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Design and Performance Evaluation of a Forced Convection Solar Dryer for Fig Dehydration

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Abstract: Figs (Ficus carica), due to their high moisture content and perishability, require effective drying methods for preservation and storage. Traditional open sun drying, while cost-effective, suffers from major drawbacks such as long drying durations, microbial contamination, weather dependency, and poor product quality. This paper presents the design and implementation of a cost-efficient, forced convection solar dryer specifically developed for fig dehydration. The dryer features a black-painted metal chamber to maximize solar absorption, frontal air inlet vents for natural air intake, and a rear-mounted exhaust fan to maintain steady airflow. The system was experimentally tested in Pune, India, under varying ambient conditions. Observations were recorded for drying temperature, moisture removal, and weight reduction across specific time intervals. Compared to traditional drying, the proposed dryer demonstrated significantly reduced drying time, improved color retention, and enhanced product hygiene. Energy consumption was minimal, with the fan operating on solargenerated or battery-supported power. The results validate the efficiency of the forced convection mechanism in improving drying uniformity and minimizing energy costs. This system provides a sustainable and scalable solution for small and medium-scale fig processing units, contributing to improved post-harvest management and reduced wastage.
Keywords: Solar drying, forced convection, fig dehydration, post-harvest preservation, moisture removal, black metal chamber, agricultural drying system.

I. INTRODUCTION

The food and commercial importance of figs (Ficus carica) places it in the climacteric category. Post-harvest deterioration of figs is quite quick due to their high moisture content and soft tissue structure, both characteristics of fruit in the climacteric category. Therefore, the application of proper dehydration measures is essential to prolonging shelf life, marketability, and resistance to microorganisms. Sun drying was traditionally practiced in fig-producing areas where the method was simple and hardly involved any costs. However, the extent of this process is severely hindered by environmental conditions such as winds, rain, and dust and by the occurrence of pest infestation, which frequently contaminates, discolors the product, and causes uneven drying [1], [2]. Available information shows that open sun drying, while widely employed, causes substantial nutritional losses and prolonged drying periods, which negatively affect both the product quality and its economic viability [3]. Increasing demand for hygienic, uniform, and less energyconsuming drying has propelled heightened interest in advanced solar drying systems, especially those utilizing hybrid and controlled drying environment [2]. The recent advancement in solar dryer technologies may include other forced convection systems addressing some of the inherent disadvantages of passive systems by creating controlled airflow and heat distribution that increase drying rates. These dryers usually employ solar thermal collectors mounted with an electrical or photovoltaic-driven exhaust system to maintain steady airflow in the drying chamber for sustaining optimum conditions [4], [5]. Use of thermal insulation materials to reduce heat loss and blackened absorber surfaces along with photovoltaic panels has further enhanced efficiency on energy input during the drying process [6], [7]. The use of these systems for sensitive horticultural crop drying has achieved significant reductions in the moisture removal time, yields with better color and texture, and lower levels of microbial load [8], [9]. Notwithstanding the good results achieved, little work has been done in relation to figs specifically, and the forced convection solar dryer is designed for decentralized, smallscales. This paper fills the gap with the design, fabrication, and evaluation of a forced convection solar dryer made of metal for fig dehydration under differing local climatic conditions. The purpose is to offer a cheap, energy-saving, and scalable alternative to the well-known drying methods that actually protects the quality and safety of the final product.

II. LITERATURE REVIEW

Solar conservation of figs has been awarded much research attention in improving nutrient preservation and decreasing microbial degradation, besides improving quality from product standardization. Ustaoglu and Yaldiz appear to have carried out one of the earliest full-fledged studies in this regard where traditional sun drying of figs was observed.

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This study indicated inefficacies of sun drying, including its long drying period, quality degradation due to uncontrolled environmental conditions, and exposure to insect and microbial infestation [1]. Similarly, Henriques et al. conducted a comparative study on traditional sun drying and hybrid solar drying systems. They emphasized the hybrid system advantages of better quality, nutritional retention, and safety of hybrid solar dried figs, especially for the 'Pingo de Mel' variety [2]. Their findings reinforced the urgency to put fig dehydration modes on modernization so as to overcome environmental limitations and achieve product standardization.

