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Performance Testing of Arduino-Based Hybrid Solar Dryer for Drying Apple Slices

Debashree Debadatta Behera[1,*], Shiv Sankar Das[2], Ramesh Chandra Mohanty[3], Raj Kumar Satankar[4], Bhagat Singh[5]

Abstract

A novel and high-efficiency hybrid solar dryer was designed and developed in this study to dry apple slices. The thermal analysis of the dryer is conducted by calculating collector efficiency, drying rate, and drying efficiency. Integrating an Arduino-based temperature and humidity monitoring system in a hybrid solar dryer enhances the ability to optimize performance and efficiency. Both the collector and drying chamber are made of aluminum sheet as it has good thermal conductivity and no corrosion effect. In this study, an Arduino UNO R3 microcontroller, paired with a temperature and humidity sensor is utilized to measure environmental conditions inside the drying chamber continuously. Real-time monitoring and control of major drying parameters including temperature and relative humidity are made possible by Arduino, which enhances process stability and produces consistent drying conditions. When one glass plate is used on the collector instead of two, the mean temperature inside the collector and drying chamber increases by 4–5°C. There is a 5–6°C increase in temperature in the case of using 60 rectangular fins inside the collector as compared to without using fins. By using silica gel, 13–15% less humidity is present in the heated air that flows inside the drying chamber and increased the rate at which food products dry. The highest recorded values for collector efficiency, drying efficiency, and drying rate reached up to 64.23%, 33.61%, and 1.351 kg/h, respectively. The study establishes that the material selection and design modifications significantly influence the thermal performance of hybrid solar dryers, leading to higher drying rates and improved product storage stability compared to natural and open solar drying.

Keywords: Arduino UNO R3 microcontroller, arduino-based temperature and humidity monitoring system, drying efficiency, hybrid solar dryer, thermal performance

***Author for Correspondence**
Debashree Debadatta Behera

[1]Associate Professor, Department of Mechanical Engineering, Centurion University of Technology and Management, Odisha, India
[2]Assistant Professor, School of Management, Centurion University of Technology and Management, Odisha, India
[3]Professor, Department of Mechanical Engineering, Centurion University of Technology and Management, Odisha, India
[4]Associate Professor, Department of Mechanical Engineering, Poornima College of Engineering, Jaipur, Rajasthan, India
[5]Associate Professor, Department of Mechanical Engineering, Jaypee University of Engineering and Technology, Guna, Madhya Pradesh, India

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INTRODUCTION

Solar energy can be directly or indirectly used for drying applications. In an open sun drying application, solar energy is directly used. In an indirect drying application, hot air is produced from solar energy for drying purposes, and it is called a solar dryer. Solar drying is a quick process and hygienic way to dry food products.

Numerous kinds of solar dryers are available, each utilizing hot air circulation and under direct solar exposure. The food product is exposed to the sun directly in the direct type, and the drying chamber is constructed from a material that effectively transfers heat. In the indirect type, the dryer includes a drying chamber and a collector. Instead of exposing the food product directly to sunlight, the heat produced by the collector circulates through the chamber to dry it. Direct sun radiation exposure in the drying chamber is combined with hot air from a collector in the mixed-mode category. The more recent hybrid type has been developed to be utilized both at nighttime and during the day. Because the forced convection solar dryer is connected to a blower that ensures a steady supply of heated air into the drying chamber, it is more efficient than natural convection mode. Solar dryers are used widely within the food processing industry. Two types of energy sources used by hybrid solar dryers—which integrate solar energy with other resources—are renewable and non-renewable [1]. [2], [3].

