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Design and Performance Evaluation of an Active Solar Food Dryer for Sustainable Agricultural Preservation

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Abstract: *The design, construction, and testing of an active solar food dryer for overcoming the disadvantages of the traditional open-air solar food dryer have been carried out in this research work. The construction of the solar food dryer uses a mild steel structure enclosed by a UV-resistant polycarbonate sheet. This facilitates the absorption of solar radiation by maximizing the greenhouse effect. The solar food dryer uses a 12V, 10W photovoltaic panel to generate power for the DC exhaust fan, promoting forced convection in the dryer. An XH-W3001 thermostat has also been integrated into the dryer to regulate the internal microclimate. Experimental tests were conducted on various agricultural products, including fenugreek seeds, onions, guavas, moringa leaves, roses, and chiku. In all tests, the dryer's internal temperature was kept at 45°C, with ambient temperatures ranging from 28°C to 30°C. The empirical results reveal a substantial decrease in mass due to moisture within the test specimens, occurring over 8 to 18 hours of constant operation. For example, the mass of fenugreek was reduced from 1500 grams to 250 grams within 8 hours, while the mass of onions was reduced from 6000 grams to 650 grams within 18 hours. Economic analysis reveals that the total fabrication cost is very affordable at Rs. 21,980.*

Keywords: Active solar dryer; Forced convection; Food preservation; Photovoltaic thermal system; Thermostatic control; post-harvest technology.

I. INTRODUCTION

Preservation of food is one of the oldest practices in human civilization, particularly in agricultural societies. In such countries, farmers continuously produce huge amounts of crops during concentrated seasons. One of the biggest problems in post-production processes is that some fruits and vegetables have high water content, posing a high risk of spoilage. Without proper measures taken to preserve agricultural products, there is a high risk that these commodities will spoil quickly. The use of traditional techniques leads to great losses of farm produce, about 61%, especially on perishables. Drying is among the best methods of preserving agricultural products. By reducing the water content of the food material, the biological processes of microorganisms and enzymes are greatly inhibited. As a result, this process extends the shelf life of foods without compromising their nutritional value. In the past, this traditional method of drying was widely applied by different societies around the world. The ambient heat from the sun, coupled with natural wind currents, has been historically harnessed to dehydrate agricultural products such as vegetables, fruits, fish, and meat for extended preservation. The primary advantages of open sun drying are extremely low capital and operating costs, along with minimal technical expertise required. However, this rudimentary method is fraught with severe

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limitations. The open-sun-drying process depends heavily on unpredictable weather conditions, including sunlight intensity, ambient temperature, and relative humidity.

In rainy, cloudy weather, the process's effectiveness is very low. Moreover, agricultural products are exposed to various environmental contaminants, including dust particles, insects, birds, and even wild animals. This has a significant effect on the hygiene and sanitation of the dried produce. Excessive exposure of such produce to sunlight can adversely affect its quality, especially its color and vitamin content. Drying in the open sun can result in uneven drying, with some parts of the produce drying more than others, while other parts remain moist. Thus, in the current global energy crisis, it becomes imperative to adopt green-energy-based drying processes. In today's world, the high costs and lack of fossil fuels have made the use of renewable energy sources a very important phenomenon worldwide. Renewable energy is something food processing industries and small farms need to consider when considering replacing energy-intensive unit operations with something better. Solar thermal energy has quickly become popular in agriculture.

It is highly preferable to any other energy source because it is available everywhere, renewable, and pollution-free. The use of solar energy for food drying remains highly appealing due to its efficiency, cost-effectiveness, and practicality. Although there are numerous benefits of solar energy, the lack of appropriate technological solutions still exists. Engineering a cheap yet highly energy-efficient solar dryer capable of producing high-quality dried food is considered one of the most challenging processes. The selection of appropriate structural elements and mechanical devices for a solar dryer is indispensable to ensure efficient utilization of the thermal energy collected. Solar dryers were invented to improve the efficiency, safety, and hygiene of food drying. It also removes moisture from the food, as it absorbs moisture from the food as it passes out of the compartment through the designed ventilation holes. Contemporary solar dryers are composed of several unique components, which include drying racks, transparent polycarbonate covers, insulated frames, photovoltaic solar panels, and exhaust fans. The principle behind the drying process is rather complicated and involves both heat and mass transfer. Drying is basically a two-pronged process: first, moisture from the substance's internal structure moves to the surface, and then it evaporates from there into the surrounding atmosphere.

