Experimental and economic analysis of a solar matrix collector for drying application

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This paper explains the development of a solar air heater with wire mesh as absorber of nominal porosity for drying application. A comparative study between open sun-dried and solar-dried samples was done using bitter gourd as drying product. Solar drying showed a faster drying rate, reducing the moisture content from 93% to 6.17% in 3 h less than open sun-drying. Economic analysis shows a lifetime savings of roughly INR 2,746,707 for a period of 20 years, with a payback period of 0.62 years, i.e. 161 drying days.

The world is hurtling rapidly towards energy crisis with predicted exhaustion of fossil fuels by 2050. Studies show that majority of Indian population living in the far-flung areas does not have access to electricity[1]. The ultimate way to reduce energy consumption of fossil fuel and its precious conservation is the widespread use of solar energy wherever possible. Solar energy is the primary energy source to our planet and all other energy sources are derived from it. It is estimated that solar energy received in India ranges from 4 to 7 KWh/m^2 with 300 sunny days. Many studies have revealed that even if we utilize less than 1% of the total land area available, that can generate a solar power of 3400 TWh/yr (ref. 2). In a tropical country like India most of the energy demands can be met by simple systems that can convert solar energy into appropriate forms. By proper application of technologies, excellent thermodynamic match between the solar energy resources and many end-users can be achieved.

Solar energy conversion methods include (i) thermal conversion, (ii) electrical conversion and (iii) photochemical conversion. Solar direct utilization of solar energy can be done by two technologies – solar photovoltaic (PV) and solar thermal. Solar photovoltaic can used for direct conversion of solar energy to electricity, whereas solar thermal can be used for converting solar energy to thermal energy or electrical energy. Fluid heating is the most commonly used solar thermal application. Water or air is the most commonly used fluid in solar thermal collectors. Much innovation has been achieved over the years in solar water heater with different technologies like flat plate collectors (FPCs), evacuated tube collectors (ETCs) and evacuated tube heat pipes (ETHPs). Unlike water, air does not have good thermodynamic properties and hence the efficiency will not be on par with solar water heaters. But solar air heaters are less complicated than solar water heaters because of less impact of corrosion and leakage. Solar air heaters are mostly used for crop drying, process heating, timber seasoning, space heating and other applications.

Many researchers have come forward with different innovations to improve the performance of solar air heaters. Kurtbas and Turgut[3] have experimentally studied the efficiency and exergy loss of a solar air heater with free and fixed fins. It was found that fixed fins are more effective than free fins as they produce higher outlet temperature and less pressure drop. Aissa *et al.*[4] studied the performance of a forced convection solar flat plate air heater with energy storage. Experimental and theoretical results show that the mass flow rate and solar radiation are the major parameters which determine the performance of the collector. Research on improving the efficiency of FPCs was done by Yeh and Lin[5] by dividing the air channel using parallel barriers, thereby creating subchannels for air flow. The experiment was repeated for different locations of the barriers and hence the best barrier location for the design was optimized.

Verma *et al.*[6] optimized the solar air heater design for 10 configurations of absorber plates and reported the optimum mass flow rate for each configuration and thermal efficiency was determined for optimum conditions. The study revealed that double-flow configuration with a single glazing showed better performance. Esen[7] studied the energy and exergy efficiencies of a double-pass air heater with different types of absorber plates for a wide range of working conditions. Obstacles in the absorber plate were found to increase the efficiency. Similar studies were done by Akpinar and Koçyiĝit[8] for different types of obstacles in the absorber plate.

Kapardar and Sharma[9] studied the performance of solar air heater with porous collector, for different mass flow rates and different type of materials like glass wool and steel wool and found that the efficiency increases with increasing mass flow rate. There is also increase in efficiency of about 10% for glass wool and 26% for steel wool. A rooftop solar air-heating system for drying applications was designed by Sreekumar[10] and its performance was analysed using a batch drier. The batch drier was used to dry pineapple slices with initial moisture content of about 82% to the desired level of less than 10% in 8 h. Economic analysis was done using three methods, namely annualized cost, present worth of annual savings and present worth of cumulative savings. Tyagi *et al.*[11] reviewed solar air heating system with and without thermal energy storage and reported a hybrid PV/thermal solar air heating system for better utilization of solar energy. Mohanraj and Chandrasekhar[12] performed an analysis on an indirect solar drier for chilli drying, which uses gravel as heat storage medium. The heat storage helped increase the working time to nearly 4 h with thermal efficiency nearing 21%. Om Prakash and Anil Kumar[13] reviewed the development of solar drying with various technologies. Use of PV systems to power the active systems was motivated to reduce the dependence on conventional energy sources.

