Journal of
Renewable and Sustainable Energy

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Citation: J. Renewable Sustainable Energy **4**, 063129 (2012); doi: 10.1063/1.4769199

View online: http://dx.doi.org/10.1063/1.4769199

View Table of Contents: http://jrse.aip.org/resource/1/JRSEBH/v4/i6

Published by the American Institute of Physics.

Design and performance evaluation of solar dryer for drying of large cardamom (*Amomum subulatum*)

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(Received 21 July 2012; accepted 14 November 2012; published online 29 November 2012)

A solar dryer was designed, fabricated, and evaluated for drying of large cardamom (*Amomum Subulatum*) at College of Agricultural Engineering and Post Harvest Technology, Central Agricultural University, Ranipool (27° 20′ N, 88° 40′ E), Gangtok, Sikkim. It was observed that on an average 55.7% of higher temperature was obtained in the solar dryer over the ambient temperature. A total drying time of 24 h (3 sunny days) was required for large cardamom drying in the solar dryer to reduce the moisture content from 75.6% (w.b.) to 10.1% (w.b.) compared to that of 48 h for the open sun drying to obtain the same level of moisture contents resulting in a net saving of about 50% of drying time for the solar dryer in comparison to the open sun drying. © *2012 American Institute of Physics*. [http://dx.doi.org/10.1063/1.4769199]

NOMENCLATURE

m_f	final moisture content, %
m_i	initial moisture content, %
W	weight of product, kg
M_w	mass of water to be removed during drying, kg
t_d	assumed drying time, h
w.b.	wet basis
C_p	specific heat of water, kcal/kg °C
T_d	drying temperature, °C
T_a	ambient temperature, °C
λ	latent heat of vaporization, kcal/kg
Q	total energy required, kcal
Q_t	energy required, kcal/h
I_t	solar radiation, kcal/m^2 h
η	collection efficiency, %
Q_g	heat gained by the drying air, kcal/h
m	mass flow rate, kg/h
Ca	specific heat of air, kcal/kg °C
T_1	ambient temperature, °C
T_2	dryer air temperature, °C
Q_c	heat received by the collector, kcal/h
I	solar radiation, W/m^2
A_c	area of collector, m^2
η_c	hourly collector efficiency, %

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I. INTRODUCTION

India, the largest producer of large cardamom (*Amomum subulatum*) in the world with share of about 54%, exports about 1000 metric ton each year of large cardamom to the Western and Arabic countries.[1] About 95% of large cardamom is produced in the hilly terrains of Sikkim in the Eastern Himalayas and other North Eastern states.[1] Large cardamom is a tall perennial herb growing up to 2.5 m in height. Fruits of large cardamom are harvested during the months of September to November. Fresh large cardamom fruits contain about 80% of water, which is reduced below 10% after drying, to store for longer duration.

Large cardamom is extensively used for flavouring vegetables and many food preparations in India and other parts of the globe because of its pleasant aromatic odour and high medicinal values.[2] Farmers use wet wood log to dry the green capsules (pods) of large cardamom by smoking over open wood fire.[3] The wood consumption by the traditional process is estimated to be approximately 40 000 Metric ton per year.[4] This is a traditional method used for centuries to dry any food item. The large cardamom produced in the tradition way is brownish black and contains about 1.5% to 2.3% essential oil in the seeds. The spice value of the large cardamom depends on the quality of essential oil present in the seed. There is an urgent need of proper drying of the large cardamom to retain its medicinal value and typical characteristic flavour and aroma as the green capsules having more than 80% of water deteriorate fast. Thus, the green capsules of the large cardamom have to be dried immediately after harvest. The "traditional furnace" used for drying of large cardamom is made with locally available construction materials, viz., mountain rocks or stones, bamboo or wire mesh mat, and wooden frame, etc.[3] The "traditional furnace" has thick stone walled structure on three sides, top opening covered with a bamboo or wire mesh mat, and a wide opening on the front wall for feeding of large size wood logs for burning. The average size of a furnace is 3 $\times$ 3 m with height of 1.5 m.