The method is entirely controlled by the following external factors: temperature, humidity, and speed of the air stream. Internal factors that may control the efficiency of moisture removal from surfaces include physical structure, porosity, chemistry, and surface features. The efficiency with which air can remove moisture depends primarily on its temperature and humidity. Hence, the higher the air temperature and the lower the humidity, the greater the absolute capability to remove moisture. It is important to understand that absolute humidity refers to the moisture content of the air itself. In contrast, relative humidity is the ratio of the moisture content of the air at a specific temperature to that when the air is completely saturated. In active drying, in an ideal case where the process is carried out adiabatically, sensible heat in the circulating air continuously converts to latent heat as moisture is extracted from the foodstuffs. For making effective use of thermodynamics in this case, the current project aims at the design, construction, and evaluation of an active solar food dryer based on principles of forced convection using flat-plate collectors to ensure optimum temperatures in the range of 50°C to 70°C, cutting down traditional drying time requirements up to three to five times. The purpose of the current project is to design and develop an efficient solar food dryer. The system includes a specially made drying chamber, which helps protect food items against dust, pests, and animals, resulting in maximum hygiene. The judicious selection of materials, such as stainless steel 304 for the interior mesh trays, results in a food-safe and non-corrosive setup, which is ideal for drying fruits and vegetables without any fear of chemical contamination. Another important advantage of using the material of choice is its optical clarity and impact resistance, which are further enhanced by its heat-trapping properties.

The continuous powering of the DC exhaust fan by the 12V solar panel photovoltaic system ensures a constant airflow throughout the drying process. With this engineered system, even drying occurs across multiple trays, without any risk of microbial growth, and with excellent food quality preserved. The addition of temperature sensors and thermostats offers an important control mechanism to achieve thermodynamic efficiency in the drying process. Overall, this scientific work demonstrates how effectively advanced solar energy technologies can be applied to food preservation in agriculture. The resulting system is robust and energy-efficient, and can be widely used by small farmers with no stable electricity supply.

II. REVIEW OF EXISTING METHODOLOGIES

A new method for a solar dryer incorporating thermal energy storage (TES) was proposed by Rulazi et al. [1] to maximize the performance of continuous drying of farm produce. The method consisted of installing thermal energy storage materials in the drying system to store excess solar energy during sunny hours and release it during non-sunny hours. Proximate analysis was utilized in this study to measure nutrient destruction relative to sun-drying. Efficiencies of 45% for thermal energy and 74.5% for energy stored in TES materials were found. This process provided continuous heating for 3 to 4 hours after sunset, improving both drying time and the quality of the final product. The main research gap identified in the study is the long-term impact of these TES materials under harsh, humid climatic conditions.

According to Muthuvairavan et al. [2], a detailed study was conducted on the efficacy of solar dryers for different types of food items, including fruits, vegetables, and marine products. The technique used mathematical models to estimate critical factors, such as moisture diffusivity and activation energy, in the drying process. Their findings revealed that solar dryers designed for forced convection are highly efficient compared to passive systems, with better control and a higher rate of moisture removal. The study also indicated that solar drying enhanced energy efficiency and nutritional matrix more efficiently than other forms of drying. Nevertheless, a major drawback in research is the lack of universally applicable mathematical models that can effectively adapt to the changes in weather conditions in tropical regions.

Pal et al. [3] suggested exploring quality profiles of some high-moisture vegetables dried using inexpensive solar dryers. This would include testing a rotary chimney-type dryer and a tunnel-type dryer, both covered with different polyethylene films, for drying tomatoes, onions, cabbage, and spinach. It also involved monitoring differences between ambient and internal temperatures, drying time, color retention (as measured by L*, a*, and b* values), and vitamin C content. The findings revealed that solar dryers kept the internal temperature of the dryers 5–15°C higher than ambient air and cut down drying time by 20-44 hours as compared to drying in the open sun. Although the colors and rehydration ratio were excellent, a considerable reduction in vitamin C content was observed. It is an important research area that needs urgent attention from researchers to develop low-cost pretreatment methods to reduce heat-labile nutrient losses during solar drying.