Many researchers studied the performance of air heater with wire mesh absorber. Wire mesh may be a wire woven or crossed rod matrix with pores in them through which fluids can pass. This type of flow over the wire will increase the convection heat transfer from the collector to the fluid. Tong and London[14] explained the heat transfer phenomenon in woven screen and cross rod matrices. The effect of porosity on the heat transfer and friction factor is well explained. Design of a matrix air heater with longitudinal flow and its thermal performance was studied by Bharadwaj *et al.*[15]. The efficiency was found to decrease from 38.9% to 27.4% for a gap of 20 days, because of the effect of weather. Al-Nimr[16] generated a mathematical formulation to explain the transient behaviour of the matrix solar collector for sudden changes in the solar radiation and inlet air temperature. Ahmad *et al.*[17] experimentally studied the effect of matrix geometry, inlet temperature and mass flow rate on the thermo hydraulic performance of a packed bed solar air heater. The efficiency was found to increase with increase in mass flow rate; after reaching a maximum value, it declined with further increase in mass flow rate. Development of a metal matrix solar air heater to reduce the drawback associated with conventional air heaters was done by Kolb *et al.*[18] for copper matrix with different types of selective coatings. The pressure loss in the air heater was found to depend only on the mass flow rate and not on the matrix composition and coating.

Thakur *et al.*[19] carried out experimental study on heat transfer and friction factor correlations for a low-porosity packed solar air heater for different number of layers. The findings show that geometric parameters of the wire mesh packed bed have direct impact on heat transfer and friction factor. Mittal and Varshney[20] studied the thermal performance of a wire mesh packed bed solar air heater with beds of different porosity and optimized the parameters which can affect the performance of the collector like mass flow rate, geometry of the wire mesh, etc.

Literature survey reveals the development of solar air heaters with different modifications in absorber plate like fins, baffles, porous plates, increased roughness, matrix plates, wire mesh, etc. In the present development, a double-layered wire mesh was used as absorber material and air was allowed to flow through the mesh. Use of wire mesh with nominal porosity was intended to increase the heat transfer area and also to reduce pressure loss in the air heater, which helps reduce the blower capacity. Also the positioning of the wire mesh is highlighted as the novelty of the design. The wire mesh is kept inclined in the longitudinal direction to minimize the hot air contact with the glazing, which is further explained in the latter sections.

Performance equation

Solar air heater

For the performance analysis, various properties of air, viz. density, viscosity, specific heat, Prandtl number, etc. were calculated for the arithmetic mean of air inlet and outlet temperature. The heat transfer rate, Q from the absorber to air is given by

$$Q = F_R A_p[(\tau\alpha)_e I - U_L(T_p - T_a)], \quad (1)$$

where F_R is the collector heat removal factor, A_p the collector area, $(\tau\alpha)_e$ the product of transmittance the glass plate and the absorptivity of the collector material, I the solar irradiance per unit area, U_L the heat loss, T_p the absorber mesh temperature and T_a is the ambient temperature.

For calculating F_R rather than A_p wetted area or heat transfer area A of the collector is used, which can be found using the following equation

$$A = \frac{4A_p l(1-P)}{d_w}, \quad (2)$$

where l is the length of the duct, P porosity of the wire matrix and d_w is the wire diameter of the mesh wire.

Drier

Drying is the removal of moisture from a product. Moisture content in any material is expressed in wet and dry basis. Mostly for agricultural products, moisture is expressed in wet basis as

$$X_w = \frac{m_w}{m_w + m_d}, \quad (3)$$

where m_w is the mass of moisture/mass of wet solid (in kg) and m_d is the mass of moisture/mass of dry solid (in kg).

