Evaluation of a solar dryer in a high altitude area of Nepal

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Abstract

Nepal is a poor country and is ranked 138 out of 177 countries in terms of standard of living, with approximately 38% of the population earning less than US$1 per day. Of the 75 province in Nepal, Humla has been judged to be the second poorest. Using a ranking of 1 (best) to 75 (worst), Humla was overall ranked 74th in terms of poverty, deprivation and women's empowerment (73rd), and 72nd in terms of socio-economic and infrastructure development. Humla is also a permanent food deficient area and to improve general food security, a small number of solar dryers have been introduced into the area to increase and improve crop preservation. This paper describes the evaluation of one of the solar dryers located at RIDS-Nepal's High Altitude Research Station (HARS) in Simikot, the main town of the Humla District. The purpose of the evaluation was to determine the effectiveness of the current design. The results of the evaluation indicate that in terms of drying efficiency the solar dryer is not superior to sun drying. In large part, this is due to the poor air distribution through the dryer. Collector and drying efficiencies of 20-31% and 13% respectively were calculated. These are considered to be low for this type of solar dryer. Although theoretically the solar dryer could pay for itself in approximately two years of continuous use in the non-winter months, there appears to be little justification for the additional capital outlay, other than the possibility of more hygienic drying conditions, when sun drying could achieve similar results. As a result of the evaluation, some suggestions are made on an alternative and perhaps more suitable type of solar dryer for the Humla District.

1. INTRODUCTION

Nepal is a developing country and is ranked 138 out of 177 countries in terms of Human Development Index (UNDP, 2006). The UNDP also ranks Nepal as 68th out of 102 developing countries with an annual GDP per capita of US$ 252 (UNDP, 2006). In 2006, the country had an estimated population of 28.3 million (CIA, 2007), of which 40% were aged 15 or less; approximately 80% of the population lived in rural areas. In terms of energy, traditional fuel consumption (mainly wood) represents 93% of total usage and the average per capita electricity consumption is only 91 kWh per annum, although electricity is only accessible to approximately 25% of the nation's population. Infant mortality, compared to developed nations, is high ranging from 86 to 53 per 1000 live births for the poorest and richest 20% respectively. The UNDP estimates that in 2001-3, 17% of the population was estimated to be malnourished. In children under five years old, this was reflected in 48% and 51% being under weight and under height for age respectively. Over one fifth of babies were born underweight. These average statistics, alarming as they are, mask a more serious situation for rural and remote people in Nepal, where malnutrition and its effects are much worse.

The World Bank defines 'food security' as "access by all people at all times to enough food for an active healthy life" (NPC/UNDP, 2005). As part of an aim to improve general food security, a small number of solar dryers have been introduced into a mountainous region of northwest Nepal with the aim of increasing and improving crop preservation. This paper describes the evaluation of one of the solar dryers. The purpose of the evaluation was to determine the effectiveness of the current design.

The paper first presents a description of the solar dryer and its location. This is followed by an outline of the methodology used to evaluate the dryer. The results of the evaluation are then presented and discussed.

2. THE HUMLA VALLEY

According to Hagen (1980), Nepal can be divided into seven natural topographical "units", which can be clearly distinguished from each other. One of these regions is known as the Inner Himalayas. It is the name given to the valleys, which lie to the north of Nepal's principal and well-known chain of mountains, the Himalayas. Hagen describes these inner valleys as "the real high mountain valleys of Nepal, surrounded on all sides as they are by ice clad giants". One of these valleys, located on the western end of the country, is the Humla Valley. Of the 75 provinces in Nepal, Humla has been judged to be one of the poorest. Using a ranking of 1 (best) to 75 (worst), Humla was ranked 74th in the overall index in regard to poverty, deprivation, socioeconomic and infrastructural development, and women's empowerment (ICIMOD, 2003).