The authors in Natarajan et al. [4] have provided an extensive comparative review of traditional and modern technologies utilized for drying fish, fruits, and vegetables through solar energy in developing countries. The paper employs a method to evaluate the mechanisms of operation, initial investment costs, and heat-transfer efficiency of direct, indirect, and combined dryers to address the enormous losses encountered in consumer markets. The findings showed that almost 60% of food loss in the region is attributed to the absence of appropriate technology for food preservation, and an advanced forced-convection solar dryer could minimize processing time and lower the risk of pathogen contamination. Notwithstanding these benefits, the researchers identified a significant research gap in the scale-up of such systems; there is very limited literature on the technoeconomic feasibility analysis of building a hybrid system locally after a disaster.

A bibliometric and technical trends analysis on the integration of advanced energy technologies into solar dryer systems was developed by Villagran et al. [5]. The approach involved a systematic literature review of 126 scientific publications from 1984 to 2024, focusing on improvements in energy simulation, Computational Fluid Dynamics (CFD), and phase change material (PCM) technology. The findings showed a significant increase in research concerning solar drying techniques during the past decade. It became evident that whereas CFD proved an effective technique for optimizing air movement and thermal distribution, the addition of PCM technology greatly improved thermal stability but increased implementation costs. A notable knowledge gap is the mismatch between computer-simulated models and their practical application.

Eco-environmental assessment of a greenhouse-based solar dryer developed for dehydration purposes of Solanum lycopersicum (tomato) was conducted by Patel [6]. The assessment method involved an interlocking polycarbonate module that harvested infrared radiation to create a passive greenhouse effect. The solar dryer contained 5.8 kg of tomatoes and underwent thermodynamic performance analysis, including calculations of embodied energy and economic payback time. The findings indicated a thermal efficiency of 26.66%, effectively protecting fruits from dust and rain and greatly reducing the normal drying time. As for economic viability, the system showed a very short payback time of only 1.6 years. However, the major research limitation lies in the need to harvest infrared radiation only during sunny periods of the day, prompting further investigation into the development of inexpensive thermal backup systems for cloudy or rainy monsoons.

According to Suherman et al. [7], the hybrid solar dryer used for the dehydration of red chili peppers was evaluated. In the analysis, variation was made of the independent variable, which included drying air temperature (40°C to 80°C), to evaluate the performance of the hybrid dryer using drying curves, thermal efficiency, exergy input and output, beta-carotene, and vitamin C levels. The study demonstrated that the hybrid dryer effectively dehydrated the red chili peppers to a moisture content of ⩽10.78%, the national standard requirement of dried chili peppers. However, the collector's efficiency was highest at 40°C; higher temperatures led to greater exergy destruction and energy losses. This gap lies in exergy utilization, where future hybrid dryers must use heat recovery ventilators to recover wasted exergy.

According to Semwanga et al. [8], the performance of the upgraded version of the HIP solar dryer, whose structure was modified by installing collectors and a cabinet, requires analysis. For this study, the standard solar collector plate was retrofitted with several metallic solar concentrators and plastic greenhouses used to cover the cabinet walls. Performance was evaluated by drying succulent fruits such as mangoes and pineapples using standard active-mode dryers and the open-sun drying method. The performance was very encouraging, as the HIP dryer reduced drying time from 30 to 18 hours (a 12-hour reduction) and improved efficiency by 18% compared to conventional dryers, making it almost equivalent to more expensive electric dryers. The research gap lies within the materials' lifetime; no studies have been conducted about their resistance to galvanic corrosion and oxidation under high humidity conditions.

According to Onyenwigwe et al. [9], the research on ecological thermal modeling and response surface optimization focused on the drying rate of potato slices in a hybrid solar dryer system. This process entailed experimentation with active and passive sun-drying of blanched potato slices, based on which hourly mass-loss, temperature, and relative humidity readings were used to estimate the potential for carbon reduction. The results showed that the dryer used only 4.562 MJ to reduce the moisture content from 64% to 7.56%, with an average efficiency of 39.46%. Importantly, this system showed substantial potential for decarbonization, as much as 237.71 tonnes of CO2 could be saved annually, unlike those using diesel engines. In this context, the identified research gap concerns the limitations of optimization modeling in handling static constraints, which necessitate the development of AI-based systems capable of adjusting airflow based on ambient carbon levels and temperatures.

