Experimental Performance Analysis Of Free And Forced Fully Developed Air Flow Green House Solar Dryer Using Curry Leaves

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Abstract. The world is beginning to move away from its consumption of fossil fuels. Various technologies are being developed to make use of renewable energy sources such as wind, solar, and tidal, etc. Solar energy is the best choice among these sources because it is readily available, abundant, and capable of producing both electric energy and space heating. Solar energy can be used directly or indirectly to dry agricultural and non-agricultural products to preserve them for long a period without formation of fungi. Drying of herbal leaves is an important process in Siddha and Ayurvedic industries to produce herbal medicines in powder form. However, as herbal leaves are dried in the open sun, they are susceptible to environmental factors such as rain, insects, and livestock. These disadvantages of open-air drying shall be overwhelmed by greenhouse solar dryer. Greenhouse solar dryer with natural convection, forced convection with hot air supply are the existing methods, but when supplied with hot air, the rise in temperature leads to nutrient loss in herbal leaves. In order to avoid this loss in nutrients, the current work gives a solution that the temperature of forced convection greenhouse dryer can be reduced and controlled by supplying the ambient air at inlet flow in a fully developed air region, and this method can also lead to reduction in colour loss with possibly same or higher drying rate compare to natural convection greenhouse dryer.

1 Introduction

Radiant light and heat from the sun are known as solar energy and it is an essential source of renewable energy. Solar radiation is the radiant energy that is released from the sun as a result of nuclear fusion, which produces electromagnetic energy. Solar Energy is used in solar heating, photovoltaic, solar thermal energy, solar architecture, molten salt power plants and greenhouse solar dryer.

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Harvesting energy through appropriate systems is a viable method for various applications, such as the Solar Air dryer. This system utilizes atmospheric air to remove moisture, making it particularly valuable in the drying of food crops for purposes like herbal medicine preparation. Drying plant leaves can be challenging because inadequate drying can lead to reduced drying rates, color alteration, and nutrient loss. One method employed for drying is the greenhouse drying technique, where solar energy serves as the sole source of heat. The dryer is equipped with openings at the top and bottom to allow for the circulation of ambient air for ventilation and the release of evaporated moisture. The products to be dried are spread thinly on trays and exposed to direct sunlight. Inside the solar greenhouse dryer, the air is heated naturally through the greenhouse effect, and air movement occurs through buoyancy effects. This dynamic thermal mechanism, characterized by the movement of air masses around the components, facilitates concurrent heat and moisture transfer, ultimately enhancing the drying process [1].

The efficiency of heat and moisture transfer in the greenhouse dryer depends on factors like air velocity and temperature inside the system. In a natural convection dryer, air velocity is determined by the temperature difference between the interior and exterior air, resulting in a draft. However, for drying products with higher moisture content, a forced convection greenhouse dryer is more suitable. This type of dryer employs fans to control the airflow, ensuring efficient drying while preserving the nutrients of the herbal leaves [2]. Numerous studies have been conducted in this field, with the implementation of a parabolic-shaped forced convection greenhouse dryer yielding significant results. For example, the moisture content of bananas in the dryer was reduced from 72% to 28% within four days, compared to 40% in the same period without the dryer. This approach led to a 48% reduction in drying time and produced high-quality dried products [3]. Similarly, greenhouse solar drying of cassumunar ginger resulted in a 67% reduction in drying time compared to natural sun drying, with an average efficiency of 38.9% [4]. To enhance the temperature inside the solar dryer, a forced convection mixed mode solar dryer was designed, achieving a temperature increase of 10 to 20°C above ambient air. This approach reduced drying time by 50% compared to natural open sun drying, with measured convective and evaporative heat transfer coefficients of 1.63 and 49.7 W/m°C, respectively [5]. Among the various shapes of solar dryers, the quonset shape was found to be the most effective, generating 64% higher temperatures than the surrounding atmosphere. In summer, the quonset shape reached a maximum temperature of 72°C, while in winter, it reached 66°C [6]. Comparing open sun drying and greenhouse solar drying methods for reducing moisture content in onion flakes, different drying processes were employed. As the mass of onion flakes increased from 300g to 900g, there was an observed increase in convective mass transfer ranging from 30% to 135% [7].