A solar dryer with forced convection mode was employed for drying ginger slices and ghost chili peppers. Different performance parameters were calculated [4]. A greenhouse solar dryer with PV integrated was developed and testing was conducted under no-load conditions [5]. An energy analysis was performed on a solar dryer integrated with a hybrid air heater. The performance was assessed utilizing N_2, CO_2, and air. As the working fluid, CO_2 produced the highest temperature and second law efficiency, while air produced the highest thermal efficiency, according to the data [6]. A hybrid solar dryer was developed through a systematic design process to estimate the temperature of the drying chamber [7]. To dry mint leaves, a solar dryer with forced convection mode was developed. Galvanized iron tubes serve as the dryer's absorber sheet, and the effectiveness of the collector was assessed at various mass flow rates [8]. To dry spinach and chilies, a solar dryer integrated with a solar photovoltaic panel was designed. It incorporated two DC fans powered by a 10 W Photovoltaic panel and a 3 m^2 drying space. The backside air circulation improves the efficiency of the PV panel [9]. An indirect solar dryer's maximum evaporation rate was determined. To determine the evaporation rate, factors including temperature, aspect ratio, and humidity of air inside the chamber were incorporated [11]. A solar dryer with an indirect type was analyzed to dehydrate apples. The coefficient of performance and mass reduction achieved was 87% and 89% respectively [12]. An exergy analysis was conducted on an indirect solar dryer for drying green chilies using forced and natural convection mode. For both varieties of solar dryers, estimates were made of the specific energy consumption, average energy efficiency, average drying efficiency, and useable heat outputs.

By integrating smart connected devices through the IoT, the drying process may be remotely observed by obtaining real-time data. Temperatures and humidity data at particular sections of the dryer can be read through sensors and passed to a cloud-based platform for further analysis and monitoring. IoT-enabled data collection facilitates the assessment of several recorded variables like temperature and humidity within the chamber, to estimate the remaining moisture percentage in dried fish [13]. The operation of a coffee bean drying apparatus (solar driven) was examined utilizing a cost-effective telemetry system based on the Internet of Things, which transmits temperature and relative humidity data to a server [14]. The Internet of Things may monitor and supervise parameters including temperature, humidity, air mass flow rate, periodic image capture, and weight loss measurement during the drying process. This IoT-integrated system could enhance efficiency and predictive maintenance which is very useful, especially in large-scale applications.

An experiment on a photovoltaic solar dryer with and without the use of aluminum oxide nanoparticles was conducted. When nanoparticles were used in heat storage units, a 15–22% reduction in the drying period was achieved [15]. A hybrid PVT solar dryer to dry cassava slices was studied. In comparison to the ambient air, the drying chamber's inside temperature was enhanced by 30–40°C [17]. A hybrid solar dryer was investigated for drying tomato, ginger, and bottle guards. For crops indicated above, the efficiency ranged from 14.22–27.99% when using an evacuated collector and from 9.63–24.88% when not using one [18]. A hybrid solar dryer was constructed for drying red pepper and integrated with an electric heater. According to the results, the energy and collector efficiency varied from 13.2–35.6% and 23.7–72.4%, respectively [19]. A hybrid solar drying system was utilized to dry vermicelli. The energy utilization ratio, drying, and energy efficiency are enhanced by 0.32, 17.02%, and 83.6%, respectively [20]. The temperature of the air heater increased to 94°C, and its instantaneous efficiency was enhanced to 69% [21]. Two hybrid mode solar dryers, such as the electric and biogas

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modes, were used to conduct a study on hybrid solar dryers. The efficiency is 6% higher in the case of the biogas type as compared to the electric type hybrid solar dryer [22]. A comparison study on hybrid solar drying and conventional shade drying was conducted. The thermal and exergy efficiency were enhanced by 30% and 27% respectively for solar collector [23]. An entirely novel solar dryer for drying apple slices was assessed. The maximum thermal efficiencies of the chamber and flat plate collector were determined as 25% and 78%, respectively [24]. A hybrid solar drying system with an organic paraffin wax as PCM for drying vegetable crops had been experimentally investigated. It is found that the drying period is reduced using micro and macro PCM as compared to without using PCM [25]. An assessment was conducted for a hybrid smart solar dryer. There was 19–36% of energy consumption saved for drying various medicinal herbs [26].