Fresh cardamom capsules are spread, in 0.21 to 0.31 m thick bed, over the bamboo or wire mesh mat for drying. The farmers use freshly cut wooden logs for drying of cardamom as dry fuels are generally not available during the harvesting season in Sikkim. The large cardamom bed is exposed to the thick smoke generated during the burning of the wet wood, which destroys the true colour and flavour of large cardamom. The quantity of essential oil in the seeds of large cardamom is reduced and it leads to the smokey smell as well. The lack of control of fire in the traditional drying process leads to overheating which causes charring and reduction of volatile oil content. The traditional drying process takes about 48 to 72 h and consumes about 10 kg of firewood per 1 kg of dried large cardamom.

Open sun drying, one of the oldest techniques employed for processing agricultural and food products, has been traditionally practiced in India for drying agricultural products.[5] Considerable savings can be made with the open sun drying since the source of energy is free and sustainable. However, this method of drying is extremely weather dependent and has to face the problems of contamination, infestation, microbial attacks, etc., thus affecting the product quality. Additionally, the drying time required for a given commodity is quite long and results in post-harvest losses.[6]

Solar drying relies, as does the sun drying, on the sun as its source of energy. However, the solar drying differs from sun drying. In solar drying, a structure, often of very simple construction, is used to enhance the effect of the solar radiation. Compared to the sun drying, solar dryers can generate higher air temperatures and consequential lower relative humidity, which are, both conducive to improved drying rates and lower final moisture content of the drying crops.[6] This method has several advantages such as less spoilage and less microbiological infestation, which leads to improved and more consistent product quality. Solar drying can also be a feasible alternative to those natural convection dryers that use wood or agricultural waste products as fuel. The saving of wood would probably be the main attraction of solar dryers, which ultimately would help in saving the precious and fast-dwindling forest-natural resources in India. Solar drying of agricultural products in enclosed structures by natural and forced convection is an attractive way of reducing post-harvest losses and low quality of dried products associated with the traditional sun-drying methods.

Solar dryers are generally classified into two basic categories: the passive (natural-convection) dryers and the active (forced-convection) dryers.[7] The principle of the natural-convection aeration is based on the temperature difference and, consequently, the difference in the density of the air inside and outside the drying chamber. The main features of the natural-convection dryers are as follows: (i) No need of any mechanical or electrical power to run a fan, (ii) simple to construct, (iii) easy to maintain, and (iv) inexpensive. On the other hand, the working mechanism is strongly dependent on the temperature difference and the pressure drop, which occurs when the air is forced through the crop.[7] The forced-convection solar dryers generally have several advantages such as high reliability.[8] On the other hand, forced-convection dryers require a cover to force the air through or over the product, and in contrast to the natural-convection dryers the forced convection dryers are dependent on electrical power.[8] Hence, the electricity costs have to be compensated with the reduction in drying time, higher drying capacity, reduction of mass losses, and better quality of the product.

II. DESIGN OF SOLAR DRYER

The purpose of drying is to reduce the moisture content of the product to a safe level to minimize the deterioration of the quality of product during storage. The drying rate of the product is controlled by the rate at which the product's internal moisture is released from its surface and the rate at which the moist air is removed from the area surrounding the product.[8] A suitable size forced-convection type solar dryer for drying large cardamom was designed for the humid climatic conditions of Sikkim state located in the northeast region of India. The forced-convection type solar dryer was designed to bring down the moisture content from about 80% (w.b.) to 10% (w.b.) during the drying process of large cardamom. The conditions and assumptions summarized in Table I were used for the design of the dryer.

A. Design procedure

The size of the dryer was determined as a function of the drying area needed per kilogram of fresh large cardamom. The drying temperature was established as a function of the maximum limit of temperature which the fresh large cardamom may support.

The following procedure was adopted in the design of solar dryer for drying large cardamom.

The mass of water to be removed during drying, M_w, kg,

$$M_w = \frac{m_i - m_f}{100 - m_f} \times W. \tag{1}$$

The mass of water removed per hour m_w, kg/h,

TABLE I. Design conditions and assumptions for design of the solar dryer.

