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Development and evaluation of thermally efficient solar drier with temperature controller system

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Abstract
Post harvest losses account for 10 to 30% due to perishable nature, bad weather or lack of transportation facilities and damage by wild animals resulting in huge loss to the farmers. To reduce post harvest losses an indirect solar drier has been designed with temperature controller to enable the solar drier operational throughout the year as well as for the drying of various crop products. Thermal storage system has also been introduced to increase the efficiency of solar air heater besides providing heat during late hours after sunset. The fans have been provided at the inlet of solar air heater to reduce the humidity of air entering into the solar air collector. The quality parameters of dried products found to be better as compared to oven dried and open sun dried products. The shelf life of dried products has also been enhanced considerably. The solar drier is suitable around the developing countries.

Keywords: Solar drier, crops drying, temperature controller, thermal storage and shelf life

1. Introduction
Fruits and vegetables are damaged largely due to perishable nature, erratic weather, shortage of transportation and storage facilities resulting in loss to the farmers. About 20% tomatoes, 10% ginger, 10% mushroom, 30% *Emblica officinalis* and 5% apples are generally damages or waste every year [1]. The perishable crop like tomatoes and pomegranate produced during rainy season are destroyed due to erratic weather and requires more labour to carry products inside to outside of the house. Farmers dry fruits apple, peach, palm nut, and vegetables chilly, turmeric, ginger and pomegranate in open sun resulting poor quality of the dried product due to dust, fungus, infection, insects, sudden rains, wild animals and particularly monkeys due to which the farmers have shifted from farming to some other work. This gives low return to the farmers.
The Indirect solar dryer is an important device for drying of fruits, vegetables, seeds and medicinal plants without changing basic properties. Indirect solar dryer preserves foods by removing enough moisture from food to prevent decay and spoilage. Water content of properly dried food varies from 5 to 25% depending on the type of food. The drying enhances the shelf life of the crop product [2, 3, 4, 5, 6]. Different types of grains and their products are well dried in the indirect solar dryer under clean conditions and in a reasonably short time. The traditional method of dying is open sun dying, which is low cost and does not require technology, but, it has number of demerits such as, contamination of the product due to dirt and insects, attack of birds and mice, damage due to erratic weather, uncontrolled temperature, attack of wild animals, labour intensive, poor quality of dried products and low market price [7, 8, 9] resulting loss of nutrients due to direct exposure to ultraviolet rays [10]. Study reveals that about 10 to 25% of crop damaged due to post harvest losses. About 90 % of women of hilly areas remain engaged in the drying of products in the traditional way and they spent at least 2 hours daily in the drying activities, which costs at least $1 per day as labour input [11]. However, drying in solar drier has many merits, such as, quality dried product, drying time reduction, maintains drying hygiene, protection from erratic weather, insects & pests and wild animals, better market rates and reduces carbon emissions [8]. In indirect solar dryer, the temperature, humidity and drying rate can be changed to some extent [12].
Several types of driers are available in the country but these are not popular in rural areas due to high costs, lack of technical knowhow, or lack of skill to use these driers [13]. The solar driers of variegated types can be made locally and of different size [14, 15, 16]. There are two types of solar driers viz. forced and natural convection solar drier.

The forced convection solar drier is considered to be efficient, reliable, faster and can dry large quantity of crop products as compared to natural convection solar drier [17, 18]. Efficient and low cost solar dryers have been developed by number of scientists [19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30] for the drying of agriculture products. Some of the researchers have tried to introduced new modifications such as Ezeike [31] has used dehumidification chamber containing silica gel, fans powered by solar photovoltaic panel were used in indirect solar drier [32, 33], Hossain *et al*. [34] have used aluminum reflector to increase the efficiency of solar collector and Șevik [35] has used double pass solar air heater with fins for the drying of carrot.