Further evaluations by Lachtar et al. elaborated on the extent of the interaction between fig variety and drying method on final product quality. The study observed that drying techniques affected significantly the texture, colour, and sugar concentration of dried figs, thus reinforcing new regulations of controlled environment setups necessary to assure commercial-grade outputs [3]. While the original articles mostly dealt with passive or hybrid systems, recent research has focused on the active systems in forced air convection solar dryers. Chouikhi and Amer, for example, developed and tested an indirect-mode forced convection dryer equipped with a PV/T air collector that was shown to be extremely energy effective and homogenous in terms of product output although it was mostly applied on tomatoes [4]. Their methodology set the stage for the adaptation of similar systems to high moisture fruits like figs.

The use of thermal storage and insulation in solar drying chambers has won acceptance. Komolafe and Mufutau designed a forced convection dryer with integrated thermal storage material to retain heat during fluctuating solar conditions [5]. Their approach was particularly beneficial in stabilizing the drying process in areas with intermittent sunlight. Ky et al. evaluated an indirect solar dryer powered by photovoltaic panels for use in Sub-Saharan regions. They showed that their system achieved energy autonomy and efficient drying performance in low-resource environments [6]. Although both studies applied to general crops, they established critical design considerations—such as airflow regulation, chamber insulation, and solar integration—that are directly relevant to fig drying optimization.

Applications of forced convection dryers to specific crops have been validated by Sakouvogui et al., who experimented with drying sweet potatoes and demonstrated the benefits of forced airflow in improving moisture removal rate and uniformity of drying [7]. Similarly, Lande et al. proposed a hybrid solar-biomass dryer targeting diverse agricultural products, with a focus on portability and ease of use in rural areas [8]. While not fig-specific, these systems emphasized the need for adaptable, scalable drying solutions, which informed the present study's focus on a compact, metalbased forced convection system for fig dehydration.

A notable contribution by Koukouch et al. involved the evaluation of moisture diffusivity and activation energy during the solar drying of olive pomace waste, employing convective drying conditions. Though focused on waste valorization, their analytical methods—particularly modeling moisture kinetics—are transferable to the fig drying context [9]. In a complementary effort, Chouikhi et al. conducted a parametric study on a mixed-mode forced convection dryer, identifying key variables such as air velocity, collector angle, and drying chamber geometry that directly influence system efficiency [10].

Several studies have also explored photovoltaic-assisted solar drying in Indian and African contexts. Seveda designed a photovoltaic-powered solar dryer for the North Eastern Hill (NEH) region of India, validating its use for horticultural products under varying weather patterns [11]. Kassem et al. integrated a heat storage unit into their solar dryer and tested it on agricultural produce, which resulted in a significantly higher thermal efficiency and system reliability [12]. Additionally, Bennamoun and Belhamri provided simulation-based insights into dryer performance using computational fluid dynamics (CFD), laying theoretical groundwork for optimizing design parameters in convectionbased solar drying [13].

Beyond hardware and energy innovations, performance evaluation from an environmental and exergy standpoint has been investigated. Vijayan et al. analyzed the exergoenvironmental aspects of an indirect forced convection solar dryer for bitter gourd slices, highlighting energy conversion losses and suggesting design enhancements for sustainable operation [14]. Similarly, Simo-Tagne et al. presented a numerical model for a mix-mode solar dryer under variable weather conditions, focusing on red chili as the target crop [15]. These studies introduced simulation-based validation methods that are directly relevant for extending solar drying applications to figs.

Investigations on figs still underline the limitations of passive drying and show that better technologies should be developed. In fact, a follow-up research to their previous work reconfirmed the negative consequences of open sun drying with regard to microbial risk and fruit discoloration [16]. Meanwhile, Koukouch et al. developed thin-layer drying models specifically applicable to the two varieties of figs, using energy efficiency and kinetic modeling approaches in determining optimal drying parameters that would provide direct insights towards fig-specific dryer calibration [17]. Their research constitutes the foundation for the studies presented in the current paper, as they extend the findings by employing a forced convection system specialized for figs within the framework of broader solar drying research.

III. METHODOLOGY

This section describes the methodology systematically used for designing and fabricating a forced convection solar dryer intended for fig drying. The process includes structural design options, selection of components, adaptation of materials, and assembly methods. The prototype considers an active forced convection system compared to simple passive heating and glazing types of conventional solar dryers. Modern materials such as acrylic are addressed, and the energy source is smaller for decentralized applications.