Items	Condition or assumptions
Location	Ranipool, Gangtok (27° 20′ N, 88° 40′ E)
Orientation	South facing
Product dried	Large cardamom
Drying period	December, 2010
Loading capacity	5 kg per batch
Initial moisture content	75.6% (w.b.)
Final moisture content	10.1% (w.b.)
Sunshine hour	8 h
Drying period required	24 h
Global solar radiation (I) for Gangtok region	5.1 kWh/m^2
Glazing materials	Glass
Air circulation mode	Forced convection

$$m_w = \frac{M_w}{t_d}. \tag{2}$$

The total energy required Q kcal,

$$Q = W \times C_p \times (T_d - T_a) + (M_w \times \lambda). \tag{3}$$

The energy required per hour Q_t kcal/h,

$$Q_t = \frac{Q}{t_d}. \tag{4}$$

Collector area required, A_c m^2,

$$A_c = \frac{Q_t \times 100}{I_t \times \eta}. \tag{5}$$

B. Construction of the solar dryer

The materials used in the construction of the solar dryer are frame structure, box, insulation, glazing, drying trays, and exhaust fan. These materials should be cheap and easily available in the local market. Fig. 1 shows the essential features of the dryer including the solar collector cum drying chamber and drying trays.

1. *Frame structure*

The frame structure consists of legs, base frame, and a supporting frame. The mild steel angle of $19 \times 19 \times 3$ mm was used to fabricate the base frame. On the other hand, the mild steel angle of $25 \times 25 \times 3$ mm was used in the fabrication of the supporting frame of the solar dryer. This frame structure was mounted on six legs each of 0.8 m height.

2. *Box*

The box consists of an angle iron frame. The sheets with the galvanised iron sheet cover were fixed on the back, top, and one side of this box for the insulation. The insulated door was

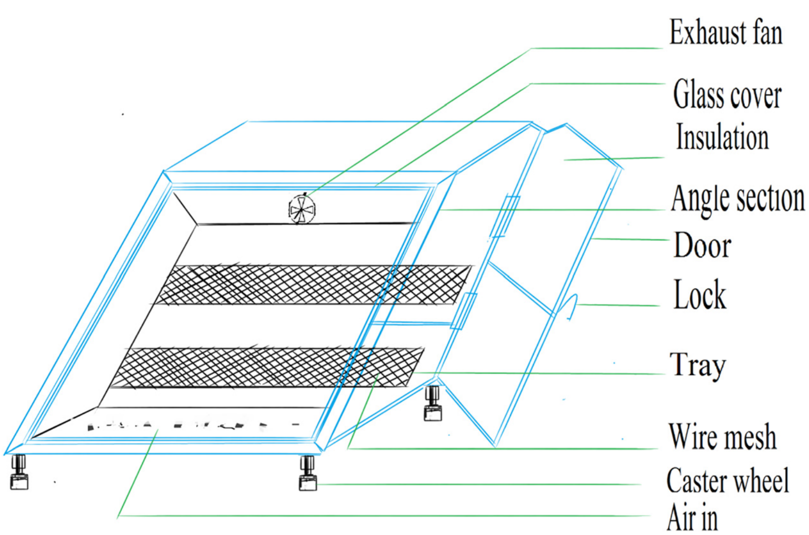

FIG. 1. Sectional view of the solar dryer.

fitted on the other side of this box to facilitate the loading and the unloading of perforated trays. The food items to be dried were spread evenly over the perforated trays for drying.

3. Insulation

The bottom and the sides of the solar dryer were insulated with the thermocole sheet. The insulation was provided in the solar dryers to minimize the heat loss from the system.

4. Glazing

The glazing was fixed on the front of the frame for the interception of solar energy. The ordinary glass of 4 mm thickness was used for this purpose.[9]

5. Drying trays

The drying trays were contained inside the drying chamber and were constructed from wire mesh and angle iron with a fairly open structure to allow drying air to pass through the large cardamom. There were two perforated trays.

6. Exhaust fan

The hot air produced inside the drying chamber due to the solar energy was circulated methodically in the solar dryer with the help of a direct current fan (100 W capacity). The exhaust fan was fitted on the opposite wall of drying chamber of the solar dryer. The exhaust fan helps in faster removal of moisture from the product.

III. DIMENSIONS AND DESCRIPTION OF SOLAR DRYER

The solar dryer is designed as per the procedure mentioned in Sec. II and its dimensions are given in Table II. Figure 2 shows the different parts of the solar dryer designed and developed at solar yard, College of Agricultural Engineering and post Harvest Technology, Central Agricultural University, Ranipool (27° 20′ N, 88° 40′ E), Gangtok, Sikkim, India for drying large cardamom. The detailed description of these parts of the solar dryer is given in Sec. II B.