A parabolic-shaped natural convection greenhouse solar dryer was created, incorporating the concept of a black body and utilizing a black concrete floor. This dryer had a capacity of drying 1000 kg of fruits or vegetables. In the case of drying 1000 kg of bananas with an initial moisture content of 68%, the developed model achieved the desired moisture reduction in 5 days, whereas the open sun drying method took 7 days. Similarly, drying 300 kg of chili with a moisture content of 75% required 3 days in the developed model compared to 5 days in open sun drying. For drying 200 kg of coffee with an initial moisture content of 52%, the developed model took 2 days, while open sun drying required 4 days [8].

A mixed-mode forced convective solar dryer with a transparent plastic cover plate collector was developed for drying hot red and green chili. The solar dryer reduced the moisture
content in 80 kg of red chili from 2.85 to 0.05 kg/kg (db) in 20 hours, while open sun drying required 32 hours. For green chili, the solar dryer took 35 hours to reduce the moisture content from 7.6 to 0.06 kg/kg (db) [9]. In the analysis of a chapel-type forced convection greenhouse solar dryer, the average Turbulent Kinetic Energy (TKE) increased to 3.8 m²/s², resulting in a 36.5% reduction in Global Horizontal Irradiance (GHD). TKE ranged from 1.27 m²/s² to 6 m²/s² in a discrete ordinate model. Preheated air was supplied through a diffuser [10]. A natural convection solar dryer was designed and analyzed using experimental and simulation methods. It successfully reduced the moisture content in mangoes from 85.5% to 13% within 9 hours. The air temperature reached 65.8°C, and solar radiation ranged between 568.4 and 999.5 W/m². The average temperature difference between ambient air and chimney air was 12.1°C, providing sufficient airflow through the dryer [11]. The forced convection solar dryer utilizes a PV/T air collector to harness both electrical and thermal energy. Mode 2, which incorporates seven DC fans at the entrance and 12 circulation fans on both sides of the drying chamber, exhibits a significant reduction of 45.4% in comparison to mode 1, which only includes seven DC fans at the air entrance of the drying chamber [12]. A rack-type conventional drying greenhouse solar dryer was employed to dehydrate wild ginger. Among the three tested conditions, the best performance was achieved when drying 60 kg of sliced wild ginger, resulting in an 8% drying efficiency over a period of 30 hours [13]. For peppermint plants, a solar tunnel greenhouse dryer with forced convection was developed. This system features two fans dedicated to the drying process, leading to a 22.78% increase in drying rate and a reduction in drying time [14]. An indirect, active type greenhouse solar dryer, comprising glass covers and absorber plates, was designed to remove moisture from bananas by varying the air flow rate. The top flow configuration and bottom flow configuration achieved moisture reductions of 27.5% and 38.21% respectively [15]. A hemi-cylindrical shaped walk-in type greenhouse solar dryer was constructed to remove moisture from crops using natural convection. Within two days, the moisture content decreased from 62.87% to 10.62%. The performance of the solar dryer was evaluated under both no load and full load conditions [16]. Extensive literature surveys highlight the necessity and ample room for developing new designs to enhance the drying process across various fields, particularly in the context of drying food products.

2 Material used

2.1 Polycarbonate sheet

Polycarbonates are a type of thermoplastic polymer that has carbonate groups in its chemical structure. Polycarbonates are a solid, tough material that is optically transparent in certain grades. They are commonly used in engineering. The key benefit of using polycarbonate in a solar dryer is its ability to retain heat (once the heat enters into the dryer there is no heat loss except through the outlet). The picture of the polycarbonates is given in Fig.1 and the properties have been given in Table 1.

