EXPERIMENTAL STUDIES ON A HYBRID DRYER[1]

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Abstract - A solar-biomass hybrid tunnel dryer has been designed and fabricated. A biomass stove-heat exchanger-chimney using briquetted ricehusk as fuel, complements the solar tunnel dryer and thus extends the working time of the dryer. Experiments have been conducted to test the performance of the dryer, and chilli and mushroom have been dried. During the load test conducted for chilli, 19.5kg of ripe, fresh chilli, with a initial moisture content of 76% (wet bulb) was dried to a final m.c of 6.6% (w.b) within 12 hours. Similarly, the moisture content of 21kg of fresh harvested mushroom was reduced from 91.4% to 9.8% during 12 hours of drying. The results indicate that for both the products, drying is faster, and is within 12 hours in normal sunny weather, against 2-3 days in 'solar-only' operation of a tunnel dryer and 3-5 days in open sun drying. This paper evaluates the performance of the hybrid tunnel dryer against 'solar-only' operation of the same dryer and open sun drying. Efficiency of the dryer during its two mode of operation has been estimated and compared with other similar dryers.

1. INTRODUCTION

Drying is an essential process in the preservation of agricultural products. Various drying techniques are employed to dry different food products. Each technique has its own advantages and limitations. Industrial drying offers quality drying whereas its high cost limits its use. Open sun drying suffers from quality considerations though it enjoys cost advantage. Choosing the right drying system is thus important in the process of drying agricultural products. Especially, in the tropical regions, where some crops have to be dried during rainy season, special care must be taken in choosing the drying system.

Studies comparing traditional sun drying and other solar drying techniques show that the use of solar dryer leads to a considerable reduction of the drying time and to a significant improvement of the product quality in terms of color, texture and taste. Besides, the contamination by insects and microorganisms can be prevented. Solar tunnel dryers are a class of solar dryers that have been successfully tested under field conditions in about 30 countries under different climatic conditions, drying numerous agricultural commodities ranging from fruits, vegetables, root crops, oil crops, medicinal plants to fish and even meat (Grupp et al., 1985; Lutz et al., 1987; Sodha and Chandra, 1994; Esper et al., 1994; Schrimer et al., 1996).

A solar tunnel dryer was first introduced by the Institute of Agricultural Engineering in the Tropics and Subtropics of University of Hohenheim (Germany), for use in the tropical region. The dryer proved to be successful in drying a variety of agricultural products including tropical fruits and vegetables, due to its economic viability (Esper et al., 1996). This dryer was however designed with a capacity that is suitable for use in single farm and small cooperatives. In an effort to adapt its design for small rural farmers, a scaled down version of the tunnel dryer was fabricated (Mastekbayeva et al., 1998). To reduce its dependence on solar radiation for operation and to improve the quality of drying, a biomass stove - heat exchanger system was incorporated in this dryer, thus converting it to a hybrid dryer.

The biomass stove - heat exchanger system was designed mainly to complement the solar operation of the dryer, and to sustain the drying process even during cloudy weather. However, it can also be used to extend the period of drying beyond sunshine hours, and perhaps during night as well, while drying high value addition crops. This paper evaluates the performance of the hybrid tunnel dryer against 'solar-only' operation of the same dryer and open sun drying, for comparison. The experimental set-up, data and its analysis, and results are described.

2. DESIGN OF THE HYBRID DRYER AND EXPERIMENTAL SET-UP

The prototype solar-biomass hybrid dryer consists of a flat plate solar collector and a drying tunnel, fabricated as a single unit. The dryer is 1.8m wide, with a collector length of 4m and a dryer length of 4.25m. Glass wool insulation, with a thickness of 4cm was used to reduce the heat losses from the bottom of the collector (absorber). A 0.2mm thick UV stabilized polyethylene sheet was used as glazing. A cross flow shell and tube type heat exchanger was incorporated at the ambient air inlet to the collector. Five fans, each of 14W capacity, were used to force ambient air into the dryer, through the heat exchanger 'shell'. The fans had an air handling capacity of $130m^3$/hour each. The 'tubes' of the heat exchanger were connected to a biomass stove at one end, and a chimney at the other.