IV. PERFORMANCE EVALUATION OF THE SOLAR DRYER

The performance evaluation of the solar dryer to dry large cardamom was carried out at the solar yard, College of Agricultural Engineering and Post Harvest Technology, Central Agricultural University, Ranipool, Gangtok, Sikkim, India. The test to evaluate the performance of the solar dryer includes the measuring of the solar radiation, the ambient temperature, the ambient relative humidity, wind velocity, air flow rate inside the dryer, air temperature, and relative humidity inside the solar tunnel dryer.[9] During the full load testing of solar dryer, three days are required for drying the total amount of large cardamom in the solar dryer from moisture

TABLE II. Dimensions of solar dryer.

Components	Specifications
Aperture area	0.39 m^2
Front base of solar dryer	0.63 m
Width of solar dryer	0.62 m
Number of trays	Two
Tray size	620 × 350 × 50 mm
Loading per batch	5 kg
Drying time per batch	3 days
Inclinations of the dryer	45°

FIG. 2. Closed view of solar dryer for drying of large cardamom.

content of 75.6% (w.b.) to 10.1% (w.b.). The testing on the full load was carried out for three consecutive days in the month of December, 2010 under the lab conditions at the College of Agricultural Engineering and Post Harvest Technology, Ranipool, Gangtok, Sikkim located in the northeast India.

A. Temperature and solar radiation variation

1. First day of drying

Figure 3 shows a first day of drying results of the hourly variation of the temperatures in the solar collector cum drying cabinet compared to the ambient temperature. It was observed

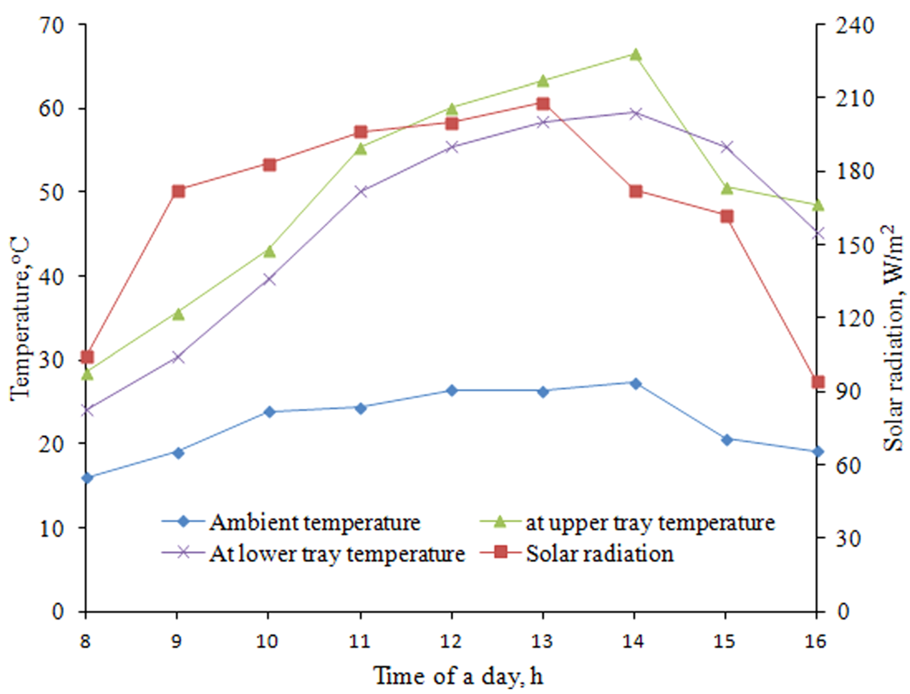

FIG. 3. Variation of solar dryer air temperature and solar radiation during the month of December, 2010 in first day of drying stage.

that the maximum temperature inside the solar dryer in the upper and the lower trays was found to be 66.5 °C and 59.5 °C at 14 h, respectively, and the minimum temperature inside the solar dryer in upper and lower trays was found to be 28.5 °C and 24.1 °C at 8 h, respectively, in the month of December, 2010. The maximum ambient temperature was 27.3 °C at 14 h while the minimum temperature was 16 °C at 8 h in month of December, 2010. It was also observed that the maximum solar radiation in December was found to be 208 W/m^2 at 13 h. On the other hand, the minimum solar radiation in December was found to be 94 W/m^2 at 16 h.