According to the Nepali Trust (2007), "in this food deficient area, a subsistence economy runs on inter-village trade, livestock and the cultivation of food-grains". Less than one percent of the land is arable due to steep slopes, rocks, rivers and forest cover (DPH, 2004) and snow cover for five months of the year reduces fresh food production to just 3-4 months per year. As a result, and unsurprisingly, there is chronic malnutrition among the local population. In a study of children in the districts of Humla and neighbouring Mugu, Emeriau (2006) found that global acute and chronic malnutrition rates were 12.3% and 63.9% respectively. As the Nepal Trust (2007) succinctly states "survival is a serious business for the people of the Hidden Himalayas".

Humla is 430 km northwest of Kathmandu and its main town is Simikot. Kathmandu University initially established the High Altitude Research Station (HARS) (Figure 1) in Simikot in 2002 for research purposes. Since 2004, the HARS has been run by RIDS-Nepal, an independent Nepali-based NGO. The station acts as the base from which RIDS-Nepal conducts its long-term community-based development programme in the villages north of Simikot.

Figure 1 HARS in Simikot, Humla District, N.W. Nepal

RIDS-Nepal has seven Simikot-based staff members working in the Humla district. In addition to its technical staff, RIDS-Nepal employs a health motivator and a non-formal education programme worker. Their work is an integral part of the NGO's holistic community development programme where technical and non-technical solutions are complementary. The HARS is powered by a 900 W tracking solar photovoltaic system, which supplies all its electricity needs without interruption. Currently a constant and uninterrupted supply of electricity is a luxury in Nepal, where load shedding and voltage reductions are commonplace. One of the functions of HARS site is to test and evaluate various solar and other technologies prior to their introduction into villages. For example, hot water is produced at HARS by a 6 m^2 thermosyphon solar water heating system, the prototype for a future much larger system for a community bathing centre in a nearby village. Currently under evaluation at HARS are a greenhouse and a solar dryer, which are seen as integral parts of the current food security and nutrition programme of RIDS-Nepal. Testing and evaluation are vital to ensure the best and most appropriate technologies are introduced to villages.

3. SOLAR DRYER DESCRIPTION

Between 2001-2003, the Department of Mechanical Engineering at Katmandu University developed a number of small solar dryers, one of which is now produced commercially by a Nepali company. Three of these commercial units have been installed in various villages in the Humla Valley. The solar dryer can be defined as an 'indirect type' of solar dryer because the drying cabinet is opaque to solar radiation and heated air is generated in a solar air collector attached to the drying cabinet (Figure 2).

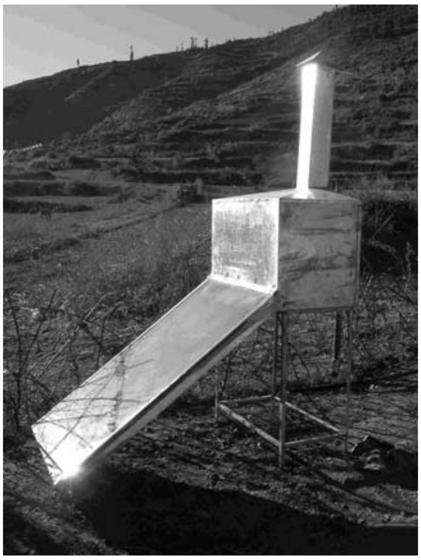

Figure 2 External view of the solar dryer evaluated

The external collector dimensions are 1.68 m by 1.01 m, giving a collector area of 1.7 m^2. The collector casing is made of galvanised iron (GI) sheet. The glazing is 3 mm thick standard window glass. The absorber consists of two layers. The bottom layer is a black-painted GI sheet on top of the back insulation. The top layer is a black-painted perforated plate, which rest on supports fixed to the bottom layer. Air enters the collector through an insect-proof opening on the underside of the bottom of the collector, which is inclined at 40° to the horizontal. A baffle at the bottom of the collector directs air in between the two absorbing layers. Some of this air (presumably) passes through the perforated upper layer. The remainder stays between the two layers. Both air streams meet at the top of the collector, where the heated air enters the dryer cabinet through a 7.5 cm by 95 cm opening covered with insect mesh.

