Development and Assessment of a Direct Solar Dryer for Bananas

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Abstract— Experimental assessment of the solar assisted dryer intended for dehydrating banana slices in the environmental conditions of Bhusawal is the aim of this work. The creation of the dryer was made up of one-inch mild steel framework, black transparent cloth, and a forced convection system to optimize drying efficiency. Fresh banana slices weighing 1000 g were dried over 8 hours, resulting in a final weight of 300 g, with 0.65 kg of moisture removed during the process. The drying chamber's internal temperatures ranged from 30°C to 60°C, and it attained a thermal efficiency of 20.18%. When compared to outside conditions, the dryer's relative humidity dropped from 45% to 30%, allowing for quicker moisture removal. The findings show that solar dryers are a highly efficient means of moisture removal and preservation of product quality thus providing a beneficial as well as a time-saving post-harvest processing technology for agricultural produce.

Index Terms- Solar drying, banana slices, moisture removal, thermal efficiency, post-harvest processing, relative humidity, forced convection system.

I. INTRODUCTION

The upward trend in the world's transition to energy sources that are renewable is principally due to the factor of climate change, the increasing cost of fossil fuels and post-harvest losses in the agricultural produce, which have to be trimmed soon. Solar energy, with its sustainable and eco-friendly characteristics, holds significant promise in food processing systems, particularly in drying agricultural products. This method not only extends shelf life but also enhances product quality by preserving nutritional value and preventing microbial growth through moisture removal [1–4].

Post-harvest losses in developing countries, including India, remain a major concern, with losses estimated between 30–40% of total agricultural produce and exceeding 80% under unfavorable conditions [5]. These losses, often linked to perishable crops such as bananas, mangoes, and tomatoes, hinder economic returns for farmers and threaten agricultural sustainability. Despite India's status as a leading producer of fruits and vegetables, improper post-harvest handling and limited processing infrastructure contribute to significant wastage, affecting the availability of nutritious food for its population [5,6]. Drying has long been employed as a fundamental technique to preserve food, reduce waste, and increase its economic value. Traditionally, sun drying has been a common practice; however, its reliance on direct sunlight, exposure to contamination, and inefficiency necessitate the adoption of advanced drying methods. Recent developments in solar drying technologies offer controlled environments that improve drying efficiency, maintain product quality, and reduce dependency on conventional fuels [7–9].

About 17.87% of the crop is wasted each year which is a consequence of poor processing and storage facilities, therefore, bananas that contribute 32.6% of India's total fruit production are particularly prone to post-harvest losses [12]. This research focuses on addressing these challenges by designing fabricating and testing an innovative drying system based on solar radiation for drying bananas in Bhusawal a region characterized by abundant solar radiation.

The aim of the study is:
The main purposes of the trial were
1. To evaluate the effectiveness of the designed system in the environment of Bhusawal.
2. To improve the shelf life of banana quality.
3. Utilization of renewable energy sources would encourage agricultural sustainability and lower post-harvest losses in developing countries.

This investigation is a great point, introducing yet another piece of information in the subject matter, which is renewable energy technology for food processing, and as it seeks to identify the most cost-effective and most practical drying solution for not only small businesses but also the rural farmer and agriculture sector of India, but they also can be sure that this technology is widely used on the ground.

Nomenclature used

Isc – Solar Constant (1353 W/m^2)
I_{DN} – Direct Radiation
B- Atmospheric extinction (value is in range of 0.14 – 0.21)
n - the day of the year.
C – coefficient 0.058 in the winter and 0.135 in the summer.
Fss - ratio coefficient
$I_{r\theta}$ - radiation reflected
$k_{r\theta}$ - coefficient of reflect
Fsg – Collector angle
T_d = dew point temperature
It = Total radiation
θ – incidence angle
Φ-Solar Azimuth
latφ - latitude of the collector location
e: vapour pressure (Actual)
T_d: Dew point (in °C)
e_s: vapour pressure (saturation)
T: Air temperature (in °C)
m_a = Mass of air
V'a = volume of air flow
ρ_a = air density
Am = mass flow rate (air) (kg/sec)
h_2 = Hot air enthalpy
h_1 = environment air enthalpy
Mc = moisture content (%)
W_1 = Sample's wet weight
W_2 = sample weight upon drying
E = Energy required
M = mass of the product
E = Heat needed to vaporise the humidity
Eo = Overall energy
m_w = Mass of water in the product
Cp= Specific heat
ΔT = temperature difference
l_v = latent heat of vaporization
td= time of drying
Eff = dryer efficiency
w = weight of water evaporated (kg)
i = solar radiation (W/m^2)
a = area of collector (m^2)
l = latent heat of water (J/kg)
Ec = energy consumption of water (J)

