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# “Development and Performance Evaluation of a Hybrid Solar Dehydration System for Food Preservation”

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## Abstrict

This study explores the creation and performance assessment of a hybrid solar drying system aimed at improving food preservation through energy-efficient methods. The system combines a flat plate solar collector, paraffin wax as a Phase Change Material (PCM) for storing thermal energy, IoT-based monitoring for real-time data collection, and optional forced convection elements like blowers, infrared (IR) bulbs, and electric heaters. The main objective is to facilitate continuous drying, especially during periods of low solar irradiance or at night, and to evaluate the efficiency of natural versus forced convection drying modes. Experiments were conducted on five vegetables: chili, onion, potato, spinach, and grapes, under different configurations. In the natural drying mode, which relies solely on solar-heated PCM, moisture removal of 80–85.6% was achieved within 70 to 105 minutes for chili, onion, and potato. Conversely, forced drying, which incorporates blowers and IR bulbs, significantly shortened drying time, achieving 80% moisture reduction in spinach in just 40 minutes, and consistent drying of chili and onion within 2 to 2.5 hours even in less than ideal sunlight conditions. The drying of grapes took longer due to their high moisture and sugar content. The IoT integration allowed for continuous monitoring of temperature, humidity, and airflow, optimizing drying conditions and enhancing process control. Comparative results suggest that the natural PCM-based mode is more appropriate for small-scale, energy-efficient applications, while the forced mode provides faster, uniform drying suitable for larger or commercial-scale operations. This research highlights the effectiveness of a hybrid solar dehydration system in offering a sustainable, adaptable, and efficient solution for agricultural drying and food preservation, with potential applications in rural and off-grid areas.

**Keywords:** PCM, Forced convection, Natural drying, IoT monitoring, Food preservation, Thermal energy storage, Sustainable drying technology.

## 1. INTRODUCTION

This research on solar dryers is limited due to frequent daytime and evening clouds hindering drying. Ensuring solar energy storage in the dryer allows for evening drying. CFD analysis is conducted on 2D converging and diverging sections. Latent heat storage materials are

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advantageous for energy storage, storing more energy compared to sensible heat storage materials. (PCMs) are effective for solar energy storage. Results show that the converging section yields accurate results, as the inlet wind speed is consistent in both cases, but the exit wind speed in the converging section is nearly double the inlet speed, whereas it significantly decreases in the diverging section **[1]**. The article explores a low-cost, eco-friendly solar dryer for drying bananas. It compares two air flow configurations and drying methods, finding that the bottom flow setup is more efficient and that wooden skewers improve drying rates. Bananas dried at 1 m/s air flow had the best quality. The dryer offers energy savings and reduces post-harvest losses, making it a viable solution for small-scale farmers **[2].** This study compares two solar dryers for drying black pepper: mixed-mode (Case-I) and indirect (Case-II), integrated with a latent heat storage system. Case-I reduced drying time by 76% compared to open sun drying, with 20% higher efficiency than Case-II. Case-I also preserved more nutrients and antioxidants. The findings highlight the economic and quality benefits of these dryers, though further research on scalability and environmental impact is needed **[3].** This study compares two photovoltaic-thermal solar dryer systems: a double-pass solar dryer (DPSD) with a black matte-coated aluminium absorber and a nano-enhanced double-pass solar dryer (NDPSD) with a graphene-coated absorber. NDPSD showed higher thermal (73.36% vs. 57.23%) and exergy efficiency (27.77% vs. 16.64%) compared to DPSD. The results highlight the improved performance of nano-enhanced systems for solar drying applications **[4].** have worked on to increase the amount of recycled air, an orifice was added to the pipe's inlet. The impact of the orifice's diameter was examined, and its ideal value was identified. Ultimately, two dryer designs one with fins and the other without were put forth. determining the CFD result **[5].**

IoT-based seed drying systems use sensors like DHT-11 and LM-35, controlled by microcontrollers like the Raspberry Pi Pico-W, to optimize drying conditions. These systems offer precise control over temperature and humidity, preventing over-drying. Remote monitoring through web interfaces allows farmers to manage the process easily, making it cost-effective and energy-efficient while improving seed preservation and agricultural productivity **[6].** She is working on various solar dehydration systems, and the main goal of this experiment is to create a dehydration that satisfies the fundamental requirements of dehydration and is enhanced by altering the indirect forced solar dehydration system's design. The idea behind building a dehydration unit is to preserve food and save energy through solar dehydration's moisture removal process **[7].** This researcher reviewed the capacity of solar dryers for drying. They studied research papers from 2000 to 2023 and provided a detailed review of solar dryers (direct, indirect, mixed, and hybrid), including their types and drying capacities, ranging from 1 kg to 250 kg in the drying process **[8].** The researcher conducted a numerical investigation on apple slices using TRNSYS software. The humidity of the fruit in the apple slices was reduced from 86% to 11% in about 270 minutes at 70°C. The maximum thermal capacity of

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the drying system was also obtained **[9].** this article, experimental results of growing spinach using forced convection are presented, reducing the humidity of spinach from 93% to 2%. Drying time is reduced from 3 to 4 hours by forced convection. They recycle 90% of the air **[10].**

A PV/T mixed-mode solar dryer with forced convection reduced tomato moisture from 91.94% to 22.32%, outperforming open sun drying. It improved drying efficiency, quality, and provided extra electricity, benefiting rural farmers **[11].** A PVT solar dryer was used to dry star fruit under forced and natural convection. Moisture reduced from 10.11 to 0.19 (d.b.) in 12.5 h (FCD) and 14.5 h (NCD), compared to 22 h in open sun. FCD mode showed higher energy (69.27%) and exergy (31.12%) efficiency. The system had short payback times (1.40–1.70 years), proving it to be a sustainable and efficient drying method **[12].** A study comparing natural and forced convection solar dryers for carrot slices showed that the forced setup (with PV-powered fans) had higher collector (68.74%) and drying (9.55%) efficiencies. It also achieved better heat and mass transfer, lower activation energy, and higher moisture removal, confirming its superior drying performance **[13].** Due to the high energy demands of mechanical drying, there is a growing interest in solar-based alternatives. A study introduced a natural convection solar dryer, which includes a solar air heater and a drying chamber, specifically for agricultural products. Using this system, grapes were dried in just 4 days, whereas drying them in direct sunlight took 7 days, and shade drying required 15 days. The raisins produced through solar drying were of higher quality, demonstrating the system's superior efficiency and effectiveness compared to traditional drying methods **[14].** A research project assessed a cabinet-style passive solar dryer for dehydrating Indian gooseberries through natural convection. This system, which relies entirely on solar power, presents an environmentally friendly and economical alternative to traditional drying methods. The study examined both sliced and whole gooseberries, achieving a reduction in moisture content from 78% to 5% (w.b.). The sliced samples dried more quickly and exhibited higher effective moisture diffusivity. The passive solar dryer not only shortened the drying duration but also yielded superior-quality dried gooseberries compared to open sun drying, underscoring its efficiency for sustainable post-harvest processing **[15].** A study using numerical simulations investigated a cocoa-bean drying system, focusing on natural, forced, and combined convection methods in the tropical climate of Yaoundé. The drying kinetics, energy consumption, $CO_2$ reduction, and economic aspects were predicted using finite-difference and fourth-order Runge–Kutta methods. Natural convection alone was insufficient to achieve equilibrium moisture levels, but a system using forced convection during the day and natural convection at night reduced moisture content from 1.2 to 0.15 kg $kg^{-1}$ (db) within 32 hours throughout the year. The specific energy consumption for the combined convection mode ranged from 5 to 15 kWh per kg of water removed, with the collector's thermal efficiency surpassing 30% and overall efficiency between 5% and 18%. The potential for $CO_2$ mitigation was between 15 and