The thermal storage system has been used by number of researchers to increase the efficiency of solar air heaters and to provide heat after sunset for continuous drying. Bolaji [36] investigated an indirect solar dryer using a box type absorber collector with opaque crop bin, and a chimney to provide thermal storage. Ehiem *et al*. [37] designed and developed an industrial fruit and vegetable dryer with thermal storage system. Bolaji *et al*. [38] used absorber mesh screen placed midway between the glass cover and the black absorber plate for effective air heating. Saravanakumar *et al* [39] have developed a solar collector integrated with a FP-SAH with heat storage unit and revealed that a mixture of gravels with iron scrap found to be better storage materials. Ayyappan *et al* [40] have integrated a natural convection solar tunnel dryer with sand as heat storage material. Jain [41] presented a solar crop dryer having reversed absorber plate type collector and thermal storage with natural flow. Tiwari *et al*. [42] have introduced two storage systems, one is crop dryer cum water heater and second crop dryer rock bed storage system. Chauhan *et al*. [43] studied the drying characteristics of coriander with rock bed storage unit. Kamble *et al*. [44] studied drying of chilli using solar cabinet dryer coupled with gravel bed heat storage system. A solar air heater with long term heat storage system using Granular carbon was studied by Saxena *et al*. [45]. Farid *et al*. [46] constructed a latent heat storage module consisting of 45 cylindrical capsules fixed made of copper tubes. Fatah [47] developed a solar air heater with copper tubes filled with thermal energy storage material. Fath [48] and Enibe [49] have designed solar air heater with corrugated set of tubes filled with a phase change material (paraffin wax) as a thermal energy storage material. Singh *et al*. [50] have used thermocole for insulation, whereas, Mursalim *et al*. [51] used saw dust for insulation. Mohanraj and Chandrashekhar [52] have developed an indirect forced convection drier with heat storage system (Gravel) for chilli drying in Pollachi, India.

Above discussed literature revealed that solar drier with temperature control has not been developed elsewhere which can work throughout the year and various seasonal crops could be dried. In the present study, indirect solar drier has been designed and fabricated having temperature controller to control the temperature during drying of crops and thermal storage system to provide heat after sun set and fans at inlet of solar air heater to increase efficiency of solar drier. The quality parameters of dried products have been presented.

2. Design and material

Indirect solar drier consists of two parts. One is solar air heater and second is drying chamber.

