Performance analysis of solar tunnel dryer with thermal storage and Photovoltaic system for drying star fruit

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Abstract. The aim of this research work to analyse the performance of the proposed solar tunnel dryer and photovoltaic (PV) system to dry star fruit. Star fruit (Averrhoa carambola L.) is a native fruit in the north eastern states of India. Due to its rich nutritional composition and medicinal property, the demand for this fruit increased nationally. The proposed design consists of a tunnel type drying chamber and thermal storage unit. Paraffin wax (PCM) was used as a thermal storing material mounted in the tunnel dryer chamber to use the thermal energy at off sunshine hours. The thermal insulation coating on the outer surface of the solar drying chamber enhances the thermal performance of the tunnel dryer. The overall efficiency of this proposed design was analysed. The results indicated that drying of star fruit occurred in the falling rate period, where no constant rate period of drying rate was observed. The quality analyses data revealed that higher values of TPC (47.59 mg GAE/gram of sample) and DPPH (73.59 μmol of TE/gram of sample) are obtained in the samples dried in solar dried as compared to open sun-dried samples. Sensory analysis (taste, aroma and flavour) carried out on slices of star fruit indicated that the solar-dried slices provided better scores compared to open sun-dried samples.

Keywords: Star fruit; Solar tunnel dryer; PCM; Sensory analysis

1. Introduction
Star fruit (Averrhoa carambola L.) is a derivative from the Sanskrit word “Karama ranga” denoting food appetizer. It was termed as Carambola by Malayalam community until Portuguese took it to South America and Africa for trading [1, 2]. It is a native fruit of Sri Lanka and Indonesia [3], and currently widespread throughout the world [4]. The fruit contains a significant amount of bio-active health promoting non-nutritive elements like total phenolics, antioxidants, dietary fiber, minerals and vitamin-C [5,6,7]. Presence of high moisture (more than 90 % w.b.) at harvesting time renders the fruit perishable and seasonal availability constraints the use of the fruit throughout the year. This necessitates the preservation of this nature’s gift through proper processing techniques for safe storage with more retention of nutrient [8]. Drying is the removal of water by evaporation of the material. The advantages of using the drying process are numerous, including: ease storage of the dry product, stability of aromatic compounds at room temperature for long periods protecting against oxidative and enzymatic degradation reduction of weight product, saving energy by not requiring refrigeration and product availability during any season [9].

In India, the drying of agricultural products through open sun drying is the natural, cheap and oldest dehydrating technique. The major drawback of the open sun drying is that the fruits kept unprotected environmental conditions like sudden rain, dirt, dust, and proneness to the insect and birds attack leads to the quality degrade of dried product. The loss of dried product quality affects the market value and the acceptance of consumers. To improve the dried product quality, the drying process must be carried
out in a closed system that is completely dependent on specific unit operations. [10]. The solar drying techniques are classified depending on the type of air flow: natural convection type dryers and forced convection type dryers (11). Due to the air density gradient along the natural convection type dryer, air flow in the drying process can be obtained (12). Hence, the long drying times due to the lesser air flow results in lowering drying ability, reduction in overall thermal performance and deceasing dryer efficiency. Forced conversional dryer operated on PV source to operate a blower or fan to enhance air flow in the dryer. A solar tunnel driers, green house dries and roof integrated solar dryer are few high capacity and thermal efficient forced convection types of dryers (13). The solar tunnel type dryers can be more efficient solar thermal application systems in compared to natural open sun drying technique. This method of drying is appropriate to practice in the far-flung areas of northeastern states of India having ample solar energy supply. The thermal energy storage unit in the tunnel dryer are in higher demand to meet the energy crisis in the off sunshine hours. In general, thermal energies are stored in two modes: sensible heat and latent heat are widely applicable in solar thermal energy systems. The materials like gravels, sands, stones and water are used to store the heat energy in the sensible mode [14] and in the latent mode, phase change materials (PCM) [15] and Calcium chloride hexa-hydrate [16] are widely used for storing the heat by transition of phase in the thermal applications. In the phase changing materials, paraffin wax are widely used in the thermal storage applications in recent days due to its wide energy storing capacity and constantly delivering the heat energy stored and wide range availability. The paraffin wax with the melting temperatures at 50°C and 60°C are widely applicable for the dryers for drying fruits and savers 34 – 42% of energy are saved at drying process are reported. The main aim of this work to design and study the performance of a solar tunnel dryer with thermal energy storage and PV system for drying star fruit and compared with natural open sun drying.

2. Materials and Methods
2.1 Design solar tunnel dryer
The experimental work was done at the Department of Instrumentation Engineering, Central Institute of Technology, Kokrajhar, Assam.