The drying cabinet sits on an angle-iron frame. The internal dimensions of the drying cabinet are 55 cm deep by 95 cm wide by 63.5 cm high. The cabinet is constructed from GI sheet on the outside and aluminum sheet on the inside with 25 mm of polystyrene foam between the layers. The cabinet contains six drying trays, each 48 cm by 93 cm. The useable drying area is 2.39 m^2. The trays are made of timber with insect mesh fixed to the underside. Stops have been welded on the tray runners at various positions so that the drying air is encouraged to flow across the top of each tray. After passing across the trays, air is exhausted from the drying cabinet through a 16 cm by 16 cm chimney, 84 cm high and insulated with polystyrene foam. A small 12-volt battery-powered fan located inside the chimney draws air through the collector and dryer.

Overall, the solar dryer is well made. Sealing strips have been used around the cabinet doors and under the edges of the glass. Despite these seals, some leakage through the doors is likely to occur because the seals are not compressed when the doors are closed. Some of the drying trays have warped and this is likely to cause some short-circuiting of airflow around their edges instead of across the tray as intended.

4. EVALUATION METHODOLOGY

4.1 Flow Rate Measurements

Initially the dryer was tested without a crop i.e. in the 'no load' condition. Temperature, humidity, solar radiation and flow measurements were taken on each hour between 9am and 5pm. The purpose of these measurements was to indicate the best achievable collector efficiency and the maximum daily energy that could be collected for the given ambient conditions. These factors are dependent on flow rate through the dryer and this was determined using the following procedure:

- the hot wire anemometer was inserted in holes halfway up the chimney.
- three positions - quarter, halfway and three quarters across the chimney- were chosen as measuring points.
- after inserting the probe at these pre-determined positions, one minute was allowed for the sensor to equilibrate.
- four readings were then taken at 15-second intervals at each position.
- this procedure was repeated along east-west and north-south axes.
- the average velocity in the chimney was calculated from the 24 readings.

Drying efficiency is determined by how effectively the heated air passes over the crop. Airflow velocities were therefore measured both through and across the centre of each tray by inserting the hot wire anemometer in holes drilled in the side of the cabinet between trays. Flow across and up through the trays was estimated by orientating the tip of the anemometer in the appropriate direction. Four measurements were made at the centre of each of the six trays. Prior to all flow rate measurements, the gaps around the doors were taped to ensure that there was no entry of air at this point i.e. short-circuiting.

4.2 Efficiencies

There are various efficiencies associated with this type of solar dryer and the following equations may be used to evaluate its performance. The overall drying efficiency (E_d) of the dryer may be defined simply (Eqn 1).

$$E_d = \frac{energy \quad content \quad of \quad water \quad evaporated}{energy \quad input} \quad .... \ .... \ ...... \quad (Eqn.1)$$

In general, overall drying efficiencies of 10-15% might be expected for a solar dryer relying purely on natural convection for air movement, while higher efficiencies (20-30%) might be expected for solar dryers using forced convection i.e. using fan.

Since this solar dryer has an attached solar collector, this part of the dryer may be evaluated in the conventional way used to evaluate the performance of any solar collector. This procedure involves measurement of inlet and outlet temperatures, mass flow rate and solar radiation on the plane of the collector. Eqn 2 generally defines solar collector efficiency (E_c).

$$E_c = \frac{energy \ collected}{incident \ solar \ radiation} \quad .... \quad (Eqn.2)$$

5. INSTRUMENTATION

In order to determine the various efficiencies described above, average global solar radiation on the plane of the collector, and dry bulb air temperatures at the inlet and outlet of solar collector were recorded at hourly intervals. Total solar radiation on the plane of the collector was measured using a photoelectric pyranometer (Pacific Systems Pty. Ltd., SolData SPC80 SN 243). Battery-powered data loggers (Onset Corp., Hobo H8 Series) were used for the dry bulb measurements. The loggers were cross-calibrated against each other at the start of the experiments. A hand-held hot wire anemometer (TSI Inc., VelociCalc Model No 8350-1) was used to measure airflow at various points through the dryer.