2.2. The solar radiation modelling

Direct radiation [18]

$$I_{DN} = Isc\ e^{\frac{-B}{\sin(\beta)}} \quad (1)$$

Diffuse radiation [18,19]

$$I_{d\theta} = C.\ I_{DN}.\ F_{ss} \quad (2)$$

$$Fss = \frac{[1+\cos(S)]}{2} \quad (3)$$

Reflected radiation

$$I_{r\theta} = (I_{DN} + I_{d\theta}).k_{r\theta}..\ F_{sg} \quad (4)$$

Collector angle [12,20]

$$F_{sg} = \frac{[1-\cos(S)]}{2} \quad (5)$$

Total radiation [18,19]

$$I_t = I_{DN}.\cos(\theta) + I_{d\theta} + I_{r\theta} \quad (6)$$

Relative Humidity

$$\text{Relative Humidity (RH)} = \frac{\text{Vapor Pressure (actual)}}{\text{Vapor Pressure (Saturation)}} \times 100 \quad (7)$$

Vapour Pressure (actual):

$$e = 6.11 \times 10^{\left(\frac{7.5\,T_d}{237.3+T_d}\right)} \quad (8)$$

Vapour Pressure (saturation):

$$e = 6.11 \times 10^{\left(\frac{7.5\,T}{237.3+T}\right)} \quad (9)$$

Relative Humidity (RH):

$$RH = \left(\frac{e}{e_s}\right) x100 \quad (10)$$

Air mass flow rate [20]

$$Am = V'a \times \rho a \ \text{kg/s [20]} \quad (11)$$

Overall energy needed [20]

$$Eo = Am\ (h_2 - h_1) \quad (12)$$

Amount of moisture removed [20]

$$Mc = ((W_1 - W_2)/W_1) \times 100 \quad (13)$$

Heat needed to vaporise the humidity in KJ [20-21]

$$E = MCp\Delta T + m_w\, l_v \quad (14)$$

Power [20]

$$Power = E/t_d \quad (15)$$

Dryer Efficiency [20]

$$Eff = (w*l)/\ i*a + Ec \quad (16)$$

Experimental Procedure

Dryer's Construction

It was constructed using one-inch mild steel angle framework, chosen for its durability and structural strength. The design of the dryer, as illustrated in Figure 1, was optimized to provide a compact and portable drying solution. The dryer's overall dimensions were 50 inches in height, 38 inches in width, and 13 inches in breadth. A spacing of 10 inches was maintained between each tray to allow sufficient airflow and even drying of food items.

At the top of the dryer, a dome-shaped structure was fabricated with a vent measuring 5 inches by 5 inches to facilitate the escape of hot air, functioning similarly to a chimney. The entire framework was enclosed with a black transparent cloth, which not only helped maintain the internal temperature but also protected the food items from dust and insects during the drying process.

To enhance drying efficiency, a fan was installed at the base of the dryer to create a forced convection system. The fan speed could be regulated using an adjustable speed controller, providing flexibility in airflow management. Each tray within the dryer was made with a fine mesh net that allowed uniform air circulation around the food items. Additionally, the dryer was designed for mobility, making it easy to relocate and position in optimal sunlight conditions.

Figure 1. Solar dryer

Preparation of Banana Slices

Fresh bananas were procured from a local market peeled, and sliced into uniform thicknesses of approximately 2 mm. To prevent oxidation and discoloration of the slices during drying they were immersed in lemon juice for a brief period. This step ensured the dried slices retained their visual appeal and nutritional quality. After treatment the banana slices were evenly spread across the trays to avoid overlapping, ensuring uniform drying.

