PERFORMANCE EVALUATION OF A WIRE MESH SOLAR AIR HEATER

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Abstract

A solar drier integrated with a matrix solar air heater having an area of 6 m² was developed and undertaken a detailed performance analysis to explore the techno-commercial feasibility of the system. The maximum temperature recorded at the outlet of the air heater was 70 ˚C, when the system was subjected to no loaded condition. The dryer was loaded with 30 kg fresh tomato of 4 mm thick slices. The initial moisture content of 90.62 % reduced to 18.28 % in 3 hours. The economics of the drier was analyzed in detail by three methods namely annualized cost, present worth of annual savings and present worth of cumulative savings. The payback period worked out to be 1.05 years, which was much less than the estimated life of the system (20 years). The cumulative savings of the dryer at the end of 20 years was estimated to be Rs. 28,52,503.00

Key words : *Solar drier, porous bed solar air heater, tomato drying, moisture content, economic analysis*

Nomenclature

A_p area of absorber plate (m²)
C_{cc} capital cost of drier (Rs.)
C_p specific heat of air (kJ/kg˚C)
d rate of interest on long term investment
F_R collector heat removal factor
F' collector efficiency factor
h_e effective heat transfer coefficient (W/mK)
I intensity of solar radiation (W/m²)
i inflation rate
$\dot{m}$ mass flow rate ($kgm^{-2}h^{-1}$)
N payback period (year)
S_1 saving during first year for solar dryer (Rs.)
T_1 inlet temperature (°C)
T_a ambient temperature (°C)
U_L overall heat loss coefficient

Greek symbols

ç overall efficiency factor (%)
á solar absorptance
ô transmittance of glass cover
$(ôá)_e$ effective transmittance absorptance product

Improving the quality of agricultural produces is always remaining as a challenge to the producers. In fact, superior quality product hails more capital investment and advanced technology, which together leads to increase in energy consumption and production costs. Storage of product is an important stage after post harvesting, wherein a considerable quantity and quality loss of product is observed. Drying is considered as an ancient method of food preservation. Open sun drying is the common method practiced in developing countries for drying wheat, paddy, spices, fruits, vegetables, etc. This method alleges many disadvantages: drying depends on weather conditions and hindrance due to birds, animals, and also wind washes away considerable food quantity. The preservation of organoleptic characteristics (odor, flavor, texture and color) and nutritional values of dried products is also an important parameter during dying process(Bennamoun & Belhamri, 2003). Technological advancements facilitate high quality drying but resulted in enormous energy consumption and costly equipments. Hence, solar driers are considered to be best alternatives to overcome the disadvantages of traditional method and the use of fossil fuel (VijayavenkataRaman, Iniyan, & Goic, 2012). Solar driers are classified into two namely direct and indirect types. In direct type, the product is exposed directly to the solar radiation. A solar air heater is connected to a drying cabinet in indirect type, which protects the products from direct exposure to solar radiation. Flat plate collectors are the conventional type of solar air heater and in order to improve the efficiency, several modifications in design have been evolved out over many years of research. One such design is matrix collector in which a wire mesh absorber is used instead of a flat plate. There is a considerable thermal enhancement in such kind of collectors and this is due to the influence of geometrical parameters of absorber matrix such as depth to bed element size ratio, porosity of the bed and extinction coefficient (Ahmad, Saini, & Varma, 1995). Many researchers have designed and studied matrix solar air heaters with different mesh parameters. Aldabbagh, Egelioglu, & Ilkan (2010) analyzed single and double pass solar air heater with wire mesh as packing bed. The collector design consists of 10 layers of steel wire mesh as absorber. The porosity of the packing was above 0.85. System was studied for different mass flow rates. Another design by Dhiman, Thakur, & Chauhan (2012) had 2 mm thick aluminium sheet as absorber plate and several layers of wire mesh screens packed one above the other. Thermal and thermo-hydraulic performance of the system for parallel and counter flow was studied both theoretically and experimentally with varying bed porosities and mass flow rates. The study reported that thermal efficiency of packed bed heater decreased as the porosity increased. The effect of using fins in between the wire mesh absorber was studied by El-khawajah, Aldabbagh, & Egelioglu (2011). In their study, twelve sheets of steel wire mesh arranged in 6 layers with 3, 3, 2, 2, 1, 1 sheets from bottom to top respectively. The diameter of the wire used was 0.02 cm with 0.18 cm × 0.18 cm cross sectional opening of the layers. Results show that thermal efficiency increases with increasing mass flow rate between 0.0121 kg/s and 0.042 kg/s and maximum efficiency reached 85.9 % at