![Figure 1](image)

Figure 1 a) Modified Solar Tunnel Dryer b) Thermal Storage Unit c) PV Module

The experimental setup consists of the following components: Modified solar tunnel dryer Fig 1(a), Thermal storage unit (200 ml PCM per tin) Fig 1(b) and PV module system Fig 1(c). The tunnel dryer was made of transparent polycarbonate sheets of 2mm thick as a collector of solar radiation integrated with sample drying tray and thermal storage unit. The dimensions are 1.5 m length, 0.7 m width and height of 0.8 m out of 0.6 m cast iron chamber with drying tray and thermal storage unit and hemispherical structure on the top of tunnel dryer is of 0.35 m radius (17).
2.2 Thermal storage unit and Insulation
The paraffin wax (PCM) of range 58-60 °C are used to store the excess heat energy at hours of peak sunshine to reduce fluctuations in the drying temperate process. The selection of PCM material depends on its wide range of melting temperature and its melting temperature should be 5 - 10 °C more than the desired drying temperature [17]. The 5 kg of PCM are taken in the aluminum tins of 200 ml each. Due to the lower thermal conductance on the PCM material, thin aluminum strips of 5 mm thickness are used to charge or discharge thermal energy faster. The insulating paint are used to reduce the conduction losses in the thermal process, Industrial type (UGAM HR 200) was an epoxy Silicon base Product in liquid form are used to coat on the dryer. An insulating paint was coated twice at 0.75mm thickness each at the ambient temperature [18].

2.3 Instrumentation
A DC fan are fitted in the dryer to circulate or pump the air at the velocity of 0.4 - 0.6 m/s, depending on the desired set temperature. The fan is driven by the PV system consists of PV solar panel, control circuitry and a battery. The solar isolation in measured by solar power meter (MECO 936) and anemometer (HTC AVM-06) are used to measure the humidity and air flow velocity. The temperature was measured (LM35) at both ambient (t_a) and chamber temperature (t_d), PCM temperature (t_p) was measured by resistance temperature detector (PT100).

2.4 Sample preparation
Star fruits of golden star variety of appropriate maturity, greenish yellow in color (Abdullah et al., 2006) were procured from a tree near to Bodoland University, Kokrajhar, India and stored in the food product department laboratory for further use.

![Figure 2 a) Fresh Sample of Star Fruit b) sliced sample c) Sample in the solar tunnel dryer](image)

Figure 2 a) Fresh Sample of Star Fruit b) sliced sample c) Sample in the solar tunnel dryer

The stored fruits were carefully cleaned in the tap water and then the surface moisture was removed with tissue paper Fig 2(a). The cleaned samples were cut using a designed slicer. The thickness of the slices were 10 mm (Fig 2(b)). Fresh cut sliced moisture content was measured gravimetrically using a hot air oven at 80°C for 17 hours [19]. After carrying out three experiments, data were average out and final average data was recorded. Chemicals which was used for quality and nutritional profiling were bought from Merck and Zenith Chemicals (Guwhati, India).

2.5 Quality analysis

2.5.1 Ascorbic Acid Content
Ascorbic acid content of fresh as well as osmo-dehydrated star fruit slices was estimated using standard procedure centered on the reduction of 2, 6-dichlorophenol indophenols dye by ascorbic acid [19].
2.5.2 Oxalic acid
The procedure described by Archer et al. (1957) [20] was standardized for star fruit and was used in the present investigation. The principle of the method is to produce calcium oxalate precipitate to be titrated with potassium permanganate.

2.5.3. pH
pH of the juice samples (fresh and treated) were checked by using a digital pH meter (OAKTON pH Testr30, USA). 10 ml of juice sample was taken and mixed thoroughly in a magnetic stirrer and pH reading was recorded.

2.5.4 Total soluble solids (TSS)
The amounts of TSS present in the juice samples was checked by using a refractometer [21].

2.5.5 Anti-Oxidant activity
The anti-oxidant ability of the juice samples was calculated by using DPPH free radical assay [22]. The findings of the experiments were presented as percentage inhibition of DPPH radicals.

2.5.6 Total phenols
The levels of total phenols in the fruit samples was computed by the method followed in the research work of Nayak et al., 2017 [23]. The results from the analysis were expressed as gallic acid equivalents (GAE) per millilitre of juice sample.

2.5.7 Total flavonoid contents (TFC)
TFC of fruits samples was estimated using the technique furnished by Nayak et al., 2018 [24].

