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# Thermal Investigation and Food Quality Analysis on a Solar Tunnel Drier

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**Abstract** A comprehensive study carried out in a solar drier in regards to thermal performance and food quality is appended in this paper. A lab-scale solar drier has been designed and tested for thermal performance, economics, and food quality. The drying temperature ranged between 32 and 54 °C. Ivy gourds were chosen for drying experiment, and the dried products were subjected to color and texture analysis. The color deviation (ΔE) for solar dried and open sun-dried samples was 4.59 and 10.1, respectively. The hardness of solar dried and open sun-dried sample was 84.29 and 30.87 N, respectively. The economic analysis was done by three methods. The annualized cost method showed that the cost of drying unit weight of product using solar tunnel drier was ₹ 10.94 and using conventional drier was ₹ 17.39. The payback period of the drier was estimated to be 3.5 years with a lifetime savings of ₹ 397,011.00.

**Keywords** Solar drier · Quality analysis · Color · Texture · Economic analysis

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**Nomenclature**

| | |
|---|---|
| a* | Redness |
| b* | Yellowness |
| $C_{cc}$ | Capital cost of drier (₹) |
| d | Rate of interest on long-term investment |
| i | Rate of inflation |
| L* | Lightness |
| N | Payback period (year) |
| $S_1$ | Saving during the first year for solar drier (₹) |
| $w_i$ | Initial weight (kg) |
| $w_d$ | Dry weight (kg) |

## Introduction

Drying of agro-products plays a predominant role in the post-harvesting sector as a mean of food preservation. Dehydration reduces spoilage, increases shelf life, reduction of product mass, and gives value addition as it takes place without any chemical processing. Drying is an excellent way to preserve food, and solar driers are appropriate preservation device for a sustainable world. The reduction of moisture content to a safer level is the primary objective of drying of agricultural products, which allows storage of products over an extended period. The drying process is a combination of simultaneous heat and mass transfer phenomenon. Open sun drying is the traditional method of drying. Even though this method is simple, it undergoes several drawbacks including quantity loss and quality deterioration. Hence, solar driers can be effectively used as an attractive drying technology in developing countries, which can help reducing crop losses and improve the quality of dried products. There are many solar driers developed in different parts of the world, yielding varying degrees of technical performance. Chimney-dependent solar crop drier was designed and analyzed for no loaded and loaded conditions [1, 2]. Abdullah and Aydin studied energy and exergy analyses of thin layer drying of mulberry using forced convection solar drier [3]. Mustafa et al. designed heat pump and solar drier and analyzed experimentally by drying apple slices [4]. Solar tunnel drier for copra drying was developed and tested [5]. Solar tunnel drier for drying silkworm pupae was developed and tested in Thailand [6]. Direct and indirect solar drier for drying whole mint plant was designed and tested at Cairo University, Giza [7]. A multi-purpose solar tunnel drier was developed and tested with drying cocoa, coffee, and coconut. It was reported that solar drying improves the quality of the products in terms of color, flavor, and appearance that reduces the risk of microorganism growth and prevents insect infestation and contamination by foreign matters and mycotoxins [8]. Development of solar collectors for drying application has been reported [9, 10]. There are many works reported in the literature regarding the quality analysis of the products dried by other means of drying like freeze drying [11], electric tray drying [12], microwave drying [13], microwave-convective drying [14], hot air convective drying [15], but reports on quality analysis of the solar dried products are a few. In this paper, the design of solar tunnel drier, testing of the solar drier with drying vegetable, economic analysis, and quality analyses of the dried vegetable have been presented. The quality analysis includes color and texture.