A computational fluid dynamics analysis of a solar dryer using various PCMs as latent heat storage has been proposed by Mamulkar et al. [10]. This approach involved simulating the thermodynamics of paraffin wax, lauric acid, and palmitic acid incorporated into the base of the solar dryer to dry 5 mm-thick potato slices. By determining the amount of thermal energy required to dry 2 kg of potatoes, Mamulkar et al. [10] conducted comparative evaluations of the enhanced design against a basic solar dryer. It was conclusively proven that paraffin wax was the most efficient of the three, with a thermal efficiency of 87%, while lauric acid had a thermal efficiency of only 40.2%. One limitation of the work done here is its complete digitalization. There is a need for physical prototypes to investigate the risk of chemical leakage from PCMs.

Rana et al. [11] described the design, construction, and performance of an active, forced-convection food solar dryer. The methodology involved the construction of a hybrid design incorporating a mild-steel skeletal structure covered with polycarbonate sheeting and a solar PV battery-driven DC power supply, which continuously powered an exhaust fan to control relative humidity levels. The system was subjected to direct load testing using measurements of internal microclimates. The results were spectacular; the forced airflow design helped achieve temperatures of 71° C in the

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internal chamber, maintaining an astounding 30° C above the outside ambient air temperature. The system had a total efficiency of 49.2%. The research gap calls for extensive economic scaling matrices to be done. On the other hand, while the design is technically perfect, more research is needed to optimize manufacturing and minimize costs.

Tieu et al. [12] introduced an exciting experimental design, which was a combination of numerical simulation and testing of the solar drying process through a specially designed ventilated attic. The method included designing the attic with a black roof to facilitate heat absorption and PVC pipe chimneys to create airflow. Six kilograms of cassava were loaded into the system. Thermodynamic behavior was simulated using the fourth-order Runge-Kutta method to solve for heat and mass transfer. The results revealed that cassava was successfully dried within 3 days, with mathematical predictions consistent with the physical outcomes (relative error < 14%). However, there was a drastic drop in drying efficiency from 25% on day 1 to 0.2% on the final day. This study gap illustrates that the process is highly inefficient during falling-rate drying. It is necessary to consider using a microwave or a desiccant to accelerate drying in deep tissues.

Optimization of energy use in a hybrid solar-electric dryer was carried out by Nwakuba [13] using the response surface method to optimize drying of tomato slices using the hot-air method. This study used a central composite design with three parameters manipulated: air velocity (1.0-2.0 m/s), slice thickness (10-20 mm), and drying air temperature (50°C-70°C). Quadratic models emerged from this experiment and identified the most favorable parameters for energy savings (1.94 m/s air velocity, 10.36 mm slice thickness, and 68.4°C temperature), resulting in a saving of only 5.68 kWh while maintaining the maximum desirability index at 0.989. A thermal efficiency of 58% was achieved in the process. In light of the findings, the research gap indicates an excessive dependence on grid-tied auxiliary electric heaters; therefore, future iterations should focus on replacing the electric coil with high-density renewable biomass furnaces.

An operational performance assessment and economic viability evaluation of an inclined solar dryer specifically tailored for drying Capsicum annuum L. (red chili) were conducted by Poonia et al. [15]. The technique involved a movable, tilted solar collector made of galvanized iron and glass, aimed at permanently maximizing the angle of incident solar rays at Jodhpur, India. The findings indicated that the tilted solar dryer dried a 10 kg batch of red chilies from 80% moisture content to 9% in only 7 days, thus cutting the 14 days required by the conventional open-sun drying method in half. An energy efficiency of 16.25% was achieved, with an internal rate of return of 82.5%. The main knowledge gap lies in manual tilting, which future models should aim to eliminate by adopting low-energy automatic sun-tracking devices.

III .METHODOLOGY

The development of the proposed active solar food dryer was systematically executed through a multi-phase engineering approach, comprising conceptual design, material selection, mathematical modeling, mechanical fabrication, and electronic integration. The primary objective was to engineer a robust, forced-convection drying chamber capable of maintaining an internal microclimate of 45°C independent of fluctuating ambient conditions, while strictly adhering to food-safety and hygienic standards.