The experimental study was conducted on a solar dryer with PCM as paraffin wax and used to dry mango pulp. By utilization of PCM, the drying period was reduced as well as drying efficiency increased [27]. A hybrid solar dryer was designed and developed for drying basil leaves at air temperatures and three bed thickness levels. The exergy efficiency is evaluated between 31.78 and 86.55% [28]. Studies on hybrid solar dryers that use phase change material (PCM) to dry a variety of medicinal plant species were conducted. There was 90% less moisture present and the energy efficiency ranged from 17.68 to 57.66% [29]. An assessment of the effectiveness of a newly developed solar dryer was conducted that uses soapstone as a heat storage device. The thermal, collector, and storage efficiency were estimated as 45%, 43%, and 74.5% respectively by using heat storage material [30]. An indirect solar dryer was constructed for drying dhekia using heat storage materials like paraffin wax. The drying time decreased by 40 ± 2.1%, and the thermal efficiency increased by 11 ± 0.2% when compared to a traditional solar dryer [31]. To dry wood fuels like coconut oil, a hybrid solar dryer experiment was carried out using PCM. The thermal and exergy efficiency were evaluated as 30–35% and 13–14% respectively [32]. To dry potato slices, an experiment was done on an indirect solar dryer that integrated PCM. Moisture content is reduced from 78.58% to 10% within 24 hours using PCM while 33 hours without using PCM [33]. To dry a blood fruit, an experiment was done on a modified solar dryer that used PCM. The drying chamber's inside air temperature was raised by 15–18% [34]. An investigation was conducted on a hybrid solar dryer and paraffin wax as PCM to dry vegetable products. Using PCM, the maximum drying rate, collector efficiency, and drying efficiency were enhanced by 27–30%, 4–5%, and 6–8%, respectively [35]. Various types of solar dryers using PCMs were studied. Efficiency gains from PCM-integrated solar dryers range from 2.98–39%, respectively [36].

FABRICATIONS OF HYBRID SOLAR DRYER

Experimental Setup

Before the fabrication process, different components of the solar dryer with proper dimensions are designed using CATIA V5. A 3D model is obtained through the assembly from the part design of various components as shown in Figure 1.

The fabrication of the experimental setup has been discussed in this section. In this study, a new experimental setup has been designed with several specific changes in the construction to obtain improved thermal performance. Solar dryers are constructed and fabricated using materials that are purchased from the local market. The institute's workshop is utilized to fabricate and assemble the dryer's components. Aluminum sheet is utilized for the fabrication process because of its excellent heat conductivity and resistance to corrosion. To construct the experimental setup, 25 kg of 2.5 mm thick aluminum sheet is required. This experimental setup consists of 60 uniformly spaced rectangular fins fixed to the absorbing plate. At the top of the drying chamber, a conical chimney has been constructed for the exhaust of moist air. Under the absorbing plate, three aluminum containers filled with paraffin wax are positioned to absorb latent heat during the day. The dryer operates at night using the heat that has been stored. Different components during the fabrication process are presented in Figure 2.