The design of the biomass system was based on the following considerations:

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(i) The heating will be indirect, i.e, flue gas from the biomass stove and the drying air would not be mixed. This will protect the product being dried from contamination by the smoke, soot and ash of the flue gas.
(ii) The temperature of air heated by the heat exchanger, entering the dryer, would be in the range of 65-70°C. This is based on the allowable maximum drying temperature for most of the tropical fruits and vegetables.
(iii) Temperature control of the drying air would be possible, by controlling the combustion in the stove, by opening or closing the primary air supply gate in the stove.
(iv) Biomass operation could be carried out for extended periods of time, unattended. The stove was designed to operate continuously for about one hour for a single fuel loading, with briquetted rice husk as fuel.

For the above considerations, a channel stove of rectangular shape was chosen, and the main dimensions of the stove were designed. The thermal energy required to supply hot air (by the heat exchanger) at 70°C for drying was found to be 12.7 kW. From the calorific value of briquettes (18.8MJ/kg), the rate of fuel consumption was estimated as 2.44 kg/hr. A mild steel stove was fabricated with a width of 0.3 m, length of 0.275 m, and height of 0.4 m. A grate punched with 44 holes of 1.5 cm diameter was used to increase the efficiency and quality of combustion (Mastekbayeva, 1998). The stove used a high chimney to produce hot flue gas in natural draught. The chimney was designed for a flue gas flow rate of about 139 m3/hr. A rectangular shape was chosen for the chimney design with a cross section of 0.275 m× 0.16 m and the height of chimney was calculated to be about 1m.

A cross-flow shell and tube heat exchanger was chosen, with heated air in the shell side. Noting that the maximum permissible temperature for fruits and vegetable drying is about 60^{o}C, the temperature at the outlet of heat exchanger was to be not less than this value. During the combustion process, as volatiles burn at about 600^{o}C (Baldwin, 1987), this was taken as the design inlet temperature of flue gas to the heat exchanger. The flue gas outlet temperature was assumed to be about 300^{o}C.

A rectangular shape was chosen for the shell side to connect the heat exchanger with the solar tunnel dryer, with the following dimensions: length: 1.72m, width: 0.6m and height: 016m. To provide an estimated total required heat transfer area of 1.74m^2, eight galvanised iron (GI) pipes with outer diameter 50mm and inner diameter 44mm were used. Tubes were arranged in a staggered manner, as shown in figure 1.

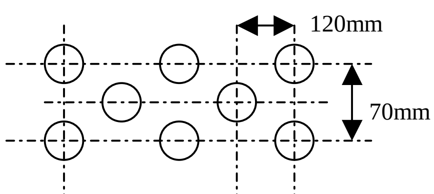


Figure 1: Arrangement of tubes in the heat exchanger

The biomass stove-heat exchanger unit, with attached chimney is shown in figure 2. The heat exchanger was insulated with 100mm thick rockwool and clad with 1mm thick aluminium sheet, to reduce thermal losses. The biomass stove was insulated with castable refractory mortar, along the inside walls.

Figure 2: Biomass stove-heat exchanger unit, before insulation

The completed hybrid dryer is shown in figure 3.

Figure 3: Solar-biomass hybrid dryer

3. INSTRUMENTATION AND MEASUREMENTS

Air probe sensors (thermocouples) were used to measure the temperature of air at different points. The K-type thermocouples (JB 10) were calibrated before fixing them in the tunnel dryer. Surface probe sensors were used to measure the surface temperature of the collector plate, and air probe sensors, to measure the dry bulb and wet bulb temperatures at various points inside the collector and dryer parts of the tunnel. The locations of the sensors are given in figures 4 and 5.

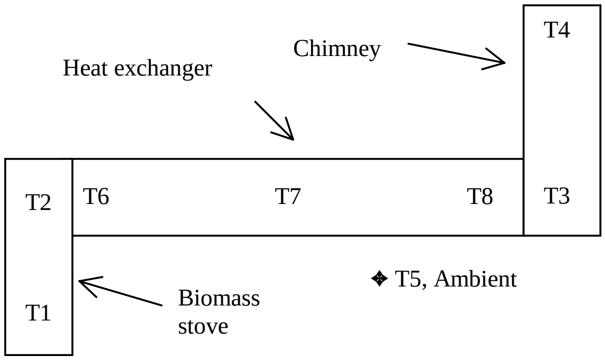
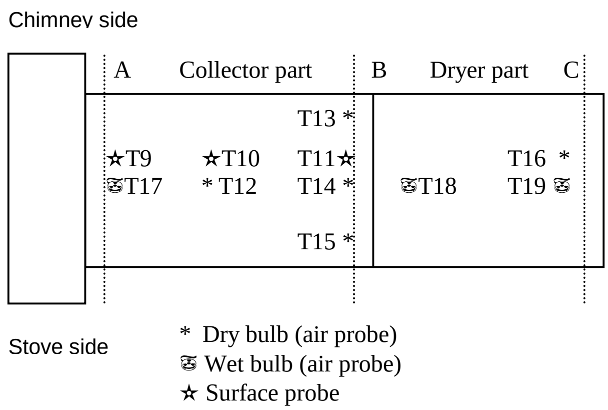