2. Second day of drying

Figure 4 shows the second day of drying results of the hourly variation of the temperatures in the solar collector cum drying cabinet compared to the ambient temperature. It was observed that the maximum temperature inside the solar dryer in upper and lower trays was found to be 70.3 °C and 60.3 °C at 14 h, respectively, and the minimum temperature inside the solar dryer in upper and lower trays was 30.4 °C and 29.1 °C at 8 h, respectively. The maximum ambient temperature was 27.6 °C at 14 h while the minimum ambient temperature was 16.4 °C at 8 h in the month of December, 2010. It was also observed that the maximum solar radiation in this month was 207 W/m^2 at 13 h and the minimum solar radiation was 90 W/m^2 at 16 h, respectively.

3. Third day of drying

Figure 5 shows a third day of drying results of the hourly variation of the temperatures in the solar collector cum drying cabinet compared to the ambient temperature. It was observed that the maximum temperature inside the solar dryer in upper and lower tray was 72.4 °C and 66.9 °C at 14 h, respectively, and the minimum temperature inside the solar dryer in upper and lower tray was 30.5 °C and 28.1 °C at 8 h, respectively, in the month of December, 2010. The maximum ambient temperature was 27.4 °C at 14 h while the minimum was 19.4 °C at 8 h in the month of December, 2010. It was observed that the maximum solar radiation in this month was 209 W/m^2 at 13 h and the minimum solar radiation was 98 W/m^2 at 16 h, respectively. The

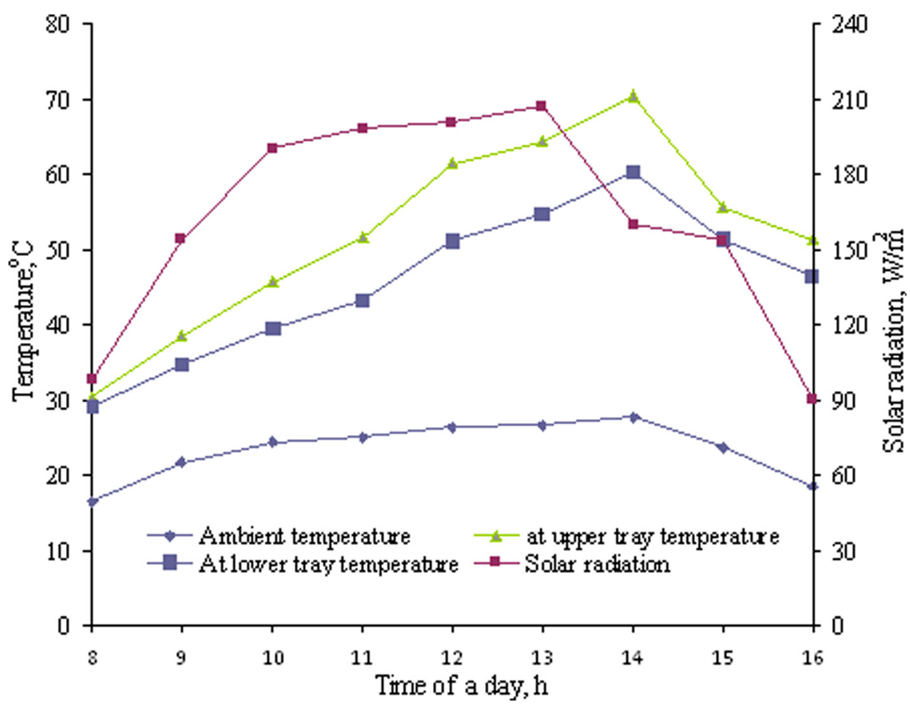

FIG. 4. Variation of solar dryer air temperature and solar radiation during the month of December, 2010 in second day of drying stage.