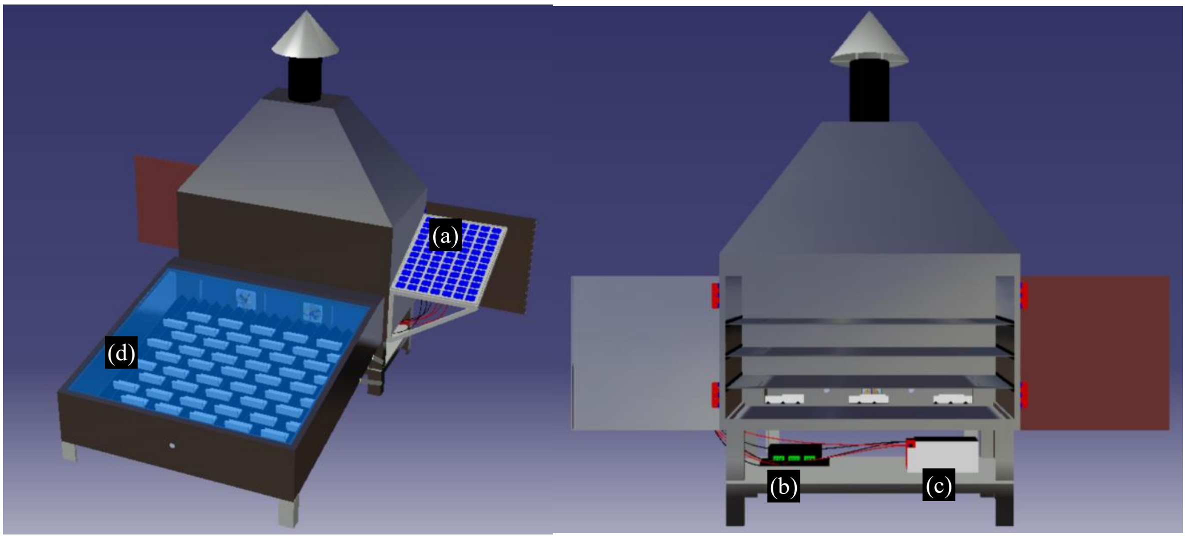

Figure 1. Different components of CATIA model; A. Solar panel, B. Charge controller C. Battery, D. Collector.


Figure 2. Front and back view of solar dryer.

EXPERIMENTAL SETUP

The hybrid solar dryer's primary parts include a drying chamber, solar collector, and auxiliary devices, such as a DC blower, a battery, maximum power point tracking charge controller, and a solar photovoltaic panel. Two transparent glass cover plates, each 4 mm thick, are attached to the solar collector. They are positioned 40 mm apart and one above the other. Beneath the absorbing plate and at the base of the collector, a layer of 80 mm thick insulating glass wool is provided. The incoming solar radiation's transmissivity can be increased by using the two glass plates and reducing the amount of heat wasted because of the re-radiation from the absorbing plate. To enhance heat transmission by increasing surface area and generating turbulence in the incoming air, 60 numbers of fins are evenly spaced around the absorbing plate. Trays are stacked inside the drying chamber, one above the other, using three vertically stainless-steel wire mesh. To maintain a constant temperature throughout the trays, a uniform 110 mm space is kept between each tray. To utilize natural convection to eliminate moisture from the drying chamber, a cone-shaped chimney had been constructed and inserted at the exhaust section of the chamber.

Five kilograms of silica gel is placed at the base part of the chamber which acts as a solid desiccant which absorbs moisture from the circulating hot air. For maximum solar radiation incidence, the collector and solar panel are tilted at a 20° angle according to the latitude of the location. Three DC blowers (2 V, 0.6 A) are driven by a battery (12 V, 10 Ah), a charge controller (12 V, 10 A), and solar photovoltaic panel (20 W). They are electrically connected in series. Three blowers are utilized: one at the inlet section of the collector, and two are positioned to the entrance of the chamber. The experimental setup is displayed in Figure 3.

Figure 3. Experimental setup of hybrid solar dryer.
(1, 2): Front and rear side; (A. DC) blower connected at the entrance of the collector; (B). Rectangular Fins; (C). Transparent cover plate; (D). Thermometer; (E). Photovoltaic panel; (F). Wire mesh trays; (G). Drying chamber; (H). Cone-shaped chimney (I). Charge controller; (J). Battery

RESULTS AND DISCUSSION

Measurement Of Collector and Drying Chamber Temperature Using Single and Double Glass Cover Plates

