Enhancing natural convection solar drying of high moisture vegetables with heat storage

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Abstract: African Leafy Vegetables hold a high potential as an income source for resource poor rural dwellers in Cameroon but this potential has not been realized because of lack of appropriate post harvest packages resulting in high losses. A solar tunnel dryer was designed and constructed using local materials and evaluated for drying leafy vegetables and other agricultural products. Four drying trays made of wood and plastic mesh with a total surface area of 3.25 m^2 were used for drying. The dryer was south facing with an inclination of 6º, and the solar radiation falling on the dryer surface was estimated at 12.13 kJ/m^2 per day. At sunset during the wet harvesting period, the temperature inside the dryer was 5ºC above the ambient because of additional heating due to heat storage. The complete dryer could dry 17 kg of sliced cabbage from 95% moisture content wet basis down to 9% in five days in a period characterized by intermittent downpours and permanent cloud cover. The overall dryer efficiency was 17.68%, with a moisture extraction efficiency of 79.15% and airflow of 9.68 m^3/hr. The relative humidity of the air inside the dryer varied from 75% in the morning down to about 35% at noon. Tests on other high moisture products showed that the dryer could reduce the drying time by 30 to 50% depending on the product and the final product was acceptable in taste and colour.

Keywords: leafy vegetables, post harvest losses, solar dryer, natural convection, sun drying, Cameroon

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1 Introduction

One of the oldest uses of solar energy has been the drying and preservation of agricultural surpluses. The methods used are simple and often crude but reasonably effective. Basically crops are spread on the ground or platforms often with no pre-treatment and are turned regularly until sufficiently dried so that they can be stored for later consumption. Little capital is required on the expenditure of equipment but the process is labour intensive. These technologies have originated in many of the developing countries so there is no major social problem in their acceptance, or in the use by local populations. There are however, several technical problems with this basic drying process, including cloudiness and rain, insect infestation, high levels of dust and atmospheric pollution and intrusion from domestic animals.

These technologies are still a common way of conserving agricultural commodities by small producers in Cameroon. They spread cereals, legumes, fruits and vegetables (including coffee and cocoa) on the ground to dry, sometimes on the road side to take advantage of additional heating by the tarred surface. Since harvesting of the major crops is generally in the months of heavy rainfall, and because of the limitations cited above, the final product is poor in quality and of low market value (Berinyuy, Nguy and Boukong, 1997).

The total number of species of subsistence crops forming the base of agricultural development and cultivation in developing countries is large (Tindal, 1977). A large proportion of this is vegetable, which plays an

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important role in African agricultural and nutritional systems. Westphal (1981) and Stevel (1990) list several varieties of leafy as well as root and fruit vegetables in Cameroon. This diversity is more remarkable in the central and southern parts of the country where rainfall is relatively high. Due to the lack of documentation of their yields and sales, these indigenous vegetables have been regarded as minor crops and have been given low priority in most agronomic research and development programmes, but leafy indigenous vegetables are assuming an increasingly important commercial role especially for farming households living near urban centres (Gokowski and Ndumba, 1997). This potential is however not realized because of a lack of post harvest technologies for conservation that result in very high losses (Berinyuy, Nguy and Boukong, 1997).

Dryers have been developed and used to dry agricultural products in order to improve shelf life (Esper and Mühlbauer, 1996; Mühlbauer, Müller and Esper, 1996; Lutz et al., 1987). Some of these either use an expensive energy source such as electricity (El-Shiatry, Müller and Mühlbauer, 1991; Berinyuy, 2000) or a combination of solar energy and some other form of energy (Sesay and Stenning, 1997) that render the purchasing cost of the dryer become high. Most projects of this nature have not been adopted by end users, either because the holding capacity of the dryer is relatively small to justify the corresponding investment, (Lutz et al., 1987); the final design and data collection procedures are frequently inappropriate or the cost has remained inaccessible and the subsequent transfer of technology from researcher to the end user has been anything but effective.

Use of solar dryers for agricultural purposes in the tropics has often been hampered because crops mature during the peak of the rainy season when frequent downpours and overcast skies are the norm. This often slows down drying, causes rewetting during periods of downpours even in cases where forced convection is used for the dryer (Fagunwa, Koya and Faborode, 2009). The final dry product takes longer to dry and does not have an attractive appearance because of moisture pick up during drying resulting in mould growth. The end result is that the technology is considered unacceptable because it does not meet the end user’s expectations.