## Materials and Methods

The solar tunnel drier is installed in the department of Green Energy technology of Pondicherry University, Puducherry (latitude: 11° 56′N; longitude: 79° 53′E). The drier is classified as directly forced convection type. Each drying test started at 9:00 am and continued till 5:00 pm. A schematic diagram and photograph of the solar tunnel drier are illustrated in Supplementary Figs. 1 and 2. Specification of the solar tunnel drier is given in Supplementary Table 1. The drying system consists of two axial fans powered by photovoltaic panels. In order to increase the transmissivity of solar radiation, solar toughened glass of 4-mm thickness (2 m × 1 m) was used as glazing material in the tunnel drier. Absorber plate used was a selectively coated aluminum sheet for maximum absorption of solar radiation in the short-wave region and 50-mm-thick polyurethane foam as insulation on sides and bottom to suppress heat loss to the ambient. The area of the absorber plate is 2 $m^2$ approximately. The product is loaded into eight perforated stainless steel trays of dimension (30 cm × 45 cm) each with 2 kg capacity of fresh products. The atmospheric air is allowed to pass through the inlet via axial fans. The hot absorber plate in the chamber transfers heats to the incoming air. The hot air is utilized for moisture removal of agricultural products kept in the tray. The air gaining the moisture leaves the chamber through the outlet holes. *Coccinia grandis* also known as ivy gourd was selected for the drying experiment. The fruit is rich in beta-carotene, and it is regarded as an excellent source of protein and fiber. It is available widely from Africa to Asia and is called a tropical vine. *C. grandis* has been considered as a therapeutic herb in traditional Thai as well as ayurvedic medication.

### Thermal Analysis and Drying Kinetics

The solar drier operated in direct drying mode was tested under no load and loaded condition. The drier was run on clear sunny days. Under no load condition, the ambient temperature, absorber temperature, hot air temperature, glazing temperature, and solar irradiance were recorded at 10-min interval. To test the drier with load, *C. grandis* was selected. The initial moisture content of the fruit was evaluated by oven drying method. The slices of ivy gourds were kept in hot air oven at 110 °C for 24 h. The initial and final weights of the slices were measured for calculating initial moisture content. The moisture content of the ivy gourds was determined with reference to the dry weight of the gourds using Eq. (1)

$$m_i = \frac{w_i - w_d}{w_d} \times 100\ \% \tag{1}$$

where the terms $w_i$ and $w_d$ refer to the initial and dry weight, respectively. The equilibrium moisture content (EMCs) was determined by drying until no further change in weight was observed for the gourds in each drying method. All the experiments were repeated in triplicate.

### Color Measurement

Hunter colorimeter Lab systems measure reflected and transmitted the color of food products. It gives numerical values that correlate to what we see and are ideal for measuring raw materials through final product. A Hunter Lab colorimeter is used to measure the reflectance of batches of samples. *L* measures lightness and varies from 100 for perfect white to zero for black, approximately as the eye would evaluate it.

The chromaticity dimensions (a and b) give understandable designations of color as follows:

(i) *a* measures redness when positive, black when zero, and greenness when negative.
(ii) *b* measures yellowness when positive, black when zero, and blueness when negative as shown in Supplementary Fig. 3.

Colorimeters are used to measure color using three filters that are similar to human color receptors. Tristimulus color parameters are measured using a colorimeter. The values are based on reflection measurements. Objects are characterized by the amount of light reflected or transmitted at each wavelength. The tristimulus colorimeter showed in Supplementary Fig. 4 measures the true colors and correlates them to what the eye sees, using specialized glass color filters and light detectors (up to 10 million different shades of color can be quantified [16]).

Instrumental surface color (CIE L*a*b*) of fresh and dried samples was evaluated using a Hunter Lab Mini Scan XE Plus Color Meter (Illuminant D65, 2.5 cm diameter aperture, 10° standard observer; Hunter Associates Laboratory, Inc., Reston, VA). Calibration was performed by using standard black and white tiles prior to the color measurement. CIE (L*, a*, b*) values were used to calculate saturation index/chroma $[(a^{*2} + b^{*2})^{1/2}]$ and hue angle $[\tan^{-1}(b^*/a^*)]$. The color change is given as follows:

$$\Delta E = \sqrt{(L - L^*)^2 + (a - a^*)^2 + (b - b^*)^2} \quad (2)$$

where L, a, and b are the color parameters of fresh product and L*, a*, and b* are the color parameters of dried products.

### Texture Measurement

The texture is the sensory and functional manifestation of the structural, mechanical, and surface properties of foods detected through the senses of vision, hearing, touch, and kinesthetics [17]. Texture property of dried product is measured as cutting force by using HDP/BS probe. The force required to deform the dried samples was measured using texture analyzer (Model No.: 5197, Stable microsystems HD Plus, Goldalming, surrey, GU71YL, UK). The cutting probe attached to the analyzer is moved at a constant speed of 1.00 mm/s. The force was measured in Newton. The readings were taken in triplicate.