A. System Architecture and Working Principle

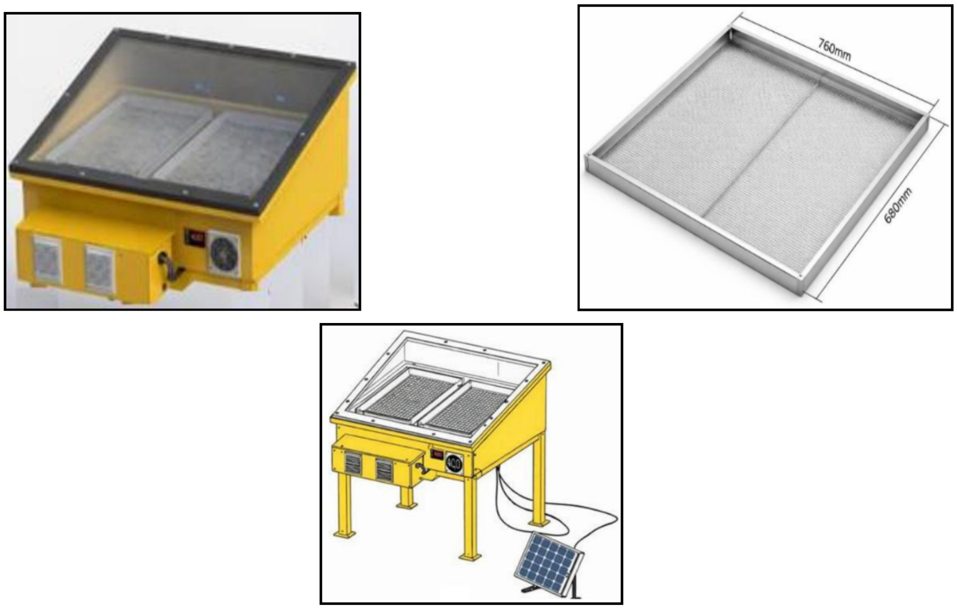
The fabricated system operates on the principle of a direct-mode, active solar thermal collector. In this architecture, the solar drying chamber itself acts as the solar collector. The system is designed as a fully enclosed rectangular cabinet with a sloping transparent roof. Solar irradiance passes through the transparent roof, strikes the internal absorption surfaces, and directly impinges on the food products. The trapped infrared radiation generates a pronounced greenhouse effect, rapidly elevating the internal temperature. Unlike passive systems that rely on natural updrafts, this system employs an active forced-convection mechanism. A DC-powered exhaust fan is strategically mounted at the chamber's apex. This fan continuously extracts warm, moisture-laden air, creating a negative-pressure zone that draws in fresh, dry ambient air through lower ventilation inlets. This active airflow ensures continuous thermodynamic mass transfer, preventing moisture condensation on the internal walls and ensuring uniform drying across all tray levels.

B. Material Selection and Justification

Material selection was strictly governed by thermal efficiency, structural integrity, and compliance with food-grade safety standards.

- Structural Framework: Mild Steel (MS) square tubing (25 mm times 25 mm) was selected for the primary skeletal framework. Mild steel provides excellent tensile strength and weldability, ensuring the structural stability required to support the entire assembly under wind and static loads.
- Glazing Material: A 3 mm thick UV-stabilized Polycarbonate sheet was utilized for the chamber enclosure. Polycarbonate was chosen over traditional glass due to its superior impact resistance (virtually unbreakable), lightweight nature, and high solar transmittance (approx 85%). The UV stabilization prevents material degradation and protects the food from harmful ultraviolet radiation, which degrades volatile organic nutrients.
- Drying Trays: The internal perforated drying trays were fabricated from Stainless Steel 304 (SS 304). SS 304 is the industry standard for food processing equipment due to its exceptional corrosion resistance against acidic food juices and its hygienic, easy-to-clean surface, thereby eliminating the risk of biochemical contamination.

The solar food dryer is designed with insulation frames and heat-absorbing materials to create an ideal drying environment. Mild steel forms the box's structure, while the cover is made of 4-8 mm clear glass or polycarbonate, allowing the sun's rays to enter the box. The heat-absorbing plates, which are normally black-painted sheets of galvanized iron, convert solar energy into heat, while the food is placed in wire-mesh trays to ensure proper airflow around it. The construction and assembly of the solar dryer are presented in Fig. 1.



(a) (b)

(c)

Fig.1.Construction and Assembly (a) Actual Dryer Sample (b) Tray of Solar Dryer (c) Structure of Solar Food Dryer

C. Mathematical Modeling and Thermal Calculations

To ensure the system met the required thermodynamic parameters, foundational empirical calculations were established before fabrication.