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25 g $CO_2$ per kg of water evaporated, and the payback period was calculated to be 2.19 years, demonstrating the system's technical and economic feasibility for drying cocoa in tropical regions **[16].** Natural rocks are gaining attention as low-cost thermal storage materials for solar dryers in Sub-Saharan Africa. Most studies focus on indirect solar dryers (66.67%), with others on mixed-mode and solar-assisted heat pump dryers. Using rocks improves dryer efficiency by up to 17.48%, reduces drying time by 50%, and extends operation after sunset. However, gaps remain in thermal property analysis and techno-economic evaluations, highlighting the need for further research and optimization **[17].** Solar thermal technologies are being increasingly investigated for their potential in drying applications, aiming to enhance the efficiency of storing and transporting agricultural products. A recent study assessed the thermo-electrical performance of a forced-air convection PVT air-collector system used for drying tomatoes in Ghaziabad, India. This system comprises a PVT air-collector, a drying chamber, a heat recovery unit, and a DC fan. Simulations indicated average thermal, electrical, and overall efficiencies of 36.04%, 12.09%, and 48.83%, respectively. The moisture content of tomatoes decreased from 78% to 8.5% over a period of 20 hours, with quicker drying rates observed at higher air velocities ranging from 0.5 to 2 m/s. The system demonstrates significant potential for energy conservation and reducing $CO_2$ emissions in food processing **[18].**

## 2. MATERIALS AND METHODS

### 2.1 Introduction

A solar dehydration system is used to dry five types of vegetables with all the necessary materials. The materials used in the solar dryer include 250 kg of PCM (paraffin wax). The system features a dehydration chamber equipped with six infrared bulbs; each rated at 150 watts. The chamber also contains four air heaters that increase the temperature inside the drying chamber. Additionally, four DC fans are used in the drying chamber. The system is powered by three batteries and a 335-watt solar panel. There are also two blowers, each rated at 500 watts. An IoT kit is used to monitor the temperature and humidity in the drying chamber

### 2.2 Material

#### A. Use of IOT in solar dehydration system

FIG 1. IOT KIT

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Fig 1. Shown IOT kit in a solar dehydration system includes sensors for monitoring temperature and humidity inside the drying chamber, a microcontroller (like Arduino or Raspberry Pi) for processing data, and Wi-Fi or Bluetooth for remote connectivity. It allows real-time monitoring through a mobile app or web interface, providing data logging and alerts. This system can automate drying conditions by controlling fans and heaters, improving energy efficiency and ensuring optimal drying conditions. Data can also be stored in the cloud for analysis and future improvements.

### B. Energy storge tank using paraffin wax

The choice of Phase Change Material (PCM) is crucial due to the need to consider several key factors, including melting temperature, latent heat, and heat storage capacity. PCMs are employed to store solar energy, which can be accessed after the sun sets. A phase-change material is a substance with a high heat of fusion that can store and release significant amounts of energy when it melts and solidifies at a specific temperature. Energy is absorbed or released as the material transitions between solid and liquid states. Therefore, PCMs are categorized as latent heat storage (LHS) materials. Paraffin wax, weighing 250 kg, serves as the PCM. It has a melting point of 58 to 60°C, a latent heat of 210 kJ/kg, and a specific heat of 2.1 kJ/kg°C. At room temperature, it appears as a white solid. Paraffin wax is stored in an energy storage tank. The density of paraffin wax is 900 kg/m³. The energy storage tank has a collector area of 8.4 m², with dimensions of 1.2 m x 3.5 m (L x W) and a height of 15 cm. There are three types of phase-changing materials: one that changes from solid to liquid and another that changes from liquid to high-temperature steam. Showing below Fig 2.

**Fig 2. Paraffin wax**

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Fig 2 showing Paraffin wax is chosen for solar dehydration systems due to its high latent heat storage capacity, thermal stability, and ability to maintain a consistent drying temperature. Its wide range of melting points (40–70°C) allows

flexibility for different drying needs, preventing overheating and ensuring uniform drying. Additionally, paraffin wax is cost-effective, non-toxic, and chemically stable, making it a reliable phase change material (PCM) for improving energy efficiency and extending drying hours in solar dryers.

**Explain their paraffin wax phase changes**

### a) Solid to Liquid (Melting)

When paraffin wax is subjected to heat, it initially changes from a solid to a liquid form. This transformation takes place at its melting point, which generally ranges from 46°C to 68°C, depending on its specific makeup. During this phase transition, the wax absorbs latent heat without experiencing a temperature change. This mechanism is vital for thermal energy storage, as it enables the wax to retain a substantial amount of heat that can be released later when it solidifies.

### b) Liquid Phase

After melting, paraffin wax enters its liquid phase, where it continues to absorb heat. In this state, its temperature increases gradually until it reaches the boiling point. This phase is typically stable and can be maintained for various thermal applications, such as heat transfer or regulated heat release in heating systems.