6. RESULTS AND DISCUSSION

6.1 No Load Conditions

Collector inlet and outlet temperatures, as well as those at Tray 2 and Tray 5[1], and at the entrance to the chimney were measured on 30th March 2007 (Figure 3). As expected, the conditions inside the cabinet have a similar pattern and value as the collector outlet temperature.

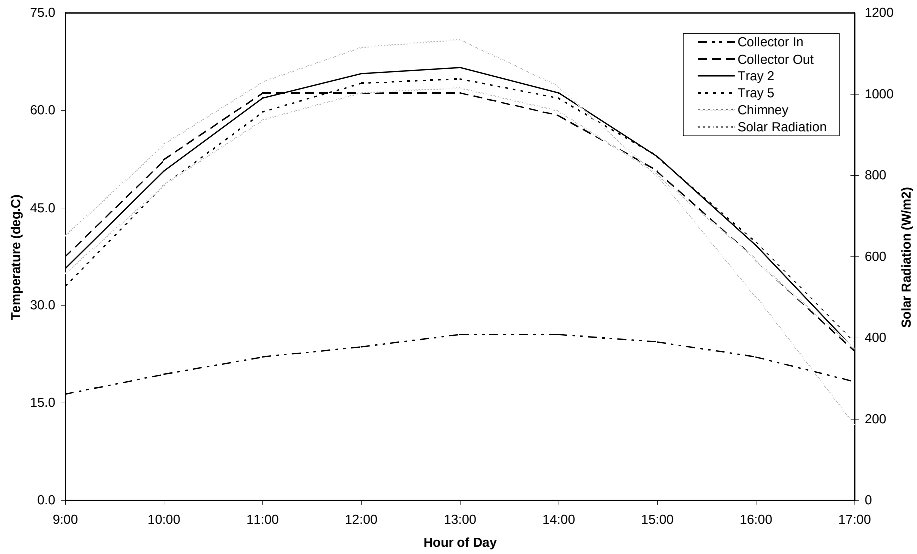

Figure 3 Collector inlet & outlet, plus other cabinet temperatures, measured on 30/3/2007

[1]Note: Bottom tray = Tray 1; top tray = Tray 6 i.e. trays numbered in ascending order

Air velocities were measured at the same intervals in the dryer chimney. This location was chosen because it offered the best opportunity to produce repeatable results. Prior to the measurements, the sides of the doors and at the junction of the solar collector and drying cabinet were taped to minimise the ingress of outside air. There was little or no wind during testing. Table 1 shows the average of 12 air velocities measurements made across the E-W and N-S axes respectively. The average velocity is 1.38 ms^{-1} with a standard deviation of 0.097 ms^{-1}. Given the conditions for testing, this was considered acceptable and the average value was used in all subsequent calculations. The specific air mass flow rate through the solar dryer was calculated to be 29.7 $kgh^{-1}m^{-2}$. This mass flow rate is only 43% of that suggested by Peck and Proctor (1983) for a forced convection solar air heater. The low flow rate is main reason for the high temperature of the outlet air (Figure 3). The inlet air temperature is raised more than 40°C on one occasion.

The relatively low air volume flow rate through the empty dryer also indicates that at best the velocity of air passing the crop cannot exceed 0.03 ms^{-1} or 0.5 ms^{-1} if the air moves vertically or horizontally respectively. These velocities are significantly lower than the 2-3 ms^{-1} used in other forced convection dryers. Some horizontal flow (0.21-0.25 ms^{-1}) was measured below the bottom tray (Tray 1), but otherwise no flow could be detected. This finding indicates that the strategy to encourage the heated air to follow a serpentine path across the face of the stacked trays is not working.

