DEVELOPMENT AND PERFORMANCE EVALUATION OF A PASSIVE MODE GREENHOUSE SOLAR DRYER WITH PEBBLES AND SAND BED ENERGY STORAGE SYSTEM

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Abstract - *A passive solar greenhouse dryer incorporating a combined sand and pebble bed as a thermal energy storage medium was designed, fabricated, and experimentally evaluated using locally sourced materials. The drying chamber measured 1.0 m × 0.758 m × 0.5 m (length, height, and width) and was developed specifically for vegetable dehydration. Air circulation within the system relied entirely on natural convection. Fresh okra (Abelmoschus esculentus) served as the drying material. Representative samples were randomly selected to determine initial moisture levels, while post-drying moisture content was established through the standard oven-drying procedure. Drying experiments were performed concurrently in the solar greenhouse dryer and under direct sun exposure. Equal starting weights were maintained for both methods to ensure valid comparison. Greenhouse drying was conducted from 9:00 to 13:00 h, while open sun drying continued until 14:00 h to achieve comparable final moisture content. Observations and measurements were recorded at one-hour intervals. The greenhouse dryer achieved a reduction in okra moisture content from 86% to 10% (wet basis) within four hours. The system recorded a mean drying efficiency of 79% under average solar irradiance values of 1255.33 W/m^2 on the first day and 993.17 W/m^2 on the second day. Drying rates inside the greenhouse averaged 23.50 g/h and 44.84 g/h across the two days, whereas corresponding open sun drying rates were slightly lower at 23.09 g/h and 38.88 g/h. Thermal performance analysis showed that, on the first day, the heat utilization factor varied between 1.63 and 5.68, while the coefficient of performance (COP) ranged from −0.63 to −4.68. Average values were 3.12 and −2.12, respectively. On the second day, heat utilization factors extended from 1.06 to 13.36, and COP values ranged from −1.79 to −2.68, producing mean values of 13.09 and −2.18. The accelerated moisture removal observed in the greenhouse system confirms its superior drying capability compared to traditional open sun drying. Efficient harnessing of solar energy contributed to shorter drying periods and improved process reliability. In addition, the dried okra retained a more desirable color, indicating better quality preservation. Reduced exposure time also minimizes contamination risks and post-harvest losses. These findings highlight the suitability of the developed passive solar greenhouse dryer as an effective and sustainable solution for vegetable drying in sun-rich regions.*

Key Words: Greenhouse solar dryer; Passive solar drying; Thermal energy storage; Okra drying; Drying efficiency; post-harvest preservation

1. INTRODUCTION

Drying is one of the earliest and most widely applied methods for preserving agricultural commodities, yet it is inherently energy demanding. Rising fuel prices and the depletion of fossil resources have intensified interest in renewable energy alternatives for agro-processing. Solar energy, in particular, offers a sustainable option for reducing the environmental footprint of crop drying operations. The drying of agricultural produce involves coupled heat and mass transfer processes and is recognized as one of the most energy-consuming stages in post-harvest handling. Although traditional sun drying has been practiced for centuries due to its simplicity, the growing global population has increased pressure on food systems and consequently on energy consumption throughout the supply chain [1],[2]. Projections indicate that worldwide energy demand may increase by 40–50% by 2030 to meet food production and processing needs [3],[4]. Therefore, improving drying technologies with respect to energy efficiency, exergy utilization, cost-effectiveness, and environmental performance has become increasingly important [5].

Solar dryers are commonly classified based on their collector configuration, with cabinet and chimney-type dryers being among the most prevalent. In cabinet dryers, solar radiation passes through a transparent cover and is absorbed within the drying chamber itself. Chimney-type dryers, on the other hand, separate the collector from the drying chamber and incorporate a vertical chimney to intensify buoyancy-driven airflow. This arrangement enhances ventilation and often produces higher internal temperatures. Additionally, the use of multiple trays allows more effective use of space. For these reasons, many recent studies have favored designs with externally positioned collectors [6].

Fresh vegetables are highly perishable due to their elevated metabolic activity, which limits their storage life. Postharvest deterioration leads to both quality and quantity losses, ultimately reducing market value. In Nigeria, significant portions of fruits and vegetables are lost before reaching consumers, with postharvest handling accounting for a substantial share of these losses. Such losses may occur during harvesting, transportation, storage, and processing. They manifest as nutritional degradation, reduced edibility, and physical damage arising from pests, rodents, or microbial spoilage [7].

