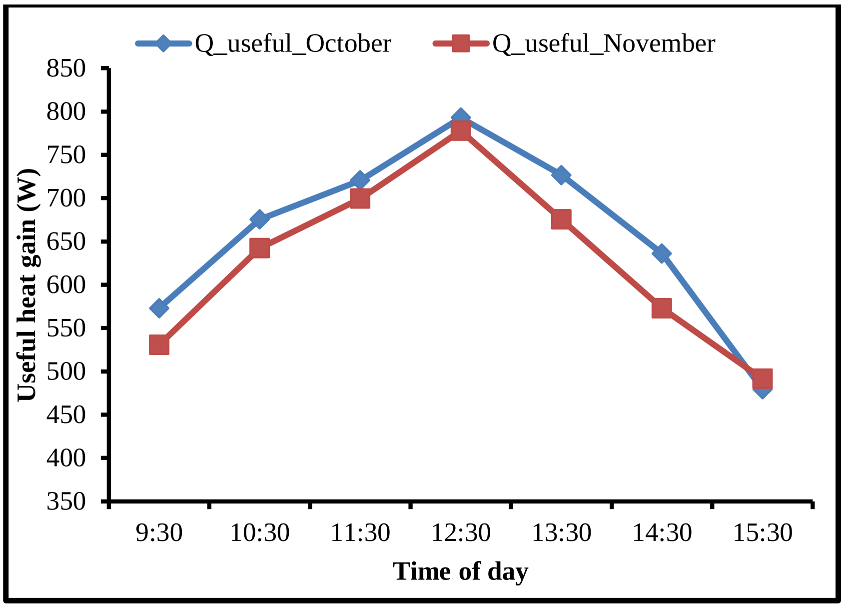


Fig. 5.6. Useful heat gain with time of the day

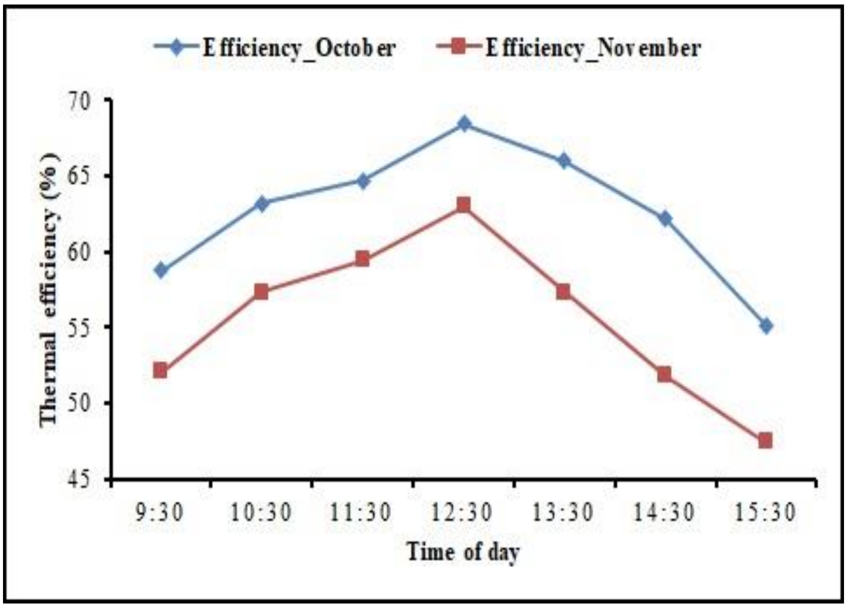


Fig. 5.7. Thermal efficiency with time of the day

5.2.2 Withering characteristics of the green tea leaves in an enclosed trough

The temperatures inside the withering trough during the experiments were maintained at the average values of 32 °C, 27 °C and 23 °C in the months of October and November’ 2019. The hot air at an average temperature of 50 °C at the outlet of the corrugated SAH was mixed with the low temperature air through an arrangement to get the required temperature ranges within the withering chamber. The average mass flow rate of the SAH was measured to be 0.03 kg/s. However, only a fraction of the total hot air flow rate from the SAH was used for the withering operation because the desired air temperatures for tea-leaf withering ranges were within (23-32) °C. The remaining part of the hot air from the solar air heater might be used for preheating of combustion air during black tea complete drying operation that needs average (100 ± 10) °C hot air temperature in an industrial drying process of black tea if solar energy (partial) is adopted by tea industries. The mean values of temperature and solar radiation for estimating the overall efficiency of the withering trough were taken as 30 °C and 859 W/m^2 respectively. For comparison, the withering process was conducted at 23 °C without using solar thermal energy as the ambient indoor air temperature was near 23 °C on a particular day (November' 2019).