One or two glass plates were attached to the collector, and temperature readings were taken hourly for three days on consecutive days. At first, a single glass plate was used for the tests. In May, tests were conducted from 10 AM to 4 PM. At 1 PM, the highest recorded temperatures were 42°C at the collector's inlet, 70.5°C at the outlet, 85.5°C inside the absorbing plate, 62.5°C for the drying chamber, and 55.5°C at the exhaust of the drying chamber. For the second day, the corresponding maximum temperatures were 41°C, 70.5, 83.5, 61.5, and 53.5; for the third day, they were 41.6°C, 67.5, 84.5, 62.5, and 52.5, respectively. Figures 4 and 5 illustrate the average temperatures obtained with the use of two transparent glass plates, respectively. When one glass plate was used instead of two, the mean temperatures inside the collector and drying chamber enhanced by 4–5°C. This is explained by the fact that incoming solar radiation through a single glass plate has a higher transmissivity. However, heat is lost due to thermal emission from the absorbing plate; variations in temperature inside the collector were more prominent with single glass plate. Using single glass cover plates results in less heat loss, less temperature variation, and lower average collector temperature.

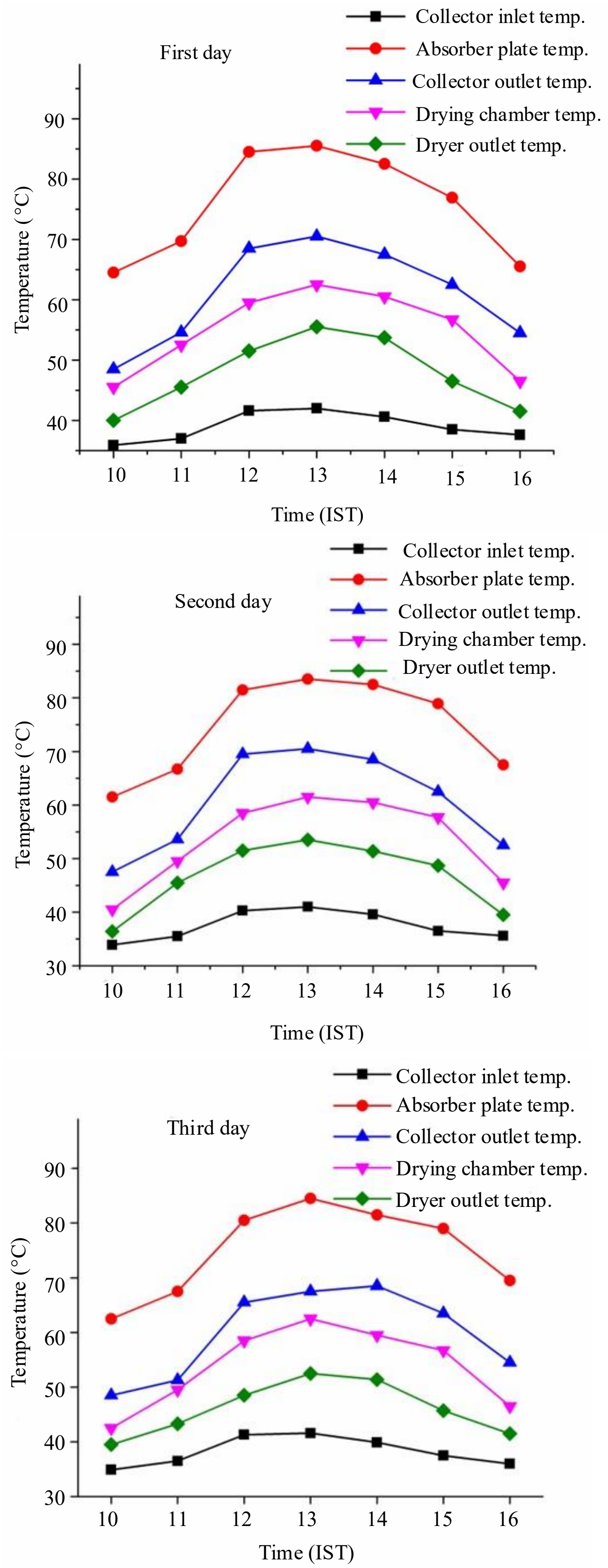

Figure 4. Variation of temperature for collector and drying chamber utilizing one glass plate.