0.042 kg/s. Copper screen matrix of 1.5 m^2 area was studied by Kolb, Winter, & Viskanta (1999). The study was conducted with varying duct heights and mass flow rates. The results showed that the thermal performance depends on mass flow rates and it was least affected by channel height. The matrix air collector yielded higher thermal performance with less friction losses compared to flat plate air collector. Thermo hydraulic performance of wire screen matrix was analyzed and proved that the performance is higher compared to conventional flat plate collectors by Mittal & Varshney (2006). Optimization of bed parameters like number of mesh layers, pitch to diameter ratio and porosity for maximum efficiency was presented by Paul & Saini (2004). Different tests and analysis like transient behavior (Al-Nimr, 1993), performance in terms of energy augmentation ratio (Gupta & Kaushik, 2009), dimensionless analysis to study the effect of different boundary conditions (Sodha, Bansal, & Mishra, 1984), effect of recycle ratio on the heat transfer efficiency enhancement (Ho, Lin, Chuang, & Chao, 2013), economic analysis for drying application (Aravindh & Sreekumar, 2014) of matrix solar air heaters were reported. Though the efficiency of the wire mesh solar air heater over other conventional type air heaters are studied theoretically and experimentally, their application on drying of agricultural products is seems to be rare as published work. In this work, an attempt has been made to design a pilot scale air heater with wire mesh absorber. The developed air heater was integrated with a drying cabinet and performance under loaded condition was tested with drying tomatoes.

Performance Equation : The generalized performance equation of a conventional solar air heater is given by

$$\eta = F_R\left[(\tau\alpha)_e - U_L\,\frac{T_1 - T_a}{I}\right] \tag{1}$$

Where ç is the overall efficiency of the collector, F_R is the collector heat removal factor and U_L is the overall heat loss coefficient.

$$F_R = \frac{\dot{m}c_p}{U_L A_p}\left[1 - \exp\left(-\frac{F' U_L A_p}{\dot{m}c_p}\right)\right] \tag{2}$$

$$F' = \left[1 + \frac{U_L}{h_e}\right]^{-1} \tag{3}$$

F' is the collector efficiency factor; h_e is the effective heat transfer coefficient.

Experimental Setup and Procedure

Experimental Setup : The experimental set up as shown in Fig. 1(a) essentially consists of matrix solar air heater, blower and a drying chamber. The area of solar air heater is 6 m^2 with length and width of 2 m and 1 m respectively. The developed dryer consists of two parts: solar air heater and drying chamber. The peculiarity of the design is that the food is protected from direct exposure to sun. This type of indirect drying helps to retain the color of the agricultural products. The collector consists of an outer glass cover, two layers of wire mesh followed by a bottom plate and then finally an insulation layer. The upper cover is made up of toughened glass of 4 mm thickness and 90% transmissivity. The bottom plate is made up of Aluminum (Al) coated with selective paint of higher absorptivity. The schematic diagram of the wire mesh absorber is shown in Fig. 1(b). The absorber comprises of two parallel layers of selective coated wire mesh made up of Galvanized Iron (GI), which is separated by a spacing of 2 mm each other. The diameter of the wire is 1 mm and pitch is 3.175 mm. Introducing wire mesh with smaller diameter and lower porosity of packing between the glass cover and the bottom plate improves the efficiency significantly, due to the turbulence provided by the packing in the airflow passage (Choudhury & Garg, 1993). The bottom and sides are insulated with 50 mm thick polyurethane foam (PUF) with a thermal conductivity of 0.16 W/mK, shown in Fig. 1(c). The inlet area of the air passage of the collector is 172 cm^2.