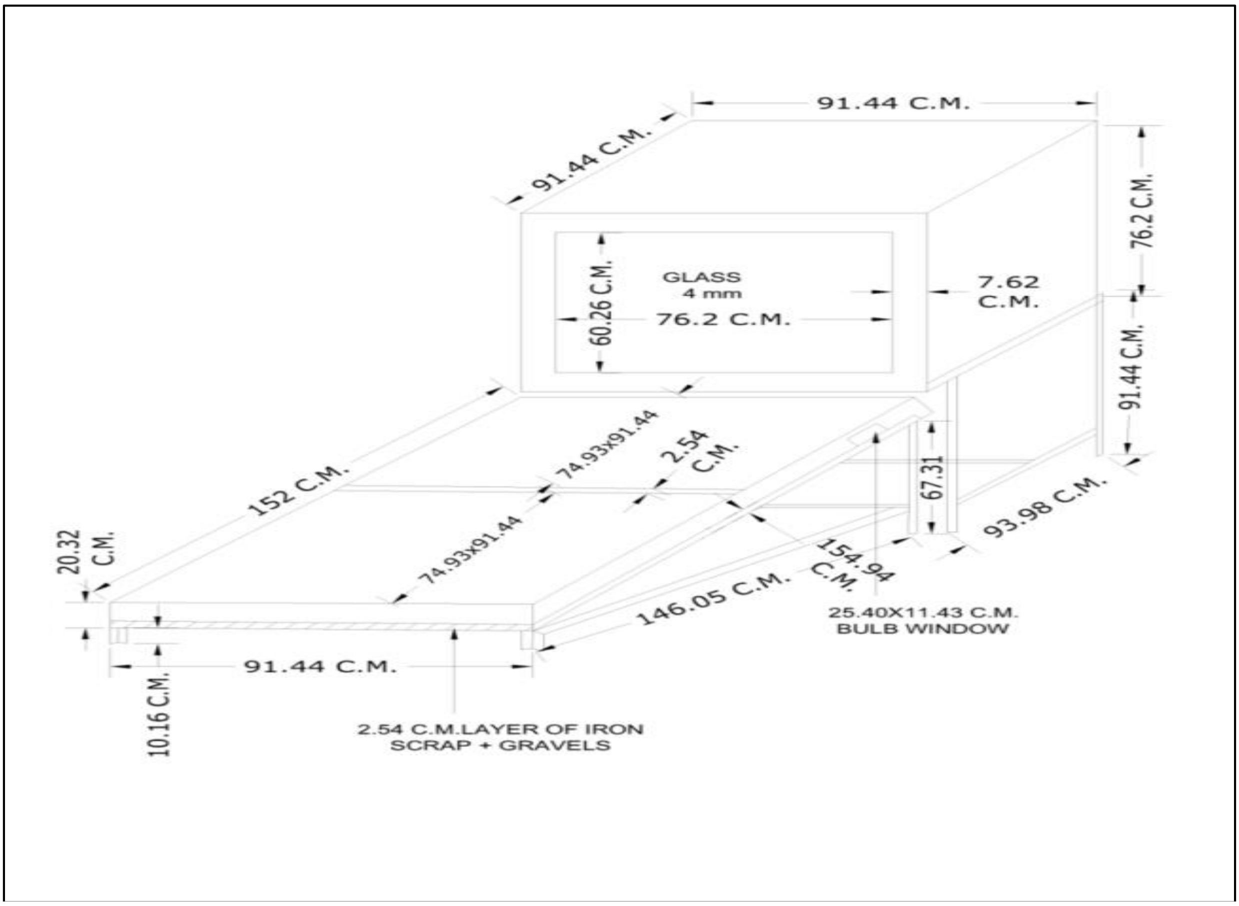


Fig 1: Isomeric view of solar drier

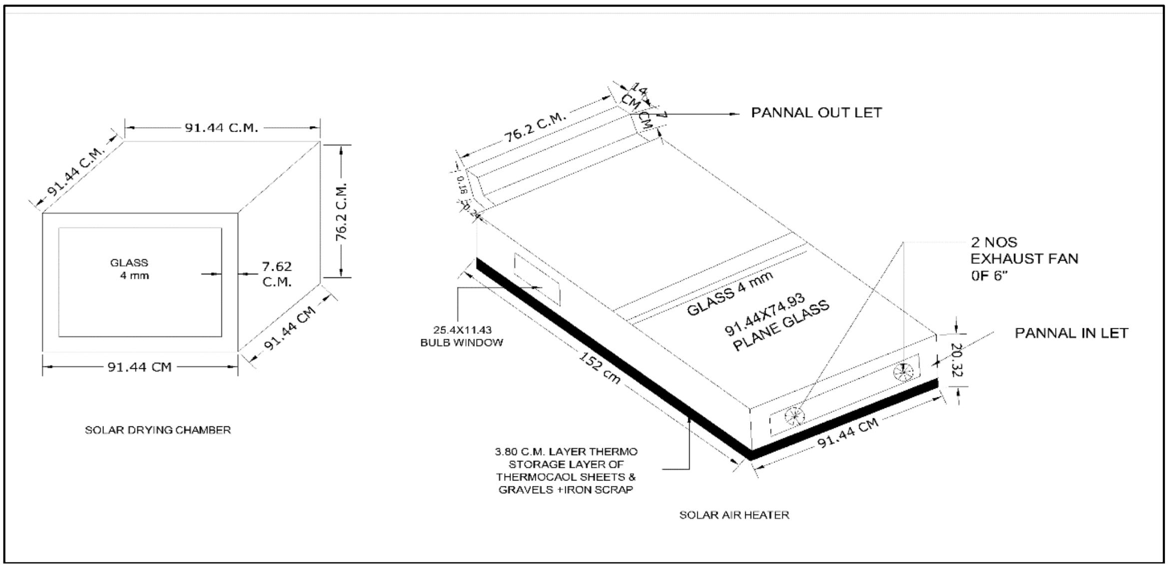


Fig 2: Design parameters of solar air heater and drying chamber

Solar air heater is consisting of wooden board and ply of size 5' x 3' covered with 4 mm hick glass to receive solar radiation (Fig 1). The area of solar air heater is 152 x 91.44 cm^2 having thickness of 20.32 cm. A thermal storage system which is mixture of iron scrap and gravels has been provided at the bottom covered with aluminum sheet to increase the efficiency of solar air heater. It will also radiate the heat after sunset stored during day time. Insulation of thermocole has been provided at the bottom of solar air heater to reduce heat loss. Two fans have been fixed at the inlet of solar air heater south side of the drier to reduce the humidity of air entering into the solar air heater. Provision of bulbs has been kept for lighting up during bad weather. Two DC fans have been fixed at the south side of air collector to introduce dry air at the inlet of solar air heater for increasing its efficiency. The wheels have been provided at the base of the stand to move manually in the direction of the sun to receive maximum solar radiation particularly during early morning and late evening.
Drying chamber is consisting of wooden board to keep the products to be dried having 40 kg capacity having dimension of 91.44 x 76.2 sqcm (Fig 2). It has three trays fixed with channels to move the tray in or out. Two fans have been fixed at the top of drying chamber north side of the drier i.e. the out let for moisture removal. The slop of solar air heater has been kept at the latitude of the place 30.86° N to receive maximum solar radiation throughout the year.