Drying rate, DR, for the sample depends on its initial moisture content m_i, and the equilibrium moisture content m_e and is given is given by

$$\text{DR} = \frac{\text{d}M}{\text{d}t} = -k(m_i - m_e), \quad (4)$$

where k is the drying constant.

Materials and methods

Experimental set-up

The experimental set-up consists of an air heater with a drying chamber and a blower. The air heater consists of a wire mesh absorber material and a rear plate with insulation at the sides and bottom. The solar collector was developed using normally available materials with required properties. Area of the collector developed was 2 m^2 with 2 m length and 1 m width. Absorber material was a GI wire mesh with a wire diameter of 1 mm and a pitch of 3.175 mm. The absorber plate has two layers of wire mesh with a spacing of 2 mm diameter in between. The absorber mesh was inclined along the length of the collector as shown in Figure 1. The inclination helps to make the air flow from top to bottom through the wire mesh and thus the hot air does not come in contact with the glazing, resulting in reduced top convection loss. The wire mesh and the back plate were painted with selective coating with an absorptivity of 0.95. The glazing was made up of toughened glass of 4 mm thickness with a transmissivity of 0.92.

The side and bottom parts of the collector were packed with 50 mm poly urethane foam (PUF) insulation with a thermal conductivity (0.16 W/mK). Three such collectors were connected in parallel. The outlet from the collector panels was connected to the drying cabinet through a centrifugal blower. The capacity of the dryer is 30 kg. The mass flow rate of the centrifugal blower is 500 m^3/h, powered with a 0.5 HP motor. The centrifugal blower has the capacity to suck air through the solar collector panels at the required flow rate. Figure 2 shows a photograph of the installed set-up.

The moisture content in the samples was found by drying them using an electric oven at 105° ± 1°C until constant weight was reached. The initial mass m_i and the final mass m_f were found out using an electronic weight gauge. The moisture content M_w was found for a regular interval using the following equation

$$M_w = \frac{m_i - m_f}{m_i} \times 100\%. \quad (5)$$

The inner and outer walls of the drying chamber were made up of SS304 and galvanized iron respectively. Also, 50 mm PUF insulation was provided between the walls to suppress heat losses from the drying cabinet. Air plenum chamber with baffles was provided in the drier so as to distribute the air evenly into the drying area. Figure 3 shows the schematic diagram of the drying cabinet and tray.

Working principle

When the solar radiation falls on the collector, the absorber gets heated up. Good absorptivity of the black chrome-coated wire mesh helps in increasing the absorption capacity of the mesh. The glazing having high transmissivity helps in allowing the incoming shortwave radiations to pass through and reflects back the longwave radiation from the absorber and back plate. The incoming air gets in contact with the absorber wire mesh and the heat is transferred by convection to the hot air. The air will pass through the wire mesh and gets heated up. Once it passes through the wire mesh, the hot air has less chance of getting in contact with the glazing. This helps in reducing the heat loss due to cooling effect of the glazing. Further, the air will also get heated up by convection from the back plate.

The centrifugal blower provides the pressure drop inside the collector panels to suck air from the atmosphere and also to pump the air into the drying chamber. The hot air is allowed to pass through the trays where the product is to be dried. The air circulation is maintained using baffles which divert the air uniformly to all sides. The hot air absorbs the water vapour from the product and exits into the atmosphere.

Instrumentation

A sophisticated LP PYRA 03 pyranometer having measuring range of 0–2000 W/m^2 with a typical sensitivity of 10 μV/(W/m^2) was used to measure solar radiation intensity. The temperature sensors used were RTD PT-100 with a sensitivity of 0.01°C (make: Apna Scientific Supplies Pvt Ltd), placed at required points, which was connected to a computer through RS 232 interface. A digital weighing machine (± 0.001 g) (model no. TTB 31; make: Wenser Weighing Scales Limited) was 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 performed using three methods – annualized cost, life cycle savings and payback period[10]. Annualized cost method helps in finding out the cost of drying for unit weight of the