A centrifugal blower is provided to suck the hot air. The volume flow rate of the blower is 500 m^3/h. The blower blows the hot air into the drying chamber where the product is loaded for drying. The dimension of the chamber is (140 cm × 70 cm × 94 cm). The loading capacity of the chamber is 30 kg fresh product per batch with 10 trays made up of Stainless Steel (SS). The wall of the chamber is made up of 50 mm PUF sandwich with SS304/GI. The collector is mounted at 12° with respect to horizontal surface according to the latitude of the place.

Experimental Procedure : Experiments were conducted at Pondicherry, India with Latitude and longitude of 11.56°N and 79.53°E respectively. Basically two types of studies were undertaken on the system: no loaded and loaded condition. The experiments were conducted during the months of December 2013 and May 2014. The average day light hours of the December month was 11 hours and that of May was 12 hours. The daylight hour or sunshine hour is dependent on the latitude of the place and the hour angle.

Working : The photons utilized for solar thermal applications belongs to the wavelength ranging from 0.2μm (middle ultra violet) to 3.5μm (middle infra red) region of the electromagnetic spectrum. The photons emitted from the sun gets absorbed by the absorber plate material. The absorbed photons induce molecular vibration, increasing kinetic energy of the molecules. This in turn increases the temperature of the absorber plate. When solar radiation falls on the toughened glass of the collector, it gets transmitted. The radiation passes through the black painted GI wire mesh. The absorber mesh absorbs the radiation and converts it into thermal energy i.e. long wave radiation. The long wave radiation cannot pass through the glass and thus it bounces back. The ambient air enters through the collector duct and passes through the wire mesh. Meanwhile it acquires turbulent flow due to the friction factor in the geometry. The turbulent flow enhances the thermal conductance of the fluid. The absorber plate which is in higher temperature transfers the heat to the fluid according to the thermodynamics first law. The hot air is drawn towards drying chamber by centrifugal blower which is used for removing moisture.

Instrumentation : Intensity of solar radiation was recorded using LP 471 Pyranometer with an accuracy level of 1°. RTD temperature sensors with 0.1°C accuracy placed at required points measured the temperature and was connected to a

951D-16U universal datalogger for recording the temperatures. A digital weighing machine ($\pm$0.001g) of Model No.TTB 31 (Make-Wenser weighing scales limited) is used to measure the weight of the samples. A hot air oven (Make: Techniq, Model: 341P, 0-250°C) was used for estimating the moisture content of the product.

Economic Analysis : Economic analysis was done by comparing the solar dryer with electric dryer, assuming that the market value of solar dried product is equivalent that of product dried through a conventional dryer, say electric dryer. Sreekumar. et. al, 2008 used similar economic analysis to determine the cost-effectiveness of a solar dryer developed for drying agricultural crops. Three methods were used for carrying out the economic analysis. First one is annualized cost method. This method is used to calculate the cost of drying for the starting year using solar drier and compared with electric dryer. The calculation involves capital cost, salvage value, debt interest rate, capital recovery factor and maintenance cost. Another method called life cycle method is used for calculating the savings throughout the lifetime of the solar drier. Life cycle method is used for determining savings per day, present worth of annual savings and present worth of cumulative savings. The cost of drying per kilogram of dried product was evaluated. The savings per batch and savings per year were also evaluated using this method of analysis. The annual savings for drying pineapple in the 20th year was also calculated. Cumulative savings is the summation of the annual savings. The last method is payback period, which is the period required to retrieve the investment. The payback period should be necessarily short comparing to the life span of the drier. This is because people come forward to buy the equipment if they get back their investment soon. The following equation was used for finding out payback period.

$$\text{Payback period, } N = \frac{\ln\left(1-\frac{C_{cc}}{S_1}(d-i)\right)}{\ln\left(\frac{1+i}{1+d}\right)} \tag{4}$$

Results and Discussion

Test of the drier without load : To evaluate the performance of the solar drier, it was tested under unloaded condition. The experiment was performed for 8 hours from 9:00 AM to 5:00 PM. The temperature sensors were placed in appropriate places to monitor the temperature. The temperature of glazing, wire mesh absorber, bottom plate, inlet air, and outlet air of the solar air heater and the inlet temperature, tray temperature, hot air temperature and outlet temperature of the drier were also monitored for every ten minutes. The test was repeated for 4 sunny days for accurate results. Intensity of solar radiation corresponding to each temperature was recorded.