The aim of this work was to apply technologies that allow the utilization of renewable energy to improve the food situation and living standards of the rural population in Cameroon. Specifically, this study was set out to modify and test a solar tunnel dryer for drying indigenous vegetables in the high plateau region of Cameroon where during harvest the climatic conditions are characterized by frequent downpours and cloudy weather conditions; design the dryer based on locally available material that allow for production using simple tools; incorporate the storage of heat into the system to overcome periods during which insolation is not sufficient to dry; and evaluate the product quality with respect to colour and taste.

2 Dryer design considerations

Solar dryers maybe designed with the drying trays stacked so that drying progress from the lower tray upwards. In this case, the airflow can be determined using the following equation:

$$\upsilon = a\left(\frac{\Delta P}{h}\right)^b \tag{1}$$

where, v is the air flow in ms^{-1}; ΔP is the pressure drop across the dryer, in Pa; h is the depth of the material being dried in m; a and b are constants (Brenndorfer et al., 1987). The useful energy for drying transferred into the air is given by

$$q_u = M_a C_{pa}(T_e - T_0) \tag{2}$$

For air,

$$M_a = \rho V t \tag{3}$$

where, q_u = useful energy in watts; C_{pa} = Specific heat capacity at constant pressure, in J/kg ºC; T_e and T_0 = exit and entry temperatures respectively from collector in ºC; M_a = mass flow rate in kg/s; ρ= density of the air, kg/m^3; V = volume of air in m^3 and t = time in seconds. Although forced ventilation reduces considerably the drying time, using forced ventilation, even if the fans are solar powered may be suitable for high value crops such as cash crops (Fagunwa, Koya and Faborode, 2009; Esper and Mühlbauer, 1996), but this option is often not available to the rural users of dryers because of the extra cost and their low income.

For natural ventilation, the difference in pressure between the inside and exterior of the drying system can be written as

$$\Delta p = (\rho_0 - \overline{\rho_a})gH \tag{4}$$

where, ρ_0 and $\overline{\rho_a}$ are respectively the density of the air at ambient temperature and the average density of air in the system in kg/m^3, H is the height of the chimney in m and g the acceleration due to gravity (Othieno, 1986). For a temperature ranged between 25℃ and 90℃, the density of air depends on the temperature as follows;

$$\rho = 1.11363 - 0.00308T \tag{5}$$

where, T is the temperature in ℃ (Brenndorfer et al., 1987). Back substituting Equation (5) into (4) and then into (1) gives an equivalent airflow for natural convection as

$$\upsilon = a\left(\frac{0.00308\Delta TgH}{h}\right)^b \tag{6}$$

where, a and b have been given for rice as 0.0008 and 0.87 respectively (Brenndorfer et al., 1987).

Thermal energy can be stored in various media as sensible heat, where the heat gained or lost by the media is given by

$$\Delta Q = m\int_{T_1}^{T_2} C_p dT = V\int_{T_1}^{T_2} \rho C_p dT \tag{7}$$

Although ρ and C_p vary with temperature, average values are usually used so that $\Delta Q = C_p\Delta T$ per unit mass and $\Delta Q = \rho C_p\Delta T$ per unit volume (Swet, 1981). The thermal performance of any type of solar collector can be evaluated by an energy balance that determines the portion of the incoming radiation delivered as useful energy to the working fluid. For a flat plate collector, this energy balance is

$$I_c A_c \overline{\tau_c} \alpha_c = q_u + q_{loss} + \frac{de_c}{dt} \tag{8}$$

where, I_c is solar irradiation on the collector surface, W/m^2; A_c is collector area, m^2; τ_c is effective solar transmittance of the collector cover; α_c is solar absorptance of the collector – absorber plate surface; q_u is rate of heat transfer from the collector absorber to the working fluid, W/m^2; q_{loss} is rate of heat loss from the collector – absorber to the surrounding, W/m^2; and $\frac{de_c}{dt}$ is rate of thermal energy storage at the collector (Kreith and Kreider, 1981). The instantaneous efficiency, n_c, of the collector is the ratio of the useful energy delivered to the total incoming solar radiation expressed as

$$n_c = \frac{q_u}{A_c I_c} \tag{9}$$

where, q_u is as defined in Equation (2) above (Kreith and Kreider, 1981).

3 Materials and methods

The materials used for the tests were mainly African Leafy Vegetables, *Vernonia amygdalina* (bitter leaf), *Amaranthus* spp. (Amaranth), *Brassica* o. (Cabbage), *Capsicum spp*. (African red and yellow pepper), and *Manihot esculenta* (fermented cassava chips). The *Vernonia amydalia* (bitter leaf), *Amaranthus spp*. Amaranth and *Brassica oleracea* (cabbage) were sliced before drying, while the others were dried either as whole fruits or whole leaves.