<table>
<thead>
<tr>
<th>Properties</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Specific gravity</td>
<td>1.20 g/cm³</td>
</tr>
<tr>
<td>Tensile strength</td>
<td>62 MPa</td>
</tr>
</tbody>
</table>


<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tensile modulus</td>
<td>2.4 GPa</td>
</tr>
<tr>
<td>Elongation to break</td>
<td>110 %</td>
</tr>
<tr>
<td>Flexural strength</td>
<td>93 MPa</td>
</tr>
<tr>
<td>Flexural modulus</td>
<td>23 GPa</td>
</tr>
<tr>
<td>Impact strength notched Izod</td>
<td>854 J/m</td>
</tr>
<tr>
<td>Heat deflection temperature</td>
<td>138°C</td>
</tr>
</tbody>
</table>

**Fig. 1.** Polycarbonate sheet

### 2.2 MS Square pipe

Mild steel (MS) pipes are made of steel with a low carbon content (less than 0.25 percent). The pipes do not harden and are safe to use due to the low carbon content. MS Pipes are easy to weld and mould in different shapes and sizes for pipelining and tubing since they are made of mild steel. Plumbing, fire fighting, and HVAC are popular uses, but they can also be found in a number of other Manufacturing and Technical applications. These pipes are normally painted with other metals, paints, varnishes, and the like to keep them from rusting, but special caution should be taken in bad weather. The photograph of MS square pipe by which the frame work are constructed given in Fig.2.
**Fig. 2.** MS Square pipe

### 2.3 3D Model and flow pattern of Greenhouse dryer

Totally six type of air flow arrangement were made with different inlet and out pattern among which the Fig. 3 modelled pattern (Zig-Zag inlet at bottom of each side and 2 outlets at top of each side) have the fully developed air flow condition inside the dryer (The airflow pattern simulation is give in Fig.4), this model is fabricated and experiments were conducted. It is clear from the simulation that the flow of air inside the dryer is turbulent and there is uniform mixing of air during forced convection mode.

**Fig. 3.** 3D Model of greenhouse dryer with flow arrangement

**Fig. 4.** Simulation of air flow pattern – Fully developed

### 3 Fabrication

Purchased polycarbonate sheets \((4 \times 36)\) ft\(^2\), MS metal sheet \((4 \times 8)\) ft\(^2\), MS metal strip, self-drilling screw, AC cooling fans, temperature and humidity sensors (8 pieces) are wed in fabrication of experimental setup.
3.1 Fabrication of frame

MS metal pipes are cut into 8 pieces of 3.5ft and 6ft. Then those pieces are arc welded to make a rectangular frame. MS Metal Strips are cut into 8 pieces and it is bent to radius of 0.5m. Then those bended strips are welded to the rectangular frame to get a dome shape. Metal Sheet are cut and welded to the bottom portion of the frame. The frame photograph is given in Fig. 5.

![Frame of Greenhouse dryer](image)

Fig. 5. Frame of Greenhouse dryer

3.2 Fitting of polycarbonate sheet

The polycarbonate sheets are cut into 3 pieces of 4 x 8 ft² and it is fastened to the frame using self-drilling screw. The polycarbonate sheets are cut into the shape of fans, for attachment purpose. The photograph of fitting the polycarbonate sheet on the frame is given in Fig. 6.

![Fitting of polycarbonate sheet](image)

Fig. 6. Fitting of polycarbonate sheet

3.3 Fabrication tray
The metal pipes are cut into 2 pieces of 2.5ft and 5ft each and welded to make tray. The mesh is fastened on the tray using fastener.

### 3.4 Fitting of electronic devices

Eight temperature and humidity sensors are positioned in the tray and bended metal strips. AC Fans are fixed in the cut portion of polycarbonate sheet and they are wired in series to operate in series connection.

### 3.5 Finished product

The completely fabricated natural convection solar greenhouse dryer with Zig-Zag inlet at bottom of each side and 2 outlets at top of each side photograph is given in Fig. 7 and forced convection experimental setup is given in Fig. 8.

![Greenhouse dryer – natural convection](image-url)
4 Experimental procedure

Drying tests were conducted in both the fabricated setup Natural and Forced greenhouse solar dryer. There are 4 temperature and humidity sensors were fixed at different position to measure the average temperature and humidity inside the solar dryer. The curry leaves were taken as a drying product. The temperature and humidity readings inside the greenhouse solar dryer for each hour from 6.00 AM to 6.00 PM are tabulated. In the initial stage, the tray for the natural convection setup and the forced convection setup, respectively, was filled with 3000 grams of curry leaves and allowed to dry.