Temperature Controller

The temperature controller provide with the solar drier has been discussed in this section. This Circuit was build around Arduino Uno Board. Arduino Uno is the Heart of the Circuit as all the functions of the circuit is controlled by the Arduino. LM35 is a precision integrated circuit whose output is linearly proportional to Celsius temperature. Its range is of -55^0C + 155^0C. It has +10.0Mv/Celsius linear scale-factor.
Temperature Sensor Senses the temperature and converts it into an analog signal. Which is directly fed to the Arduino UNO R3 board through an analog to digital converter and this is the main input to the controller board the speed of the fan and the value of the temperature is shown on the LCD board. The microcontroller unit on the Arduino drives the motor driver to control the speed of the fan. Fan Speed Control: A low frequency pulse width modulation (PWM) signal which is ranging around 30Hz. And the duty cycle of this signal varied to adjust the speed of the fan a transistor is used as a switch which is BD139. The temperature suitable to particular crop i.e. the optimum temperature is fixed with coding. When temperature inside the drier reached to that point then fan automatically runs, resulting reduction in temperature.

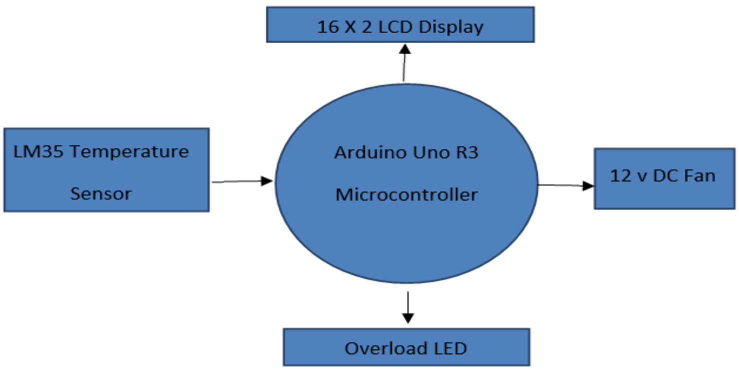


Fig 3: Block Diagram of the temperature controller

3. Methodology

3.1 Drying of crops

In the present study, three crops viz. pomegranate arils (P), oyster mushroom (D) and red chilli (R) were selected for drying so as to evaluate the performance of solar drier in comparison to cabinet drier (oven) and open sun drying. Before the samples were dried, two set of each sample (i) pre-treated and (ii) without pre-treatment were prepared and dried with three different modes of drying (a) solar drier and (b) cabinet drier and (c) open sun. The pomegranate arils were pretreated by steam blanching for 30 seconds followed by sulphuring @ 0.3% sulphur powder for 60 min in sulphur fumigation chamber. Whereas, oyster mushrooms were pretreated with 10 g citric acid/kg for 10 min. and red chilies were pretreated with 2% NaCl for 10 min. The detail of different treatment combinations are as under:

$P_1/D_1/R_1$= Open sun without any treatment (control)
$P_2/D_2/R_2$= Open sun with treatment
$P_3/D_3/R_3$= Solar drier with treatment
$P_4/D_4/R_4$= Solar drier without treatment
$P_5/D_5/R_5$= Cabinet drier with treatment
$P_6/D_6/R_6$= Cabinet drier without treatment

The weight of the samples was recorded periodically to find out the drying rate. The temperature variation in the three modes of drying was recorded on hourly basis with temperature and humidity sensors. The moisture content of products was recorded using automatic moisture balance. The water activity of dried products was observed using water activity meter. The temperature in the cabinet drier was kept at 50^0C and t was intermediate drying from 10AM to 5 PM.

3.2 Drying efficiency

The drying efficiency of solar drier has been calculated using formula

$$\eta = ML / I A_c$$

Where
η is drying efficiency
M = Mass of moisture evaporated per sec (Kg/s)
L = Latent heat of evaporation of water (kJ/Kg)
I = solar radiation (W/m^2)
A_c = Collector area (m^2)

3.3 Carbon reduction

The carbon reduced during drying of crops in comparison to cabinet drier has been estimated using following formula
C = power of cabinet drier x number of hour /1000 x 0.87 (kg)

3.4 Drying cost

The cost of drying has been calculated on the basis of current market prices of raw material, nominal processing charges, depreciation on machinery and reasonable profit margins.

4. Results and Discussion

4.1 Quality parameters of dried products

The quality parameters of three products (pomegranate, Oyster mushroom and red chilli) have been presented in table 1.