Fig. 4: Location of temperature sensors at the biomass stove - heat exchanger - chimney



Section A: Collector inlet
Section B: Dryer inlet/ Collector exit
Section C: Dryer exit

Figure 5: Location of surface and air probe, dry bulb and wet bulb temperature sensors in the hybrid dryer

The temperature data were recorded in a 21X Campbell data logger, at five minutes intervals. Global solar radiation data was measured using a pyranometer.

The airflow rate inside the tunnel was measured with a vane type anemometer. Average airflow was 632 m^3/hour with five fans working (biomass operation), and 385 m^3/hour with three fans working (solar operation).

Humidity of air inside the tunnel dryer was estimated using the wet bulb temperature data recorded. The moisture content of the product during the drying process was determined using oven method, by taking samples periodically.

Experiments were conducted to evaluate the performance of the dryer at no-load and at full-load conditions. Two separate full load experiments were conducted, one for chilli and the other for 'ear-lobe' mushroom.

4. NO-LOAD EXPERIMENTS

No load tests were conducted with five AC-operated fans (14W each) at the heat exchanger/dryer inlet to know the temperature gradient between the stove side and the chimney side of the tunnel dryer, as well as the temperature profile along the tunnel dryer.

Three kg of rice husk briquettes was burned in the biomass stove during one hour of operation. Figure 6 shows the temperature profile across the tunnel, at the inlet of the dryer (exit of the collector). The temperature profile along the width of the dryer inlet was observed. The maximum temperature reached 57.9 ^{0}C at the stove side, while at the chimney side, it was 38.5^{0}C. At the middle of the dryer inlet, the temperature was 54.5 ^{0}C. The average temperature rise at the chimney side, middle, and stove side were 4.75^{0}C, 14.93^{0}C and 18.32^{0}C respectively.

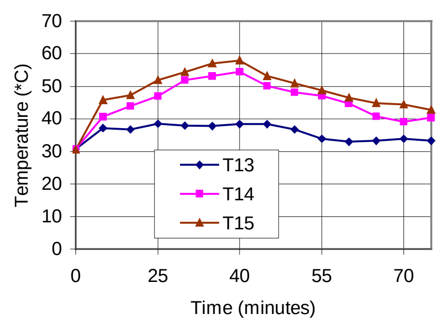


Figure 6: Temperature profile at dryer inlet
(Location of temperature sensors are shown in figure 5)

The uneven temperature distribution across the tunnel would affect the dryer performance, due to non-uniform drying of the product. Faster drying will occur at the stove side, while drying will be slow at the chimney side. This could result in over drying at the stove side, and under drying at the chimney side. To overcome this, mixing fans were used to mix the hot air so that the air temperature is uniform across the tunnel, before it enters the dryer.

Six kg of rice husk briquettes were used in the biomass stove, which burnt for about two hours, and temperature at various point of the dryer was observed. The experiment was performed during 7:30 to 9:30 a.m. Two DC fans were used at the collector inlet, just after the heat exchanger, to facilitate effective mixing of air. The fans have an air handling capacity of 80m^3/hour each.

The maximum temperature recorded at the stove side of the tunnel was 50.9 ^{0}C, while that at the other end (chimney side) was 45.4^{0}C (figure 7). At the middle of the dryer inlet, the temperature was 48.5 ^{0}C. The average temperature rise at the dryer inlet across the tunnel at the stove side, middle, and at the chimney side were 13.0^{0}C, 15.1^{0}C and 17.8^{0}C respectively.

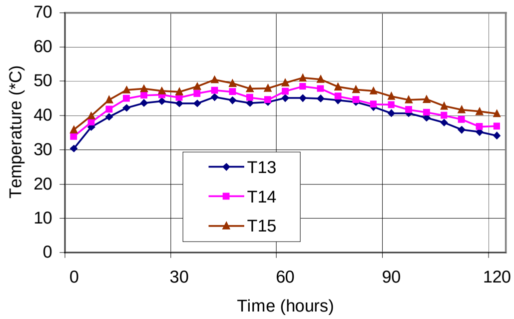


Figure 7: Temperature profile across dryer inlet with mixing fans (Location of temperature sensors are shown in figure 5)

The difference in temperature rise at the dryer inlet, across the tunnel reduced considerably from 13.57^{0}C to 4.73^{0}C, without and with the mixing fans respectively.