Drying tests were conducted with curry leaves in both natural convection and forced convection set up. Experiment was started in the morning by 6.00 AM and for every one hour the temperature and relative humidity were measured at four nodal points of the dryer and also the weight of the curry leaves were measured in each hour up to 6.00 PM.

5 Calculation

\[ \text{Moisture Removal Rate} = \frac{W_i - W_f}{T} \text{ in g/s} \]  

Where,

- \( W_i \) - Initial weight of curry leaves (g)
- \( W_f \) - Final weight of curry leaves (g)
- \( T \) - Time duration (s)

6 Result and Discussion

6.1 Temperature variation for natural and forced convection drying

The change in temperature inside the greenhouse dryer with respect to time is given in Fig. 9.
Experimental procedure
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Calculation
\[ \text{Rate of mass transfer} (\text{g/m}^2 \cdot \text{sec}) = \frac{W_i - W_f}{MT_g} \]  

Where,
- \( W_i \) - Initial weight of curry leaves (g)
- \( W_f \) - Final weight of curry leaves (g)
- \( T \) - Time duration (s)

Result and Discussion

6.1 Temperature variation for natural and forced convection drying
The change in temperature inside the greenhouse dryer with respect to time is given in Fig. 9.

![TIME VS TEMPERATURE](image)

Fig. 9. Time Vs. temperature graph

The temperature at initial state (6.00 AM) was 23℃. With increase in intensity of the sun, the temperature inside the natural convection setup increases drastically and reached the maximum value of 57℃ at peak intensity and start to reduce because of decrease in intensity of the radiation. The average value of temperature is 45.07℃. In the forced convection setup the temperature increased gradually and reached the maximum value of 44.25℃ and the average value of 37.29℃ because of controlled continuous air flow provided by fan. Lowering average temperature and maximum temperature is maintaining in forced convection setup which leads to less nutrients and colour loss.

6.2 Relative humidity variation for natural and forced convection drying
The change in relative humidity inside the greenhouse dryer with respect to time is given in Fig. 10.
Fig. 10. Time Vs. relative humidity graph

The Fig. 10 shows the graphs of change in relative humidity (RH) with respect to time, at initial stage (6.00 AM) the humidity of each setup was 90%. With increase in intensity of the sun, the humidity inside the natural convection setup decreases drastically with time, but in the forced convection setup the humidity is reduced gradually with time. In natural convection setup the humidity value reached the minimum value of 10%, whereas in forced convection the humidity reached 27%. So, a controlled removal of moisture is done by using forced convection. The change in temperature with respect to time causes for change in humidity, the higher in temperature leads to lower in relative humidity because the moisture carrying capacity of air is increased with respect to increase in temperature, so that for same specific humidity the higher in temperature decreases the relative humidity.

6.3 Weight of drying product for natural and forced convection drying

The weight of present curry leaves with respect to time is given in Fig. 11
The Fig. 10 shows the graphs of change in relative humidity (RH) with respect to time, at initial stage (6.00 AM) the humidity of each setup was 90%. With increase in intensity of the sun, the humidity inside the natural convection setup decreases drastically with time, but in the forced convection setup the humidity is reduced gradually with time. In natural convection setup the humidity value reached the minimum value of 10%, whereas in forced convection the humidity reached 27%. So, a controlled removal of moisture is done by using forced convection. The change in temperature with respect to time causes for change in humidity, the higher in temperature leads to lower in relative humidity because the moisture carrying capacity of air is increased with respect to increase in temperature, so that for same specific humidity the higher in temperature decreases the relative humidity.