### c) Liquid to Vapor (Boiling)

If heating continues and the temperature rises beyond the boiling point of paraffin wax (which is very high), the wax begins to vaporize, turning into gas or "steam." During this phase change, it again absorbs a large amount of latent heat of vaporization. However, in most practical applications, paraffin wax is not heated to this extreme because vaporization can lead to decomposition or safety hazards. This phase is mostly studied in controlled industrial processes.

there are showing there below Fig 4 phase change process

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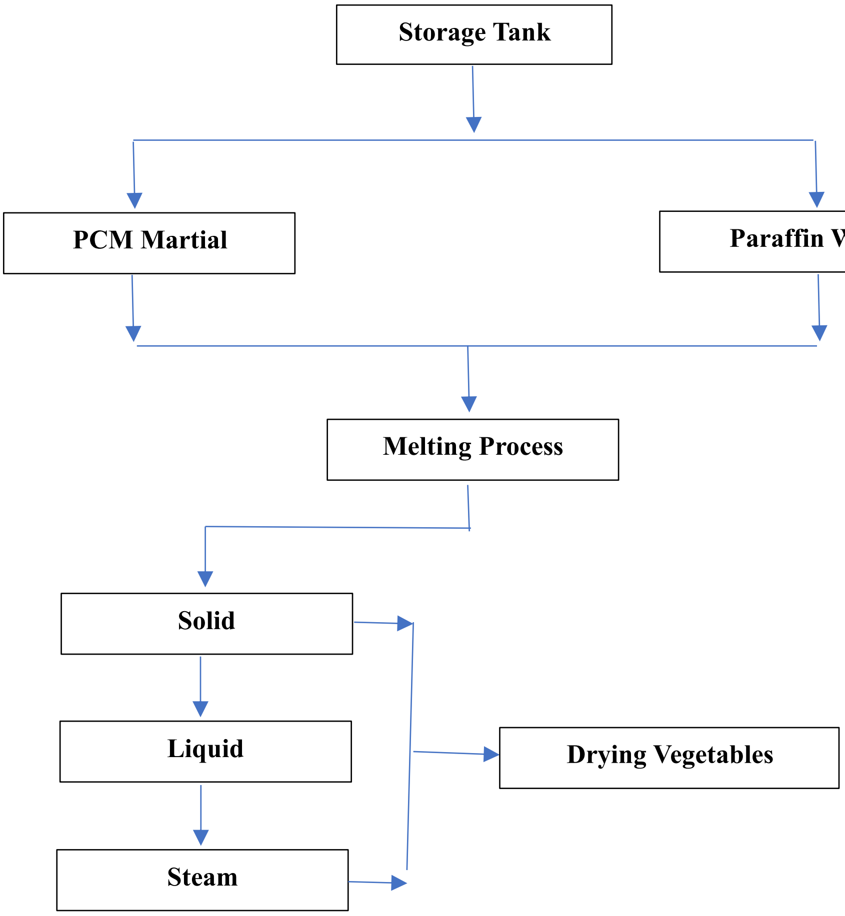

**Fig 4. Follow chat paraffin wax**

## 2.3 DRYING PROCESS

Fig 5. In the solar dehydration system process, the process begins with sunlight falling on a flat plate collector. This collector is connected to a PCM (Phase Change Material) tank filled with paraffin wax. As the sun's rays heat the flat plate collector, the heat is transferred to the PCM tank. The paraffin wax absorbs this heat and changes from solid to liquid, storing thermal energy. This stored heat is then used to produce hot steam, which is directed into a combustion chamber where the vegetables are dried. A blower is activated to circulate air; as the hot steam mixes with incoming cool air, it increases the air temperature. The resulting hot air flows through the combustion chamber, aiding in the drying process. Additionally, a heater and infrared (IR) bulb are installed in the combustion chamber to help maintain a consistent temperature. An IoT-based kit is used to monitor and calculate the temperature, humidity, and moisture content of the vegetables throughout the process. Finally, the exhaust air exits the system through a chimney into the atmosphere.

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### A. Natural Drying:

In natural drying, paraffin wax-based PCM (Phase Change Material) is used as the main heat source. The PCM absorbs solar heat through a flat plate collector and stores it by changing from a solid to a liquid state. This stored heat is gradually released over time, maintaining a warm environment inside the drying chamber without any external force. The hot air circulates naturally by convection, without using any fan or blower. This method is energy-efficient and low-cost, but it may result in slower and uneven drying, especially in larger systems or during cloudy weather.

### B. Forced Drying:

In forced drying, along with the heat stored in PCM, additional components like a blower, infrared (IR) bulb, and heater are used to improve drying performance. The blower actively circulates hot air throughout the drying chamber, ensuring faster and uniform drying. The IR bulb and heater provide supplementary heat to maintain a constant high temperature, especially when solar energy is insufficient. This system offers faster drying, better temperature control, and consistent moisture removal, making it suitable for commercial or large-scale drying operations.