- **Solar Heat Gain:** The total active transparent area (A) of the dryer was calculated to be 1.034 m^2. Assuming a peak average solar irradiance (I) of 800 W/m^2 under standard clear-sky conditions, the theoretical incident solar power (P_in) is defined as:

$$P\_in=I\times A=800\ 〖\text{"W∕m"}〗^2\times 1.034\ \text{"m"}^2=827.2\ \text{"W"}\ \ldots(1)$$

Assuming a conservative system thermal efficiency (eta) of 30% due to convective and conductive edge losses, the useful continuous thermal energy (Q_u) generated by the dryer is approximately 248.16 W, which is sufficient to drive the latent heat of vaporization for the targeted moisture mass.

- Structural Load Capacity: The system was designed to support a total dead weight and operational load of 35 kg (343.35 N). The MS square tubes possess a cross-sectional area of 625 mm^2. The minimum required cross-sectional area to prevent compressive failure under this load is mathematically negligible (1.07 mm^2), proving that the chosen 25 mm tubing provides a massive factor of safety, rendering the framework exceptionally rigid and secure.

- Moisture Content Determination: The primary metric for evaluation is the Moisture Content on a wet basis (MC_wb), governed by the equation:

$$MC_{wb}=\left(\frac{m_i-m_f}{m_i}\right)\times 100\ldots\ldots\ldots\ldots\ldots\ldots(2)$$

where m_i is the initial mass of the fresh product and m_f is the final mass of the dried product.

D. Mechanical Fabrication Process

The fabrication sequence commenced with cutting the MS square tubes to the predetermined CAD dimensions using an abrasive cut-off saw. The segments were joined using Shielded Metal Arc Welding (SMAW) to form the base rectangular chassis and the sloped roof profile. The weld joints were subsequently ground flush and coated with anti-corrosive primer and black enamel paint to absorb stray radiation and prevent oxidation. The polycarbonate sheets were precision-cut and secured to the exterior faces of the MS frame using self-drilling screws with EPDM rubber washers to ensure an airtight thermal seal. The SS 304 wire mesh was stretched and spot-welded onto sliding tray frames, which were then slotted into internal guide rails spaced 150 mm apart to allow unimpeded airflow between layers.

E. Electronic Integration and Control System

To achieve energy independence, a standalone 12V Photovoltaic (PV) system was integrated. A 12V, 10W poly-crystalline solar panel was mounted externally to capture solar energy. This panel directly powers a high-RPM 12V DC brushless exhaust fan installed at the upper ventilation port.

To prevent the thermal degradation of the agricultural products (overheating), an automated thermal regulation loop was implemented using an XH-W3001 digital thermostat controller. An NTC thermistor probe was suspended in the geometric center of the drying chamber. The thermostat was programmed with a highly specific hysteresis curve: it activates the exhaust fan vigorously when the internal temperature exceeds 47°C to vent excess sensible heat, and modulates airflow when the temperature drops to the optimal operating baseline of 45°C. This closed-loop control maintains stable psychrometric conditions within the chamber, maximizing moisture diffusivity while safeguarding the food's structural integrity.

F. Experimental Testing Procedure

To empirically validate the fabricated system, comprehensive load tests were conducted using six distinct agricultural samples: Fenugreek (Methi), Onion, Guava, Moringa Leaves, Rose Petals, and Chiku. Before loading, each sample was thoroughly washed, sliced to a uniform thickness to standardize internal moisture diffusion, and precisely weighed using a digital analytical balance (accuracy pm 0.1 g). The samples were distributed evenly across the SS 304 trays.

The system was deployed in an open, unshaded environment. Testing was conducted during peak sunshine hours (09:00 to 17:00). Ambient temperature (T_out), relative humidity, and the internal chamber temperature (T_in) were continuously monitored and logged. The mass of the samples was recorded periodically until no further mass reduction was observed, indicating that the equilibrium moisture content had been achieved.

IV. RESULTS AND DISCUSSION

The active solar food dryer underwent rigorous empirical testing to evaluate its thermodynamic efficiency, drying kinetics, and ability to preserve the organoleptic properties of various agricultural products. The performance of the fabricated system was evaluated against baseline ambient conditions to determine its efficacy in accelerating moisture extraction while maintaining food safety.