3. Result and discussion
In the drying process, the uncertainty of measured variables arises due to environmental effect, process conditions, selected of instruments and its calibration. To estimate the uncertainty in the measured process parameters are obtained using the Holman (1994) method [25]. The total uncertainty ($U_t$) obtained by the below expression.

$$U_t = \left[ (x_1)^2 + (x_2)^2 + \ldots + (x_n)^2 \right]^{1/2} \quad (1)$$

$U_t$ = Total Uncertainty and $x_1 =$nth factor relative uncertainty

The measured process parameters are solar radiation, temperature, air velocity and moisture content. The total uncertainty of measured process parameters are shown in table 1.

| Process parameters   | Units           | Total uncertainty |
|---------------------|-----------------|-------------------|
| Solar Isolation     | W/m²            | ± 10              |
| Temperature         | °C              | ± 0.49            |
| Air Velocity        | m/s             | ± 0.53            |
| Moisture Content    | kg of water/ kg of dry sample | ± 0.25 |

The experiment is carried out to study the thermal characteristics of latent heat stored in paraffin wax (PCM) in the thermal storage unit [26]. In Fig 3, Initially PCM with different volumes are heated above 60 °C at the ambient air velocity condition, then thermal discharging behavior of PCM material in aluminum tin are studied. It is observed the thermal storage capacity increase with the increase in the volume of the PCM material compared with 100ml to 500 ml. Enhancing the process time of 20 to 30min are noted at the heat discharging period in the PCM and this thermal performance of PCM materials in the drying process are seen highly at off sun shine hours of solar tunnel dryers.
The drying of star fruit is carried out on 24th August 2019 between 8:00 am to 8:00 pm of a day with controlled air velocity of 0.6 m/s in the modified solar tunnel dryer. The experiment has to compare the thermal performance of the modified solar dryer with and without thermal storage and insulating paint. The peak solar irradiation of 830 w/m².

Figure: 3 Thermal characteristics of Paraffin Wax

(L) was recorded with the maximum ambient temperature (T_a) of 36.8 °C. The drying temperatures of the solar tunnel dryer (T_d) was compared with the modified solar tunnel dryer temperature (T_md). It is observed in the fig 4, the insulation losses are limited to minimum value in the modified tunnel dryer with 3 – 7 °C difference in compared to solar tunnel dryer throughout the drying process. At the drying time 5:30pm (570 min), the temperature in the modified tunnel dryer T_md saturated around 57 °C till 7:45 pm (720min) with is much higher than the tunnel dryer T_d. The thermal efficiency is increased by 9-12% while using the thermal storage unit and insulating paint coated in the modified solar tunnel dryers.

Figure: 4 solar irradiance w.r.t. to temperature of modified solar tunnel dryer

Quality analysis

During drying of fruits and vegetables, many physicochemical changes occur like size, shape, color, texture and nutritional quality (e.g., TSS, ascorbic acid, phenolic compounds and the like Nindo et al., 2003 [27]. In this research, ascorbic acid content is decreased 19% from 660.34±15.36 mg / 100 g DM to 532.73±12.89 mg / 100 g DM (Table 2) whereas oxalic acid content has been increased up to 64 %. Ramallo and Mascheroni, 2012 has also got same results when pineapple was dried with convective cross flow pilot dryer. The TPC and TFC of the fresh and dried samples were increased from 5.88 ± 0.27 to 8.11±0.15 mg GAE per g of sample and 1.83 ± 0.06 to 1.99±0.03 mg quercetin per g of sample.
respectively (Table 2). The projected phenolic content obtained were leads to free radical-scavenging activities in samples of star fruits [24, 27].

Table 2 Effect of drying on quality of star fruit slices

| Star fruit                  | Fresh       | Solar dried  |
|-----------------------------|-------------|--------------|
| Ascorbic Acid Content (mg / 100 g DM) | 660.34± 15.36 | 532.73±12.89 |
| Oxalic acid (mg / g DM)     | 15.76±2.21  | 25.86±3.08   |
| pH                          | 3.73±0.04   | 3.65±0.05    |
| TSS (°Brix)                 | 7.00± 0.10  | 7.00± 0.10   |
| Anti-Oxidant activity (μ mol of TE/ gram of sample) | 38.06 ± 0.99 | 63.95±2.02    |
| TPC (mg GAE/ gram of sample) | 5.88 ± 0.27 | 8.11±0.15    |
| TFC (mg quercetin/ gram of sample) | 1.83 ± 0.06 | 1.99±0.03    |

4. Conclusion
A modified solar tunnel dryer with thermal storage unit and insulation paint coated was designed and used for drying star fruit in 12 hours with the temperature range of 55 to 74 °C at controlled air flow velocity into the drying. The excess latent heat energy are stored in the thermal storage unit maintain the dryer temperature at 57 °C at 5:30 pm to 7:45 pm of the drying time, which increases the thermal efficiency of the dryer by 9-12%. The quality analyses in terms of ascorbic acid content, oxalic acid content, anti-oxidant activity, TPC and TFC were conducted for both fresh and dried star fruit sample in solar tunnel dryer. In comparison with the fresh sample of star fruit with the dried sample, the antioxidants, TPC and TFC are improved by 68%, 38% and 9% respectively. The star fruit slices dried in the solar tunnel dryer have improved quality then open sun drying method.

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