Temperature profile with solar radiation intensity is depicted in Fig. 2. Wire mesh absorber recorded a maximum temperature of 91 ˚C at 1:00 PM during the study. The solar intensity corresponding to maximum temperature was 797 W/m^2. The maximum temperature achieved by the glass plate was 53 ˚C and the maximum hot air temperature was 70 ˚C. The ambient temperature varied from 29 ˚C to 34 ˚C during the study. Other designs in the literature reported maximum temperature difference to be 27 ˚C for single pass, 38 ˚C for double pass (Aldabbagh et al., 2010), and 40 ˚C when fins were used in between mesh layers (El-khawajah et al., 2011).

Test of the drier with load : A detailed performance evaluation was undertaken on the system with product loaded in the drying chamber. The developed drier was basically intended for drying agricultural and marine products. The experiment was conducted with fresh Tomatoes loaded in the dryer. Tomato (Solanum lycopersicum), belongs to the family Solanaceae is an edible red fruit consumed throughout the world. The fruit is native to Western South America and Central America and one of the most important food crops of India. Tomato is rich in Vitamin A, C, Potassium, Minerals and fibers. Tomatoes are used in the preparation of soup, salad, pickles, ketchup, puree, and sauces and also consumed as a vegetable in many ways. Drying is one of the ways to make full use of its flavor (Ponkham, Meeso, Soponronnarit, & Siriamornpun, 2012). Dried tomatoes are best ingredients when the season for fresh tomatoes goes. Fresh tomatoes were loaded in the drier for testing. The fruit was cut into 6 mm and 4 mm slices for drying experiment. The product was dried without any pretreatment. The initial moisture content of the product was evaluated by keeping the product in hot air oven at 110 ˚C for 24 hours. The weight of the product loaded in the dryer was recorded for every one hour. The initial moisture content of the tomato at 9:00 AM was 90.62 %. The moisture content was calculated for every one hour and the percentage reduction in moisture content was estimated. The maximum temperature inside the drying chamber was recorded to be 56.8˚C at 12:20 PM. The corresponding solar radiation intensity was 856.3 W/m^2 and the average solar intensity of the day was 638.05 W/m^2. The maximum temperature attained by the transparent cover was 50.7 ˚C as shown in Fig. 3.

The United Nations Economic Commission for Europe (Nations, 2007) worked on quality standard of dried tomatoes and reported that the texture varies depending on the moisture content. The texture of the tomato is soft and pliable when the moisture content is between 25% and 50%. When moisture is between 18% and 25% it is firm and pliable. 12 percent of minimum moisture gives very firm tomatoes and that of 6% gives hard and brittle tomatoes. Fresh tomato having an initial moisture content of 90.62% got reduced to 18.28 % in three hours. The texture was hard and brittle when the moisture content was brought down nearly to 6%. The drying process was faster in solar drier compared to open sun as shown in Fig. 4. The observed advantages of solar drying over open sun drying are the product was free from fungal and bacterial infections and the loss during drying process was zero with the added advantage of considerable reduction in drying time. The original color and odor of the tomato was preserved. As described in the above section, a detailed economic analysis was performed to determine the suitability of the developed model for commercial application. For calculating the annualized cost of the drier, the capital cost of solar and electric drier are taken to be Rs.1, 40,000.00 and Rs. 1,00,000.00 respectively. The annual maintenance cost was taken to be 10% of the annual capital cost. The salvage value was assumed to be 10% and rate of interest as 8%. The fuel cost of solar drier is zero and the running cost of blower was taken into account. The efficiency of electric drier was assumed to be 80%. The dried quantity of tomato removed from the solar dryer was 351 kg per year. The unit cost of electricity was taken to be Rs. 4.00. The annualized cost of solar and electric driers worked out to be Rs. 17,254.00 and Rs. 12,173.00 respectively. In life cycle savings analysis, savings per day, present worth of annual savings and present worth of cumulative savings were calculated. The inflation rate was taken as 9 %. The calculation was done for first 20 years of operation and the savings can be extended over the lifetime of the drier. Table 1 shows the economic analysis performed on the developed system for 20 years. Payback period is the time required for the cumulative fuel savings becomes equal to the total initial investment. Analysis showed that the total investment of Rs. 1,40,000.00 can be recovered in two years of operation. The payback period of the solar drier was estimated to be 1.05 years (263 solar days) which is very small compared to the lifetime of the drier. Thus the drier can be operated at low maintenance cost throughout its lifetime.