Despite its low cost, open sun drying remains inefficient because a considerable fraction of available heat is not effectively utilized, resulting in slow moisture removal and prolonged drying times [8],[9]. The method is also highly weather-dependent and exposes produce to contamination by dust, insects, birds, and rodents. Inadequate control of drying conditions can encourage fungal growth and increase the likelihood of food-borne illnesses [10]. Consequently, there is a pressing need for reliable, small-scale drying technologies that enhance food security and farmer income in developing regions.

This study addresses these concerns by developing a passive solar greenhouse dryer suitable for the climatic conditions of Makurdi. The system emphasizes operational simplicity, energy efficiency, and sustainability through the use of passive solar heating, guided airflow, and thermal mass storage. Okra (*Abelmoschus esculentus*), a warm-season vegetable belonging to the Malvaceae family, was selected as the test crop due to its economic and nutritional importance. Okra pods are widely consumed fresh and are frequently dried for off-season use. Nutritionally, okra provides carbohydrates, protein, fibre, essential minerals, and vitamins A and C [11]. Its characteristic mucilaginous texture arises from glycans, which contribute to desirable culinary properties [12]. Given the high demand and perishability of okra, improving its post-harvest preservation through efficient solar drying technologies is both economically and nutritionally beneficial.

2. MATERIALS AND METHODS

2.1 Materials

2.1.1 Experimental Setup and Design

Figure 1 illustrates the schematic layout and detailed design of the solar greenhouse dryer used in this study. A series of experimental trials were conducted in April 2024 to assess both the performance of the solar collector and the drying behavior of okra (*Abelmoschus esculentus*). Each experimental run involved a 10 kg batch of fresh okra sourced from a local market in Makurdi, Benue State, Nigeria.

2.1.2 Solar Dryer Design and Fabrication

The dryer was designed following an extensive review of previous studies on solar drying systems, which guided the selection of a flat-plate collector configuration for this experimental investigation. Critical design parameters including the effective collector area and air mass flow rate were calculated to optimize drying efficiency. Based on these calculations, the solar collector was sized at 1.6 m^2, which was sufficient to handle a 10 kg batch of okra. The dryer was fabricated using locally available materials, ensuring practicality and replicability in similar resource-constrained settings.

Beechwood (*Gmelina arborea*) was chosen for constructing the frame of the solar greenhouse dryer due to its combination of lightweight, high strength, durability, low cost, and local availability, making it an ideal material for this application. The dryer's body was covered with clear polyvinyl chloride (PVC) film of 0.34 mm thickness, selected for its excellent transparency, high UV stabilization, mechanical strength, and resistance to aging, water, and abrasion. PVC is also non-toxic and provides good thermal insulation, enabling it to effectively trap heat and solar radiation within the drying chamber. In addition to the PVC film, 4 mm thick transparent glass was used as the primary solar collector to enhance solar energy absorption. The chimney was fabricated from PVC, chosen for its durability, thermal insulation properties, and resistance to environmental factors such as weathering, chemical degradation, corrosion, and mechanical impact. These material selections ensured that the dryer could withstand outdoor conditions while maintaining optimal performance.