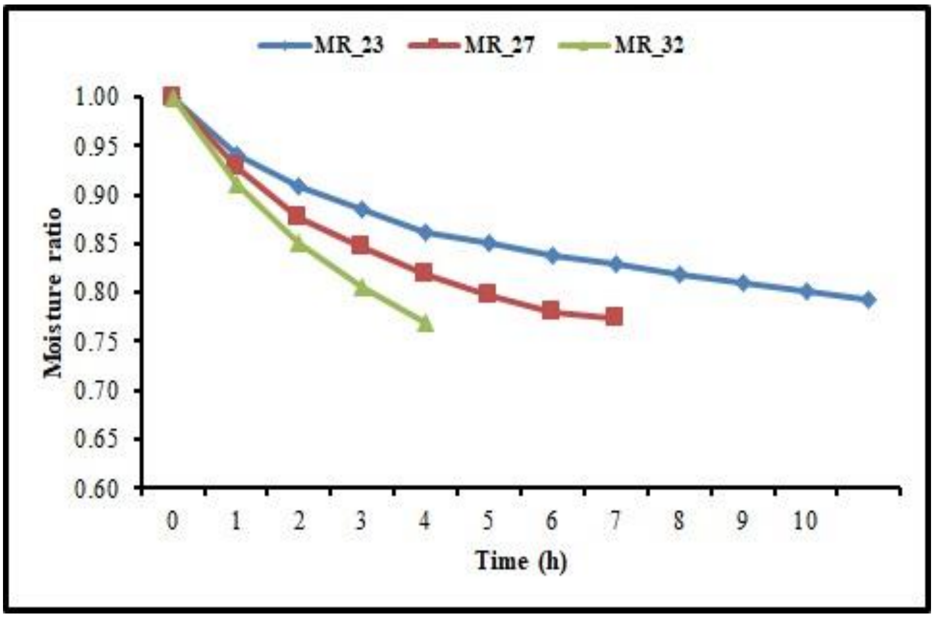


Fig. 5.8. *MR* variation with time

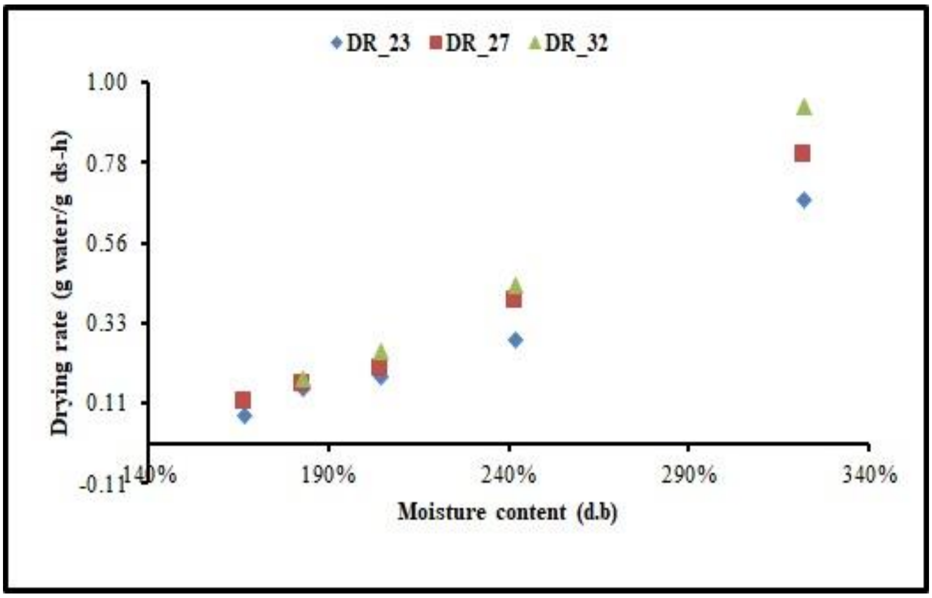


Fig. 5.9. Drying rate with MC (d.b.)