Drying Process

Once the slices were arranged the fan was activated and with the help of regulator the airflow velocity was set to 0.725 m/s and checked by the air flow meter. The black cloth cover was securely placed over the dryer to maintain internal temperature and shield the food items. The drying process commenced and observations were recorded at hourly intervals. Key parameters monitored included the inside temperature of the dryer mostly tray and after an hour the weight of the slices were recorded. Temperature was measured using a high-precision industrial thermal gun, ensuring accurate readings.

Additional Infrared Heating

To account for drying during night time or under cloudy weather conditions, an infrared lamp system was integrated into the dryer, as shown in Figure 2. This arrangement provided supplementary heat, enabling continuous drying regardless of solar availability.

Figure 2. Infrared bulb

II. RESULTS AND ANALYSIS

A weighing balance was used to record the ultimate mass of dried banana slices, which was 350 g after drying, from the original mass of 1000 g of fresh banana slices [23]. As previously demonstrated [23], the conventional formula was used to determine the initial moisture content.

Solar radiation served as the primary energy source driving the drying process in the solar dryer. As the intensity of solar radiation increased, the drying rate also improved, resulting in a consistent reduction in the moisture content of the banana slices. Based on the observation data, solar irradiance in Bhusawal started at approximately 800 W/m² in the morning, peaking between 1050 and 1100 W/m² around noon. This peak in solar radiation coincided with a significant reduction in the mass of the banana slices, indicating that higher solar radiation accelerates the drying process.

The temperature inside the solar dryer, particularly on the tray and within the drying chamber, reflected the absorbed solar radiation. The chamber temperatures ranged between a minimum of 30°C in the morning and a maximum of 60°C during peak hours. Relative humidity played an inverse role in the drying process. As relative humidity decreased, the drying rate increased. The data presented in Figure 3 shows that the relative humidity began at 55% in the morning and gradually dropped to approximately 40% by late afternoon. This reduction in humidity facilitated faster moisture removal from the banana slices. Optimal drying conditions were achieved when solar radiation was high, the air temperature elevated, and the relative humidity reduced. The relative humidity inside the dryer was significantly lower than the atmospheric humidity, which is critical for achieving a higher drying rate. The ability of dry air to absorb moisture is higher when the humidity is lower. The air in the atmosphere had an average relative humidity of 50.45%, but the air within the drying chamber had a lower relative humidity of 40.81%.

It was determined that the air mass flow rate through the dryer was 0.725 m/s. The banana sample had a starting mass of 1 kg. The sample's final mass after 10 hours of solar drying was 0.35 kg, meaning that 0.65 kg of water had been eliminated during the drying process. The thermal efficiency of the drying chamber was 20.18%.

- Figure 3 shows The solar radiation starts at around 800 W/m² in the morning (8:00 AM) and gradually increases as the day progresses.
- It peaks at approximately 1200 W/m² around noon or early afternoon (1:00 PM).
- Post-peak, the solar radiation gradually decreases, reaching around 800 W/m² by the evening (6:00 PM).
- This trend aligns with the natural solar cycle, where the intensity of sunlight increases until noon and then decreases.

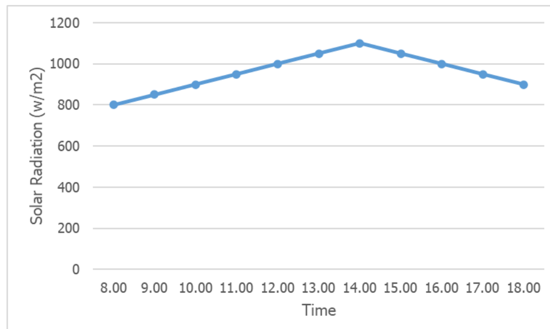

Figure 3. Radiation from the sun vs. Drying Time

- Figure 4 explain the ambient temperature starts at around 30°C in the morning (8:00 AM) and gradually rises throughout the day, reaching approximately 50°C in the afternoon (1:00 PM to 2:00 PM).
- The tray temperature consistently remains higher than the ambient temperature, starting at 40°C and reaching a peak of about 65°C.
- This difference between ambient and tray temperatures highlights the efficiency of the solar dryer in capturing and retaining heat for the drying process.