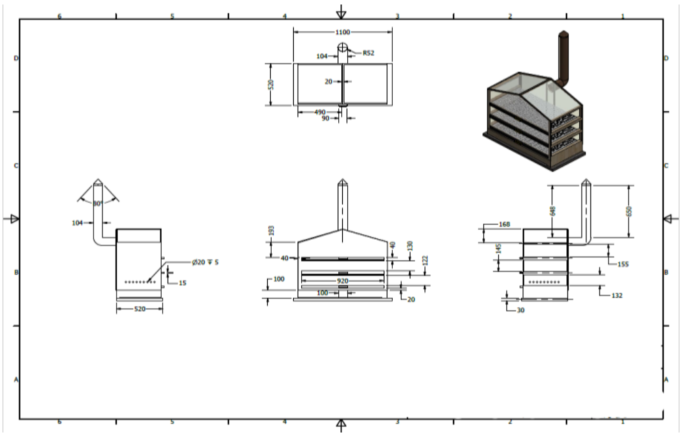

Fig -1: The proposed Design of the greenhouse solar dryer

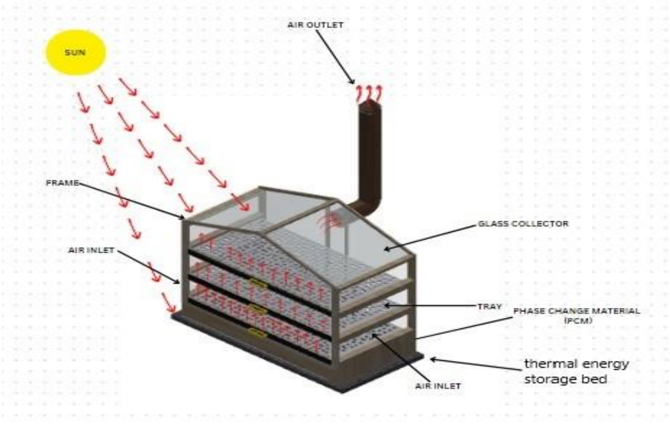

Fig -2: The proposed greenhouse solar collector

Fig -3: Greenhouse solar dryer during experiment

2.2 Methods

2.2.1 Drying Procedure

After fabrication, the solar greenhouse dryers were installed in an open, sun-exposed area to ensure maximum solar irradiation. For optimal performance, the dryers were positioned on the terrace of the facility. Fresh okra samples were prepared by measuring their initial mass, with 4 kg of okra placed in each dryer. Parallel drying trials were conducted under open sun conditions to provide a reference for performance comparison between the solar dryers and traditional sun drying.

During the drying process, key environmental and operational parameters including air temperature, solar irradiance, relative humidity, air velocity, and the mass of the food material were recorded at regular intervals. These measurements enabled a detailed assessment of the thermal performance and drying kinetics of each system. Precautions were taken to protect the dryers from rain and strong winds, ensuring consistent experimental conditions. Drying inside the greenhouse dryers also provided protection from external contaminants such as dust, bacteria, and atmospheric pollutants. Subsequent nutritional analysis confirmed that okra dried within the solar dryers retained higher nutrient content compared to open sun-dried samples. The experiments were conducted using different thermal mass bed conditions (pebbles and coarse sand) to evaluate their effect on drying performance. All trials were carried out in January 2024, under clear sky conditions, at the Department of Mechanical Engineering, Joseph Sarwuan Tarka University, Makurdi, Nigeria (latitude 7.74°N, longitude 8.37°E). Drying operations were performed daily from 09:00 to 14:00 hours for two consecutive days. To maximize solar energy absorption, the greenhouse dryers were oriented along the East–West axis (South–North alignment), consistent with the local latitude being below 40°.

2.2.2 Determination of Angle of Inclination

The inclination angle of a solar collector plays a critical role in maximizing solar energy absorption and is typically related to the latitude (ϕ) of the installation site, assuming the collector is aligned along the south–north axis. For a flat-plate solar collector, the optimal tilt angle (β) can be determined using the method proposed by Oguntola *et al.* (2010) [13] by employing equation 1.

$$\beta = \phi + 10 \qquad (1)$$

Were,

β is angle of inclination

ϕ is Latitude of experimental location

2.2.3 Determination of Solar Collector Efficiency

The efficiency of the solar energy collector is a key indicator of the dryer's thermal performance. It quantifies the proportion of incident solar radiation that is converted into usable heat for air heating within the system. Heat losses due to convection and radiation also occur and must be accounted for. The collector efficiency (ηc) can be expressed mathematically as:

Solar Energy Collector Efficiency,

$$\eta c = \frac{\dot{m} C_p (T_o - T_i)}{I_C A_C} \times 100 \qquad (2)$$

Where,

$\dot{m}$ – air mass flow rate kg/s

C_p - Specific heat capacity of air, kJ/kg°C

I_c - Insolation radiation on the collector surface, W/m^2

A_c - Collector Area, m^2

2.2.4 Drying Efficiency

Drying efficiency (η_d) represents the effectiveness of the dryer in utilizing the supplied heat to remove moisture from the product. It is defined as the ratio of the energy required to evaporate moisture from the wet material to the total thermal energy provided to the drying system [14]. This parameter provides a measure of the system's thermal performance and takes into account factors such as the type and quantity of the material being dried, the internal air temperature, and the airflow within the dryer. The drying efficiency can be expressed mathematically as:

$$\text{Drying efficiency}, \eta d = \frac{M_w L}{I_C A_C t} \times 100\% \qquad \textbf{(3)}$$

Where:
M_w is the mass of water to be removed (kg); L is the latent heat of vaporization of water at the drying temperature (kJ kg^{-1}); Ic is the solar radiation incident on the collector (W m^{-2}); Ac is the collector area (m^2); and t is the drying time (s).