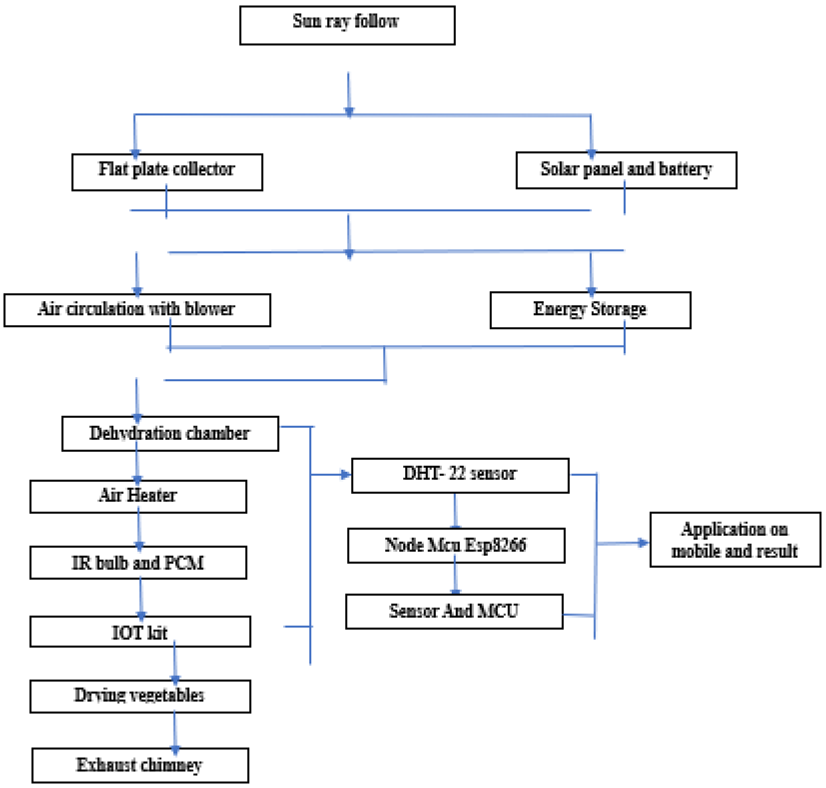

**Fig 5. Solar Dehydration System Process**

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## 3. EXPERIMENTAL SETUP

Figure 6 illustrates the frontal view of the experimental setup platform, which includes elements such as the exhaust fan, roller wheel, collector, blower, PCM tank, solar panels, and transparent glass. The solar dehydration system is composed of a flat plate solar collector (air heater) with an area of 0.5 m² (1×0.5 m) and a dehydration chamber. The absorber plate of the solar collector is made from a 2 mm thick galvanized sheet painted black to capture solar radiation, situated behind a transparent glass cover with an air gap in between. This configuration permits the passage of heated air. A 5 mm thick glass layer enhances the greenhouse effect, raising the air temperature. Infrared bulbs emit heat energy to dry agricultural products, functioning even at night due to infrared radiation. The system is powered by 600 amp-hour batteries, 1500-watt (or 1 kW) solar panels, and a 1500-watt (or 1.5 kW) inverter. The device operates in two cycles: the first from 9 a.m. to 5 p.m. utilizing solar energy, and the second from 5 p.m. to 1 a.m. using the PCM tank and infrared bulbs, as depicted in Figure 6. The proposed experimental setup comprises various components such as,

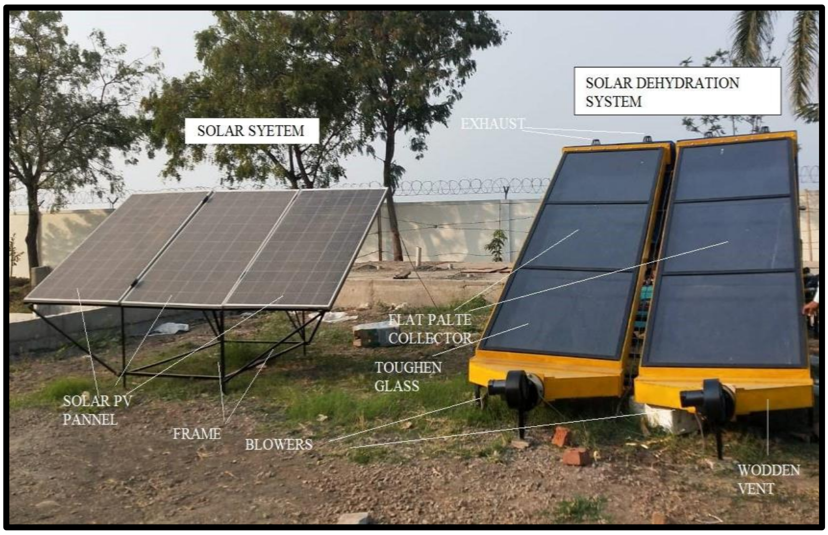

**Fig 6. Experimental Setup**

1. Solar flat plate collector
2. PCM energy storage tank
3. Dehydration chamber with three 100kg, 250kg and 400kg
4. Trays
5. Blower
6. Infra-red bulb
7. Insulation in paraffin wax

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8. Supporting system for blower and reflector
9. Measuring Instruments
10. Air heater
11. Dc fan in drying chamber

There are component solar dehydration system. Sun ray is following through flat plate collector there attached in flat plate collector absorber plate they are absorbed in solar energy and flat plate collector are heated. Flat plate collector are heater also heat in energy storage tank. Energy storage tank in paraffin wax is heater there are phase changing martial there first their soil to liquid from and second is liquid to vapor from with heigh temperature. Blower there start give heigh pressure of air through flow through a flat plate collector and there heigh temperature of air follow through a drying chamber. There heigh temperature of air in dying chamber come. There are attached in air heater and infra-red bulb there are maintain the higher temperature of dying chamber there heigh temperature of air follow through vegetables and they are dry. And also, they attached in dc fan they hot air is follow through correct vegetable direction in drying chamber and vegetables are dry. And there 100kg/day drying vegetables.

**Drying chamber**

The drying chamber sizes of 100 kg solar dehydration systems are shown in Table 1. In these drying chambers, five vegetables onion, potato, chili, grapes, and spinach are dried. Each vegetable is dried in the 100 kg chamber per day in two cycles: the first cycle dries 50 kg during the daytime, and the second cycle dries 50 kg during the nighttime, using paraffin wax as the PCM material and an infrared bulb. The drying process in the three different-sized drying chambers is shown below in Figure 7.

The dehydration chamber contains a total of 10 trays, with each tray having a capacity of 5 kg. This system is used for drying vegetables. The trays are made of food-grade stainless steel and are used to dry five types of vegetables: onion, chilli, spinach, potato, and grapes.

**Fig 7. Drying chamber**

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## 4. RESULT AND DISCUSSION

### 4.1 Experimental Result

In the solar dehydration system, multiple temperature points are strategically monitored to evaluate performance and thermal efficiency. The inlet temperature (Tin) is measured at the entry point of air into the solar collector, representing the initial air temperature before any heating occurs. Inside the drying chamber, the bottom temperature (T1) is recorded to understand the heat level where drying starts, which is crucial for effective moisture removal. After passing through the system, the outlet temperature in the drying tray (T2) reflects how much the air has been heated, indicating the collector's efficiency. The middle temperature (T3), located in the combustion chamber, helps track the internal heat distribution during the drying process. The outlet/exhaust temperature (T out) shows the temperature of the air as it exits the system, providing insight into potential heat loss. Lastly, the ambient temperature (Ta), taken from the surrounding environment, serves as a reference point to assess overall thermal gain and system efficiency. These temperature measurements, as shown in Fig. 8, are essential for optimizing drying conditions and ensuring consistent product quality.