Conclusion : Performance of the developed matrix air heater in drying application was evaluated and established. The dryer proved efficient and economic for drying fruits. Experiments were conducted with 4 mm tomato slices having an initial moisture content of 90.62 % took 3 hours to bring down to a safe moisture level of 18.28 %, which is propitious for storage. Economic analysis showed that the cumulative present worth of annual savings for drying tomatoes over the life of the dryer was Rs. 28, 52, 503.00. The capital investment of the dryer was Rs. 1, 40,000.00 and the payback period of the dryer was calculated to be 1.05 years which is very short comparing the life time of the dryer.

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Table 1

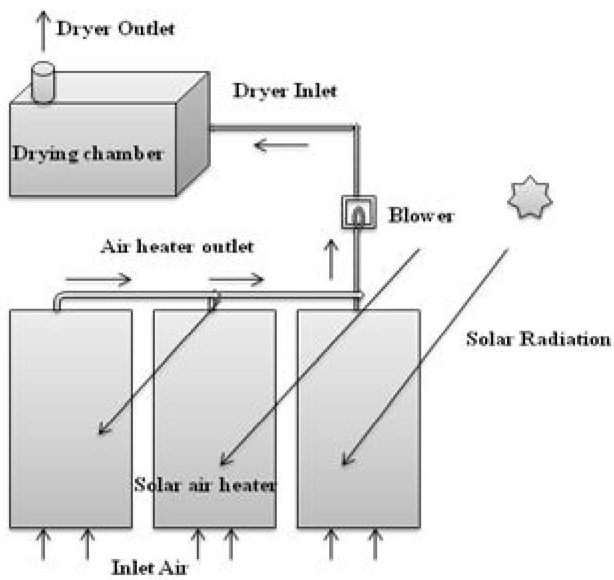
Economics of the solar dryer-annual saving, present worth of annual saving and present worth of cumulative annual saving for each year during the life of the solar dryer for drying Tomato

Year	Annualized cost of dryer (Rs.)	Annual Savings (Rs.)	Present worth of annual saving (Rs.)	Present worth of cumulative saving (Rs.)
1	17,254.00	1,41,000.00	1,30,555.00	1,29,000.00
2	17,254.00	1,53,690.00	1,31,764.00	2,60,764.00
3	17,254.00	1,67,522.00	1,32,984.00	3,93,748.00
4	17,254.00	1,82,599.00	1,34,215.00	5,27,963.00
5	17,254.00	1,99,033.00	1,35,458.00	6,63,421.00
6	17,254.00	2,16,945.00	1,36,712.00	8,00,133.00
7	17,254.00	2,36,471.00	1,37,978.00	9,38,111.00
8	17,254.00	2,57,753.00	1,39,256.00	10,77,367.00
9	17,254.00	2,80,951.00	1,40,545.00	12,17,912.00
10	17,254.00	3,16,236.00	1,41,846.00	13,59,758.00
11	17,254.00	3,33,798.00	1,43,160.00	15,02,918.00
12	17,254.00	3,63,840.00	1,44,485.00	16,47,403.00
13	17,254.00	3,96,585.00	1,45,823.00	17,93,226.00
14	17,254.00	4,32,278.00	1,47,173.00	19,40,399.00
15	17,254.00	4,71,183.00	1,48,536.00	20,88,935.00
16	17,254.00	5,13,590.00	1,49,912.00	22,38,847.00
17	17,254.00	5,59,813.00	1,51,300.00	23,90,147.00
18	17,254.00	6,10,196.00	1,52,701.00	25,42,848.00
19	17,254.00	6,65,113.00	1,54,114.00	26,96,962.00
20	17,254.00	7,24,974.00	1,55,541.00	28,52,503.00