Table 1: Quality parameters of dried products

Treatments	Moisture content (%)	Water activity	Titratable acidity (%)	TSS (^{0}B)	Reducing sugar (%)	Total sugar (%)	pH
	Pomegranate aril (*anardana*)						
P1 (control)	14.13	0.533	12.47	33.06	14.11	16.34	3.89
P2	13.20	0.521	12.87	33.72	15.55	16.97	3.76
P3	11.54	0.420	13.18	37.30	17.02	18.03	3.51
P4	11.61	0.423	13.51	37.72	17.73	18.98	3.33
P5	10.23	0.450	12.22	30.98	14.23	15.99	4.02
P6	10.31	0.461	12.54	31.54	13.86	15.06	3.98
$CD_{0.05}$	0.86	0.08	0.76	0.90	0.58	0.62	0.25
	Oyster mushroom						
D1(control)	9.46	0.404	6.01	15.2	7.89	9.55	3.98
D2	9.62	0.420	6.85	16.5	8.17	10.04	4.07
D3	8.29	0.388	6.40	17.5	10.14	13.87	4.56
D4	8.86	0.393	6.51	18.5	10.56	12.89	4.44
D5	8.20	0.403	7.50	17.5	9.51	13.44	3.90
D6	8.19	0.396	7.79	16.25	10.08	12.72	3.71
$CD_{0.05}$	0.74	0.12	0.85	0.82	0.65	0.70	0.28
	Red Chilli						
R1(control)	7.56	0.33	0.95	14.0	10.11	8.83	3.93
R2	7.53	0.32	1.03	14.5	9.87	8.05	3.14
R 3	7.04	0.29	1.27	14.6	8.99	9.41	3.01
R 4	7.41	0.31	1.60	15.2	9.43	10.86	3.07
R 5	6.83	0.28	1.59	15.7	8.56	10.04	3.25
R 6	6.54	0.26	1.28	15.3	8.90	9.96	3.41
$CD_{0.05}$	0.45	0.10	0.62	0.35	0.45	0.65	0.12

Pomegranate arils (*anardana*)

In *pomegranate* (Table 1) the highest (14.13 %) moisture content was recorded in the open sun dried untreated samples (P_1) whereas, the lowest (10.23 %) was recorded in the cabinet dried treated samples (P_5) which was at par with the untreated cabinet dried samples (10.31 %). Consequently the highest (0.533) and lowest (0.420) water activity was recorded in the same samples. The acid content was recorded highest (13.51 %) in solar dried untreated sample (P_4) which was at par with the solar dried treated samples. The lowest (12.22 %) acid content was recorded in cabinet dried treated arils (P_5). The lowest (3.33) pH was recorded in solar dried untreated sample (P_4) whereas; the highest (4.02) was recorded in cabinet dried treated arils (P_5). The TSS content was recorded highest (37.72 ºB) in solar dried untreated arils (P_4) which was at par with solar dried treated arils (37.30 ºB) whereas, the lowest (30.98ºB) TSS was recorded in cabinet dried treated arils (P_5). The highest reducing (17.73 %) and total sugars (18.98 %) content was recorded in untreated solar dried *pomegranate* (P_4) whereas, the lowest (13.86 and 15.06 %) was recorded in cabinet dried untreated arils (P_6).

Oyster mushroom

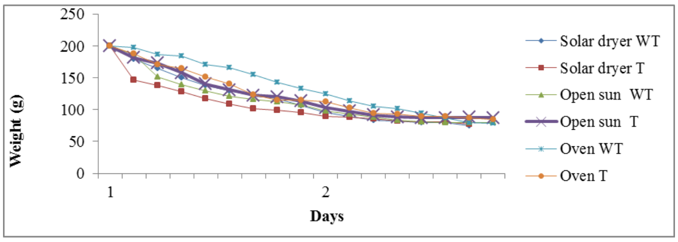
The highest (9.62 %) moisture content was recorded (Table 1) in the open sun dried treated samples (D_2) whereas, the lowest (8.19 %) was recorded in the cabinet dried untreated samples (D_6) which was followed by treatment D_5 (8.20 %), D_3 (8.29 %) and D_4 (8.86 %). The highest (0.420) and lowest (0.388) water activity was recorded in the treatments D_2 (open sun dried treated samples) and D_3 (solar dried treated samples), respectively. The acid content was recorded highest (7.79 %) in cabinet dried untreated sample (D_6) which was at par with the cabinet dried treated samples (D_5). The lowest (6.01 %) acid content was recorded in open sun dried untreated arils (D_1). The lowest (3.71) pH was recorded in cabinet dried untreated sample (D_6) whereas; the highest (4.56) was recorded in solar dried treated arils (D_3). The significantly highest (18.50 °B) TSS content was recorded in solar dried untreated sample (D_4) and the lowest (15.20 °B) TSS was recorded in control samples (D_1). The highest reducing (10.56 %) and total sugars (13.87 %) content were recorded in untreated (D_4) and treated (D_3) solar dried oyster mushroom, respectively. The lowest reducing and total sugars (7.89 % and 9.55 %) content was recorded in open sun dried arils without any treatment (D_1).