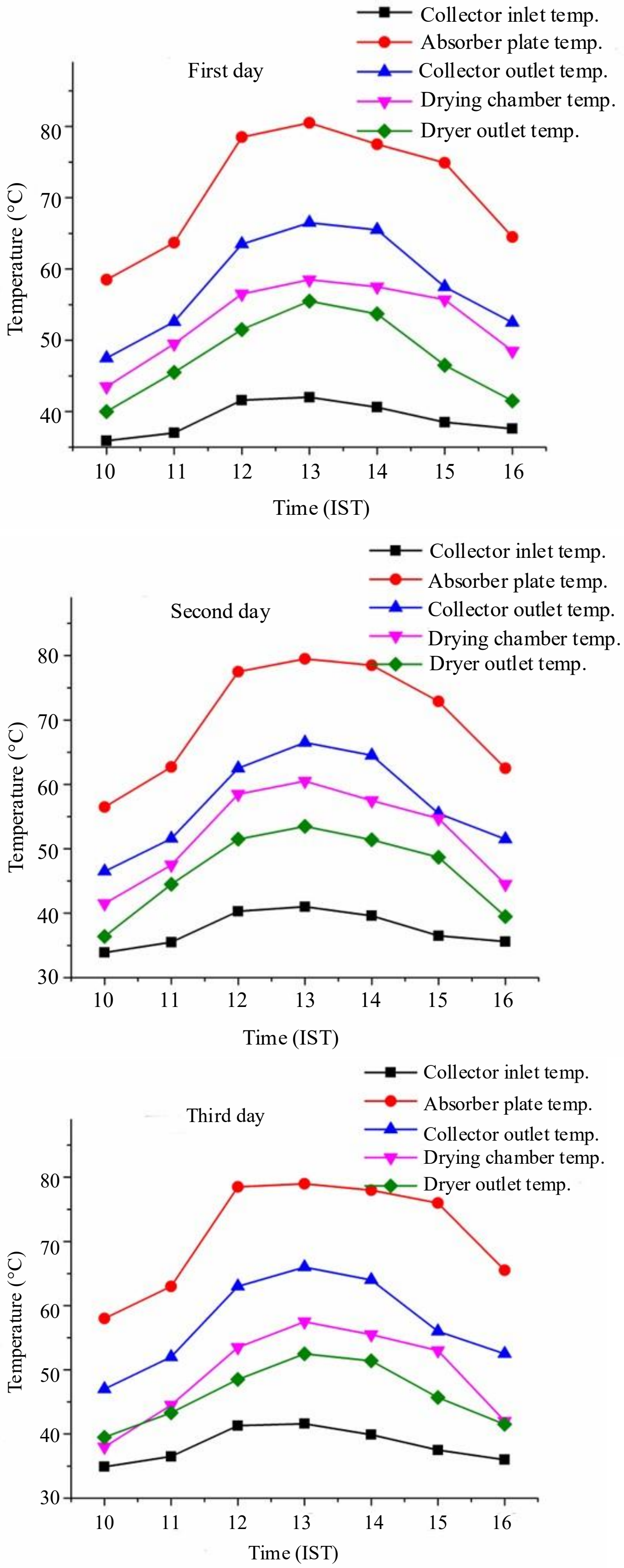

Figure 5. Variation of temperature utilizing two glass plates.