5. VEGETABLE DRYING

Full-load experiments were conducted to study the capability of the dryer to operate beyond the sunshine hours. The dryer was operated from 7:00 a.m. until 9:00 a.m. by biomass, when solar radiation was not enough for drying. It was then operated as a solar dryer from 9:00 a.m. until 5:00 p.m. Biomass operation was restored again, after 5:00 p.m. The drying was stopped when the products reached their final moisture content. The products to be dried were spread on aluminium trays of 0.85m x 1.0m size, fabricated with angles and mesh.

Control samples were dried simultaneously in open sun under the same weather conditions, for comparison.

Rice husk briquettes were burned in the stove for the biomass operation of the drier. Airflow rate, fuel (biomass) consumption, and the current and voltage across the fans were measured during the experiment. The samples from the dryer were taken at two-hour intervals, to measure the moisture content. During bio-mass operation, moisture content of the product to be dried was measured at one hour interval. Open sun drying sample was weighed every two hours on the first day of drying and every one-hour the next day, to measure the moisture content.

5.1 Chilli

Chilli, both fresh and dried, is a popular ingredient in food, and has high levels of protein and vitamins (Thanvi and Pande, 1987). It is estimated that 332, 079 tones of fresh chilli and 1,171 tones of dried chilli were produced in Thailand in 1996 (Kumar and Wattanapong, 1997). Chilli is dried as whole, like vegetables, without any chemical pretreatment. The full load capacity of the solar tunnel dryer is about 80 kg of raw chilli per batch.

For the experiment, the dryer was loaded with 19.5kg of chilli as ripe fruits, by spreading them inside in a single layer. They can be spread directly on the dryer, in contact with the metal sheet that carries heat from the absorber to the dryer. The product can thus utilise the heat absorbed by the collector (during solar operation) more efficiently.

The drying was started at 6:00 a.m., using the biomass stove. Six kg of rice-husk briquettes were loaded in the stove, and the fuel was ignited. The heat exchanger fans, mixing fans, and the data logger were switched on. The biomass operation was continued until 9:00 am. After 9:00 a.m., and until about 5:00 p.m., the system was utilized as a solar dryer. The biomass stove was started again, and the drying continued for one more hour.

Figure 8 shows the drying curves for chilli dried in the hybrid dryer, and compared with open sun drying. The final moisture content of 6.6 % (wet bulb) was achieved within 12 hours with hybrid drying, while open sun drying took about 5 days.

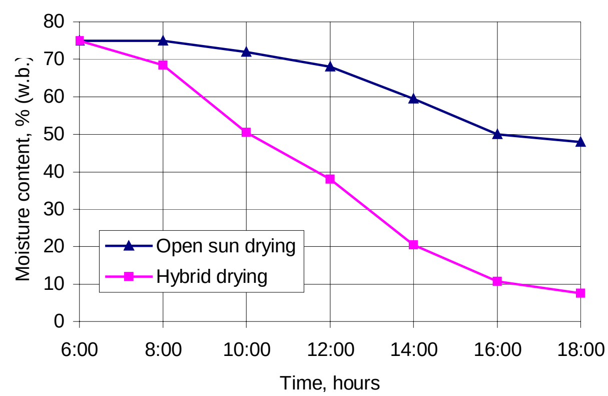


Figure 8: Drying curves for chilli with hybrid drying compared to open sun drying

5.2 'Ear lobe' Mushroom

Mushroom is an important agricultural food product used in soups and other dishes. In Thailand mushroom is used locally, and is also exported in dried form. The export of dried mushroom from Thailand was 25,173 kg in 1994 (DoEP, 1994).

Mushrooms are dried at a temperature of 60-70°C, to a final moisture content 8-13%. Fresh mushrooms are often boiled before drying, for good color and aroma. Various types of mushrooms that can be dried are: Escherichia coli, Salmonella and Staphylococcus aureus. 'Ear lobe' mushroom is usually used in dried form.

Ear-lobe mushroom is a high moisture content product, and has an initial moisture content of 90-92 % (w.b) when fresh. Market price of fresh ear-lobe mushroom was 15 Baht/kg while the dried ones cost 190 Baht/kg[2].