### Economic Analysis

Economic analysis was done by three methods namely annualized cost method, life cycle saving, and payback period. The formulae for calculation was referred from the reference [18]. In the annualized cost method, the cost required for drying using solar drier was calculated and compared with conventional drying method. The cost of the drier and other factors involved in the calculation are given in Supplementary Table 2. This method is not efficient due to the unsteady prices of electricity. The second method called life cycle saving method is more reliable as it takes into account the inflation rate to calculate present worth of annual savings and cumulative annual saving throughout the lifetime of the drier.

The savings per drying day in the base year was first calculated. The terms and values included in the calculations are: the cost of fresh product per kg was taken as ₹ 50, the mass of fresh product loaded in solar drier per batch was 16 kg, and the mass of dried product removed from solar drier per batch was 3.12 kg. The rate of inflation was taken to be 6 %. The present worth of annual savings was then calculated for consecutive years. In the last method, say, payback period estimates the financial viability of the project in terms of recovering the investment made.

The payback period is given by the equation:

$$N = \frac{\ln\left(1 - \frac{C_{cc}}{S_1}(d - i)\right)}{\ln\left(\frac{1 + i}{1 + d}\right)} \quad (3)$$

### Instrumentation

The intensity of solar radiation was recorded using LP 471 Pyranometer with an accuracy level of 1°. RTD temperature sensors with 0.1 °C accuracy placed at required points were used to measure the temperature and were connected to a 951D-16U universal data logger for recording the temperatures. A digital weighing machine (±0.001 g) of Model No.TTB 31 (Make-Wenser weighing scales limited) was used to measure the weight of the samples. A hot air oven (Make: Techniq, Model: 341P, 0–250 °C) was used for estimating the moisture content of the product. The color parameters were measured using Hunter Lab Mini Scan XE Plus Color Meter (Illuminant D65, 2.5-cm diameter aperture, 10° standard observer; Hunter Associates Laboratory, Inc., Reston, VA). Texture analysis was done using texture analyzer (Model No.: 5197, Stable microsystems HD Plus, Goldalming, surrey, GU71YL, UK).

## Results and Discussion

### Thermal Analysis

Initially, drying tests was carried out without load. The solar drier was designed to mainly work in direct mode. Temperature profile under no load condition for three experimental days is shown in Supplementary Figs. 5, 6, and 7. During the experiment, the solar radiation varied from 129 to 902 W/m$^2$. The ambient temperature ranged from 29.4 to 34.8 °C. The maximum temperature recorded for absorber plate and glass cover was 59 and 49 °C, respectively. The hot air temperature ranged from 32 to 49 °C. Temperature profile at loaded condition is shown in Supplementary Fig. 8. As shown in the figure, the solar irradiance ranged from 224 to 995 W/m$^2$. The ambient temperature ranged from 30.89 to 33.08 °C. The temperature of absorber plate ranged from 39 to 79 °C. The temperature of glazing ranged from 35 to 44 °C. The maximum hot air temperature recorded during the day was 54 °C. The temperature inside drier depends on the solar radiation, ambient temperature, the velocity of air, and moisture content of the product. The velocity of air inside the drying chamber also has a strong affinity to solar radiation as the fans are powered by PV panels.

### Drying Kinetics

*C. grandis* with an initial moisture content of 93 %, estimated by oven drying method, was reduced to 9.06 % in the solar tunnel drier in 5 h. The moisture content reduced to 12.1 % in the open sun drying in the duration of 6 drying hours. The percentage reduction in moisture content of the product by solar tunnel drying and open sun drying is shown in Supplementary Fig. 9. The solar radiation was maximum at midday during the day of the experiment. The highest drop of moisture occurred during the first hour of drying, and subsequently, moisture removal rate decreased. The moisture reduction rate was maximum during surface moisture removal, and it decreased during interior moisture removal. The average drying temperature was 48.69 °C on the third day of the experiment. There are varieties of solar driers developed for different applications that operate throughout the years that are reported in the literature, which gives a rough comparison of the present drier and other driers developed. The initial moisture content of mulberries (80 %) was reduced to 8 % in a forced convection solar drier. The drying time varied according to the mass flow rates, 360 to 780 min at the mass flow rate range of 0.014 to 0.036 kg/s [3]. A solar tunnel drier designed for drying grapes reduced the initial moisture content to 16.2 % in 7 days [19]. Indirect solar drier designed for drying fruits reduced the mass of tomatoes from 1800 to 180 g in 2 days [20]. A parabolic shaped solar tunnel drier developed for drying *Andrographis paniculata* reduced 75 % of moisture to 7 % in 2 days. The drying temperatures ranged between 35 and 75 °C [21]. Copra of 750 kg with an initial moisture of 50 % dried to 5 % in 140 h in a multi-purpose solar tunnel drier. In the same drier, 500 kg of coffee beans was dried to 12 % moisture from 45 % in 50 drying hours [8].