Fig. 5.8 shows the variation of moisture ratio with the withering time duration. It is clearly observed that the withering rate increases with a rise in the air temperature. The withering of fresh tea-leaf samples took a maximum time of 11 h at 23 °C, while it took 7 h at 27 °C and 4 h at 32 °C. The moisture level came down to the desired value of around 60 % (w.b.) in all the considered cases. This trend was in agreement with the results of [33, 66] for similar ranges of tea-leaf withering air temperatures. Fig. 5.9 shows the drying rate variations with the moisture contents (d.b.). It is seen that the low temperature drying of tea leaves took place mostly in the falling rate period initially. The maximum rate of withering is 0.93 g water/g dry solid-h at the beginning for the air temperature of 32 °C and the minimum rate is 0.18 g water/g dry solid-h at the end of 4 h.

5.2.3 Fitting of withering data in drying models

The withering data obtained from the experiments were fitted into seven standard drying models [51,116,137,179]. The equations of the drying models are given in Table 5.3 below. The Midilli-Kucuk model gave the best fit results at 27 °C with R^2, adjusted R^2 and *RMSE* values of 0.9976, 0.9970 and 0.0024 respectively. At 32 °C, the Two-term model gave the best fit with R^2, adjusted R^2 and *RMSE* values of 0.9977, 0.9972 and 0.0025 respectively as shown in Table 5.4. Botheju et al. also obtained the Two-term model as the best fit while evaluating the drying characteristics of fresh tea leaves [33].

Table-5.3. Equations of the drying models used

Sl. No.	**Model name**	**Equation**
1.	Lewis	$MR = e^{-kt}$
2.	Henderson & Pabis	$MR = Ae^{-kt}$
3.	Logarithmic	$MR = Ae^{-kt} + B$
4.	Page	$MR = e^{-kt^N}$
5.	Two-term	$MR = Ae^{-k_1 t} + Be^{-k_2 t}$
6.	Midilli & Kucuk	$MR = Ae^{-kt^N} + Bt$
7.	Wang & Singh	$MR = 1 + At + Bt^2$

Table-5.4. Drying curve parameters

Model	**T (°C)**	**Constants**						***R²***	**Adj. *R²***	***RMSE***
		k	**k_1**	**k_2**	**A**	**B**	**N**			
Lewis	23	0.0289						0.7472	0.7472	0.0259
	27	0.0419						0.7574	0.7574	0.0353
	32	0.0672						0.8487	0.8487	0.0428
Henderson & Pabis	23	0.0221			0.9676			0.8720	0.8718	0.0199
	27	0.0324			0.9560			0.8723	0.8720	0.0277
	32	0.0555			0.9486			0.9112	0.9109	0.0355
Logarithmic	23	0.4396			0.1545	0.8440		0.9955	0.9949	0.0031
	27	0.4517			0.2142	0.7844		0.9970	0.9965	0.0042
	32	0.3888			0.3371	0.6626		0.9975	0.9969	0.0037
Page	23	0.0689					0.4637	0.9928	0.9921	0.0047
	27	0.0979					0.4710	0.9914	0.9906	0.0072
	32	0.1357					0.5559	0.9903	0.9897	0.0117
Two-term	23		0.0074	0.6699	0.8917	0.1083		0.9856	0.9849	0.0030
	27		0.6611	0.0101	0.1550	0.8454		0.9864	0.9857	0.0035
	32		0.0082	0.4492	0.7097	0.2908		**0.9977**	**0.9972**	**0.0025**
Midilli & Kucuk	23	0.0896			1.0000	0.0244	0.7542	0.9975	0.9967	0.0026
	27	0.1220			1.0010	0.0292	0.7586	**0.9976**	**0.9970**	**0.0024**
	32	0.1652			1.0010	0.0393	0.8672	0.9973	0.9964	0.0053
Wang & Singh	23				-0.0502	0.0042		0.9737	0.9729	0.0090
	27				-0.0704	0.0059		0.9725	0.9718	0.0129
	32				-0.1013	0.0082		0.9879	0.9868	0.0131