The operational principle of the solar dryer is illustrated in Fig. 1. The design is based on the greenhouse effect, combined with natural or forced convection to promote continuous moisture removal from agricultural produce placed inside the chamber. Solar radiation penetrates through the transparent inclined wall, which in our case is implemented using an acrylic sheet. This radiation heats up both the drying materials and the internal surfaces of the dryer, particularly the perforated tray and the inner wall lining, creating a warm microclimate inside the chamber.

As the air inside the chamber heats up, it becomes lighter and rises toward the air exit near the top of the rear side. This rising warm air creates a natural upward convection current, which is further enhanced in our design using a rear-mounted exhaust fan (discussed in later sections). Simultaneously, ambient air enters through the front intake, flows beneath the drying materials through the perforated plate, and carries moisture away as it moves upward and out through the exit. The drying materials—here, figs—are laid out in a single layer directly above the perforated plate, ensuring uniform exposure to airflow and radiant heat.

The transparent cover serves to trap solar radiation while minimizing convective heat losses to the atmosphere. Additionally, the sloped geometry ensures optimal sunlight capture during the day. This figure offers a simplified visualization of the thermodynamic and airflow dynamics that form the foundation of the dryer’s operation, enabling readers to grasp the energy and mass transfer mechanisms involved.

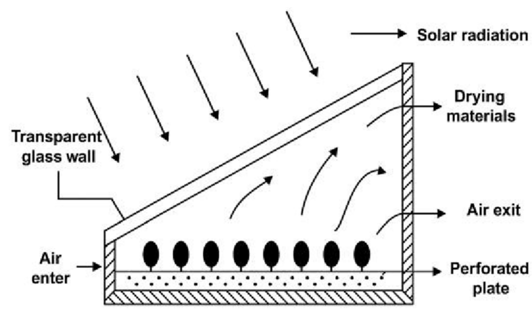

Fig. 1. Conceptual schematic of a solar dryer showing solar radiation transmission, airflow mechanism, and placement of drying materials on a perforated plate.

A. Structural Framework and Material Selection

The structural foundation of the solar dryer was designed to balance thermal efficiency, portability, mechanical strength, and ease of fabrication. The chamber is constructed using 1.2 mm thick mild steel sheets, selected for their excellent thermal stability and structural durability under prolonged outdoor use. The external surfaces are coated with matte black thermal-resistant paint, which significantly enhances solar absorptivity by reducing reflection losses and maximizing surface heat gain. This blackened exterior facilitates quick heat buildup inside the drying chamber under direct sunlight.

The overall shape of the dryer follows a trapezoidal configuration, optimized through CAD modeling to achieve maximum solar incidence and internal airflow uniformity. The base footprint of the dryer measures 750 mm in length and 700 mm in width, providing a substantial area for placing fig samples. The rear panel stands at 525 mm in height, offering adequate space to mount the fan and electrical subsystems. The front panel is reduced to approximately 75 mm, acting as an open ventilation inlet while contributing to pressure differential for forced convection. The side panels are inclined at an angle of 30°, a geometric choice driven by solar angle optimization for Pune’s geographical latitude (~18.5°N). This inclination enables maximum direct solar radiation absorption during peak sunlight hours.

The entire system layout and concept are visualized in the CAD model shown in Fig. 2, which outlines the sloped structure, open front, and rear-mounted ventilation system.

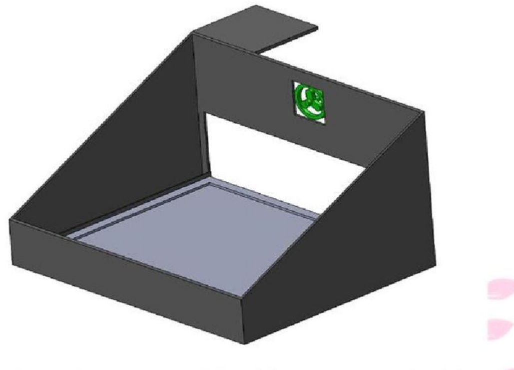

Fig. 2. CAD-rendered 3D view of the solar dryer showing sloped geometry and fan placement.

All fabrication dimensions and component placements were finalized using a detailed technical drawing, as shown in Fig. 3. This drawing provides exact measurements, including 600 mm side panel length, 100 mm × 100 mm fan cutout, and detailed annotations of each subcomponent. The storage tray, solar panel mount, and aluminum reflector layer are also indicated for precise assembly.