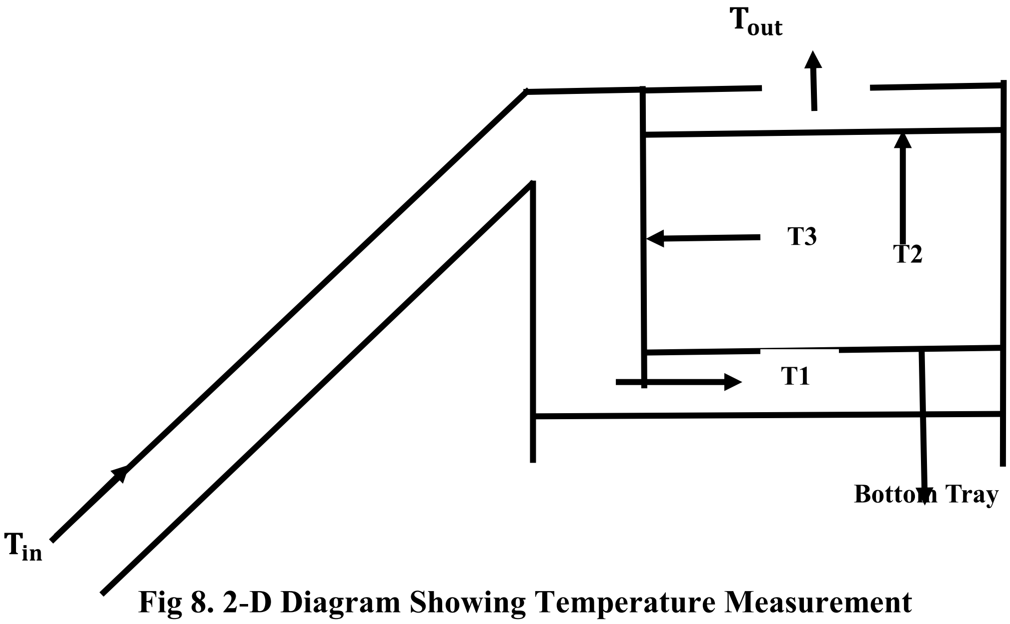

**Fig 8. 2-D Diagram Showing Temperature Measurement**

The solar dehydration system employs two drying methods: the first is natural conversion, and the second is forced conversion. It is used to dry five types of vegetables: onions, potatoes, chilies, spinach, and grapes. Natural conversion relies solely on PCM material to dry the vegetables and involves calculating the drying time. In contrast, forced conversion uses a blower, an IR bulb, and a heater to maintain the temperature within the drying chamber while drying the vegetables.

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### A. Natural conversion with PCM

**Table 1. Observation Using PCM of Chilli**

| Time | (T1) (ºC) | (T2) (ºC) | (T3) (ºC) | $T_{in}$ (ºC) | $T_{out}$ (ºC) | Ta (ºC) |
|---|---|---|---|---|---|---|
| 05:00 pm | 79 | 39 | 50 | 28 | 55 | 28 |
| 05:30 pm | 76 | 38 | 48 | 33 | 53 | 32 |
| 06:00 pm | 74 | 38 | 47 | 35 | 51 | 35 |
| 06:45 pm | 72 | 37 | 45 | 37 | 48 | 36 |

Table 1 illustrates that the system was set up under solar radiation at 10:30 a.m. At that moment, the food sample initially weighed 5 kg, and the starting temperature was 28°C. The temperature rose steadily due to the solar radiation and a wind speed of 2.50 m/s. As a result, the weight of the dried sample decreased to 144 g, with 85.6% of the moisture being removed from the food sample in 1 hour and 45 minutes.

**Table 2. Observation Using PCM of Onion**

| Time | (T1) (ºC) | (T2) (ºC) | (T3) (ºC) | $T_{in}$ (ºC) | $T_{out}$ (ºC) | Ta (ºC) |
|---|---|---|---|---|---|---|
| 05:00 pm | 40 | 28 | 38 | 28 | 32 | 38 |
| 05:30 pm | 41 | 34 | 39 | 32 | 34 | 39 |
| 06:00 pm | 50 | 36 | 41 | 35 | 48 | 41 |
| 06:30 pm | 53 | 40 | 43 | 36 | 49 | 43 |
| 07:00 pm | 56 | 41 | 42 | 38 | 54 | 42 |

Table 2 illustrates that the system was functioning under solar radiation at 5:00 p.m.; during this period, the food sample initially weighed 10 kg, and the starting temperature was 28°C. The temperature rose steadily due to the solar radiation and a wind speed of 2.50 m/s. In these conditions, the weight of the dried sample decreased to 144 g, with 85.6% of the moisture being removed from the food sample in 1 hour and 45 minutes, resulting in a dehydration rate of 489 g/hr.

**Table 3. Observation Using PCM of Potato**

| Time | (T1) (°C) | (T2) (°C) | (T3) (°C) | $T_{in}$ (°C) | $T_{out}$ (°C) | Ta (°C) |
|---|---|---|---|---|---|---|
| 05:00 pm | 79 | 39 | 50 | 28 | 31 | 28 |
| 05:30 pm | 76 | 38 | 48 | 33 | 33 | 32 |
| 06:00 pm | 74 | 38 | 47 | 31 | 35 | 35 |
| 06:10 pm | 72 | 37 | 45 | 28 | 37 | 36 |

Table 3 illustrates that the system was functioning under solar radiation at 5:00 p.m. At this point, the food sample initially weighed 10 kg and had a moisture content of 85%. In these conditions, 80% of the moisture was extracted from the food sample within 1 hour and 10 minutes.

**Table 4. Observation Using IR Bulb and PCM of Spinach**

| Time | (T1) (°C) | (T2) (°C) | (T3) (°C) | $T_{in}$ (°C) | $T_{out}$ (°C) | Ta (°C) |
|---|---|---|---|---|---|---|
| 05:00 pm | 39 | 50 | 79 | 28 | 55 | 28 |
| 05:30 pm | 38 | 48 | 76 | 33 | 53 | 32 |

| | | | | | | |
|---|---|---|---|---|---|---|
| 05:40 pm | 38 | 47 | 74 | 35 | 51 | 35 |

According to Table 4, the system was functioning under solar radiation at 5:00 p.m. At this point, the food sample initially weighed 5 kg and had a moisture content of 85%. In these conditions, 80% of the moisture was extracted from the food sample within 40 minutes.

### B. Force Conversion

**Table 5. Observation Using with Solar and Blower of Spinach**

| Time | INTENSITY (w\m$^2$) | (T1) (°C) | (T2) (°C) | (T3) (°C) | $T_{in}$ (°C) | $T_{out}$ (°C) | $T_a$ (°C) | HUMIDITY (%) |
|---|---|---|---|---|---|---|---|---|
| 10:30 am | 380.9 | 50 | 34 | 44 | 31 | 37 | 29 | 41 |
| 11:00 am | 389.6 | 51 | 35 | 44 | 36 | 35 | 29 | 42 |
| 11:30 am | 402.6 | 49 | 34 | 42 | 33 | 39 | 30 | 43 |
| 12 noon | 401.8 | 52 | 36 | 47 | 36 | 42 | 31 | 42 |
| 12:30 pm | 398.6 | 46 | 33 | 41 | 30 | 40 | 30 | 42 |
| 01:00 pm | 403.8 | 45 | 35 | 43 | 32 | 41 | 32 | 40 |

According to Table 5, the system was in operation under solar radiation at 10:30 a.m. At that moment, the food sample initially weighed 10 kg and had a moisture content of 85%. In these circumstances, 80% of the moisture was extracted from the sample within 2 hours and 30 minutes, attributed to the low solar intensity on that particular day.