For the load test, 21 kg of fresh ear-lobe mushroom was spread on the trays in a single layer, and the trays were placed inside the dryer. The fuel (ricehusk briquettes) in the biomass stove was ignited, and the experiment was started at 7:00 a.m. The biomass operation was stopped at 9:00 a.m., and the system was then utilized as a solar dryer until about 5:00 p.m. The biomass stove was started again, and the drying continued until 7:00 p.m.

The experiment was repeated with the same quantity (21kg) of ear-lobe mushrooms, but with 'solar only' operation of the same dryer, on a day having similar weather conditions. It took two days of drying for the mushroom to attain almost the same final moisture content. Control samples dried in open sun took three days to attain almost the same final moisture content. The drying curves are presented in figure 9, for comparison.

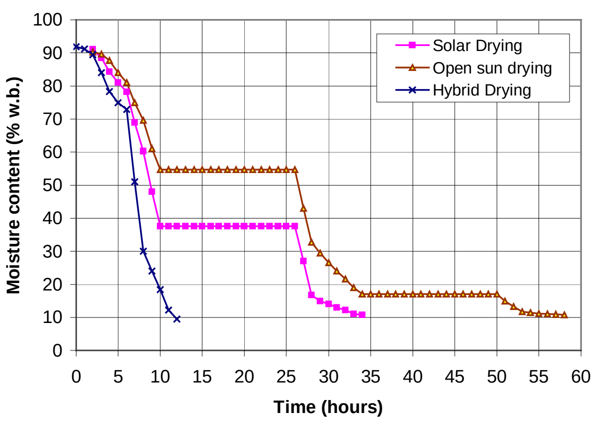


Figure 9: Drying curves for 'ear-lobe' mushroom dried in the hybrid tunnel dryer compared to solar drying and open sun drying

6. DRYING EFFICIENCY

Drying efficiency of the tunnel dryer has been estimated by considering solar energy input to the collector and dryer parts (Sodha et al., 1987). The following parameters were considered for estimating the drying efficiency for both cases:

a) Total radiation incident on the collector (considering the total duration of solar drying),
b) Total electrical energy input to the fans,
c) Total heat input by the biomass stove (during biomass operation) and
d) Initial and final weight of the product and thus the amount of water evaporated.

[2] 1US$=37 Baht; March 99

The dryer used five numbers of 14W/AC fans in its heat exchanger and additional two fans of 4.7W/DC for mixing air inside the tunnel. The electrical power requirement during biomass operation amounts to 79.4W. During solar operation, however, only three fans were used in the heat exchanger, and the mixing fans were switched off. The power consumption thus reduced to 42W during solar only operation.

The drying efficiency of the hybrid tunnel dryer shows how effectively the input energy to the dryer (biomass energy and solar radiation) is used in drying the product. The system drying efficiency is defined as the energy used to evaporate the moisture in the product divided by the energy input to the dryer, or

$$\eta_s = (WL) / [(IA_t + P_f) + (m_b * C.V)]$$

where W is the weight of water evaporated from the product, L is the latent heat of evaporation of water, m_b is the mass of biomass fuel used in the stove, and C.V is the lower calorific value (LCV) of the biomass fuel. The LCV of rice husk briquettes was estimated as 11.69 MJ/kg. The total electrical energy (P_f) required to run the three AC fans (during solar operation) is estimated at about 0.36kWh (1.3 MJ) for one day of operation (8.5 hours), which is approximately 0.5% of the daily total solar energy incident on the system, and is therefore negligible.

The total solar radiation for the first day was 17.3 MJ/m^2. The average drying efficiency of the solar-biomass hybrid tunnel dryer is thus estimated to be about 8.8% during chilli drying (Table 1).

Table 1: Performance of the hybrid tunnel dryer during its solar and biomass operation, while drying chilli

Drying time (hours)	Total energy input to the System (MJ)	Drying efficiency		
		Solar only %	Biomass %	Hybrid %
6:00-9:00	105.2	-	17.8	
9:00-17:00	256.9	6.1	-	8.8
17:00-18:00	35.1	-	3.6	

The total capacity of the solar tunnel dryer is estimated to be about 80 kg of fresh chilli, while only 19.5 kg was loaded for the experimentation. Therefore, the drying area was not used fully, which explains the low efficiency of the drying system. This was also observed from the relative humidity values of the air leaving the dryer, which were fairly low. This indicates that the drying potential of the air was not fully utilised.