2.2.5 Determination of Drying Rate

The drying rate is defined as the amount of moisture removed from the product per unit time, providing insight into the kinetics of the drying process [14]. It reflects how quickly the dryer can reduce the moisture content of the material under given operating conditions. The drying rate (DR) can be expressed mathematically as:

$$DR = \frac{M_i - M_d}{t} \quad \frac{kg}{s} \qquad (4)$$

M_i – mass of the sample before drying (kg)
M_d – mass of the sample after drying (kg)
t – drying time (s)
The moisture removal rate (moisture loss) is given by Equation (4), as reported by Rajesh and Karuppasamya (2016).

$$M.R.R\ \% = \frac{M_i - M_d}{M_d} \ \frac{kg}{s}$$

2.2.6 Determination of Moisture Content

Moisture content (MC) is a key parameter for assessing the performance of a drying system, representing the proportion of water present in the product relative to its total weight. It can be expressed on a wet basis (w.b.) or a dry basis (d.b.), depending on the reference chosen. Accurate determination of moisture content is essential for evaluating drying efficiency, drying rate, and overall system performance. Following Fudholi *et al.* (2011) [15], the moisture content on a wet basis can be calculated as:

$$M.C.(w.b)\ \% = \frac{w-d}{w} \times 100 \qquad (5)$$

w – Weight of wet sample material, kg
d – Weight of dry sample material, kg
Moisture Content on the dry basis has been given by Mercer, (2008) as:

$$M.C\ (d.b)\ \% = \frac{w-d}{d} \times 100 \qquad (6)$$

The mass of moisture removed from m kg of moist product having initial moisture content M_i when it is dried to a final moisture level of M_f is obtained from the following equation.

$$M_w = \frac{M(M_i - M_f)}{100 - M_f} \qquad (7)$$

2.2.7 Heat Utilization Factor (H.U.F.)

The Heat Utilization Factor (H.U.F.) quantifies the effectiveness of the drying system in transferring heat from the air to the product. It is defined as the ratio of the temperature drop due to air cooling during the drying process to the temperature rise achieved through air heating within the dryer. This factor provides an indication of how efficiently the system utilizes the absorbed thermal energy for moisture removal. Mathematically, it can be expressed as:

$$H.U.F. = \frac{T_{wf} - T_{cr}}{T_{wf} - T_a} \qquad (8)$$

Where,
T_{wf} is working fluid (air) temperature,
T_{cr} is crop temperature and
T_a is ambient temperature.

2.2.8 Coefficient of Performance (C.O.P.).

C.O.P. of drying system can be given as below:

$$C.O.P. = \frac{T_{cr} - T_a}{T_{wf} - T_a} \qquad (9)$$

3. Results and Discussion

3.1 Effect of Solar Radiation on Thermal Performance

Solar radiation was the primary factor governing the thermal behavior of the passive greenhouse solar dryer. As depicted in Charts 1 and 2, increases in global solar irradiance corresponded with simultaneous rises in both ambient temperature and the internal temperature of the drying chamber, for the sand bed on day one and the pebble bed on day two, respectively. Conversely, decreases in solar radiation intensity led to a decline in internal temperatures, confirming that the dryer's thermal performance is strongly dependent on incident solar energy under passive operating conditions.

Throughout the drying period, the greenhouse dryer maintained internal temperatures consistently higher than the ambient environment. On the first day, the chamber reached a maximum temperature of 52.6 °C, compared with an ambient peak of 45.7 °C (Figure 4). On the second day, the chamber temperature peaked at 49.6 °C against an ambient temperature of 43.9 °C (Chart 2). These elevated temperatures highlight the effectiveness of the transparent cover and the solar collector in capturing and retaining heat while minimizing convective losses, thereby creating favorable conditions for efficient drying.

3.2 Influence of Thermal Energy Storage Beds

The improved thermal performance of the greenhouse dryer can be attributed to the combined effect of the solar collector and the integrated thermal energy storage beds. Both the sand and pebble beds acted as sensible heat storage media, absorbing excess heat during periods of high solar radiation and gradually releasing it as irradiance decreased. This moderated internal temperature fluctuations, as reflected in the relatively stable chamber temperature profiles shown in Charts 1 and 2.