A. Thermodynamic Performance and Microclimate Regulation

The most critical operational parameter of any active solar dryer is its ability to generate and sustain a favorable internal thermal gradient. During the experimental trials conducted during peak sunshine hours, the ambient external temperature (T) fluctuated between 28 C and 30 C. In contrast, the internal chamber temperature (T) was rapidly elevated by the polycarbonate glazing's greenhouse effect and successfully maintained at a stable 45 C via the XH-W3001 thermostatic control loop.

This created a continuous and stable thermal differential (T) of 15 C to 17 C above ambient conditions. The stability of this 45 C threshold is of paramount importance. At this specific temperature range, the sensible heat of the circulating air is sufficient to drive the latent heat of vaporization required to extract cellular moisture from the food products, without crossing the threshold that causes "case hardening"—a phenomenon in high-temperature drying where the exterior of the fruit hardens prematurely, trapping internal moisture and leading to rot. Furthermore, the active ventilation, powered by the 12V PV-driven exhaust fan, kept the relative humidity inside the chamber significantly lower than the ambient air, preventing condensation on the internal walls and ensuring uniform moisture diffusion.

B. Drying Kinetics and Mass Reduction Analysis

Results of the proposed system before and after the drying process are presented in Fig.2.

Fenugreek (Methi)

Before After

Onion

Before After

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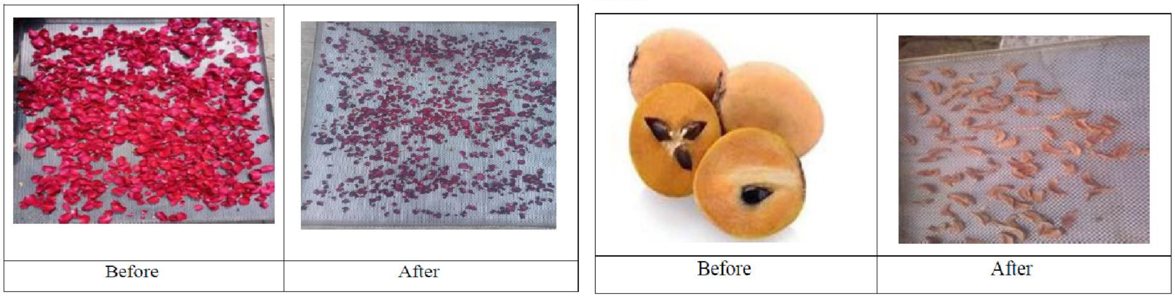
Rose Petals

Chiku



Guava

Moringa Leaves

Fig. 2. Testing Results

The primary objective of the system is to rapidly reduce the mass of fresh product to its safe Equilibrium Moisture Content (EMC). The system was tested with six distinct high-moisture agricultural samples. The empirical mass-reduction data and calculated Moisture Content on a wet basis (MC_{wb}) are summarized in Table 1.

Table 1. Empirical Drying Data and Moisture Content Reduction

Agricultural Sample	Drying Duration (t)	Initial Mass (mi)	Final Mass (mf)	Mass Removed	Moisture Loss (MCwb)
Fenugreek(Methi)	8 hours	1500 g	250 g	1250 g	83.33%
Onion	18 hours	6000 g	650 g	5350 g	89.17%
Guava	8 hours	2000 g	315 g	1685 g	84.25%
Moringa Leaves	8 hours	2000 g	270 g	1730 g	86.50%
Rose Petals	9 hours	250 g	90 g	160 g	64.00%
Chiku	10 hours	2500 g	650 g	1850 g	74.00%

C. Analysis of Drying Rates:

The results clearly indicate highly efficient drying kinetics across both thin-leaf structures (Fenugreek, Moringa) and denser, fleshy tissues (Onion, Guava, Chiku). The most significant absolute mass reduction was observed in the Onion sample, which shed 5350g of water weight over 18 hours, resulting in a phenomenal 89.17% moisture loss. For leaf-based samples such as Fenugreek and Moringa, the system required only a single standard 8-hour diurnal cycle to reduce moisture content by over 83%, effectively rendering them shelf-stable and ready for long-term storage or powdering. The active forced-convection mechanism was directly responsible for these accelerated drying rates, as the constant expulsion of moisture-laden air maintained a high vapor-pressure deficit between the food surface and the surrounding microclimate.