Similar efficiency figures for drying of ear-lobe mushroom have been given in table 2. The total solar radiation for the day was 13.13 MJ/m^2.

Table 2: Performance of the hybrid tunnel dryer during its solar and biomass operation, while drying ear-lobe mushroom

Drying time (hours)	Total energy input to the System (MJ)	Drying efficiency		
		Solar only %	Biomass %	Hybrid %
7:00-9:00	70.14	-	16.8	14.4
9:00-17:00	195.0	17.2	-	
17:00-19:00	70.14	-	0.75	

It may be noted that the drying efficiency is much higher while drying ear-lobe mushroom than while drying chilli. This is due to the much softer skin of mushroom (compared to chilli), which allows for easy diffusion of moisture through it to the drying air. The thickness of mushroom also contributed to faster drying, as the average thickness was only about 2mm. In general, the drying efficiency was reduced considerably during the final stages of drying. This is due to the much higher mass transfer resistance offered by the product after it is dried to a certain extent, which means that diffusion of moisture from inside the product to the surface of the product becomes much more difficult.

7. RESULTS AND DISCUSSIONS

The results indicate that drying of chilli and ear-lobe mushroom could be completed within 12 hours in a normal sunny weather (or even cloudy or rainy weather, when drying could be continued with biomass operation), against 2-5 days in 'solar-only operation' of a tunnel dryer. Solar-biomass hybrid tunnel dryers seem to be an attractive and reliable alternative to open sun drying and solar tunnel dryers in the tropical climates of Asia.

The experimental investigations on drying chilli have been compared with different designs of solar dryers. The moisture content of raw chilli is usually in the range of 75-90%, while the dried chilli contains about 4-7% of moisture (w.b.). The drying time varied from 12 hours to 9 days depending on the weather conditions and dryer design, against 5-18 days required for open sun drying. The results of observations from various studies are summarized in Table 3.

The quality of the dried products in hybrid drying notably improved compared to open sun drying as well as solar drying due to the fact that drying was uninterrupted until the final moisture content was attained. This eliminated possible moisture re-absorption and mould growth during overnight storage of the product during open sun drying and solar drying. In certain products, cracks tend to develop within the product due to thermal stresses resulting from alternate heating and cooling of the product during day and night, with solar and open sun drying. This is also largely minimised with hybrid drying. It may be noted that the improvement in quality of ear-lobe mushroom in terms of taste and food value was distinctly recognised.

Table 3: Summary of chilli drying with different solar dryers

Type of dryer	Moisture content (%)		Drying time	Average temp. rise (^oC)	Quantity of product dried (kg)
	Initial	Final			
1. Solar Tunnel Dryer (AC) (Mastekbayeva, 1998)	75.2	6.3	3 days	17.5	20 (25% of full capacity)
2. Solar Tunnel Dryer (DC/PV) (Mastekbayeva, 1998)	74.9	6.8	2 days	17.5	20 (25% of full capacity)
3. Hybrid Tunnel Dryer (AC) (Present study)	76	6.6	12 hours	20	19.5 (25% of full capacity)
3. Low-Cost Solar Agricultural Dryer (Thanvi and Pande, 1987, India)	86.3	4.1	9 days	28.2	10-15 (full capacity)
4. New Solar Dryer (Tiris and Dincer, 1994, Turkey)	89.2	7.22	2.5 days	16	no data

The moisture content of exit air from the dryer indicates large untapped drying potential of the exit air. If this drying potential is used more efficiently by increasing the average humidity of the air leaving the dryer, apparently, more quantity of the product could be dried. It is estimated that about 40kg of mushroom can be dried with an average relative humidity at exit of 70%, for a total drying period of 12 hours.

8. CONCLUSION

This paper describes the design and experimentation of a solar-biomass hybrid dryer. Separate experiments were carried out with two agricultural products chilli and ear-lobe mushroom in the hybrid tunnel dryer and the performance of the dryer was compared to 'solar only' operation of the same dryer, and to open sun drying.

Considerable reduction in drying time is the major advantage reported with this hybrid dryer. While overcoming the limitations of solar drying during cloudy days, the solar-biomass hybrid dryer also enables drying during nighttime. The facilitating of continuous year-round operation of the dryer and the 60-80% reduction in drying time in comparison with open sun drying and solar drying, increases the utilisation of the dryer, and improves the financial viability of the tunnel dryer considerably.

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