**Table 6. Observation Using Blower and Heater of Chilli**

| Time | INTENSITY (w\m$^2$) | (T1) (°C) | (T2) (°C) | (T3) (°C) | $T_{in}$ (°C) | $T_{out}$ (°C) | $T_a$ (°C) | HUMIDITY (%) |
|---|---|---|---|---|---|---|---|---|
| 01:00 pm | 429.2 | 45 | 32 | 55 | 41 | 58 | 32 | 38 |
| 01:15 pm | 398.2 | 44 | 33 | 52 | 32 | 42 | 31 | 39 |

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| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| 01:30 pm | 382.5 | 45 | 36 | 54 | 34 | 35 | 31 | 38 |
| 02:00 pm | 380.2 | 43 | 34 | 68 | 30 | 37 | 30 | 39 |
| 02:15 pm | 376.2 | 44 | 35 | 71 | 38 | 38 | 30 | 41 |
| 02:30 pm | 368.3 | 42 | 37 | 59 | 34 | 38 | 29 | 41 |
| 03:00 pm | 347.6 | 37 | 36 | 57 | 32 | 35 | 28 | 39 |

According to Table 6, the system was in operation under solar radiation at 1:00 p.m. At this point, the food sample initially weighed 5 kg and had a moisture content of 85%. Within a span of 2 hours under these conditions, 80% of the moisture was extracted from the sample.

**Table 7. Observation Using Blower and IR Bulb of Onion**

| Time | INTENSITY (w\m$^2$) | (T1) (°C) | (T2) (°C) | (T3) (°C) | $T_{in}$ (°C) | $T_{out}$ (°C) | $T_a$ (°C) | HUMIDITY (%) |
|---|---|---|---|---|---|---|---|---|
| 01:00 pm | 689.5 | 44 | 32 | 42 | 29 | 35 | 30 | 42 |
| 01:15 pm | 657.2 | 44 | 31 | 49 | 31 | 39 | 30 | 41 |
| 01:30 pm | 745.2 | 42 | 34 | 50 | 35 | 39 | 31 | 39 |
| 02:00 pm | 748.8 | 47 | 38 | 54 | 40 | 55 | 31 | 39 |
| 02:15 pm | 658.9 | 41 | 39 | 55 | 36 | 43 | 32 | 38 |
| 02:30 pm | 625.3 | 43 | 32 | 58 | 32 | 49 | 32 | 38 |

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| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| 03:00 pm | 628.5 | 42 | 35 | 68 | 34 | 38 | 30 | 38 |

According to Table 7, the system was in operation under solar radiation at 10:00 a.m. At this point, the food sample initially weighed 5 kg and had a moisture content of 85%. Within 120 minutes under these conditions, 80% of the moisture was extracted from the sample.

**Table 8. Observation Using Blower and IR Bulb of Potato**

| **Time** | **INTENSIY (w\m$^2$)** | **T1 ($^o$C)** | **T2 ($^o$C)** | **T3 ($^o$C)** | **$T_{in}$ ($^o$C)** | **$T_{out}$ ($^o$C)** | **$T_a$ ($^o$C)** | **HUMIDITY (%)** |
|---|---|---|---|---|---|---|---|---|
| 10:30 am | 352.1 | 55 | 31 | 33 | 30 | 52 | 27 | 43 |
| 11:00 am | 384.6 | 61 | 34 | 36 | 32 | 54 | 28 | 44 |
| 11:30 am | 363.2 | 63 | 35 | 38 | 30 | 59 | 28 | 46 |
| 12 noon | 584.4 | 65 | 34 | 42 | 39 | 57 | 29 | 44 |
| 12:30 pm | 511.1 | 50 | 34 | 46 | 41 | 49 | 31 | 42 |
| 01:00 pm | 489.4 | 48 | 32 | 43 | 38 | 47 | 30 | 42 |

Table 8 illustrates that the system was in operation under solar radiation at 10:30 a.m. At this point, the food sample initially weighed 10 kg and had a moisture content of 85%. In these conditions, 80% of the moisture was extracted from the sample within 2 hours and 30 minutes.

**Table 9. Observation Using Blower and Heater of Potato**

| **Time** | **INTENSIY (w\m$^2$)** | **(T1) ($^o$C)** | **(T2) ($^o$C)** | **(T3) ($^o$C)** | **$T_{in}$ ($^o$C)** | **$T_{out}$ ($^o$C)** | **$T_a$ ($^o$C)** | **HUMIDITY (%)** |
|---|---|---|---|---|---|---|---|---|
| 10:00 am | 396.4 | 45 | 31 | 51 | 32 | 42 | 30 | 42 |
| 10:15 am | 392.1 | 43 | 32 | 52 | 36 | 49 | 30 | 41 |

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| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| 10:20 am | 395.6 | 44 | 36 | 56 | 38 | 50 | 31 | 39 |
| 10:30 am | 426.1 | 41 | 39 | 59 | 45 | 54 | 31 | 39 |
| 10:40 am | 414.4 | 44 | 34 | 62 | 42 | 55 | 32 | 38 |
| 11:00 am | 489.2 | 45 | 32 | 55 | 41 | 58 | 32 | 38 |

Table 9 illustrates the system set up in solar radiation at 10:00 am. At this point, the initial weight was 5 kg, and the starting moisture content was 85%. Within one hour, 80% of the moisture was extracted from the food sample due to the low intensity throughout the day.

**Table 10. Observation Using Heater and IR Bulb of Onion**

| **Time** | **INTENSITY (w\m$^2$)** | **(T1) (°C)** | **(T2) (°C)** | **(T3) (°C)** | **$T_{in}$ (°C)** | **$T_{out}$ (°C)** | **$T_a$ (°C)** | **HUMIDITY (%)** |
|---|---|---|---|---|---|---|---|---|
| 10:00 am | 678.5 | 29 | 32 | 51 | 31 | 37 | 30 | 42 |
| 10:30 am | 654.2 | 31 | 36 | 52 | 36 | 35 | 30 | 41 |
| 11:00 am | 712.2 | 35 | 38 | 56 | 33 | 39 | 31 | 39 |
| 11:30 am | 748.8 | 45 | 55 | 59 | 36 | 42 | 31 | 39 |
| 12:00 pm | 689.9 | 36 | 42 | 62 | 30 | 40 | 32 | 38 |
| 12:30 pm | 666.3 | 32 | 41 | 55 | 32 | 41 | 32 | 38 |
| 01:00 pm | 628.3 | 27 | 26 | 36 | 27 | 28 | 32 | 39 |

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| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| 01:30 pm | 688.4 | 32 | 39 | 43 | 31 | 32 | 32 | 39 |

According to Table 10, the system was set up under solar radiation at 10:00 a.m. At that moment, the food sample weighed 10 kg and had an initial moisture content of 85%. In these conditions, 80% of the moisture was extracted from the sample within 3 hours and 30 minutes.