D. Organoleptic and Physical Quality Assessment

Beyond pure thermodynamic efficiency, the quality of the dried end-product is the ultimate metric of success. Samples dried in the fabricated solar chamber were physically compared with baseline samples subjected to traditional open-sun drying.

1. **Hygiene and Contamination:** The fully enclosed polycarbonate structure achieved a 100% reduction in external contamination. While open-sun samples accumulated wind-blown dust and attracted insects, the chamber-dried samples remained entirely pristine, validated by the use of food-grade Stainless Steel 304 trays.
2. **Color and Nutrient Retention:** The UV-stabilized nature of the polycarbonate sheet proved crucial. Traditional sun-dried Moringa and Fenugreek often suffer severe photobleaching (loss of the green chlorophyll pigment) due to intense ultraviolet exposure. The experimental samples retained a vibrant, natural color, visually indicating greater retention of thermolabile nutrients, particularly volatile organic compounds and vitamins.
3. **Texture:** Due to the thermostatic regulation preventing temperature spikes, the Guava and Chiku samples dried evenly from the core to the epidermis, avoiding the textural degradation and scorching frequently seen in uncontrolled direct solar drying.

E. Economic Feasibility

The total fabrication cost of the entire standalone system—including the MS framework, SS 304 trays, polycarbonate sheets, PV panel, and thermostatic electronics—amounted to approximately Rs. 21,980. Given that the dryer requires no grid electricity for operation, its operating cost is negligible. By drastically reducing post-harvest spoilage rates from an industry average of 30-40% down to near zero, and allowing farmers to sell high-value dehydrated goods (like onion flakes and moringa powder) during off-season peak-pricing periods, the system presents an exceptionally short economic payback period. This firmly establishes the prototype not just as a successful thermodynamic experiment, but as a highly viable, scalable techno-economic solution for rural agricultural implementation.

V. CONCLUSION

The design, fabrication, and empirical evaluation of an active, direct-mode solar food dryer were successfully executed in this study. The primary objective of developing a highly efficient, hygienic, and economically viable alternative to traditional open-sun drying was conclusively met. The integration of a standalone 12V photovoltaic system to power a forced-convection exhaust fan, coupled with precise microclimate regulation via an XH-W3001 thermostat, proved to be highly effective. The thermodynamic evaluation demonstrated that the system consistently maintained an optimal internal operating temperature of 45 C, establishing a stable thermal differential of up to 17 C above ambient conditions. This active regulation successfully maximized moisture diffusivity while completely preventing the thermal degradation and "case hardening" of the agricultural products. Empirical testing across diverse high-moisture samples, including fenugreek, onions, guava, and moringa leaves, yielded exceptional drying kinetics. The system achieved significant mass reductions, recording moisture losses of 64.0% to 89.17% within accelerated timeframes of 8 to 18 hours. Furthermore, the structural utilization of UV-stabilized polycarbonate sheets and food-grade Stainless Steel 304 drying trays ensured zero exposure to environmental contaminants, resulting in a physically pristine end-product with superior color and nutrient retention compared to conventional methods. Economically, with a total fabrication cost of approximately Rs. 21,980 and strictly zero grid-electricity operational costs, the system presents an outstanding payback period. It provides a highly accessible, off-grid technological solution that empowers rural farmers and small-scale agricultural clusters to drastically reduce post-harvest spoilage and convert perishable crops into high-value, shelf-stable commodities.

Even though the current prototype is efficient in terms of thermal performance during peak sunlight hours, future research could focus on extending its operational period and making it more effective year-round. One solution is the addition of a Phase Change Material (PCM), which consists of either paraffin wax or an organic fatty acid to absorb extra thermal energy from the collector base during the day. As a result, this latent energy could be slowly released after dusk, which will extend the time of the higher temperatures retained by the dryer and thus increase the rate of the drying process. In addition, it might be possible to design future prototypes with dehumidifying mechanisms, such as desiccant wheels and low-power dehumidifiers, to control relative humidity inside the structure during rainy monsoon seasons or other weather conditions with high moisture content. Finally, future models might also include a monitoring and regulation system based on an Arduino connected to the Internet of Things, using DHT22 sensors to monitor humidity, temperature, and tray weight changes via a smartphone application.

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