3.1 Dryer

A natural convection tunnel dryer (Figure 1) adapted from Mühlbauer, Müller and Esper (1996) was constructed using locally available hard wood (*T. scleroxylan and E. escelsa*) and mounted on a wooden structure that could be dismantled. It consisted of a collector, a drying tunnel and a chimney whose role was to facilitate natural convection by the "chimney effect" (Equation (6)). The collector and drying tunnel were 1 m wide by 4 m long each, and rested on wooden columns 0.6 m high. The collector absorber and the dryer floor were made of corrugated aluminum, and painted black to enhance heat absorption. To minimize q_{loss} (Equation (8)), the drying tunnel and the collector had composite walls made of 15 mm thick plywood that sandwich a layer of compacted wood shavings, 5 mm thick. Heat storage was provided to the collector absorber and to the drying tunnel floor by crushed basalt rocks (c_p = 880 J/kg℃) and the whole was covered by two layers of polyethylene sheets. Air intake was from the bottom of the collector and travelled bellow and above the collector absorber, thereby following a double pass (Figure 2) and a deflector made of aluminum that was provided between the two passes to reduce the angle of turn thereby reducing heat loss by eddies. The chimney base, made from aluminum sheets measured 1 m by 0.7 m and by 0.9 m high, connected to a 12-cm PVC pipe, was 3.8 m high. The whole chimney was also painted black.

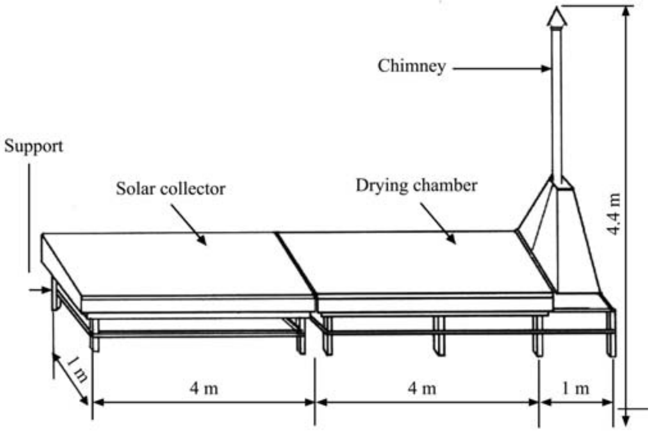

Figure 1 Solar tunnel dryer with integrated collector and chimney built for drying vegetables

During the operation, air from the collector moved into the drying chamber where it passed simultaneously, over and below the product suspended on drying trays (Figure 2). The exhaust air then moved through the chimney after heat and moisture exchange with the drying product.

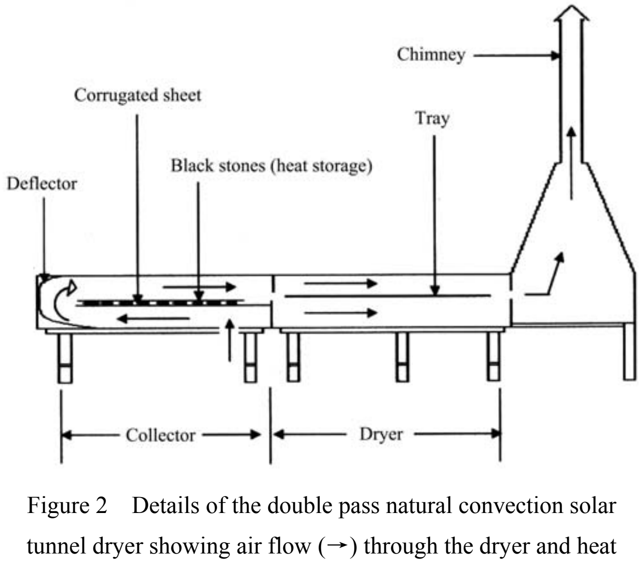

Figure 2 Details of the double pass natural convection solar tunnel dryer showing air flow (→) through the dryer and heat storage