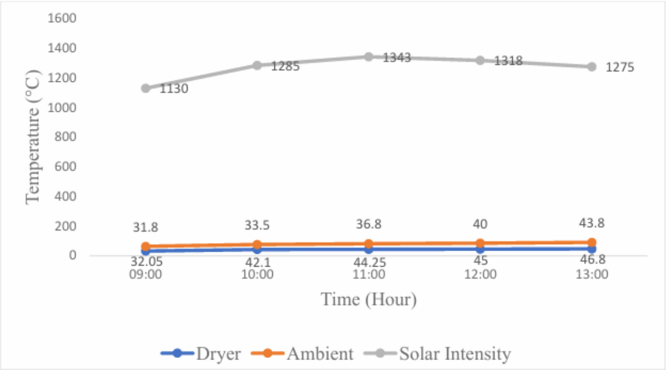

Chart -1: Chart of dryer, ambient temperature and solar radiation against time for day one (Sand bed)

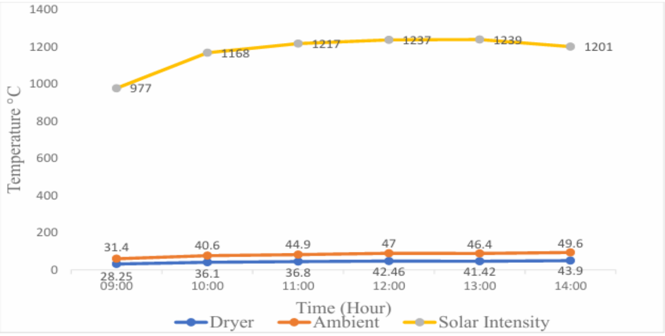

Chart -2: Chart of dryer, ambient temperature and solar radiation against time for day two (Pebble bed)

The sand bed exhibited slightly higher average temperatures compared to the pebble bed, suggesting material-dependent differences in heat storage and release characteristics. Nevertheless, both storage media effectively maintained elevated drying temperatures, which are essential for efficient moisture removal.

3.3 Moisture Content Reduction and Drying Kinetics

The evolution of okra moisture content over time for both the greenhouse dryer and open sun drying is presented in Chart 3. A rapid reduction in moisture content occurred during the initial stages of drying, particularly within the first hour, due to the high surface moisture of the fresh samples.

Throughout both experimental days, the greenhouse dryer consistently removed moisture faster than open sun drying. Okra samples inside the greenhouse reached a final moisture content of approximately 10% (wet basis) by 13:00 h, whereas open sun drying required up to 14:00 h to achieve the same level, demonstrating a time saving of roughly one hour. The higher drying rates observed in the greenhouse system (Chart 4) can be attributed to the elevated internal temperatures and lower relative humidity, which increased the vapor pressure gradient between the product surface and the surrounding air.

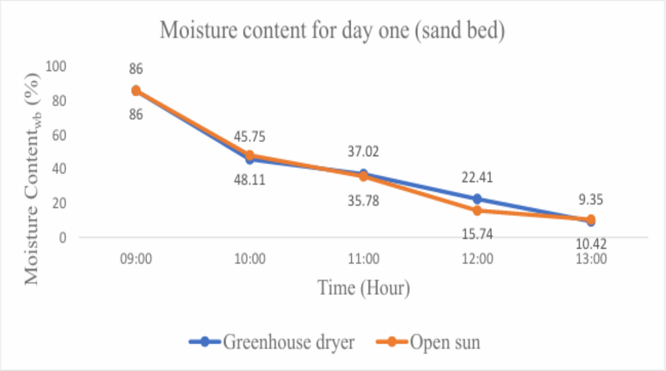

Chart -3: Moisture content of greenhouse dryer and open sun against time for day one

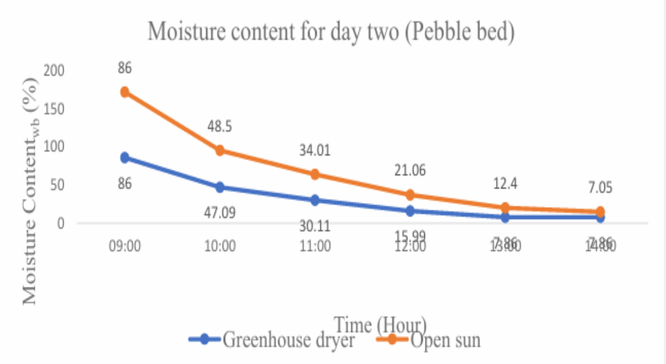

Chart -4: Moisture content of greenhouse dryer and open sun against time for day two

3.4 Role of Airflow and Chimney Effect

The incorporation of a chimney significantly enhanced natural convection within the dryer. The chimney induced a continuous upward airflow, efficiently removing humid air from the drying chamber and preventing moisture accumulation around the product. This facilitated consistent drying rates and improved temperature regulation.

As a result, the greenhouse dryer maintained a more controlled and favorable drying environment compared to open sun drying, where airflow and temperature are largely uncontrolled. The benefits of the chimney-assisted airflow are reflected in the improved moisture reduction patterns shown in Charts 3 and 4.