### Color Analysis

Supplementary Table 3 shows the color parameters for the ivy gourd, in the fresh form and after drying. The values for the L*, a*, and b* coordinates of the fresh product were 46.72, 10.96, and 29.87, respectively. The lightness (L*) increased to 50.92 in the solar dried sample and to 48.23 in open sun-dried sample. The redness parameter (a*) decreased to 9.24 and 4.21 in solar dried and open sun-dried sample, respectively. The red color faded when product dried. The loss in color was more in open sun-dried sample. The yellowness (b*) of the product remained in a solar dried sample where it got faded to 19.5 from 26.87 in open sun-dried sample. The results of chroma and hue angle show color stability of the samples dried in solar tunnel drier. The total color difference which is a combination of L*, a*, and b* values as given by Eq. (2) is colorimetric parameter extensively used to characterize the variation of color in foods during processing. The color difference had the value of 4.59 to the solar dried sample and 10.10 to the open sun-dried sample.

### Texture Analysis

Hardness is an important parameter used to investigate case hardening in dried fruits. Results of the hardness of dried samples are shown in Supplementary Table 4. Solar dried and open sun-dried samples were subjected to hardness test at equilibrium moisture content. The hardness values of solar dried samples ranged from 72.59 to 96.35 N, and the hardness of open sun-dried samples ranged from 25.63 to 38.16 N. Sun-dried samples showed lower hardness compared to solar dried samples. The difference in hardness may be attributed to the difference in drying temperatures in solar tunnel drier and open sun drying. Textural properties of dried products can be improved by pre-treatments [22].

### Economic Analysis

The cost of drying using solar tunnel drier and conventional drier was compared using annualized cost method. The annualized cost of drying ivy gourds using solar tunnel drier was ₹ 8533.00 and using conventional type drier was ₹ 13,570.00. The cost of drying unit weight of the product using solar tunnel drier was ₹ 10.94 and using conventional drier was ₹ 17.39. This shows that the energy saving opportunities are wide while using solar tunnel drier since the fuel cost is zero. For calculation purpose, the rate of interest on long-term investment was taken to be 8 %, the salvage value was taken to be 10 % of the annual capital cost, and the annualized maintenance cost was taken to be 5 % of the annual capital cost. This method does not hold good for the entire lifetime of the drier due to the unsteady prices of fuels and electricity. Therefore, life cycle method was used to calculate the lifetime savings of the drier. In life cycle method, the savings per day were calculated to be ₹ 101.87 in the base year. The annual saving and cumulative annual saving throughout the entire life span of the solar tunnel drier are given in Supplementary Table 5. Present worth of cumulative saving for 20 years of operating solar drier has been estimated to be ₹ 397,011.00. Another method called payback period was used to evaluate the time required to get back the investment. The payback period was evaluated to be 3.5 years while the lifetime of the drier is 20 years.

## Conclusion

The developed solar drier was able to produce an average drying temperature of 48 °C and maximum of 54 °C. Ivy gourd drying using solar tunnel drier was compared with open sun drying. Loaded sample with 93 % moisture content reduced to 9.06 % in 5 drying hours in the solar drier and to 12.1 % in 6 drying hours in the open sun drying. The quality analysis in terms of color and texture was done. It showed that the color deviation was less in the solar dried sample compared to open sun-dried sample. The solar dried sample was found to be harder than the sun-dried sample. The economic analysis showed that the solar tunnel drier is more energy efficient than conventional drier. The payback period was 3.5 years which is less compared to lifetime off drier (20 years approximately). The lifetime savings of the solar drier were estimated to be 397, 011. 00.

**Compliance with Ethical Standards**

**Conflict of Interest** K. Rajarajeswari, K.V. Sunooj, and A. Sreekumar declare that they have no conflict of interest.

**Human and Animal Rights and Informed Consent** This article does not contain any studies with human or animal subjects performed by any of the authors.

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