6.3 Weight of drying product for natural and forced convection drying

The weight of present curry leaves with respect to time is given in Fig. 11. Figure 11 illustrates the weight of dried curry leaves over time in both natural and forced convection greenhouse dryers. At the initial stage (6:00 AM), the weight of each setup was 3042g for natural convection and 3045g for forced convection. As solar intensity increased, the moisture removal rate escalated, resulting in a significant decrease in the weight of curry leaves in the forced convection setup and a gradual decrease in the natural convection setup. By the end of the day (6:00 PM), the weight of leaves in the natural convection greenhouse solar dryer was 1195g, while in the forced convection greenhouse solar dryer, it was 1412g. The average drying temperature was higher in the natural convection dryer at 46°C compared to the forced convection greenhouse solar dryer, which was 37.29°C. The drying rate is directly influenced by the average drying temperature, which explains why the drying rate in natural convection was 217g/12 hr. higher than in forced convection. However, it's worth noting that the maximum temperature did not exceed 50°C in forced convection, whereas in natural convection, it reached a maximum of 59.5°C. According to Babu et al. [17], higher operating temperatures can lead to increased nutrient losses.

6.4 Moisture removal rate of natural and forced convection

In Figure 12, the change in moisture removal rate (MRR) over time is depicted. At the initial stage, the MRR was the same for both setups. As the sun's intensity increased, the MRR gradually increased in both the natural and forced convection dryers. By the end of the forenoon, the MRR reached its maximum value of 0.091g/s in the natural convection dryer and 0.065g/s in the forced convection dryer. Subsequently, the MRR values started to decline due to lower solar intensity, but the decrease was more significant in the natural convection setup. Therefore, in the afternoon, the MRR in forced convection remained higher than in natural convection. Both the natural and forced convection setups experienced weight loss in the leaves over time as they dried. In the case of natural convection, the airflow is limited due to the buoyancy effect, whereas in forced convection, there is stronger airflow due to external forces. This difference in airflow velocity is the main factor leading to a higher MRR in forced...
convection compared to natural convection. By the end of the day (6:00 PM), both setups had the same moisture removal rate. However, the average moisture removal rate for natural convection is 10.23% higher than that of forced convection, primarily due to the higher average operating temperature in the natural convection dryer.

![Time Duration vs Moisture Removal Rate](image)

**Fig. 12.** Time Vs. weight of drying product

The average moisture removal rate is higher in natural convection setup, but the colour of the curry leaves is lost. The greenish colour is maintained till the end of the day in forced convection setup than natural convection and also the nutrient contents of the curry leaves will be maintained at low drying temperature. The comparative photograph of dried leaves at the end of day by forced and natural convection greenhouse dryer is given in Fig. 13.
Fig. 13. Dried leaves of forced convection (left) and natural convection (right)

7 Conclusion

A greenhouse solar dryer was constructed with two different airflow conditions: natural convection and forced convection. The performance of the dryer was evaluated using curry leaves, and the following conclusions were drawn:

- The velocity of the air flow influenced the moisture removal rate, particularly at low temperatures during the initial stages of the experiment. This resulted in a higher moisture removal rate in forced convection compared to natural convection.
- As the solar radiation increased, the temperature inside the natural convection dryer also increased. This led to a significant reduction in air humidity, resulting in a higher drying rate in natural convection. However, forced convection showed less color loss and a lower average drying temperature, which helps minimize nutrient loss.
- In the afternoon, when the weight of curry leaves decreased, better airflow was observed in the forced convection setup, leading to a higher moisture removal rate compared to natural convection.
- Forced convection exhibited less color loss compared to natural convection due to the lower temperature maintained in the forced convection setup. Additionally, the lower average temperature in forced convection helps preserve nutrients. In contrast, natural convection resulted in color fading and higher nutrient loss due to the higher average temperature.
- The natural convection greenhouse solar dryer is suitable for drying products where color and nutrient loss are not critical. On the other hand, forced convection drying is preferable for food products and herbal leaves where color and nutrient preservation are important.
- The moisture removal rate in forced convection was 10.23% lower than in natural convection. However, the average drying temperature in forced convection was maintained below 50°C, reducing the risk of nutrient loss.

Overall, these findings emphasize the importance of selecting the appropriate drying method based on the desired outcomes for color retention and nutrient preservation.

References