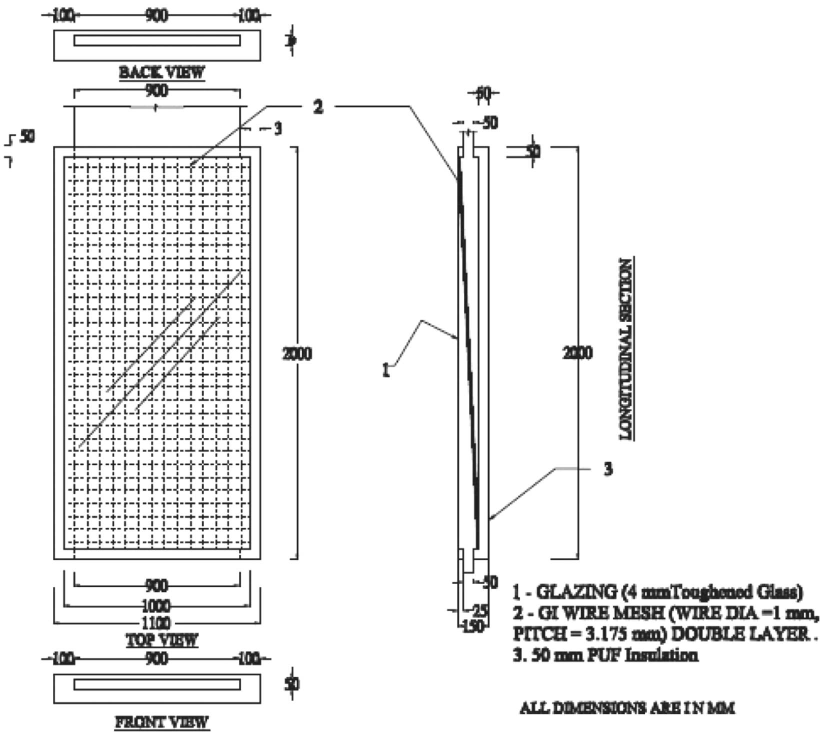

Figure 1. Schematic diagram of the wire mesh solar air heater.

Figure 2. Experimental set-up.

product by different drying techniques such as solar, electric, etc. The drying cost of solar dryer remains almost constant over the entire life of the system, but the cost is variable in the case of electric and fossil fuel-based dryer due to the fluctuating price of electricity and petroleum products. Even though the annualized cost gives a comparative study, it is not precise due to volatile fossil-fuel prices. Hence for a clearer understanding on the economics of the dryer, life savings method is used, which determines the savings made in the future years and also to make the present worth of annual savings over the life of the system. Payback period will give the investment's return period and hence this determines the acceptability of the technology.

Results and discussion

Experimental analysis

A set of experiments was carried out at Solar Thermal Energy Laboratory at Pondicherry University to determine the thermal behaviour of the developed system. Experiment was carried out keeping the mass flow rate constant throughout. Performance of air heater and drier was studied under both loaded and unloaded condition. The various parameters (ambient temperature T_a, inlet temperature T_{in}, absorber mesh temperature T_p, outlet temperature T_{out} and solar radiation intensity I) monitored during the system operated with and without loaded condition are shown in Figures 4 and 5 respectively. The mass flow rate was maintained at 500 m^3/h during the experimental period. The maximum output air temperature recorded during the unloaded condition was 70°C, with the solar radiation intensity of 767.2 W/m^2, measured at 12:00 pm. The highest temperature recorded under loaded condition was 74°C at 1:10 pm with an intensity of solar radiation of 829.5 W/m^2.

It is obvious from Figures 4 and 5 that there will be a rise in temperature of the outlet air when there is an increase in solar radiation. In the first case, the ambient temperature is found to be vary from 32°C to 35°C, whereas in the later, the ambient temperature varied from only 29°C to 32°C. But the outlet air temperature of the latter was found to be higher. This is well explained by the higher solar radiation availability during the operation of the system with load. The maximum instantaneous efficiency of the solar air heater was found to be 66.31%, with an average efficiency of 59.32%. The developed system used wire mesh as absorber material with wire diameter of 1 mm and pitch of 3.175 mm. The porosity of the wire mesh was 0.73. Mittal and Varshney[20] theoretically predicted the performance of the wire mesh solar air heater with different materials and arrived at the optimized values of different parameters. The design with a wire diameter of 0.795 mm and pitch 3.19 mm having a porosity of 0.935 was compared with this system as its parameters are much closer than other designs used in the referred system. Performance prediction of the system shows the efficiency peaking to nearly 70% for an average solar insolation of 600 W/m^2 and an ambient temperature of 30°C. Hence the efficiency of the present system was found to be nearing the optimized value generated by Mittal and Varshney[20].