**Table 11. Observation Using Solar and Blower Grapes**

| Time | $T_a$(°C) | $I_c$ (watt/m$^2$) | $T_{in}$ (°C) | $T_{out}$ (°C) | $T_t$ (°C) | $T_3$ (°C) | HUMIDITY (%) |
|---|---|---|---|---|---|---|---|
| **FIRST DAY** | | | | | | | |
| 10 am | 35 | 380.9 | 35 | 35 | 26 | 26 | 30 |
| 11 am | 35 | 389.6 | 37 | 40 | 28 | 29 | 29 |
| 12 noon | 36 | 402.6 | 39 | 43 | 32 | 32 | 31 |
| 1 pm | 36 | 401.8 | 41 | 44 | 34 | 34 | 34 |
| 2 pm | 37 | 398.6 | 42 | 46 | 36 | 37 | 37 |
| 3 pm | 37 | 403.8 | 41 | 45 | 38 | 39 | 38 |
| 4 pm | 36 | 387.2 | 39 | 43 | 40 | 41 | 39 |
| 5 pm | 35 | 384.8 | 37 | 40 | 42 | 42 | 41 |
| **SECOND DAY** | | | | | | | |
| 10 am | 34 | 368.9 | 34 | 34 | 33 | 36 | 33 |
| 11 am | 35 | 402.6 | 36 | 39 | 36 | 37 | 36 |
| 12 noon | 36 | 401.8 | 38 | 41 | 37 | 39 | 37 |
| 1 pm | 36 | 398.6 | 40 | 44 | 38 | 40 | 38 |
| 2 pm | 36 | 403.8 | 42 | 45 | 39 | 41 | 39 |

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| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 3 pm | 35 | 397.4 | 44 | 49 | 41 | 42 | 40 |
| 4 pm | 34 | 397.1 | 41 | 45 | 40 | 40 | 41 |
| 5 pm | 33 | 387.2 | 39 | 43 | 39 | 35 | 40 |
| **THIRD DAY** | | | | | | | |
| 10 am | 35 | 689.3 | 35 | 35 | 35 | 39 | 34 |
| 11 am | 36 | 720.3 | 36 | 39 | 36 | 40 | 37 |
| 12 noon | 37 | 730.2 | 40 | 43 | 38 | 41 | 39 |
| 1 pm | 37 | 639.2 | 41 | 44 | 40 | 42 | 41 |
| 2 pm | 38 | 559.6 | 43 | 46 | 41 | 41 | 42 |
| 3 pm | 37 | 489.5 | 43 | 47 | 42 | 40 | 43 |
| 4 pm | 36 | 354.3 | 41 | 44 | 40 | 36 | 42 |
| 5 pm | 35 | 201.3 | 39 | 42 | 39 | 38 | 40 |
| **FOURTH DAY** | | | | | | | |
| 10 am | 36 | 358.9 | 36 | 36 | 36 | 43 | 36 |
| 11 am | 37 | 354.6 | 38 | 42 | 38 | 44 | 38 |
| 12 noon | 37 | 433.6 | 41 | 45 | 40 | 44 | 41 |
| 1 pm | 38 | 445.8 | 42 | 46 | 42 | 42 | 42 |
| 2 pm | 38 | 357.6 | 44 | 49 | 41 | 43 | 43 |
| 3 pm | 37 | 378.8 | 44 | 48 | 26 | 44 | 44 |
| 4 pm | 36 | 295.4 | 41 | 44 | 29 | 44 | 42 |
| 5 pm | 35 | 275.1 | 39 | 41 | 32 | 40 | 41 |

Table 11. shows that the system was installed under solar radiation at 10:00 a.m. At that time, the initial weight of the food sample was 10 kg, and the initial temperature was 32°C. This observation was also conducted during the day using a blower and solar radiation.

Table 12. shows installed in solar radiations at 10 am; at that the time initial weight 50 kg and initial temperature of food sample 32 ºC and this observation also performed at Day using Blower and Solar radiations.

**Table 12. Observation of Force Convection with PCM of Grapes**

| Time | $T_a$(ºC) | $T_{in}$ (°C) | $T_{out}$ (°C) | $T_t$ (ºC) | $T_m$ (ºC) | Tb (°C) |
|---|---|---|---|---|---|---|
| 10 am | 38 | 38 | 38 | 29 | 29 | 29 |
| 11 am | 39 | 40 | 43 | 32 | 32 | 32 |
| 12 noon | 39 | 43 | 47 | 34 | 33 | 34 |
| 1 pm | 40 | 48 | 53 | 35 | 34 | 35 |
| 2 pm | 40 | 50 | 55 | 38 | 37 | 37 |
| 3 pm | 39 | 51 | 56 | 40 | 39 | 39 |
| 4 pm | 37 | 49 | 48 | 42 | 40 | 40 |

**Dehydration With PCM**

| Time | $T_a$(ºC) | TPCM (°C) | $T_{in}$ (ºC) | $T_{out}$ (°C) | $T_t$ (ºC) | $T_m$ (ºC) | Tb (°C) |
|---|---|---|---|---|---|---|---|
| 5 pm | 36 | 79 | 47 | 51 | 43 | 42 | 43 |
| 6 pm | 35 | 76 | 46 | 50 | 44 | 43 | 43 |
| 7 pm | 34 | 72 | 43 | 46 | 43 | 41 | 42 |
| 8 pm | 34 | 69 | 40 | 42 | 41 | 41 | 41 |

**SECOND DAY**

| Time | $T_a$(ºC) | $T_{in}$ (°C) | $T_{out}$ (°C) | $T_t$ (ºC) | $T_m$ (ºC) | Tb (°C) |
|---|---|---|---|---|---|---|
| 10 am | 38 | 38 | 38 | 38 | 38 | 38 |
| 11 am | 39 | 40 | 42 | 40 | 40 | 40 |
| 12 noon | 39 | 43 | 45 | 42 | 41 | 42 |
| 1 pm | 40 | 44 | 48 | 44 | 43 | 44 |
| 2 pm | 38 | 45 | 50 | 45 | 45 | 45 |