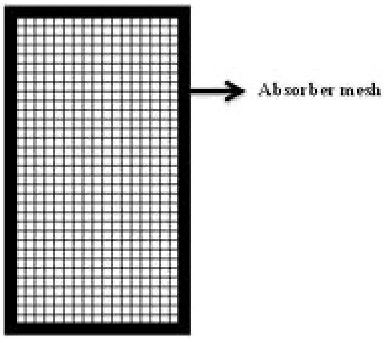
Figure 1

Designed solar drier a) Schematic representation b) Front view of collector c) Side view of collector

(a)



(b)



(c)

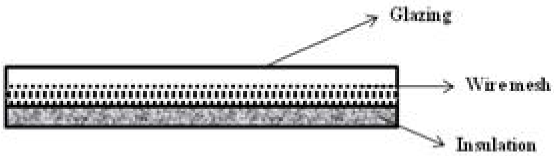


Figure 2
Temperature profile with solar radiation intensity under no load condition

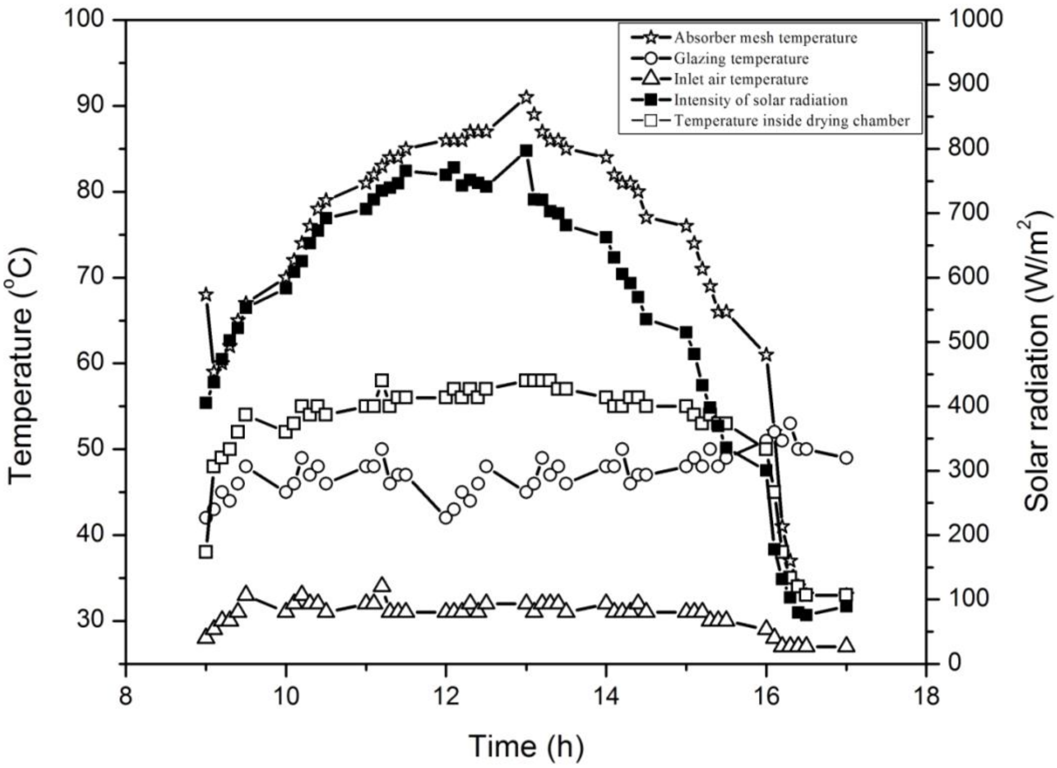


Figure 3
Temperature profile with solar radiation intensity under loaded condition