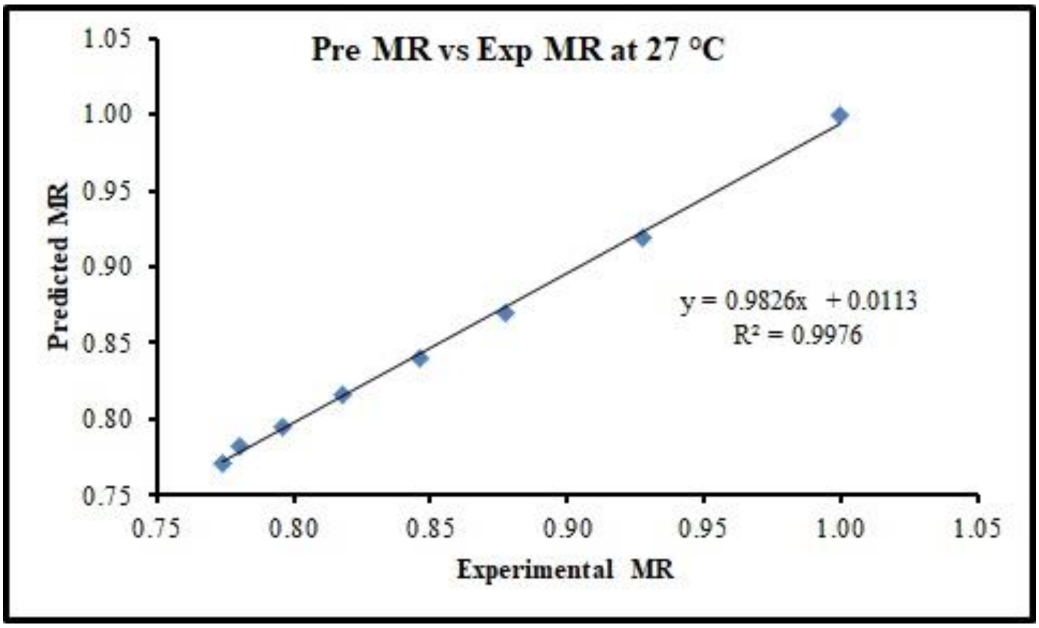


Fig. 5.10(a). Pre *MR* vs Exp *MR* at 27 °C

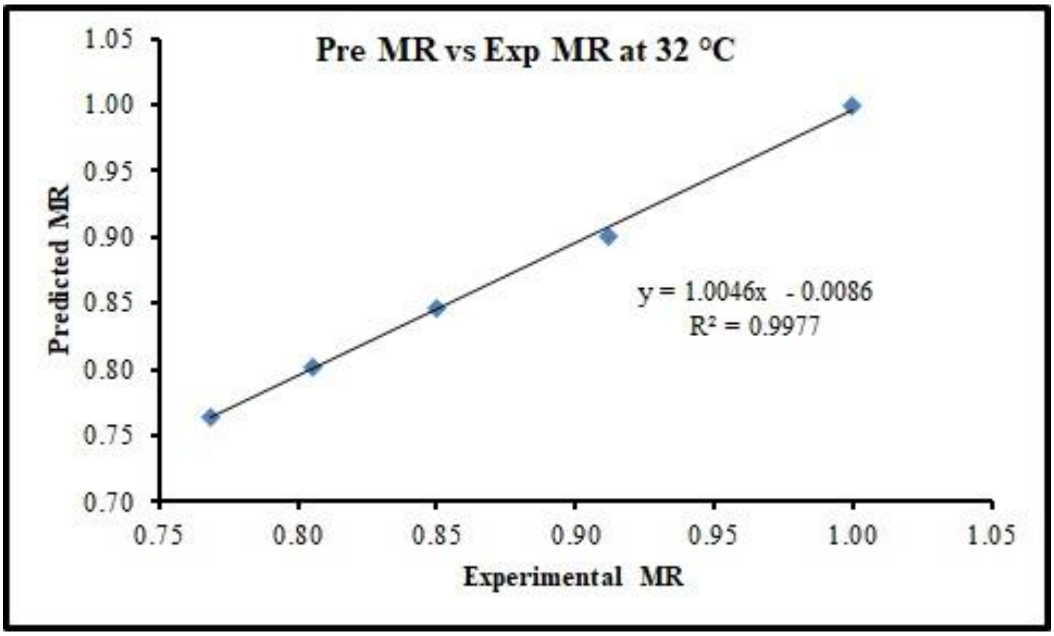


Fig. 5.10(b). Pre *MR* vs Exp *MR* at 32 °C

Fig. 5.10(a) and 5.10(b) depict the predicted *MR* variation with the experimental data for the best fit models. The best fit tea-leaf withering models are $MR = 1.001e^{(-0.122)t^{0.7586}} + 0.0292t$ and $MR = 0.7097e^{-0.0082t} + 0.2908e^{-0.4492t}$ at 27 °C and 32 °C withering air temperatures respectively.

5.2.4 Estimation of activation energy and effective diffusivity

Fig. 5.11(a) and 5.11(b) show the plots of '$lnMR$ vs t' and 'lnD_e vs $1/T$' respectively. The activation energy was estimated as 104.05 kJ/mol. This was higher than that obtained by [51] and lower than that of [137] where the activation energies were computed as 52.10 kJ/mol and 406.02 kJ/mol respectively. Ethman-Kane et al. estimated the activation energy of tea-leaf as 89.14 kJ/mol [63]. The activation energy obtained for withering of green tea leaves falls within the acceptable range. It is due to the fact that the tea-leaf withering temperatures are comparatively lower than the tea drying temperatures. The average velocity of air in the tea withering trough is much lower (0.10 m/s) than the tea drying fluidization velocity. Thus, the activation energy is estimated to be somewhat higher in case of green tea-leaf withering.