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| | | | | | | |
|---|---|---|---|---|---|---|
| 3 pm | 36 | 46 | 50 | 46 | 46 | 46 |
| 4 pm | 35 | 44 | 49 | 47 | 46 | 47 |

**Dehydration With PCM**

| Time | $T_a$(°C) | TPCM (°C) | $T_{in}$ | $T_{out}$ (°C) | $T_t$ (°C) | $T_m$ (°C) | Tb (°C) |
|---|---|---|---|---|---|---|---|
| 5 pm | 35 | 79 | 47 | 51 | 48 | 48 | 48 |
| 6 pm | 34 | 76 | 46 | 50 | 46 | 46 | 46 |
| 7 pm | 34 | 73 | 43 | 46 | 43 | 44 | 43 |

### 4.2 Instrument Measuring Device Result

In the solar dehydration system, a K-type thermocouple measures temperature at various points, ensuring accurate thermal data. An anemometer monitors air velocity for proper airflow assessment, while a manometer or pressure sensor measures pressure differences to evaluate system performance. These instruments are essential for effective process control and analysis.

**Table 11. Instrument Measuring Devices**

| Sr. No | Parameter | Instrument | Measured / Calculated |
|---|---|---|---|
| **1** | Temperature | Thermocouple, K Type | Direct measurement (°C) |
| **2** | Air Velocity | Anemometer | Measured or calculated (m/s) |
| **3** | Pressure | Manometer, Pressure sensor | Measured or calculated (Pa) |

Table 12. shown in experimental results of the solar drying system were evaluated based on key parameters such as temperature, airflow velocity, and pressure at both the inlet and outlet. The temperature showed a significant increase from 27°C at the inlet to 70°C at the outlet, indicating efficient heat transfer within the system, likely due to the use of a solar collector and phase change material (PCM). The airflow velocity also increased from 2.335 m/s at the inlet to 8.030 m/s at the outlet, suggesting enhanced air movement, possibly assisted by a blower and thermal expansion of heated air. Furthermore, the pressure rose from 0.5145 kPa at the inlet to 7.432 kPa at the outlet, reflecting increased energy and forced airflow within the chamber. These observations confirm the effective functioning of the system in raising the thermal and kinetic energy of air for improved drying performance. Ther show Table 12 below.

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Table 12. Experimental Result Overview

| Sr. No | Parameter | Unit | Location | Experimental result |
|---|---|---|---|---|
| **1** | **Temperature** | °C | Inlet | 27 |
| | | | Outlet | 70 |
| **2** | **Airflow velocity** | m/s | Inlet | 2.335 |
| | | | Outlet | 8.030 |
| **3** | **Pressure** | Pa | Inlet | 0.5145 |
| | | | Outlet | 7.432 |

### 4.3 Comparing Natural Drying and Force Drying Conversion

Table 13. Comparison of Natural vs. Force Drying

| Sr. No | Vegetable | Drying Method | Added Energy Source | Drying Time | Moisture Removed | Drying Speed |
|---|---|---|---|---|---|---|
| **1** | **Chilli** | Natural | PCM only | 1 hr 45 min | 85.6% | Moderate |
| | | Force | Heater + Blower | 2 hr | 80% | Faster (controlled) |
| **2** | **Onion** | Natural | PCM only | 1 hr 45 min | 85.6% | Moderate |
| | | Force | IR Bulb + Blower | 2 hr | 80% | Faster (consistent) |
| | | | Heater + IR Bulb | 3 hr 30 min | 80% | Slower (cloudy day) |
| **3** | **Potato** | Natural | PCM only | 1 hr 10 min | 80% | Moderate |
| | | Force | IR Bulb + Blower | 2 hr 30 min | 80% | Faster |

| | | | | | | |
|---|---|---|---|---|---|---|
| | | | Blower + Heater | 1 hr | 85% | |
| **4** | **Spinach** | Natural (with IR) | PCM + IR Bulb (150W) | 40 min | 80% | Fastest Overall |
| | | Force | Blower + Solar | 2 hr 30 min | 80% | Slow (low sunlight) |
| **5** | **Grapes** | Force only | Solar + Blower | 1 days | 80% | Fastest |
| | | Natural (with force) | PCM + Force | 1 days | 80% | |

The comparative analysis of natural and forced drying methods using a solar dryer revealed significant differences in drying time, moisture removal, and overall efficiency for various vegetables. Natural drying methods, especially when supported by Phase Change Material (PCM), performed moderately well for small sample weights (5–10 kg), with chilli, onion, and potato achieving over 80% moisture removal in less than 2 hours. Spinach, when dried naturally with the aid of an infrared (IR) bulb and PCM, showed the fastest drying time of just 40 minutes while maintaining 80% moisture reduction. On the other hand, forced drying methods using heaters, blowers, and IR bulbs demonstrated more consistent and controlled drying rates, particularly beneficial under cloudy weather or low sunlight conditions. For example, potatoes achieved the highest moisture removal (85%) in just 1 hour using a blower and heater combination. In the case of grapes, which were dried in bulk (50 kg), both natural (with PCM and force) and forced methods (solar + blower) required a full day to achieve the target of 80% moisture removal. Overall, the study highlights that while natural drying with thermal storage is energy-efficient and effective for smaller loads, forced convection methods significantly improve drying speed and reliability, especially for larger quantities and less favourable environmental conditions.

## 5. CONCLUSION

The experimental results confirm that a solar dehydration system integrating paraffin-wax PCM, IoT monitoring, and optional forced-convection components delivers flexible, round-the-clock drying. Natural drying, powered solely by solar-charged PCM, reliably removed 80–85.6 % of moisture from chilli, onion, and potato within 70–105 minutes, offering an energy-efficient option when weather is favourable. However, adding blowers, IR bulbs, or heaters dramatically accelerated and stabilised the process: spinach reached the same 80 % moisture reduction in just 40 minutes, and chilli and onion dried consistently in 2–2.5 hours

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even under low irradiance. While dense, high-sugar grapes still needed four days despite forced air, overall, the forced mode proved superior for rapid, uniform drying and for maintaining operation during cloudy periods. In short, the PCM-buffered natural mode is best suited to small, energy-conservative batches, whereas the forced-convection mode offers the controlled temperatures and airflow needed for larger or time-sensitive loads, making the hybrid design a versatile solution for sustainable food preservation.

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