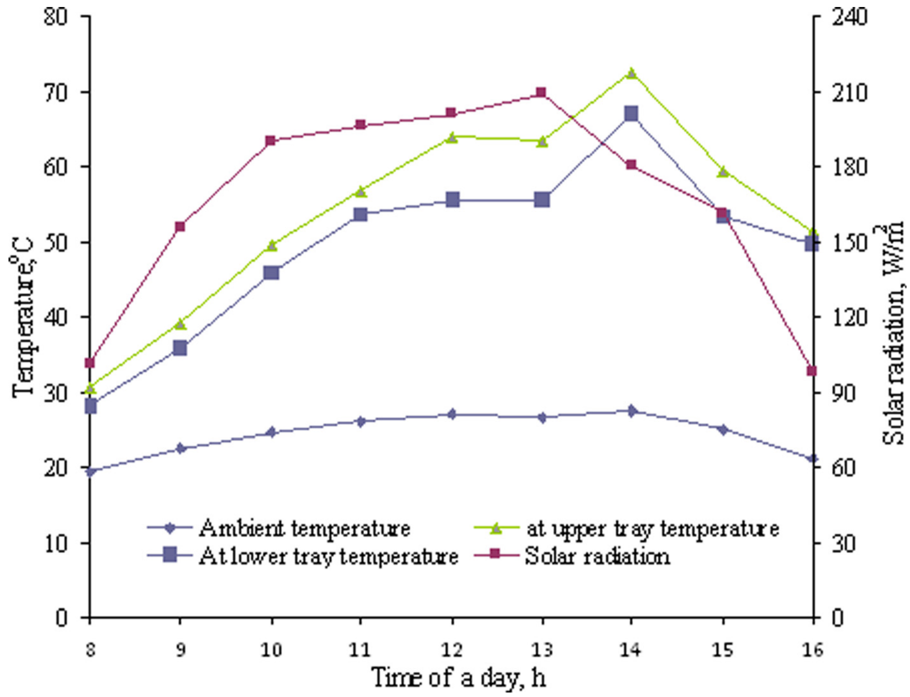

FIG. 5. Variation of solar dryer air temperature and solar radiation during the month of December, 2010 in third day of drying stage.

drying air temperatures of present study was 55–60 °C and those of Eddy *et al.* (1991) and Medugu (2010) were 58–62 °C, respectively.

B. Moisture content variation

Figure 6 shows the comparison of the variations of the moisture content with the time during solar drying of large cardamom with those of the sun drying for a typical experimental run. The initial moisture content of the material (large cardamom) in the upper and the lower trays inside the solar dryer was 75.6% (w.b.). On the other hand, the moisture content in the upper and the lower trays was 54.3% (w.b.) and 55.1% (w.b.), respectively, at the end of the first day

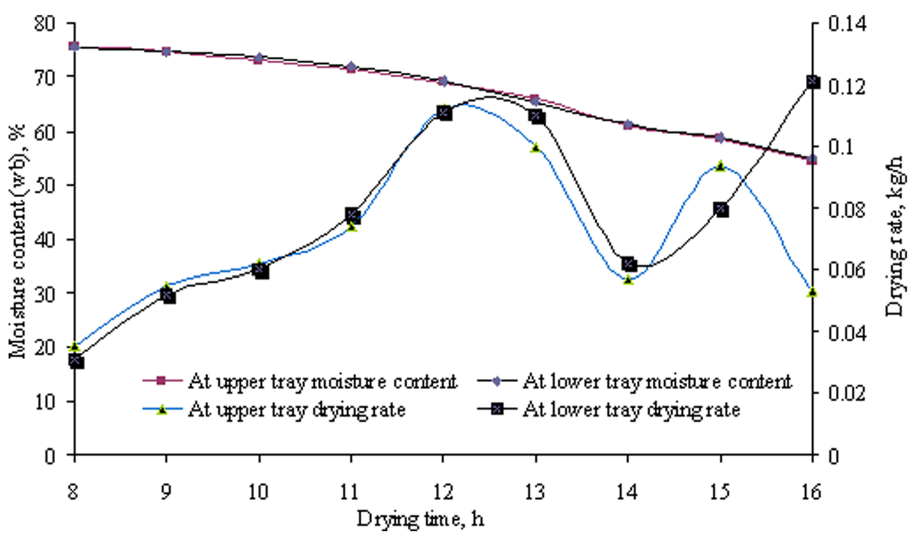

FIG. 6. Variation of moisture content and drying rate with time during the month of December, 2010 in first day of drying stage.