Figure 6 shows the comparison between open sun drying and solar drying against the hourly reduction of moisture

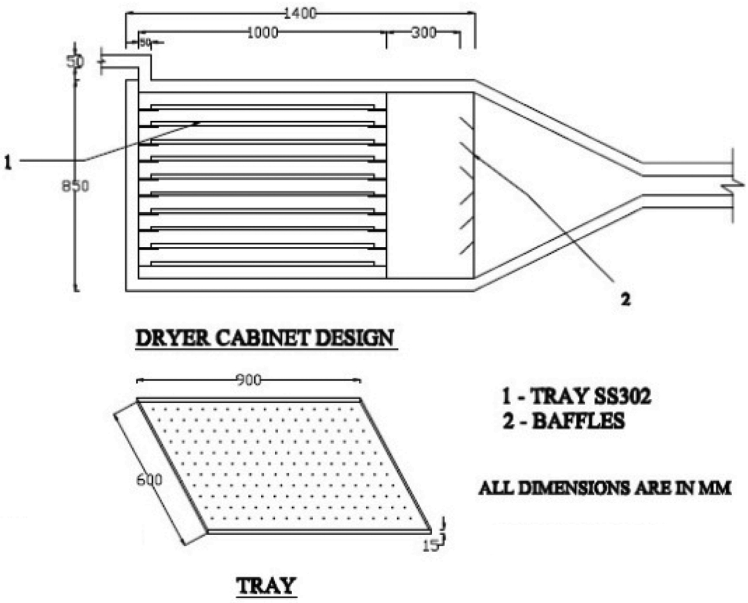

Figure 3. Schematic diagram of the drying cabinet and tray.

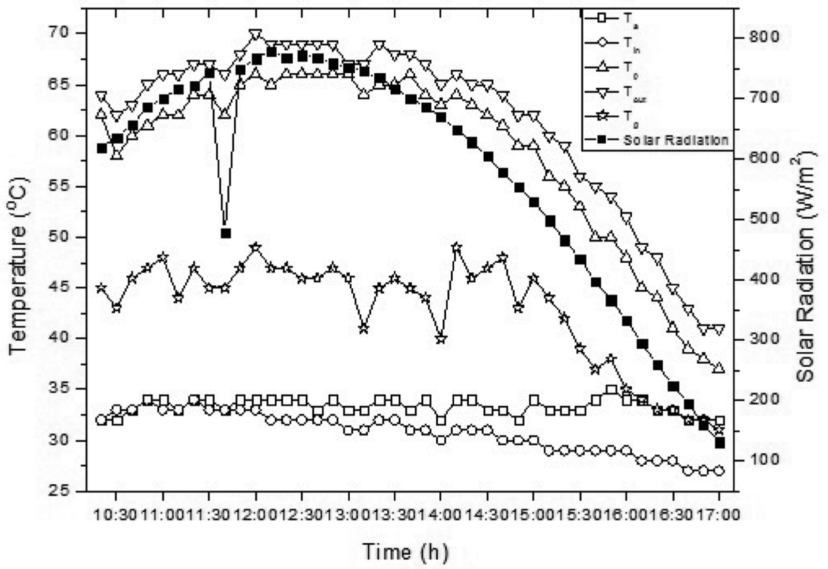

Figure 4. Temperature and solar radiation versus time (without load).

from the sample. Moisture content of the product at the time of loading was measured as 93% and it was brought down to 4.09% in the solar dryer for 6 h. The removal of same amount of moisture in the open sun drying took 3 h more. The graph shows the higher drying rate in solar drying than open sun drying. The drying efficiency of the system was found to be nearly 51.27%. The literature shows a drying efficiency of 21% for drying of chilli with a forced convention drier having a flat plate solar collector and a drying cabinet. It reduced the moisture content from 72.8% to 9.1% in 24 h (ref. 12).