Red chilli

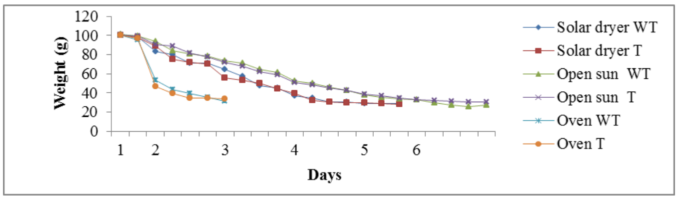
In dried red chilli (Table 1) the highest (7.56 %) moisture content was recorded in the open sun dried untreated samples (R_1) whereas, the lowest (6.54 %) was recorded in the cabinet dried untreated samples (R_6) which was at par with the cabinet dried treated samples (6.83 %). The highest (0.33) and lowest (0.26) water activity was recorded in the same samples. The acid content was recorded highest (1.60 %) in solar dried untreated sample (R_4) which was at par with all the treatments except control. The lowest (0.95 %) acid content was recorded in the control samples R_1 (open sun dried untreated samples). The lowest (3.01) pH was recorded in solar dried treated sample (R_3) whereas; the highest (3.93) was recorded in open sun dried untreated arils (R_1). The significantly highest (15.70 °B) TSS content was recorded in cabinet dried treated samples (R_5) whereas, the significantly lowest (14.00 °B) TSS was recorded in control samples (R_1). The highest (10.11 %) reducing sugars content was recorded in untreated sun dried samples (R_1) which was at par with treated open sun dried samples, whereas, the lowest (8.56 %) was recorded in cabinet dried treated arils (R_5). The highest (10.86 %) total sugars content was recorded in untreated solar dried *pomegranate* (R_4) whereas, the lowest (8.05 %) was recorded in open sun dried treated samples (R_2).

4.2 Drying rate

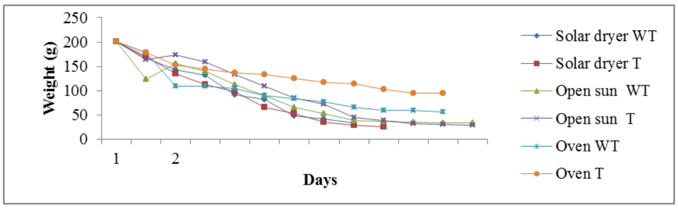
The drying rate of three crops pomegranate, red chilli and oyster mushroom have been presented in Fig 4. Fig 4 (a) revealed that drying time in solar drier and oven (cabinet drier) was same as compared to open sun drying. The drying time in cabinet drier was minimum followed by solar drier and open sun (Fig 4b). Fig 4 (c) revealed that drying time was less in solar drier followed by cabinet drier and open sun. It also revealed that drying rate was faster in solar drier during first day and after that it become constant.



(a)



(b)



(c)

Fig 4: Drying rate of (a) pomegranate arils, (b) red chili and (c) oyster mushroom

4.3 Temperature variation in solar drier and open sun

The temperature variation in solar air heater, drying chamber and open sun has been presented in Fig 5, Fig 6 and Fig 7 which revealed that temperature in drying chamber always remained above the temperature in open sun thus, resulting fast drying. This indicates that thermal storage system provided in the solar air heater has enhanced the thermal efficiency of solar drier. The wheels provided at the base of solar drier to move with the sun have helped in increasing the temperature inside solar drier during morning and evening. The temperature controller provided in the solar drier helped in controlling the temperature during summer as the average ambient temperature remains between 28-35^{0}C which can increase the temperature of solar air heater upto 90^{0}C. If the temperature controller did not provide in the solar drier then the crop would have been over dried and solar drier will not be used during summer.