3.2 Instrumentation

To determine the thermal behavior of the collector and dryer various data were measured throughout the experiments. Temperatures were measured at two-hour intervals, with a multi -channel OMEGA thermocouple reader connected to gauge 30 copper -constantan thermocouples located at 26 points (Figure 3) in both the dryer and collector. The temperature at any particular point, T_i, was taken as the average on opposite points, A and B, of each wall. The temperatures at each point were then summed and averaged over the number of days the readings were taken. The relative humidity was determined using the wet bulb depression technique, and the air flow was calculated using Equation (6) with T, the average temperature of the dryer and the constants as stated by Brenndorfer et al. (1987). Moisture contents were determined by the oven drying technique in a forced convection oven (Cole Parmer) and samples were weighed with an Ohauss GT8000 digital scale with a resolution of 0.001 g. During drying the product weight loss was measured on a digital scale (AND – FV – 30K) with a capacity of 31 kg and a resolution of 0.01 kg.

The empty dryer was monitored for seven days in early July from 06.00 to 18.00 hours each day and then filled with different products through July and August when there are frequent downpours and the sky is generally overcast.

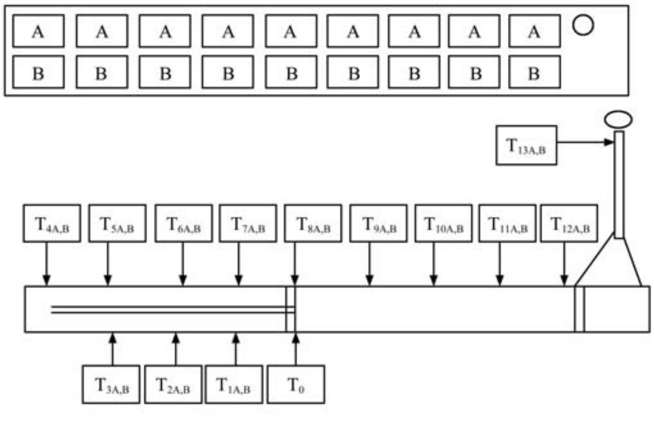

Figure 3 Arrangement of thermocouples in the dryer, T_0 measured ambient temperature and T_{13} measured the temperature at the extremity of the chimney

4 Results and discussions

4.1 Dryer performance

A solar tunnel dryer was constructed using local materials (Figure 4) and evaluated for drying different agricultural products. Four drying trays made of wood and plastic mesh with a total surface area of 3.25 m^2 were used for drying. The dryer was south facing with an inclination of 6º; hence the solar radiation falling on the dryer surface was estimated using Brenndorfer et al. (1987) at 12.13 kJ/m^2 per day. The solar parameters and characteristics of the dryer are shown in Table 1. The complete dryer could dry 17 kg of sliced cabbage from 95% moisture content wet basis down to 9% in five days with an average efficiency of 17.68%, an average moisture extraction efficiency of 79.15% and average airflow of 9.68 m^3/hr. The relative humidity of the air inside the dryer varied from 75% in the morning down to about 35% at noon.

Figure 4 The assembled solar dryer ready for use

Table 1 Some dryer characteristics measured during the trials

Parameter	Value
Solar incident radiation on the collector	12.126 KJ m^{-2} day^{-1}
Airflow through the dryer	9.68 m^3 hr^{-1}
Global Efficiency of the system	17.68%
Moisture pick up efficiency	79.15%

The temperature profile inside the drying chamber depends on various parameters such as solar radiation, ambient temperature and relative humidity, moisture content of the crop, thermophysical properties of the crop and the storage capacity of the rocks. Tests with the empty dryer showed that morning temperatures within the dryer are comparable to those outside. They increased gradually to a maximum of 61.9℃ at about noon (T_8 as is shown in Figure 3) and then fall progressively towards evening (Figure 5). A maximum temperature of 75℃ was actually obtained at this point on a clear sunny day. The steady increase in temperature indicates that heat losses from the dryer were at a minimum.