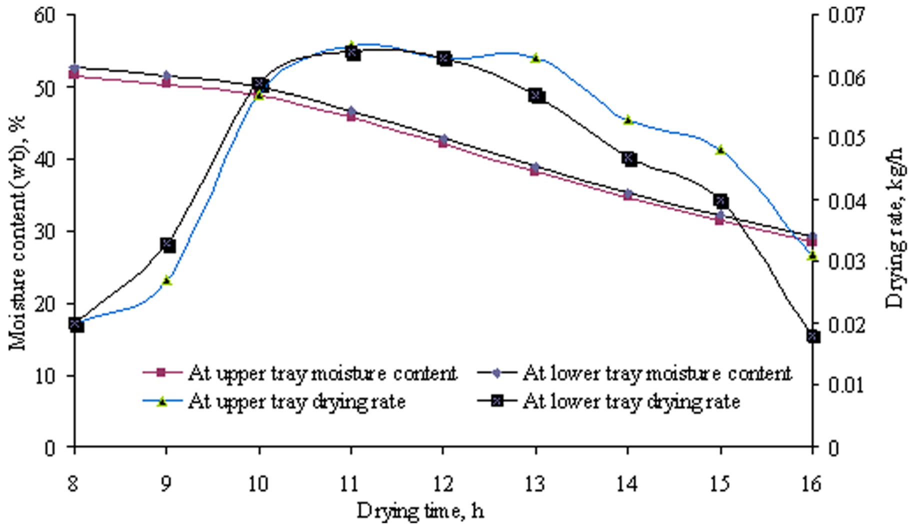

FIG. 7. Variation of moisture content and drying rate with time during the month of December, 2010 in second day of drying stage.

of experiment. The moisture content of large cardamom at the start of the second day of experiment in the upper and the lower trays was 51.6% (w.b.) and 52.5% (w.b.), respectively, and the moisture content at the end of second day of experiment was 28.4% (w.b.) and 29.2% (w.b.), respectively (Fig. 7). The moisture content of large cardamom on wet basis in the upper and the lower tray of solar dryer was found to be 26.1% and 27.9% (10.1% each), respectively, at the start of third day (at the end of third day), as shown in the Fig. 8. It is observed that large cardamom drying up to 10.1% moisture content (w.b.) witnessed in the present study was found to be similar to that of the results obtained in the study by Mande *et al*. (1999).

C. Efficiency of the dryer

Efficiency in a drying system is normally reported as: dryer efficiency, heat collection efficiency, collector efficiency. Efficiency in a drying system is specified by the change of the ratio at the specific humidity extraction.[10]

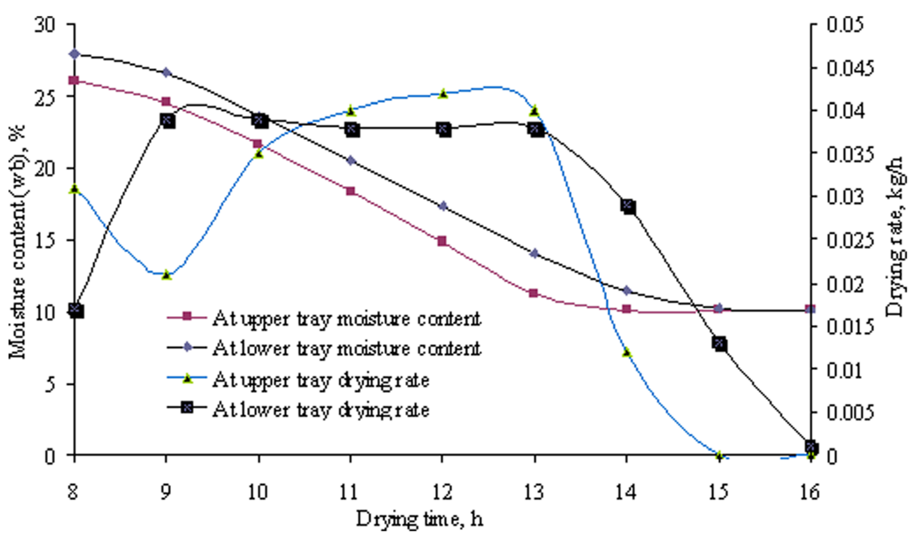

FIG. 8. Variation of moisture content and drying rate with time during the month of December, 2010 in third day of drying stage.