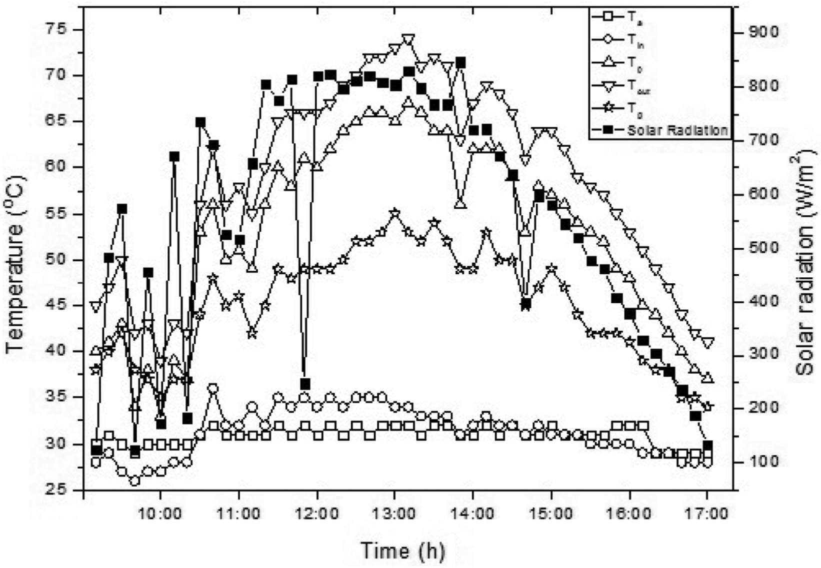

Figure 5. Temperature and solar radiation versus time (with load).

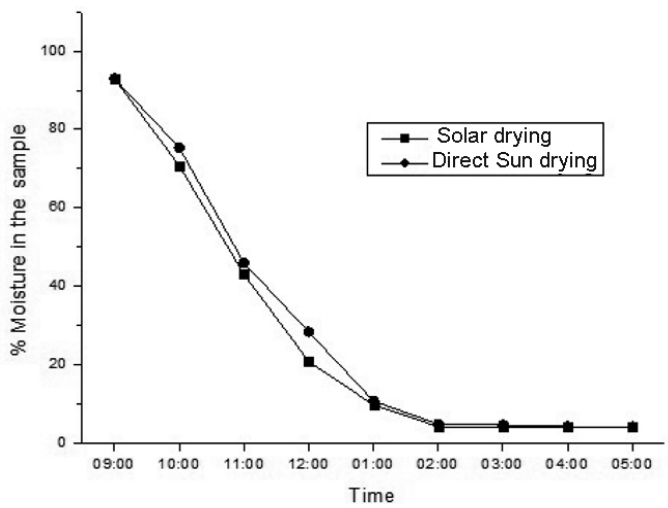

Figure 6. Drying curve for the sample.

Table 1. Parameters considered for economic analysis

Capital investment for solar dryer	120,000 INR
Capital investment for electric dryer	100,000 INR
Interest rate	10%
Inflation rate	8%
Cost of fresh bitter gourd	50 INR
Cost of dried bitter gourd	350 INR
Electricity cost	5 INR/kWh
Quantity of fresh pineapple loaded per batch	30 kg
Life span	20 yrs
Efficiency of the electric heater	75%

Photographs of the dried products for both solar and open sun drying are shown in Figure 7. The sample dried in solar dryer shows a better quality, retaining its natural colour, whereas dark patches appeared in open sun-dried sample. The discolouration of open sun-dried sample is due to exposure of the product directly to sunlight.

Economic analysis

Economic analysis was carried out to make a comparison between the solar dryer and electric drying to determine the unit drying cost for both the devices. Life cycle savings of the system analysed for a total life span of 20 years. The payback period of the system was estimated to check the suitability and reliability of the system. As detailed in the previous session, economic analysis of the system was estimated by three methods, namely annualized cost, life cycle savings and payback period.