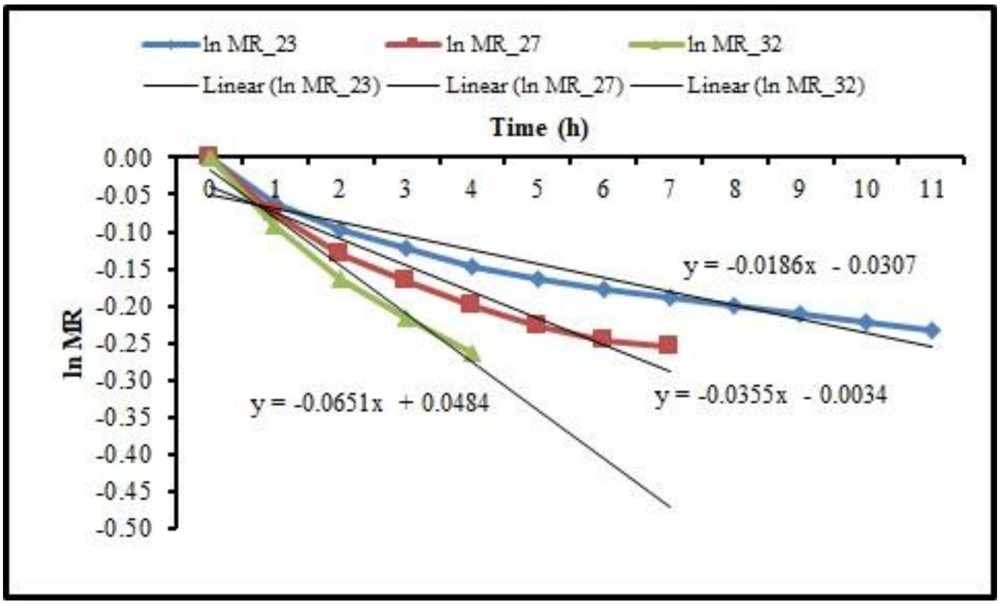


Fig. 5.11(a). Plot of ln *MR* with Time

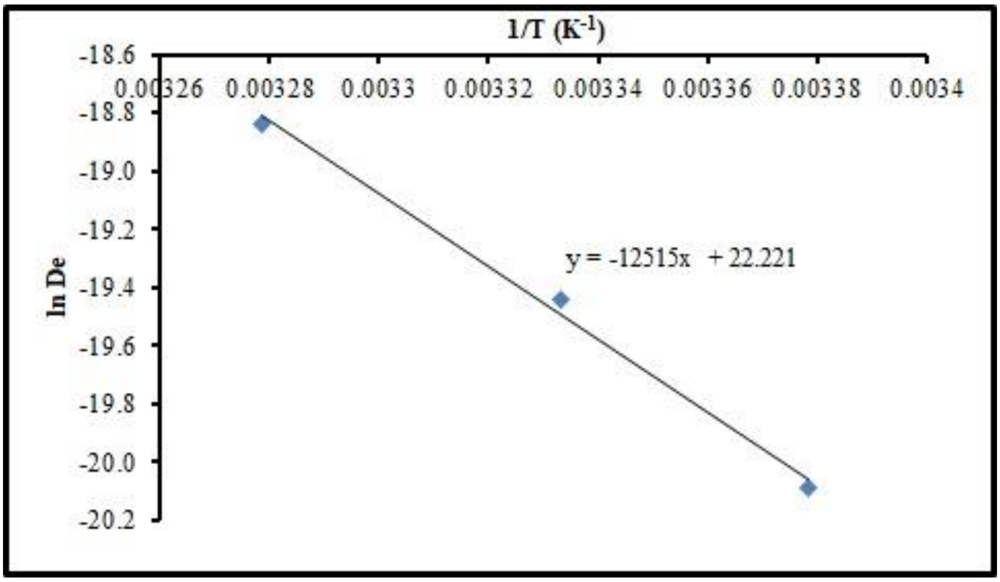


Fig. 5.11(b). Plot of ln D_e with 1/T

5.2.5 Specific energy consumption of the green tea leaves withering trough

The total energy input to the tea withering trough was calculated as 0.91 kWh with a specific energy consumption of 1.76 kWh/kg, i.e., 6.34 MJ/kg. The overall thermal efficiency of the solar-powered tea-leaf withering trough was estimated to be 40.98%. A similar specific energy consumption of 1.62 kWh/kg and a drying efficiency of 33.50% while solar drying stevia leaves was obtained by [106].

5.2.6 Economic analysis

The results of the economic analysis conducted for the solar-powered tea-leaf withering trough are presented in Table 5.5. The capital cost for the whole set-up was considered as 272.85 $ with the rate of interest as 10%. For a life-span of 20 years, the economic payback period of the arrangement was computed to be 0.90 years.

Table-5.5. Economic analysis of the solar thermal based green tea withering trough

Sl. No.	**Components**	**Parameters**
1.	Capital cost of the trough with the SAH	272.85 $
2.	Lifespan of the system	20 years
3.	Cost of green tea leaves per kg	0.41 $
4.	Cost of withering 1 kg of tea leaves in the trough	0.77 $
5.	Rate of interest [106]	10%
6.	Rate of inflation [106]	4.62%
7.	Annualized capital cost	32.05 $
8.	Maintenance cost	3.20 $
9.	Yearly salvage value	0.48 $
10.	Annualized cost	34.78 $
11.	Cost of withered tea in the market	1.02 $
12.	Savings per day	3.34 $