Table 1 Average velocities of air in chimney along E-W and N-S axes

Time	Average Velocity (m/s) along E-W axis	Average Velocity (m/s) along N-S axis
9	1.37	1.42
10	1.43	1.51
11	1.37	1.50
12	1.24	1.40
13	1.28	1.45
14	1.39	1.35
15	1.16	1.54
16	1.28	1.41
17	1.33	1.42

6.2 Full Load Conditions

The solar dryer was evaluated under 'full load' conditions by comparing its ability to dry sliced carrots against sun drying the same crop on a traditional bamboo drying tray. The carrots were first washed and then cut into approximate 5 mm thick slices. A total of 6.7 kg of sliced carrots was spread across the six drying trays and 0.5 kg of slices on the bamboo drying tray. On each tray in the solar dryer, nine slices were used as samples whose weight was measured in the morning and evening of each drying day. The poor airflow identified in the 'no load' condition was evident from these measurements taken at the end of the first day of drying (Figure 4).

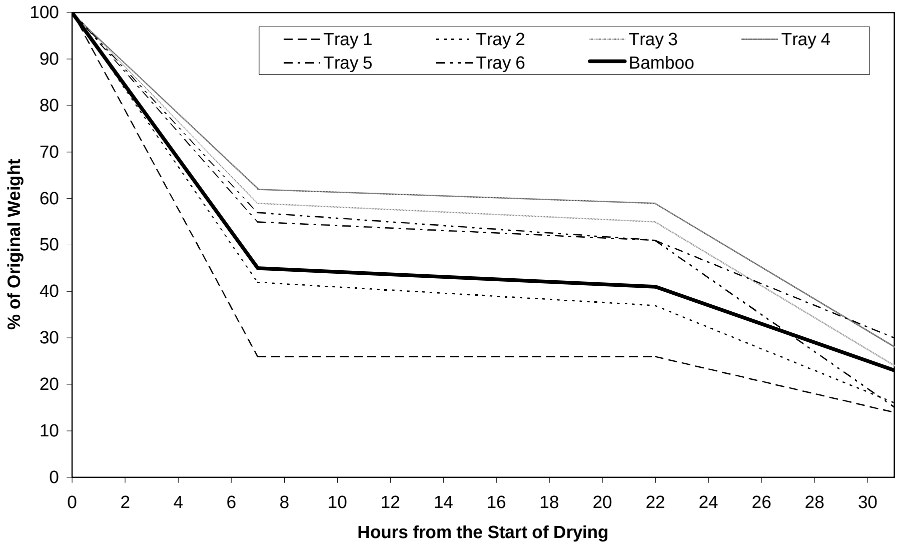

Figure 4 Percentage of original weight of sliced carrot samples during drying trial

The samples on Tray 1 at the bottom of the cabinet experienced the warmest and driest air, and their percentage of original weight lost was the greatest. The adjacent tray, Tray 2, also benefited from being close to the collector outlet. The sample on the bamboo drying tray, however, lost more of its original weight than those on Trays 3-6. Figure 5 demonstrates the temperature variation at various levels in the drying cabinet. Importantly, the temperature of the air at the entrance to the chimney can be seen to be significantly warmer than at Trays 2 and 5, indicating that the heated air is bypassing the trays.