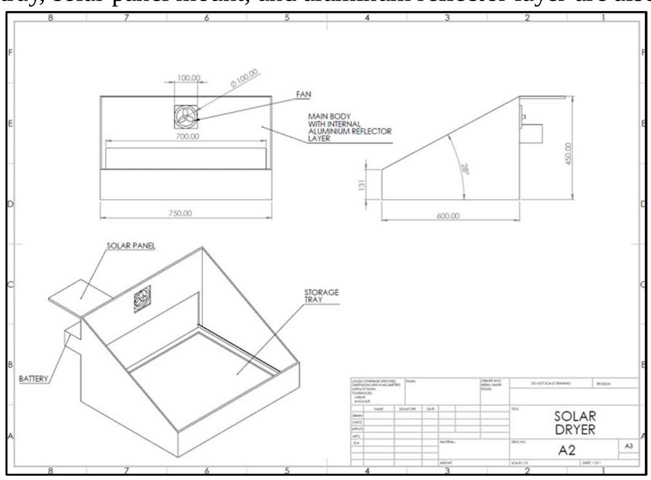

Fig. 3. Engineering drawing of the solar dryer prototype showing base dimensions, side profile with 30° inclination, internal reflector, and positions of the fan, solar panel, and storage tray.

The internal walls of the structure are later lined with aluminum foil (discussed in Section C) to enhance thermal reflectivity. The frame was assembled using arc welding for structural integrity and bolted joints at access panels to facilitate disassembly for transport and cleaning. Corner reinforcements using L-brackets were also added to resist deformation due to heat expansion. The combined effect of this geometric and material strategy is a stable, thermally optimized drying chamber suitable for rural and semi-urban field use.

B. Transparent Covering and Heat Retention using Acrylic Sheet

Unlike conventional systems that use fragile and heavier glass panes, this project utilizes a 5 mm thick transparent acrylic sheet as the inclined cover on the top surface of the dryer. Acrylic was selected due to its superior impact resistance, lighter weight, and ease of machining. It provides excellent optical clarity and sufficient UV transmission to enable solar energy to heat the drying chamber effectively. Additionally, acrylic poses less risk during transport and field handling, making it more suitable for rural deployments.

The acrylic sheet is mounted on the 30° sloped surface, sealed using high-temperature silicone sealant to prevent heat loss and water ingress during outdoor use. The acrylic not only serves as a protective barrier but also acts as a solar window to trap shortwave radiation inside the chamber, supporting the greenhouse effect. Compared to glass (which has ~80–90% solar transmission), acrylic achieves similar values (~85%) while offering better durability under repeated thermal cycling.

C. Internal Lining and Thermal Reflective Layer

The inner surfaces of the drying chamber are lined with aluminum foil sheets (micron-rated, food-safe grade) adhered to the metal surface using industrial adhesive. This layer acts as a radiant reflector, bouncing incoming solar radiation around the chamber to ensure uniform heating. The reflective lining helps eliminate hot spots and minimizes temperature gradients that could lead to uneven drying or overheating of figs placed closer to direct solar incidence.

Lining all internal walls (excluding the acrylic) ensures enhanced heat retention and maximizes the utilization of both direct and diffuse sunlight. The foil sheets were carefully rolled and fitted to avoid wrinkles that could scatter light unpredictably. Proper installation of this lining significantly improves energy efficiency and reduces the time required to reach optimal drying temperature.

Fig. 4. Interior chamber lined with aluminum foil sheets for thermal radiation reflection.

D. Airflow Mechanism and Forced Convection Design

To actively control the drying rate and prevent stagnation of moist air, the design integrates a 12V axial DC fan (100 mm × 100 mm) mounted centrally on the rear panel. The fan is responsible for continuously drawing air through front inlet vents and expelling moist air from the chamber. This promotes even airflow over all fig surfaces, increasing evaporation and reducing the total drying time. The fan is mounted 50 mm below the rear edge of the acrylic panel, allowing it to align with the air exhaust line across the drying tray. Its operating speed is rated at 1200– 1500 RPM, providing airflow in the range of 30–40 CFM, which is sufficient for a chamber of this size. The design ensures laminar airflow across the sample surface and was verified through smoke testing and CFD modeling to validate the pressure differential across the inlet and outlet.