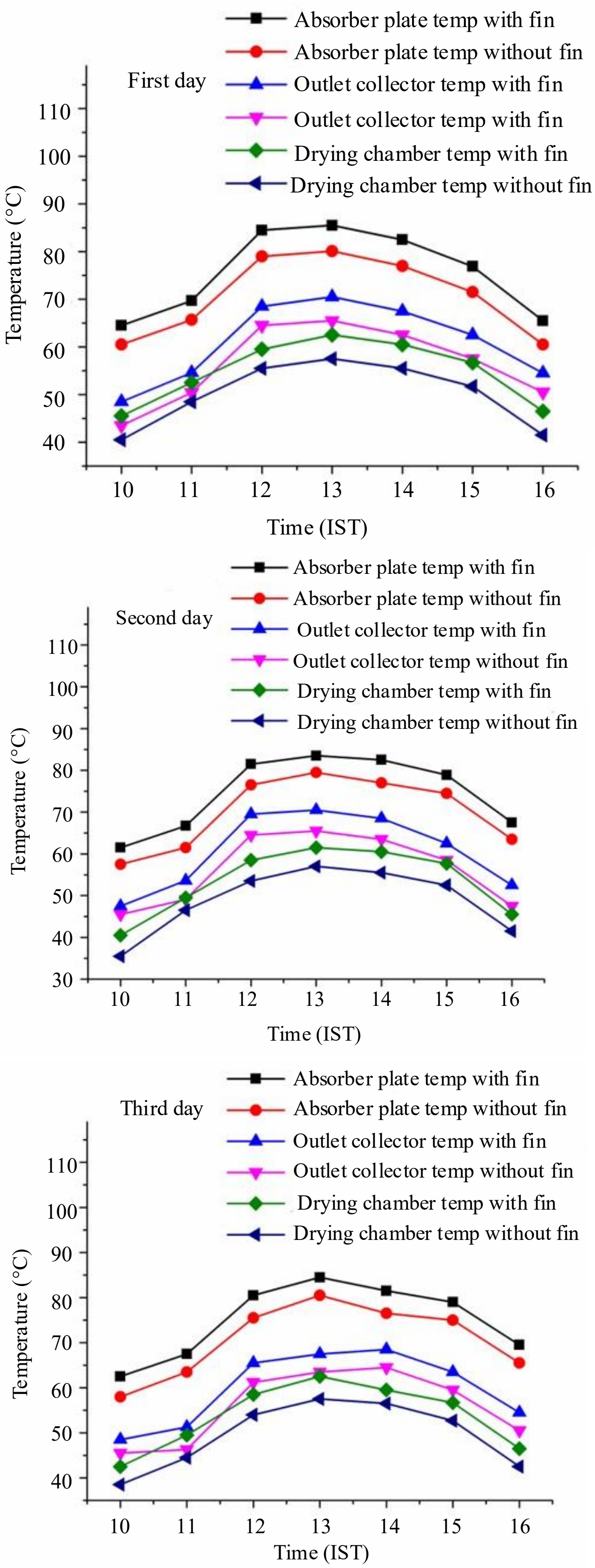

Figure 6. Variation of temperature with and without fin.

Temperature Variation of Collector and Drying Chamber Using and not Using Fins

The variation in temperature inside the collector and chamber using fins and its comparison without using fins has been investigated. It is observed that there is 5–6°C increase in temperature in the case of using 60 rectangular fins inside the collector as compared to without using fins. The temperature variation of collector and drying chamber is presented in Figure 6.

Relative Humidity of Drying Chamber Using Silica Gel

At the base and inlet of the drying chamber, 5 kilograms of silica gel (solid desiccant) was utilized to collect moisture from the hot air flowing through it. At 1 PM on the first day, the mean relative humidity of the surrounding air, within the drying chamber, and damp air coming out of the drying chamber was 51%, 25%, and 49%, respectively. Similarly using a digital hygrometer, the corresponding results for the second and third days were 50%, 24%, 38.4%, and 50%, 25.6%, and 46% respectively. The drying chamber's average humidity was about 25%, which is comparatively high and has an impact on the drying rate. Food products dry more quickly when silica gel is used because it lowers the moisture content of the warm air that distributes inside the drying chamber by 13–15%. The thermodynamic cycle of desiccant has been considered to make the drying rate effective for the next dehydration of incoming air to the drying chamber. Figure 7 displays the humidity of chamber on the 1st, 2nd, and 3rd day by the utilization of silica. Similarly, a comparison of relative humidity variation inside the drying chamber both with and without using silica gel is presented in Figure 8.