3.5 Relative Humidity Characteristics

Charts 5 and 6 illustrates the relative humidity profiles of both ambient air and the greenhouse drying chamber. While ambient relative humidity remained nearly constant at approximately 15%, the internal relative humidity of the dryer varied inversely with temperature. Lower relative humidity levels were observed during periods of peak chamber temperature, particularly in the afternoon hours.

The reduction in internal relative humidity enhanced the drying potential of the air, promoting faster evaporation from the okra samples. Controlled humidity conditions within the greenhouse thus contributed significantly to its superior drying performance relative to open sun drying.

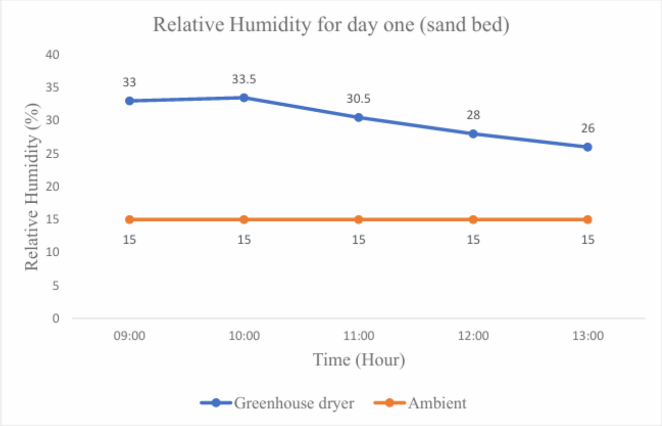

Chart -5: Relative humidity of greenhouse dryer and ambient against time for day one

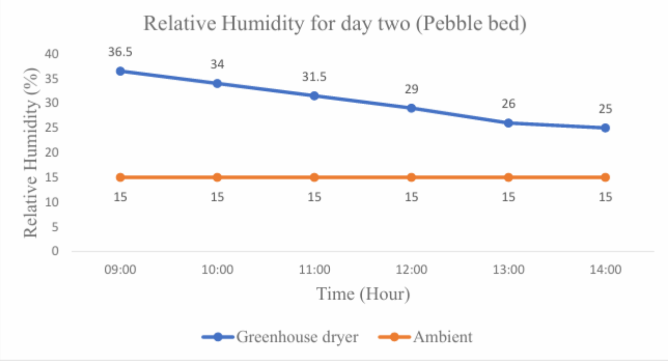

Chart -6: Relative humidity of greenhouse dryer and ambient against time for day two

3.6 Energy Utilization and System Performance Indicators

The heat utilization factor (H.U.F.) and coefficient of performance (COP) provide quantitative insights into the energetic efficiency of the drying system. Temporal variations of H.U.F. and COP for both experimental days are presented in charts 7, 8, 9 and 10. The relatively high H.U.F. values indicate efficient conversion of absorbed solar energy into heat for moisture removal, particularly during periods of peak solar radiation.

Although the COP values were negative, this behavior is typical for drying systems, where energy input primarily supports latent heat of evaporation rather than mechanical work. The higher average H.U.F. observed on the second day suggests improved thermal utilization with the pebble bed, likely due to its favorable heat storage and release characteristics. The heat energy gained by the drying air shown in Figure 14, further confirms that substantial thermal energy was available throughout the drying period, supporting continuous and efficient drying