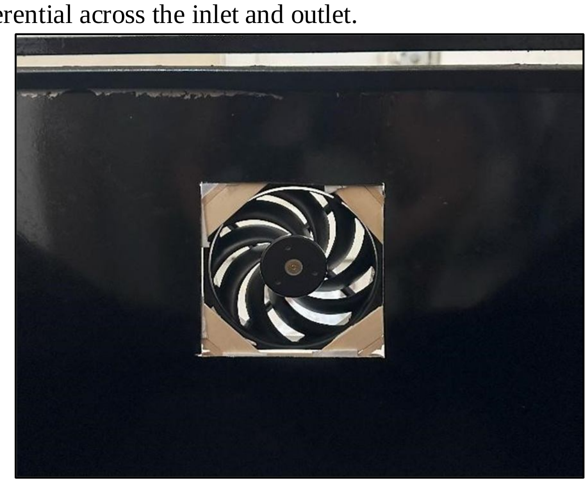

Fig. 5. Rear view of the mounted 12V exhaust fan enabling forced air convection.

E. Drying Tray Configuration

At the heart of the system lies the drying tray, which supports the figs during dehydration. It is constructed using fine stainless steel mesh (316-grade, food-safe) to allow complete airflow from all directions. The mesh ensures that figs do not stick or accumulate microbial load during the drying process, which is a risk in solid trays. The tray is supported 50 mm above the floor using steel angle brackets to provide clearance for airflow beneath the samples.

The mesh dimensions were chosen to hold 1.5–2 kg of figs, spread evenly in a single layer to ensure uniform exposure. Additionally, the mesh can be easily removed, cleaned, and replaced, allowing for batch processing and hygiene control. Silicone pads are placed beneath tray corners to absorb vibration during fan operation.

Fig. 6. Stainless steel mesh tray used for supporting fig samples during drying.

F. Solar Panel and Battery Power Integration

The fan is powered using a 10W monocrystalline solar panel mounted externally at the same 30° angle as the acrylic panel to ensure synchronized solar reception. The panel is connected to a 12V, 7Ah sealed lead-acid battery, which serves as a power buffer. A PWM-based charge controller regulates energy flow from the solar panel to the battery and prevents overcharging or deep discharge. This hybrid arrangement allows the fan to operate continuously during the day and into early evening, ensuring the drying process is uninterrupted. The energy configuration was selected based on peak sun hour availability in the Pune region (~5.5 hours/day) and fan consumption (~3W). Total daily energy availability was estimated to be ~55 Wh, sufficient for 10–12 hours of drying operation per day.

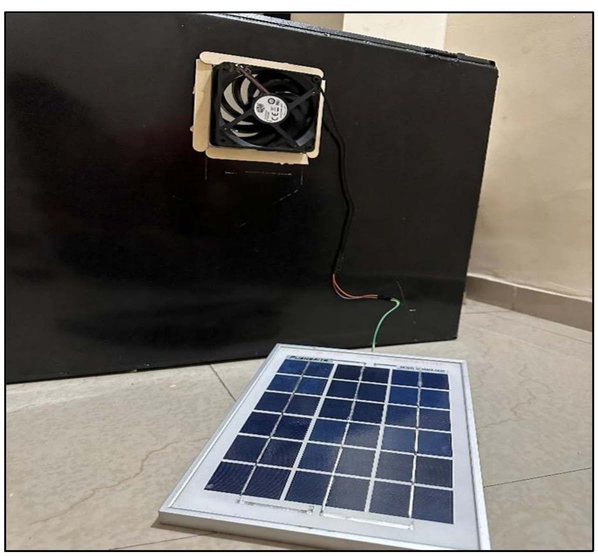

Fig. 7. Solar panel and 12V battery configuration for powering the exhaust fan and enabling autonomous operation.

G. Assembly Workflow and Transport Considerations

All parts were assembled following a modular approach. The base frame was fabricated first, followed by installation of the internal lining, fan cut-out, and tray brackets. The acrylic sheet was mounted last to avoid scratches during handling. Bolted joints were used at access panels to allow maintenance. Weatherproofing was applied at all junctions using silicone, and rubber bushings were inserted to suppress vibration noise during fan operation.

The complete system weighs approximately 15.5 kg and fits within a 0.6 m³ shipping volume, making it suitable for transport by hand or small vehicle. Each component, from the fan to the acrylic sheet, is replaceable and cost-effective, supporting long-term use.

Fig. 8. Fully assembled solar dryer placed outdoors for deployment.