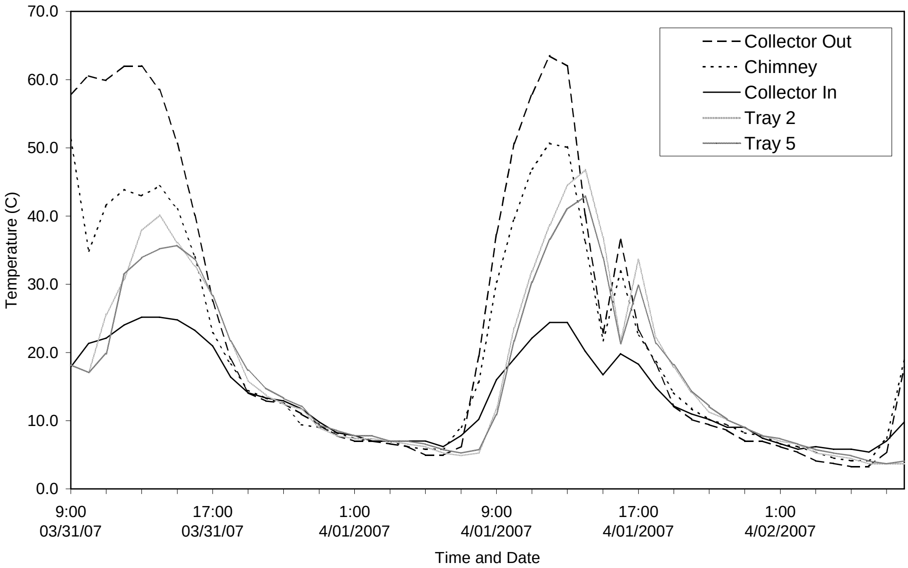

Figure 5 Air db temperatures at various positions in solar dryer

In order to provide the best opportunity for even drying, the tray positions were changed at the start of the second day. All trays were moved one level higher in the cabinet, except Tray 6, which was repositioned at the bottom of the drying cabinet. The effect of the repositioning is evident on Day 2 (hours 23-31) as the samples on Tray 6 now lose the highest percentage of their original weight. Unfortunately there was only one individually weighed sample on the bamboo tray and this sample was somewhat thicker than surrounding slices. Although not evident by sample weight, the slices on the bamboo tray were overall noticeably drier than the other trays. This observation was confirmed by weighing all of the slices on the bamboo tray at the start and end of Day 2.

Since high-resolution weighing scales and a drying oven were not available at the test location, the fresh moisture content of the carrots could not be accurately determined. The moisture content (wet basis) of fresh carrots is approximately 85% (Sandhu et al. 1979; Nayak et al., 2006). By assuming a fresh moisture content level and a desired final moisture content level for safe storage, the level of drying that had been achieved by sun drying could be confirmed. Table 2 indicates that depending on the initial moisture content, the slices on the bamboo tray reached a 10% (wb) moisture content sometime on Day 2.

Table 2 Calculated final weights at 10% (wb) for various fresh weight moisture content levels

Assumed fresh weight moisture content (%wb)	**Dry matter content (%)**	**Water content at 10% (wb) moisture content (gms)**	**Calculated final weight of initial load on bamboo tray (gms)**	**Actual weight of crop on bamboo tray (gms)**	**Day and Time**
80	20	22	118	119	Day 2 - 8am
85	15	17	89	71	Day 2 - 5pm

In the light of the above result, indicating that sun drying was as good or better than the solar dryer evaluated, the total weight of the slices on each of the six solar drying trays was measured at 8am on Day 3. The slices (5%) that were judged to require further drying were removed and also weighed. The final desired weight, assuming initial and final moisture contents of 85% and 10% (wb) respectively, and the actual-to-desired weight ratios were then calculated (Table 4).

Table 3 shows that the slices on Tray 1 appear to have been over-dried. Tray 1 was close to the outlet of the collector on both drying days. The slices on Tray 6 were at the correct moisture content, while all other slices had not reached their desired final weight. The actual-to-desired ratios were confirmed by the percentage of slices on each tray judged to require further drying. Over 70% of these were on Trays 3 and 4, while Trays 1 and 6 had only 2% of the total number that needed further drying.