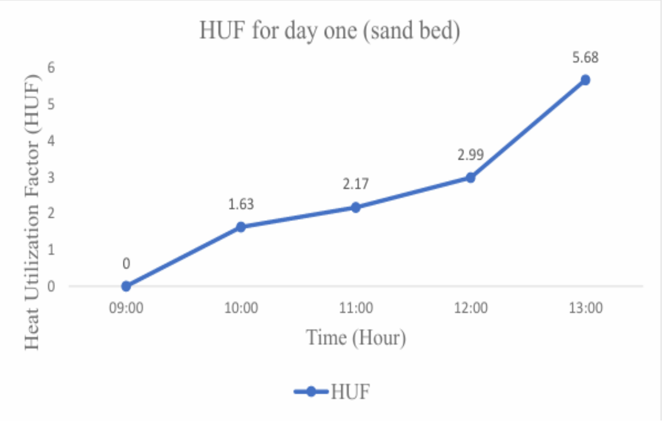

Chart -7: Heat utilization factor for day one

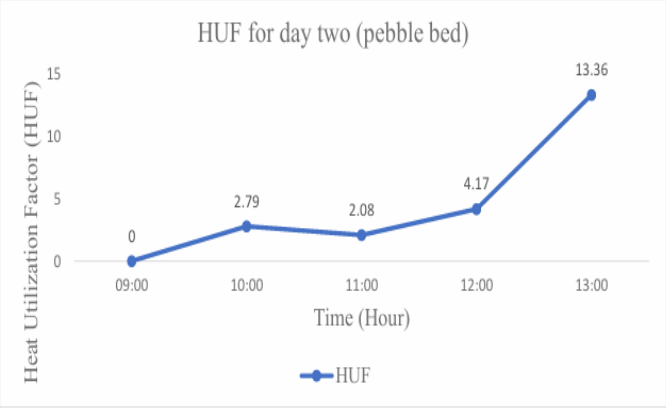

Chart -8: Heat utilization factor for day two

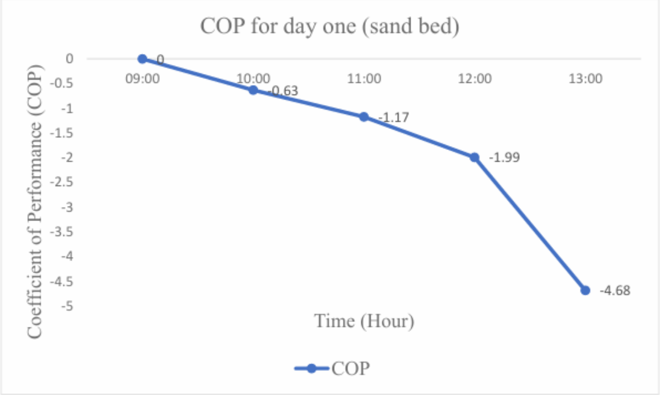

Chart -9: Coefficient of performance for day one

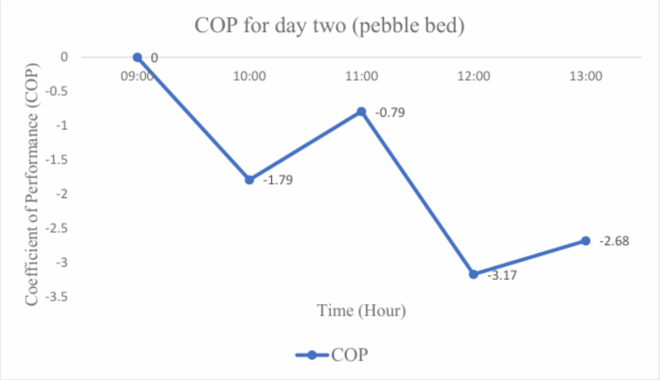

Chart -10: Coefficient of performance for day two

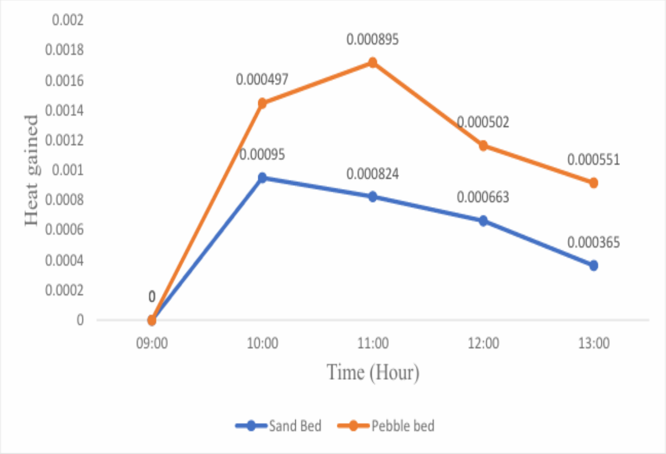

Chart -11: Heat energy gained against time for day one and two

3.7 Energy Utilization and System Performance Indicators

Overall, the results demonstrate that the passive greenhouse solar dryer outperformed open sun drying in terms of temperature elevation, moisture removal rate, and reduction of drying time. The integration of thermal energy storage beds and chimney-assisted airflow created a controlled drying environment, enhancing heat retention, lowering relative humidity, and accelerating moisture diffusion from the product.

These findings indicate that the developed greenhouse solar dryer is an effective, energy-efficient solution for vegetable drying under tropical conditions. It has strong potential to reduce post-harvest losses, improve product quality, and support small-scale agricultural production.