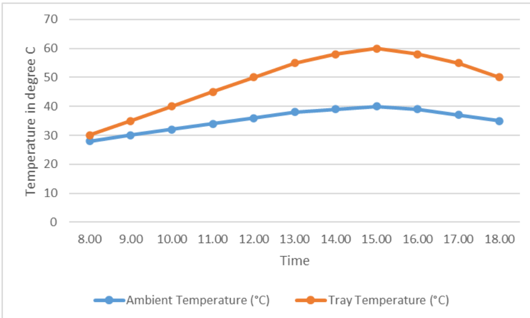

Figure 4. Temperature (Ambient and Tray) vs. Drying Time

- Figure 5 shows the relative humidity outside the dryer starts high, around 65%, in the morning and decreases to about 40% by noon. It then slightly increases in the evening.
- Inside the dryer, the relative humidity begins lower at around 45%, decreases further to approximately 30% during the peak hours (1:00 PM to 2:00 PM), and rises slightly in the evening.
- The lower humidity inside the dryer indicates effective moisture removal, facilitating faster drying of the bananas.

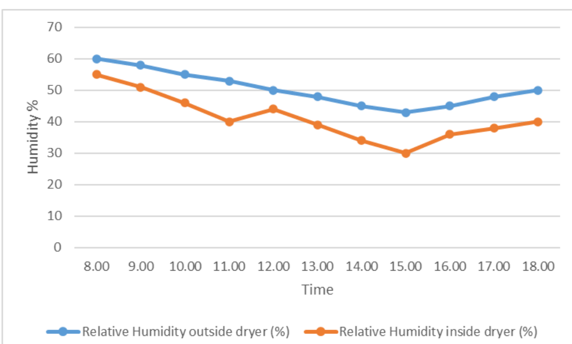

Figure 5. Humidity (Inside and Outside the Dryer) vs. Drying Time

- Figure 6 shows the moisture content of the banana slices begins at around 75% in the morning.
- As drying progresses, the moisture content consistently decreases throughout the day, reaching nearly 10% by the evening (6:00 PM).
- This steady decline demonstrates the efficiency of the solar dryer in reducing moisture content over time.

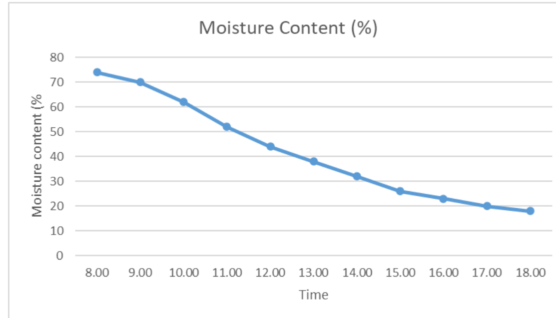

Figure 6. Moisture Content vs. Drying Time

- Figure 7 shows the initial mass of the banana slices is approximately 1000 grams in the morning.
- As drying continues, the mass decreases steadily, reflecting the loss of moisture content.
- By the end of the drying process (6:00 PM), the mass reduces to around 300 grams.
- This significant reduction in mass correlates with the decrease in moisture content, showcasing the solar dryer's effectiveness.

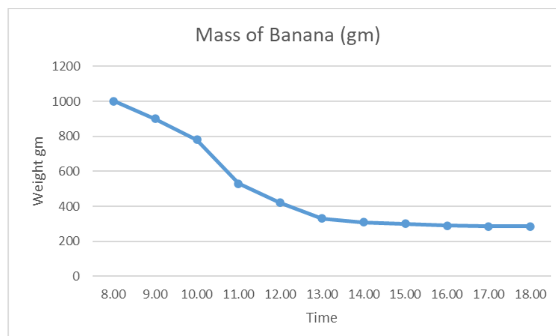

Figure 7. Mass of Banana vs. Drying Time

CONCLUSION

The experimental study demonstrates that the designed solar dryer is a highly effective solution for drying banana slices. Starting with an initial weight of 1000 g, the drying process reduced the weight to 300 g within 8 hours, effectively removing 0.65 kg of moisture. The system achieved a thermal efficiency of 20.18%, with internal temperatures ranging between 30°C and 60°C. The controlled reduction in relative humidity from 45% to 30% inside the dryer enhanced the drying rate, outperforming external environmental conditions. This design ensures the preservation of product quality, minimizes post-harvest losses, and offers an energy-efficient alternative to traditional drying methods. The results highlight the potential for solar drying systems to support sustainable agricultural practices, particularly in regions with abundant solar radiation.

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