Table 3 Calculated final weights at 10% (wb) for each tray plus actual final weights achieved

Tray No	Crop fresh weight (gms)	Calculated final desired weight of initial load on tray at initial and final moisture contents of 80% & 10% respectively (gms)	Actual weight of crop on tray (gms)	Actual:desired weight ratio
1	1309	218	179.5	0.8
2	1443	241	258.0	1.1
3	1185	198	280.0	1.4
4	1044	174	236.0	1.4
5	912	152	196.0	1.3
6	846	141	134.5	1.0

6.3 Efficiencies

Based on the calculated mass flow rate and hourly temperature and radiation measurements, the efficiency of the collector was calculated in the 'no load' condition. The collector efficiency ranged from 20-33%, which is considered low for this design. The low mass flow rate is the principle reason for the relatively low range of thermal collector efficiencies. The overall dryer efficiency was calculated assuming that 2.5 days were required to dry 6.7 kg of carrots from 80% to 10% (wb). Since the total solar radiation incident on the collector over the 2.5 days was 63.4 MJ m^{-2}, then the overall drying efficiency, as defined earlier, is approximately 13%. This value is considered low for a forced convection dryer and is another consequence of the low flow rate through the dryer and its poor air distribution.

6.4 Financial Evaluation

The financial viability of the solar dryer for use in the remote villages of Humla Province has been determined. The costs and prices used in the evaluation are shown in Table 4. Suppose a farmer is able to grow enough surplus vegetables in the months of June to October to use the solar dryer continuously. Assuming the drying time for one load is approximately 2-3 days and two loads are dried every week. Assuming there are 21 weeks of drying, then 42 'loads' will be dried. Assuming that the value of the dried crop is equal to the price of fresh produce freighted to Simikot from Nepalganj and the capacity of the dryer is 10 kg, then the value of crop is nearly 35,000 Nepali Rupees (NR) - using the cost of carrots as an example. (A$ 1 = 58 NR). Every year, the difference between operating costs and value of the dried crop is approximately NR20,000. This means that the dryer has paid for itself after nearly two years of operation. Since the dryer should last considerably longer than two years, the solar dryer appears to be a financial proposition. However, since the dryer does not appear to be superior to sun drying, there appears to be little, if any, justification to use the technology in preference to the traditional drying technique.

Table 4 Costs, prices and charges used in financial evaluation of solar dryer

Item	Cost (NR)
Cost of solar dryer ex Kathmandu	30,000
Air freight charge for transporting solar dryer to Simikot, including handling charges	6500
Cost of transportation of solar dryer to remote village	1200
Total capital costs	37,700
Growing costs in village (labour, seed, packaging etc) for 30 days @ NR450 per day	13,500
Transportation costs (porter) to Simikot once per month @ NR200 per day	1000
Total operating costs	*14,500*
Value of 420 kg of fresh carrots in Nepalganj @ NR20 per kg	8400
Cost of air freight for 420 kg of fresh carrots to Simikot @ NR63 per kg	26,460
Total value of dried crop	*34,860*

7. ALTERNATIVE SOLAR DRYER

Apart from the benefits of improved hygiene and rain protection, which can usually be attributed to any solar dryer, the unit evaluated in this paper has no obvious advantages compared to sun drying. In fact, from the perspective of the Humla District, there are several important disadvantages. The unit is manufactured in Kathmandu and has no local material or labour content. It is heavy and fragile, and must be transported first by air and then by donkey or porter to the remote villages. It is also expensive and requires electricity for its operation. An alternative solar dryer that minimises these disadvantages and is superior to sun drying, is required. One possible design is the traditional 'direct' type or Brace dryer. In this design, the crop 'sees' the sun directly and the crop temperature is raised by the direct absorption of solar radiation, rather than convection, as in the solar dryer described in this paper. Direct absorption is a more powerful heat transfer mechanism than convection, its main disadvantage in a dryer being the possibility of crop discolouration.

Such a dryer was tested extensively for drying pineapple slices by Bena and Fuller (2002). Their dryer was made of wood and covered with UV stabilised polyethylene. It was mounted on a stone chamber with air inlet holes at ground level. Driven by natural convection, heated air rose through the drying cabinet and was exhausted through adjustable vents at the top and rear of the cabinet. Their solar dryer had a 25% larger drying area than the Humla dryer, and a calculated drying efficiency of 22%, compared to the 16% efficiency measured in this study. Importantly, the timber parts of a Brace-type dryer could be constructed in Simikot, increasing the local labour content. The user could construct the base of the dryer with local stones. The only imported parts would be the tray mesh and the polyethylene, both of which are lightweight items. Components could be transported more easily. Capital and transportation costs would be significantly lower. In the light of such a comparison, a trial of such a dryer at the HARS site would be instructive.