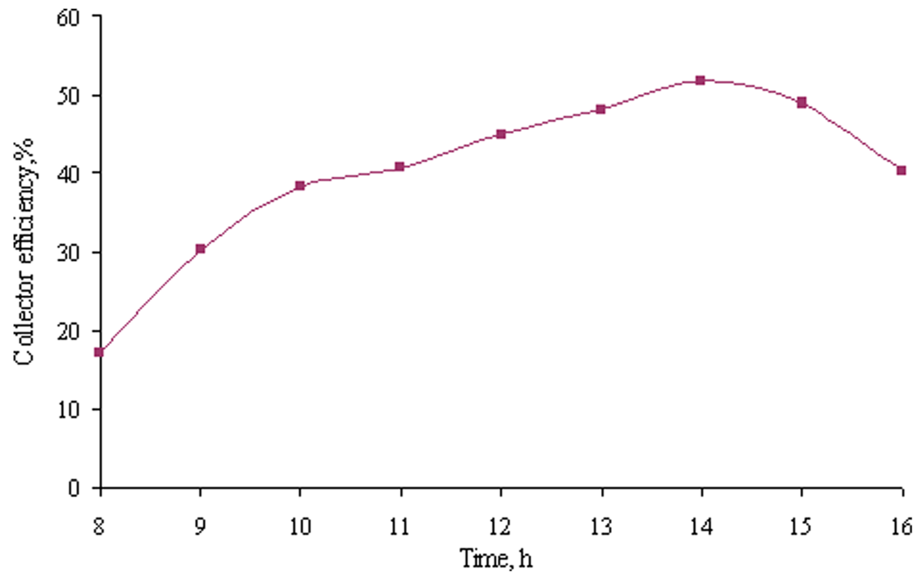

FIG. 9. Collector efficiency of solar dryer with time for drying of large cardamom in the month of December, 2010.

1. Heat gained by drying air

Heat gained by air in the solar tunnel dryer was calculated by using the formula,

$$Q_g = m\,C_a(T_2 - T_1). \tag{6}$$

2. Heat received by the collector

The heat received by the collector was calculated using the formula,

$$Q_c = I \times 0.86 \times A_c. \tag{7}$$

3. Solar collector efficiency

$$\eta_c = \frac{Q_g}{Q_c} \times 100. \tag{8}$$

Figure 9 indicates that the efficiency of the solar collector is varying from 17.23% to 51.71% in the month of December. The maximum collector efficiency of 51.71% was attained at 14:00 h. The average collector efficiency was found to be 40.02%. It is observed that the collector efficiency of the dryer witnessed in the present research was found to be more or less same as those of Forson *et al.* (2007) and Gatea (2011).

V. CONCLUSIONS

The solar dryer designed and developed for large cardamom (*A. subulatum*) drying at the solar yard, College of Agricultural Engineering and Post Harvest Technology, Ranipool, Gangtok, Sikkim, India is capable of producing the optimum temperature in the range of about 55 °C to 60 °C for drying of large cardamom. The solar dryer with total collector area of 0.39 m^2 is capable of drying about 5 kg of fresh large cardamom in 24 h. The solar drying helped to reduce the drying time from 48 h to 24 h for the same level of moisture contents in comparison to the open sun drying of large cardamom. The average collector efficiency of solar dryer for drying large cardamom was 40.02% in the month of December. The large-scale use of the solar dryer designed, fabricated, and evaluated at the College of Agricultural Engineering and Post Harvest Technology, Ranipool, Gangtok, Sikkim would definitely help to prevent the deforestation in northeast India, a high bio-diversity rich region and with some of the sub-continents last remaining rainforests, by saving the precious forest wood for drying of large cardamom in comparison to the traditional drying of large cardamom in the "traditional furnace" in the hilly terrains of the northeast India.

ACKNOWLEDGMENTS

The authors thank the Dean, College of Agricultural Engineering and Post Harvest Technology, Ranipool, Gangtok, Sikkim (India) for providing the facilities and assistance in conducting the research work. The authors gratefully acknowledge the critical reviews of the anonymous reviewers and the Editor, which eventually helped in improving the quality of the paper.

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