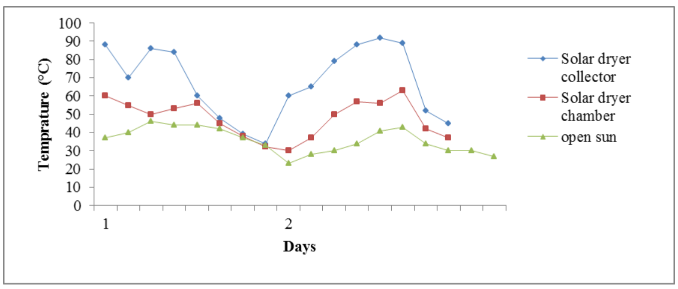


Fig 5: Temperature variation in pomegranate drying

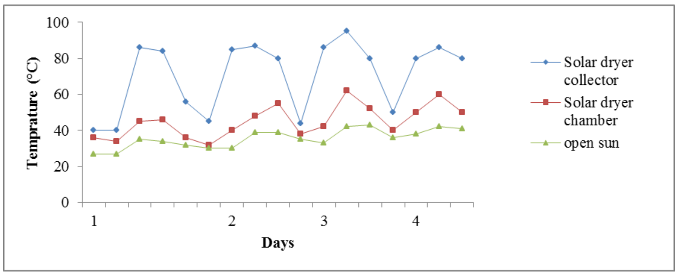


Fig 6: Temperature variation in Red Chilli drying

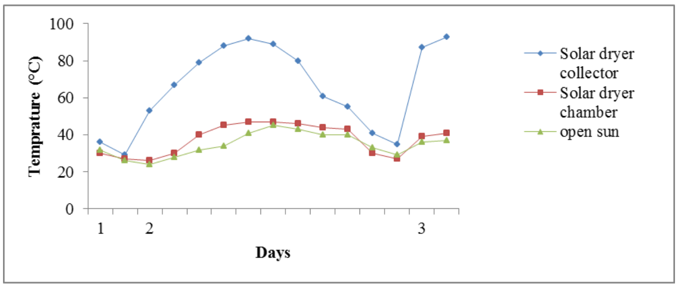


Fig. 7: Temperature variation in oyster mushroom drying

4.4 Sensory characteristics of dried products.

Data related to texture, colour, taste and overall acceptability of dried products is presented in Fig. 8. Data showed that maximum 9 point hedonic scale score for texture, colour, taste and overall acceptability was given to fruit dried in solar dryer. Highest score for colour, texture, taste and overall acceptability was given to treated fruit dried in solar dryer due to non exposure of sample to direct sun. Additive, like potassium metabisulfite and citric acid inhibit the browning reaction by binding with the carbonyl group of reducing sugars and other compound to retard the browning process, result in good colour, flavor of dried product.

Pomegranate arils (*anardana*)

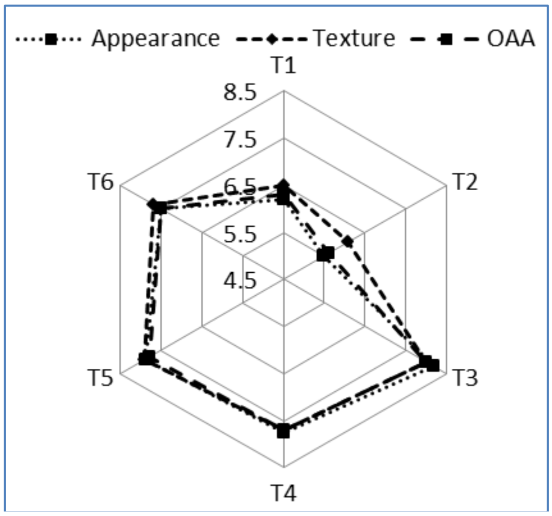
In *pomegranate* (Fig. 8 a) the highest appearance (7.80) and texture (8.00) scores were obtained in solar and cabinet dried treated arils (P_3 and P_5). The highest overall acceptability scores (8.00) were obtained in solar dried treated samples (P_3) which was closely followed by cabinet dried treated arils (P_5).

Oyster mushroom

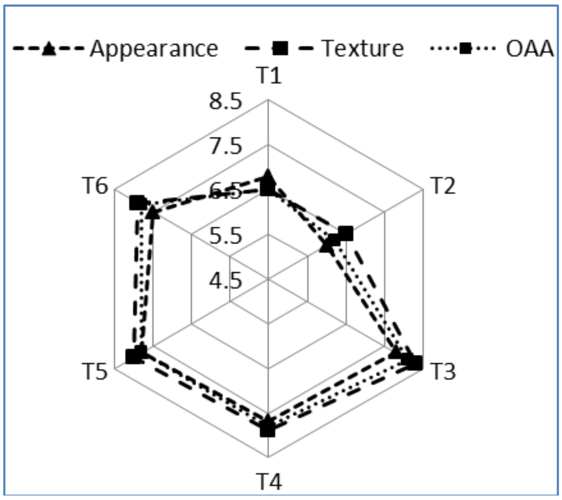
In dried oyster mushroom (Fig. 8 b) the highest appearance (7.80) scores were obtained in solar and cabinet dried treated mushrooms (P_3 and P_5). The highest texture scores (8.30) were obtained in solar dried treated samples (P_3) which was closely followed by cabinet dried treated mushrooms (P_5). The highest overall acceptability scores (8.10) were obtained in solar dried treated samples (P_3) which was closely followed by solar dried untreated (P_4), cabinet dried treated (P_5) and untreated samples (P_6).