3.7 Drying Rate

The recorded drying rates presented in charts 12 and 13, highlight the performance advantage of the solar greenhouse dryer over traditional open sun drying. During the two-day experiment, the average drying rates of the greenhouse dryer were 23.50 g/h and 44.84 g/h, whereas the corresponding values for open sun drying were 23.09 g/h and 38.88 g/h, respectively. The higher drying rates in the greenhouse dryer can be attributed primarily to elevated internal air temperatures and reduced relative humidity, which together increased the vapor pressure gradient between the product surface and the surrounding air. This gradient is the main driving force for moisture diffusion during drying. The presence of sand and pebble bed thermal storage also contributed by storing excess heat during peak radiation periods and releasing it when solar intensity declined, thereby sustaining moisture removal even under fluctuating solar input.

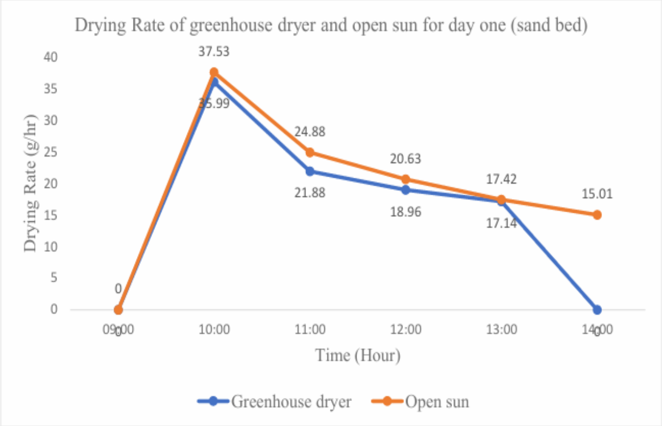

Chart -12: Drying rate for day one

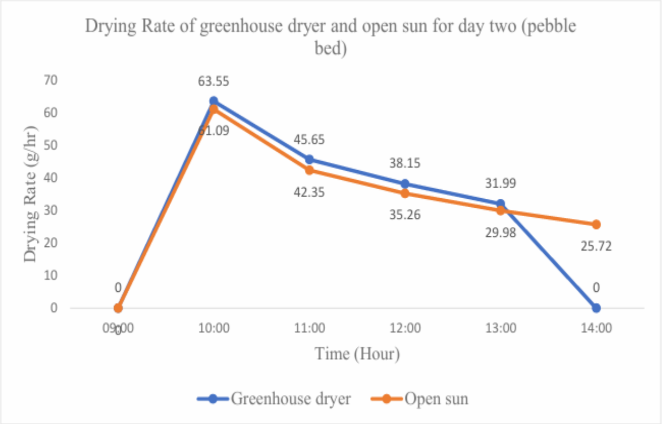

Chart -13: Drying rate for day two

3. CONCLUSIONS

This study presented the design, construction, and experimental assessment of a passive greenhouse solar dryer incorporating sand and pebble bed thermal energy storage, developed using locally available and cost-effective materials. The system was conceived as an alternative to traditional open sun drying, which is often associated with prolonged drying periods, product contamination, and inconsistent quality. Experimental trials conducted under the climatic conditions of Makurdi, Nigeria, confirmed the practicality and effectiveness of the system for drying high-moisture vegetables such as okra. The greenhouse dryer maintained temperatures consistently above ambient conditions, reaching peak values of 52.6 °C and 49.6 °C for the sand and pebble bed configurations, respectively. These elevated temperatures resulted from the synergistic action of the transparent enclosure, solar energy collection, and sensible heat storage within the thermal beds. The integration of sand and pebble media contributed to heat retention and moderated temperature fluctuations, thereby ensuring a relatively stable drying environment under natural convection. Enhanced thermal conditions within the dryer translated into improved drying performance compared with open sun drying. Okra samples dried in the greenhouse attained a final moisture content of about 10% (wet basis) within four hours, reducing drying time by approximately one hour. Higher drying rates were observed, particularly at the early stage of drying, due to increased air temperature and lower relative humidity inside the chamber.

From an energy perspective, the system achieved an average drying efficiency of approximately 79%, demonstrating effective conversion of solar energy into useful heat for moisture evaporation. Heat utilization factor values indicated meaningful use of the captured thermal energy, while the coefficient of performance trends aligned with the energy demands associated with latent heat removal during drying. Performance differences between sand and pebble beds indicate that both materials are viable thermal storage options, with pebble beds showing favorable heat utilization under certain conditions.

In summary, the passive greenhouse solar dryer developed in this study offers a sustainable and efficient solution for small-scale crop drying. Its capacity to shorten drying time, improve energy use, and maintain product quality underscores its potential to mitigate post-harvest losses and support food security in developing regions. Further studies are recommended to evaluate long-term performance, conduct techno-economic analysis, optimize storage materials, and examine the nutritional and sensory attributes of dried products to facilitate wider adoption of the technology.

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