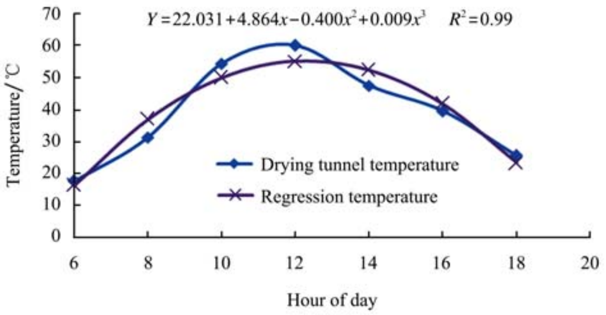

Figure 5 Temperature profile inside the drying chamber

4.2 Effect of heat storage

To assess the efficiency of the collector, the temperature difference between the collector and the outside was plotted (Figure 6). The difference between the ambient temperature and that inside the dryer varied from 0 ºC at sunrise to a maximum of 34℃ at noon. At sun set a temperature difference of 5.2℃ was still apparent between the air in the dryer and that outside, permitting drying to continue. This extra heat in the dryer was definitely due to the heat storage in the system. Although this could cause convection to draw in cold air and thereby induce rewetting of the drying commodity, we did not, notice this. Our monitoring showed that the temperature of the chimney dropped faster than that of the dryer in the evening. This would slow down the “chimney effect, thereby trapping warm air in dryer which could only escape slowly by transmission through the cover or by convection through the dryer walls. These means of heat exit were already minimized through insulation of the dryer box. Transmission of long wave radiation through the cover is slow. The product thus stayed longer in warm low humidity air and drying the following day resumed with very little moisture gain.

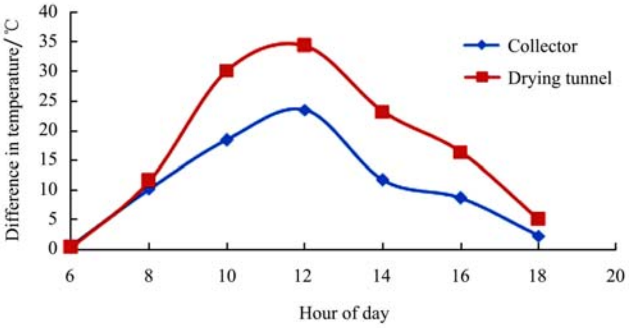

Figure 6 Temperature difference between the ambient air and the air in the system

The temperature of the air inside the system rose faster at the first pass through the collector than the second (Figure 7). However, a regression of the data shows a progressive increase along the whole length of the system. This rise in the afternoon was uniform, whereas in the morning it was not so apparent. This is probably explained by the fact that by afternoon, the dryer elements have absorbed enough energy to continue heating the air even when the direct radiation is not so apparent.

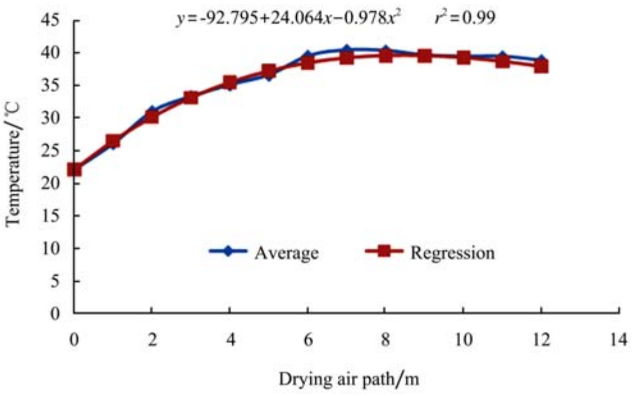

Figure 7 Average temperature variation along the air path in the drying system

4.3 Dryer performance on some vegetables

Table 2 shows that considerable time is gained by drying using the solar dryer as compared to direct natural drying. At the end of the drying cycle, the moisture content in the solar dried cabbage is half that of the sun dried one. Comparison of natural air drying and drying using the adapted dryer shows that the product under natural drying contained twice as much water after three days than that dried in the solar dryer (Figure 8). The kinks on the curve indicate over night periods when no drying was taking place. Although this was not tested, an improvement could include installing a slider over the air intake to reduce air flow during periods of no drying. These results show a 50% improvement on the drying time over sun drying. This means that the product in the dryer has less time of being infested by mould and other micro-organisms, and that the product is ready for packaging or storage sooner.

Since the drying produce was left in the dryer during downpours and over night, some moisture pick up during these intervals, with drying continuing the next sunlight period. In spite of these, the regression of the data for the whole drying period for the vegetables showed that drying did follow a standard exponential decay. The correlation coefficient r^2 in each case was greater than 0.7 and for red pepper (*Capsicum annuum*) and cabbage (*Brassica oleracea*), and this was higher than 0.9 showing a very good fit.