Red chilli

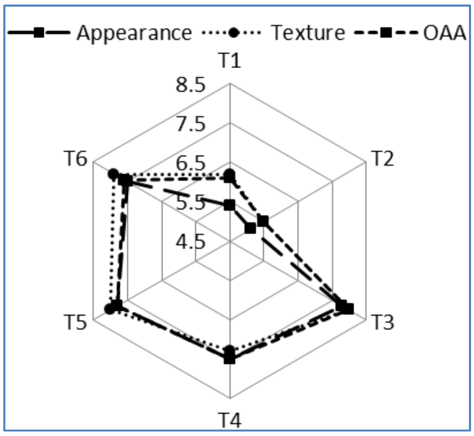
In dried red chilli (Fig. 8 c) the highest appearance (7.80) and texture (8.00) scores were obtained in solar and cabinet dried treated samples (R_3 and R_5). The highest overall acceptability scores (8.00) were obtained in solar dried treated samples (R_3) which was closely followed by cabinet dried treated samples (R_5). Similar results for sensory quality attributes were reported by Sharma *et al.* [53].



(a)



(b)



(c)

Fig 8: Sensory evaluation of (a) dried pomegranate arils, (b) red chilli and (c) oyster mushroom

4.5 Drying efficiency

The drying efficiency of the dried products has been presented in table 2. The table revealed that drying efficiency of solar drier was in the range of 15% to 21.76%.

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Table 2: Drying efficiency of solar drier

Crops	Drying efficiency (%)
Pomegranate	16.19
oyster mushroom	21.76
Red Chilly	15.09

4.6 Carbon reduction
The carbon reduction during drying of three crops has been presented in Table 3, which revealed that solar drier is consider to be eco-friendly as it saved carbon emission of 9.15kg to 15.01 kg depending on drying time as compared to electric oven.

Table 3: Carbon reduction in drying of crops

Crops	Carbon reduction in kg
Pomegranate	9.80
oyster mushroom	9.13
Red Chilly	15.01

4.7 Water activity analysis
The moisture content and water activity of dried products has been analyzed using water activity meter. Moisture content of fresh fruit (pomegranate) was 70.02% and water activity was 0.811 after drying the moisture content was reduced to 10.23 to 14.13% and water activity was recorded as 0.423 to 0.533 showing the shelf life of six months period. The moisture content of fresh fruit (oyster) was 88.53% and water activity was 0.750 which was reduced to 6.29 to 10.62% whereas, water activity was recorded as 0.388 to 0.420 showing high shelf life of dried product. The moisture content of fresh fruit (red chili) was 58.12% and water activity was 0.35 which was reduced to 6.43 to 7.41% and water activity was found to be 0.25 to 0.31 which showed high shelf life of dried product.

Table 4: Water activity of dried products

Treatments	Pomegranate		Oyster Mushroom		Red Chilly	
	Moisture content of dried product (%)	Water activity of dried product	Moisture content of dried product (%)	Water activity of dried product	Moisture content of dried product (%)	Water activity of dried product
T1	13.20	0.521	10.62	0.420	6.43	0.25
T2	14.13	0.533	10.60	0.404	6.56	0.27
T3	10.23	0.420	6.29	0.388	7.04	0.29
T4	10.31	0.423	8.56	0.393	7.41	0.31
T5	11.54	0.450	9.50	0.403	6.83	0.28
T6	11.61	0.461	9.19	0.396	6.54	0.26

5. Conclusions
The indirect solar drier with thermal storage system and temperature controller has been developed for the drying of fruits, vegetables, seeds and medicinal plants. The study revealed that the temperature in solar drier remained above the temperature in open thus, resulted reduction in drying time. The efficiency of solar drier ranged between 15.09% and 21.76%, which is considered to be high due to fact that thermal storage system provided at the bottom of solar air heater and wheels provided at the base of solar drier to move with the sun particularly during morning and evening. The shelf life of the dried products also enhanced in the solar drier. The dried products meet the quality standard. The products dried in solar drier helped in reducing the carbon emission also. This made the solar drier suitable for the drying of various crops around the developing countries.

6. Acknowledgement
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7. References
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