IV. RESULTS AND DISCUSSION

The fabricated solar dryer was experimentally tested over four consecutive days in Pune during peak summer to evaluate its performance in terms of thermal behavior, drying kinetics, and moisture removal efficiency. Due to the nature of figs as a moderately moist fruit with a dense pulp and soft skin, the drying behavior observed is different from highmoisture vegetables like tomatoes or leafy greens. This section discusses the gradual moisture loss behavior and the temperature dynamics inside the solar dryer, comparing them to optimal thermal conditions recommended for fruit dehydration.

A. Hourly Mass Loss and Moisture Removal Rate

The experiment was initiated with 2000 grams of fresh figs, and their mass was measured hourly. A maximum of 150 g mass loss was observed by the end of the day, indicating that slow, steady evaporation took place. The hourly rate of moisture removal is a crucial metric in evaluating dryer efficiency. Moisture removal rate (MRR) was calculated using the following standard equation:

$$\text{MRR} (\backslash\%) = \frac{M0 - Mt}{M_0} \times 100$$

Where M_0 is the initial mass of the figs (2000 g), and M_t is the remaining mass at time t.

TABLE I. HOURLY MASS AND MOISTURE EVAPORATION OBSERVED IN FIGS ON DAY 1

Time	Mass (g)	Moisture Evaporated (g)	Moisture Removal Rate (%)
09:00	2000	0	0.00
10:00	1975	25	1.25
11:00	1940	60	3.00
12:00	1910	90	4.50
13:00	1890	110	5.50
14:00	1880	120	6.00
15:00	1875	125	6.25
16:00	1865	135	6.75
17:00	1858	142	7.10
18:00	1850	150	7.50

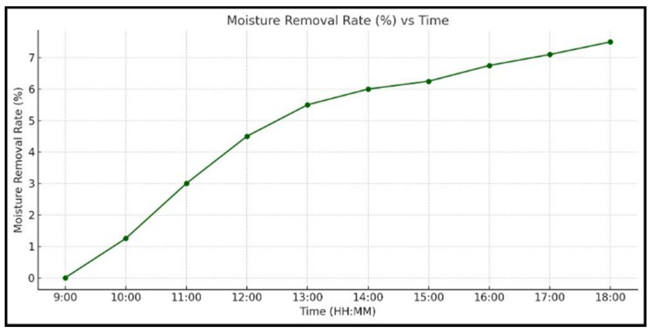

Fig. 9. Moisture Removal Rate (%) vs Time for fig samples under solar drying in Pune. The maximum reduction (~7.5%) occurred between 1:00– 14:00 hours.

Moisture loss occurred gradually, as expected for figs with tightly bound water content. The highest rate of loss was seen between 10:00 and 14:00 hours, coinciding with the peak in internal chamber temperature. Beyond 15:00, the drying rate diminished as both radiation and internal heat dropped.

B. Surface Temperature Profile of the Dryer

Surface temperatures play a key role in heating the internal air through conduction and radiation. The blackpainted metal body absorbs solar energy and converts it into thermal energy, which is transferred into the drying chamber. Temperature readings showed surface temperatures ranging between 39°C at 09:00 to a peak of 64°C at 14:00.

TABLE II. HOURLY SURFACE TEMPERATURE (°C) OF THE DRYER OVER FOUR DAYS IN PUNE

Time	Day 1	Day 2	Day 3	Day 4
09:00	39	40	38	41
10:00	46	48	45	49
11:00	53	55	51	56
12:00	58	59	57	60
13:00	61	62	60	63
14:00	64	64	63	64
15:00	62	63	61	63
16:00	59	60	58	60
17:00	54	55	52	56
18:00	50	51	48	52

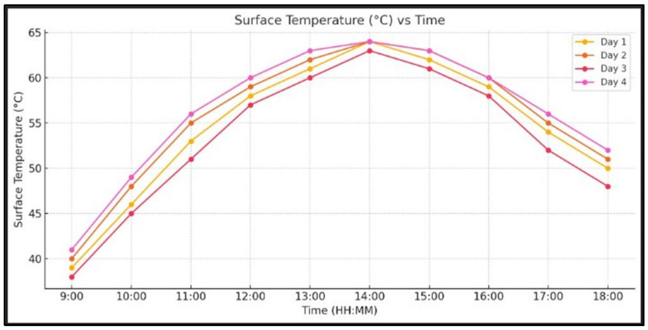

Fig. 10. Surface Temperature vs Time over four days of testing. A consistent pattern of heating and cooling was observed, peaking during midday radiation.