Table 2 Results of drying trials on some high moisture agricultural commodities

Product	Initial Moisture content % w.b.	Final Moisture Content % w.b.	Drying time/h
Amaranth (*Amaranthus spp.*)	87.9	2.9	30
African red pepper (*Capsicum annuum*)	80.9	10.8	96
Sliced Green cabbage (*Brassica oleracea*)	95.6	9.8	130
Sliced Bitter leaf (*Vernonia amydalina*)	84.3	1.2	30
Sliced Ripe plantains (*Musa acuminata*)	75.3	20.8	100
African yellow pepper (*Capsicum annuum*)	86.8	13.4	336
Fermented cassava chips (*Manihot esculenta)*	60.0	10.0	168

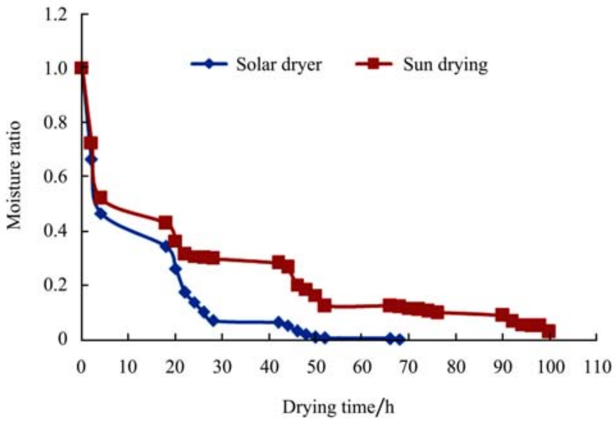

Figure 8 Drying curves of sun dried and solar dried sliced cabbage in the tunnel dryer

The estimated airflow of 9.68 m^3/hr is comparable with natural convection systems (Weka, 1999). The overall efficiency of 17.68% indicates that the percentage of energy absorbed by the collector and used to dry the product is low, but this value is similar to that reported by Brenndorfer et al. (1987). The moisture extraction efficiency was 79.15% and had resulted in good drying of the high moisture vegetables within an acceptable time limit. With an initial moisture content of 80% wet basis, bitter leaf was successfully dried to a moisture ratio of less than 0.1 in three days. Compared with amaranth, (*Amaranthus spp*.) which was not sliced, bitter leaf (*Vernonia amydalina*) dried faster (Figure 9), suggesting that pretreatment might play an important role in the efficient use of the dryer for drying leafy vegetables.

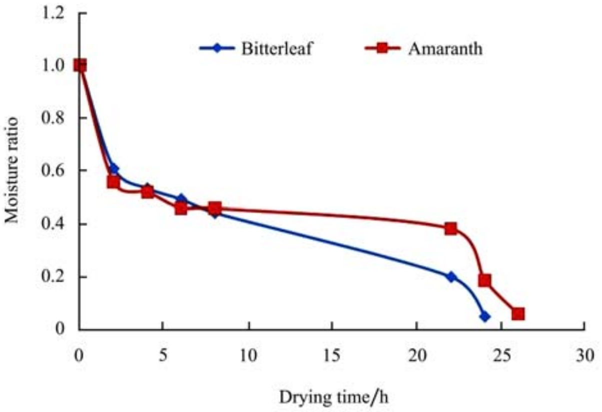

Figure 9 Drying curves of Amaranth and Bitter leaf in the solar dryer

4.4 Quality evaluation

The appearance and taste of the final product dried with the dryer was also better than that produced through sun-drying. Sun dried cabbage was darker in colour and tasted sour. This, together with the fact that a good quantity of the vegetables can be dried within a short period, means that the producer can have a higher turnover for a better quality product. The chances of better revenue are, therefore, high.

4.5 Operating cost

The main operating costs for the dryer are for labour and pretreatment of the vegetables. These are low in the rural sector where family labour is abundant. The polyethylene cover will need to be replaced periodically, but this is a low cost item as well. Analyses on the operation of drying using green pepper (*Capsicum annuum*) during the raining season showed that the initial high investments can get payback in 18 months. If other commodities are dried, and the dryer is used during the dryer months when the drying conditions are even better, this payback period will be much shorter.

5 Conclusions

A solar tunnel dryer with double pass and heat storage was constructed and tested for drying high moisture vegetables and other commodities. The investigations with cabbage, amaranth, bitter leaf and pepper showed that using this solar drying system leads to a significant reduction in drying time and an improvement of the product quality. The results further show that heat storage permits continuous drying during periods of low sunshine. The reduction in drying time was between 30% and 50% depending on the crop compared to natural sun drying. The quality of the final product is acceptable in taste and appearance. Although the initial cost is relatively high, the running cost is low and the payback period is less than two years. Heat storage therefore permits drying to continue even when the environmental conditions such as rainfall and high relative humidity make it difficult for open-air sun drying to take place.

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