13.	Yearly savings for first year	333.57 $
14.	Economic payback period of the solar withering trough	0.90 years

*1 USD = ₹ 73.30

5.3 Conclusions

The tea-leaf withering process was conducted in a newly developed laboratory-scaled solar power based tea withering trough having a corrugated absorber plate. The following are some conclusions drawn from the study-

- The average thermal efficiencies of the corrugated SAH during October and November' 2019 were evaluated as 63.15% and 56.06% respectively.
- The overall efficiency of the withering trough was computed as 40.98% with a specific energy consumption of 1.76 kWh/kg.
- The Midilli-Kucuk and the Two-Term models gave the best fits at tea-leaf withering temperatures of 27 °C and 32 °C respectively. The corresponding best fitted models for the withering attributes of fresh tea leaves at 27 °C and 32 °C were- $MR = 1.001e^{-0.122t^{0.7586}} + 0.0292t$ and $MR = 0.7097e^{-0.0082t} + 0.2908e^{-0.4492t}$.
- The activation energy for tea-leaf withering was estimated as 104.05 kJ/mol.
- The economic payback period for the arrangement was estimated to be 0.90 years for a life-span of 20 years.

From the experiments carried out, it is clearly seen that the solar withering or partial drying of freshly collected tea leaves is a technically and economically feasible process for potential tea processing industries. Further, an elaborate exergy and environmental analysis is carried out for the solar based tea withering process and is illustrated in the next chapter of the thesis.