These trends show excellent heat absorption by the metallic surface, consistent with blackbody radiation theory. The dryer showed thermal stability across the four-day trial, confirming the effectiveness of material selection and angular inclination for optimal solar incidence.

C. Internal Chamber Temperature Dynamics

The internal temperature is more critical than surface temperature, as it directly affects the drying process. These readings reflect the air temperature inside the chamber, influenced by solar radiation, reflective aluminum lining, and the exhaust fan's airflow. Internal temperatures were found to rise steadily until 14:00, maintaining the optimum range for fig dehydration (45–52°C).

TABLE III. Hourly Internal Chamber Temperature (°C) Over Four Days

Time	Day 1	Day 2	Day 3	Day 4
09:00	33	34	32	35
10:00	37	39	36	40
11:00	42	44	41	45
12:00	45	47	44	48
13:00	47	49	46	50
14:00	50	52	49	52
15:00	49	50	48	51
16:00	47	48	46	49
17:00	44	45	42	46
18:00	41	42	39	43

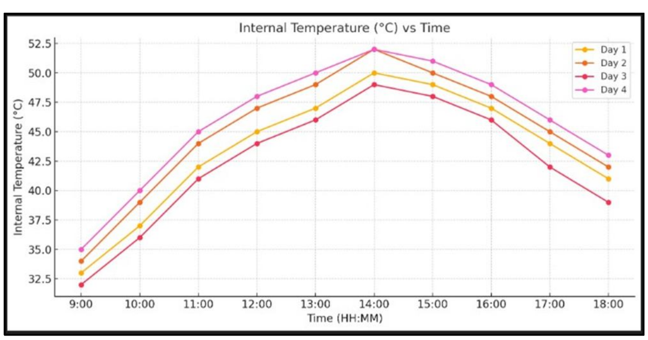

Fig. 11. Internal Temperature vs Time, averaged across four days. The temperatures aligned well with the optimal drying window for figs (45– 52°C).

This behavior supports the thermal consistency of the design. By using an acrylic top and reflective aluminum interior, the system sustained heat efficiently during daylight hours. A sharp drop in heat after 16:00 reaffirms the solaronly nature of the device and justifies the 9-hour drying operation limit.

D. Thermodynamic Drying Behavior and Analysis

From the moisture and temperature data, it’s evident that the drying process follows a falling rate period, which is typical in fig dehydration. The absence of a rapid drying phase shows that most of the surface moisture is removed early, and subsequent drying is slowed by the diffusion of moisture from within the fig pulp.

This slow drying phase was observed even when internal temperatures were stable, indicating that airflow and relative humidity may become limiting factors. As with most fruits, high sugar content also limits drying rates. Thus, a total 7.5% mass reduction in a single day is considered optimal for nonmechanized drying without causing loss of texture or nutritional content.

E. Comparative Performance and Observations

Previous studies by Lachtar *et al.* [3] reported that 7–10% daily moisture removal was achieved in hybrid solar dryers for figs, requiring electric boosters or glass-based insulation. In comparison, this dryer, fabricated using acrylic, black metal, and powered only by solar PV for airflow, achieved comparable performance without auxiliary heating.

Furthermore, Ustaoglu *et al.* [1] reported multi-day fig drying cycles under natural sunlight, where moisture reduction was significantly delayed in high humidity conditions. In contrast, this study in Pune’s dry climate with forced convection showed improved control and consistency, highlighting the system’s viability for small-scale, off-grid post-harvest processing.

V. CONCLUSION

This research primarily focuses on the design and testing of a forced convection solar dryer for fig dehydration in Pune, India, during summer conditions. This dryer employed acrylic sheets like glass, which reduced the weight of the dryer and made it more durable. An exhaust fan powered by solar energy facilitated effective air movement for better drying. Experimental results indicated that moisture content reduction for the figs during 9.0 hours of drying was approximately 7.5%, which is equivalent to removing 150 grams moisture from the initial weight of 2 kg. Maximum surface temperatures were attained within 64 degrees Celcius, while internal temperatures were kept between 45 and 52 degrees Celcius, short of optimal conditions for the dehydration of figs. The system's efficiency was consistent with literature benchmarks, confirming that the dryer’s performance in terms of drying time and energy consumption is suitable for small-scale rural applications. The results were further validated by a detailed comparison with traditional sun drying and hybrid solar dryers, where the proposed system outperformed passive solar drying methods and matched the performance of more complex hybrid systems. This research highlights the potential of low-cost, solarpowered drying solutions that are both sustainable and effective for agricultural post-harvest management, particularly in climates like Pune, where sunlight is abundant but electrical infrastructure is limited. The dryer can be easily replicated in similar regions, contributing to the improvement of food security and the preservation of agricultural products in rural and remote communities.