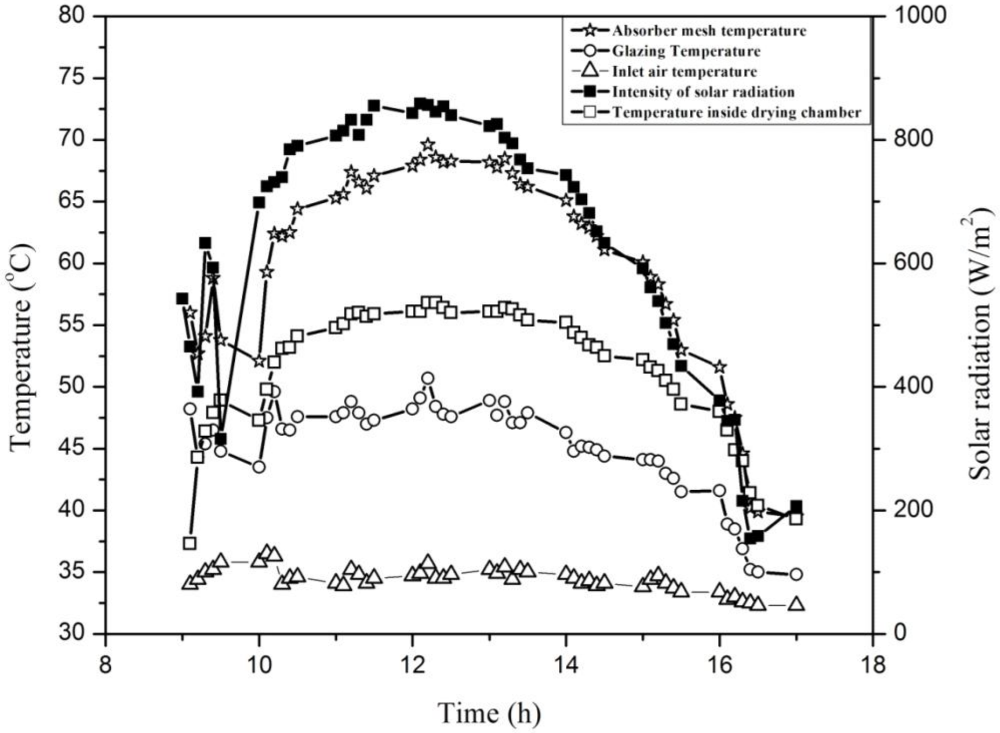
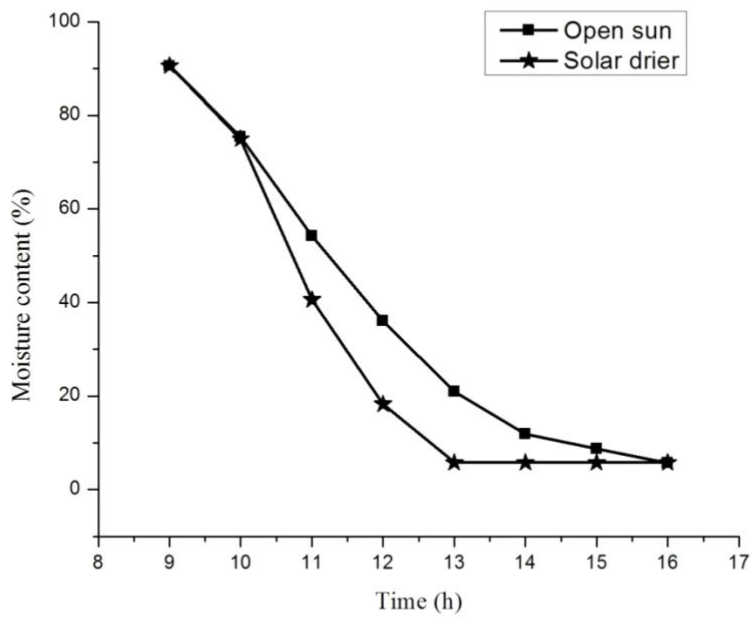


Figure 4
Pecentage moisture content present in the sample with respect to time of day during drying process



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