8. CONCLUSIONS

A solar dryer, commercially available in Nepal, has been evaluated in both the 'no load' and 'full load' conditions during the winter ‘dry season’ in a remote mountain area of the northwest of that country. While caution should always be exercised in drawing definitive conclusions from one trial in a particular climatic season, it is believed that the issues discussed above and main conclusions would not change if other trials were conducted at other times of the year.

In the 'no load' condition, the air mass flow rate through the solar collector was found to be low compared to that of another proven and widely-used design. The solar dryer itself has been designed to encourage the air to flow between the trays in a serpentine path. Measurements above and at the centre of each of the six drying trays failed to record any flow, suggesting that the air was not following this pathway. Some flow could be detected underneath the bottom tray.

In the 'full load' condition, 6.7 kg of sliced carrots were dried in the solar dryer. As a control, approximately 0.5 kg of the same crop were sun dried on a bamboo drying tray. The traditional drying method proved to be equal or better than the solar dryer in terms of uniformity and time taken to dry. To be competitive with sun drying, the trays in the solar dryer had to be repositioned at the start of each day. This action was necessary because the flow of heated air through the dryer does not pass over or through each of the drying trays. In addition, some of the crop from the solar dryer required additional drying.

The solar collector and drying efficiencies were calculated to be 20-31% and 13% respectively. These are considered low for this type of dryer and reflect the low and poorly distributed airflow through the collector and drying cabinet respectively. A simple financial evaluation of the dryer indicated that it could pay for itself in two years, given an ideal set of assumptions. However, given the solar dryer's poor performance compared to sun drying, there appears to be no justification for the additional capital expenditure.

9. REFERENCES

Bena, B. and Fuller, R.J. (2002) Natural convection solar dryer with biomass back-up heater. Solar Energy, 72, 1, 75-83.

CIA (2007). http://www.odci.gov/cia/publications/factbook/geos/np.html

DPH (2004). District Profile of Humla. District Development Committee, Government of Nepal, Simikot (in Nepali), page 10.

Emeriau, S. (2006). Nutritional Exploratory Mission. Humla and Mugu Districts. 21st February to 10th March, 2006. Action Contre La Faim, ACF International Network.

Hagen, T. (1980). Nepal. The Kingdom in the Himalayas. Kummerly + Frey, Geographical Publishers, Berne, Switzerland.

ICIMOD (2003). The International Centre for Integrated Mountain Development. http://www.icimod.org. Table of composite Index of poverty, deprivation, socioeconomic, infrastructural development and women empowerment index: http://www.hdihumla.org.np/remote-districts-of-nepal.htm

Nayak, C.A., Suguna, K. and Rastagoni, N.K. (2006). Combined effect of gamma-irradiation and osmotic treatment on mass transfer during rehydration of carrots. Jnl. Food Eng., 74, 134-142.

Nepal Trust (2007). Health - a basic human right for some ….. The Nepal Trust Organisation, Health Projects http://www.nepaltrust.org/health.html

NPC/UNDP (2005). Nepal Millenium Development Goals. Progress Report, 2005. National Planning Commission and United Nations Development Programme, Kathmandu, Nepal.

Peck, M.K. and Proctor, D. (1983). Design and performance of a roof integrated solar air heater. Solar Energy, 31, 2, 183-9.

Sandhu, B.S., Mannan, K.D., Dhillon, G.S. and Cheema, L.S. (1979). Design, development and performance of multi-rack, natural convection drier. Proc. ISES Congress, Atlanta, Georgia, US, 25-28.

UNDP (2006). Human Development Report 2006. Beyond scarcity; Power, poverty and the global water crisis. United Nations Development Program, New York, USA.

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