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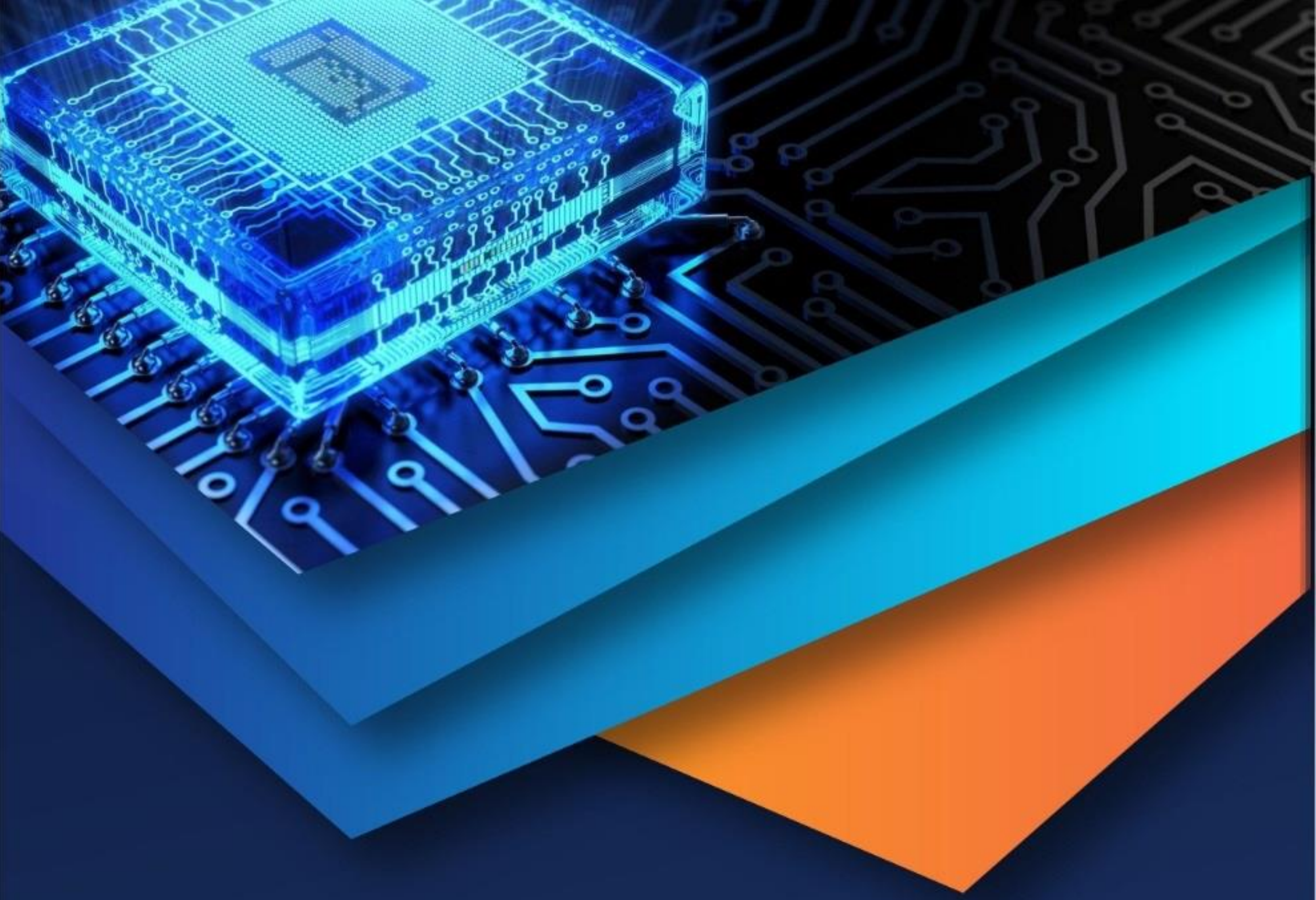

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