The annualized cost for drying was estimated by considering the capital cost, maintenance cost, salvage valve, fuel cost, operating cost and other parameters as given in Table 1.

Using the assumed values, the cost of drying was found to be INR 14.43 for solar drying and INR 29.22 for electric drying. Hence for a loading capacity of 30 kg per batch with 260 working days and 1 batch per day, the savings per day was found to be INR 570.47.

Considering an operating period of 20 years, the total savings at the end of the 20th year was calculated as INR 3,388,103.00, which is about 28 times higher than the capital expenditure for the solar drier. The annual savings and present worth of annual savings estimated for a life span of 20 years are given in Table 2.

The payback period of the system was determined using the following equation

$$N = \frac{\ln\left(1 - \frac{C_{cc}}{S_1}(d - i)\right)}{\ln\left(\frac{1+i}{1+d}\right)}, \quad (6)$$

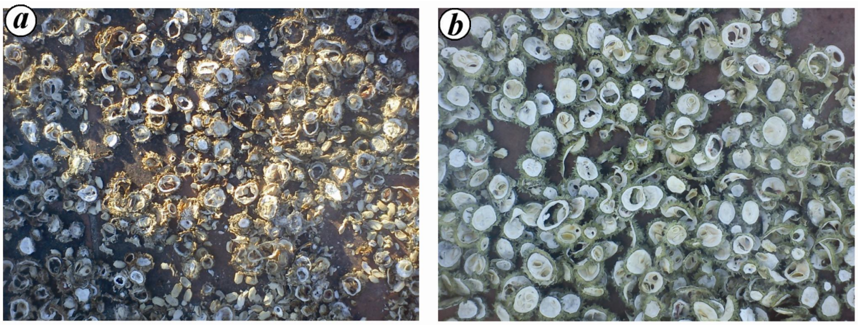

Figure 7. Dried sample: (***a***) open sun-drying; (***b***) solar drying.

Table 2. Life cycle savings

Year	Annual savings (INR)	Present worth of annual savings (INR)	Present worth of cumulative savings (INR)
1	148,322.00	137,335.00	137,335.00
2	160,188.00	139,879.00	277,214.00
3	173,003.00	142,469.00	419,683.00
4	186,843.00	145,107.00	564,790.00
5	201,791.00	147,794.00	712,585.00
6	217,934.00	150,531.00	863,116.00
7	235,369.00	153,319.00	1,016,435.00
8	254,198.00	156,158.00	1,172,593.00
9	274,534.00	159,050.00	1,331,643.00
10	296,497.00	161,995.00	1,493,639.00
11	320,217.00	164,995.00	1,658,634.00
12	345,834.00	168,051.00	1,826,685.00
13	373,501.00	171,163.00	1,997,848.00
14	403,381.00	174,333.00	2,172,180.00
15	435,651.00	177,561.00	2,349,741.00
16	470,503.00	180,849.00	2,530,590.00
17	508,143.00	184,198.00	2,714,789.00
18	548,795.00	187,609.00	2,902,398.00
19	592,698.00	191,083.00	3,093,481.00
20	640,114.00	194,622.00	3,288,103.00

where C_{cc} is the capital cost (in INR), S_1 is the savings during the first year for the solar dryer (in INR), d is the rate of interest on long-term investments and i is the rate of inflation.

The savings in the first year was worked out be around INR 137,335, which is higher than the capital cost. Payback period of the system worked out to be 0.62 years, which is around 226 days or 161 dryer operating days.

Conclusion

A wire mesh solar air heater for drying application was designed and tested. The maximum temperature recorded at the outlet of air heater was 74°C. The removal of 86.83% moisture from bitter gourd took around 6 h, which was 3 h less compared to open sun-drying. The dried product retained its original greenish colour after the complete drying process. The unit cost of drying in the solar dryer was calculated as INR 14.43, whereas it was INR 29.22 for electric dryer – roughly twofold. Life cycle savings of solar dryer was estimated as INR 3,388,103, with a payback of 0.62 years.

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