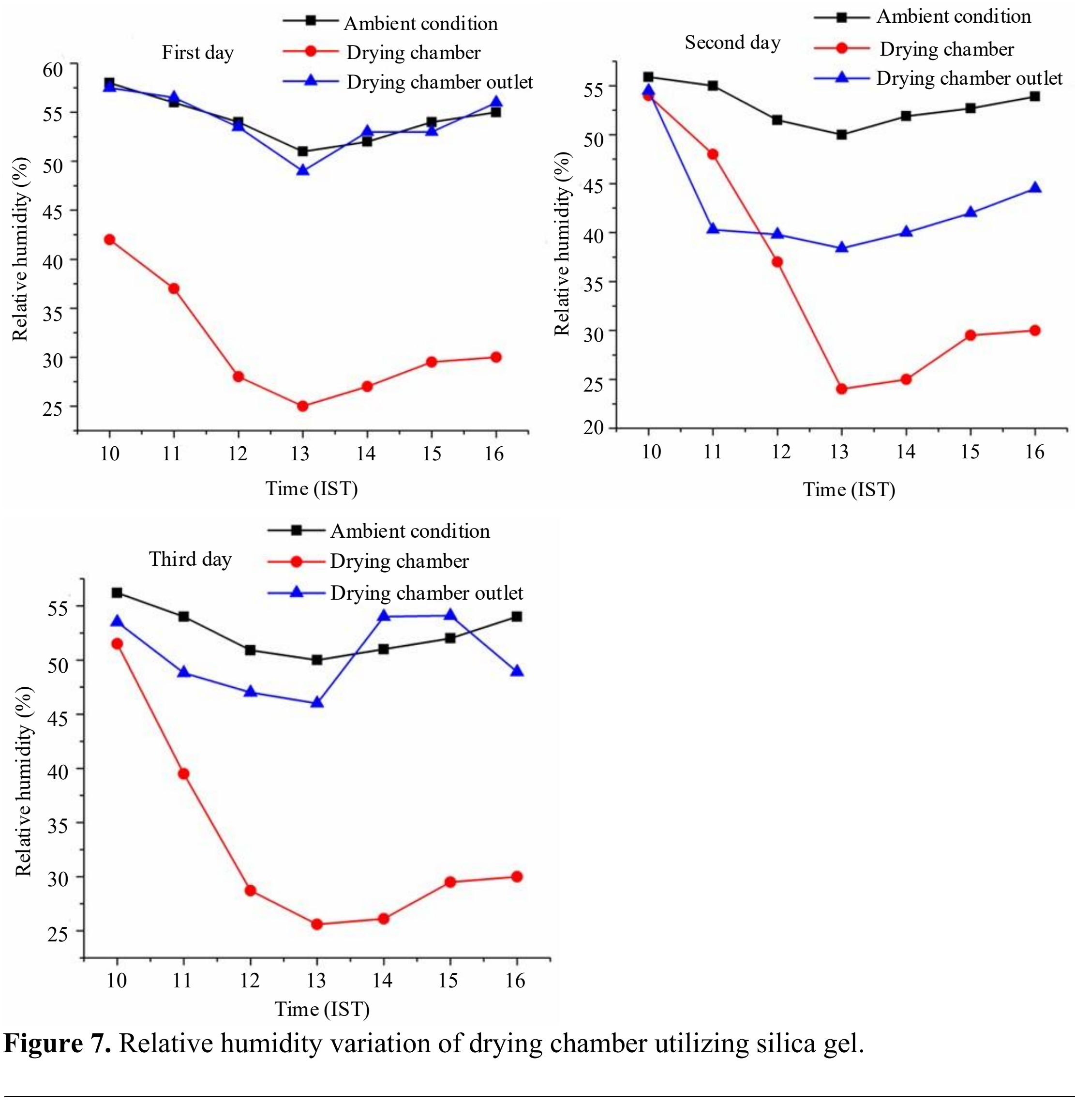

Figure 7. Relative humidity variation of drying chamber utilizing silica gel.

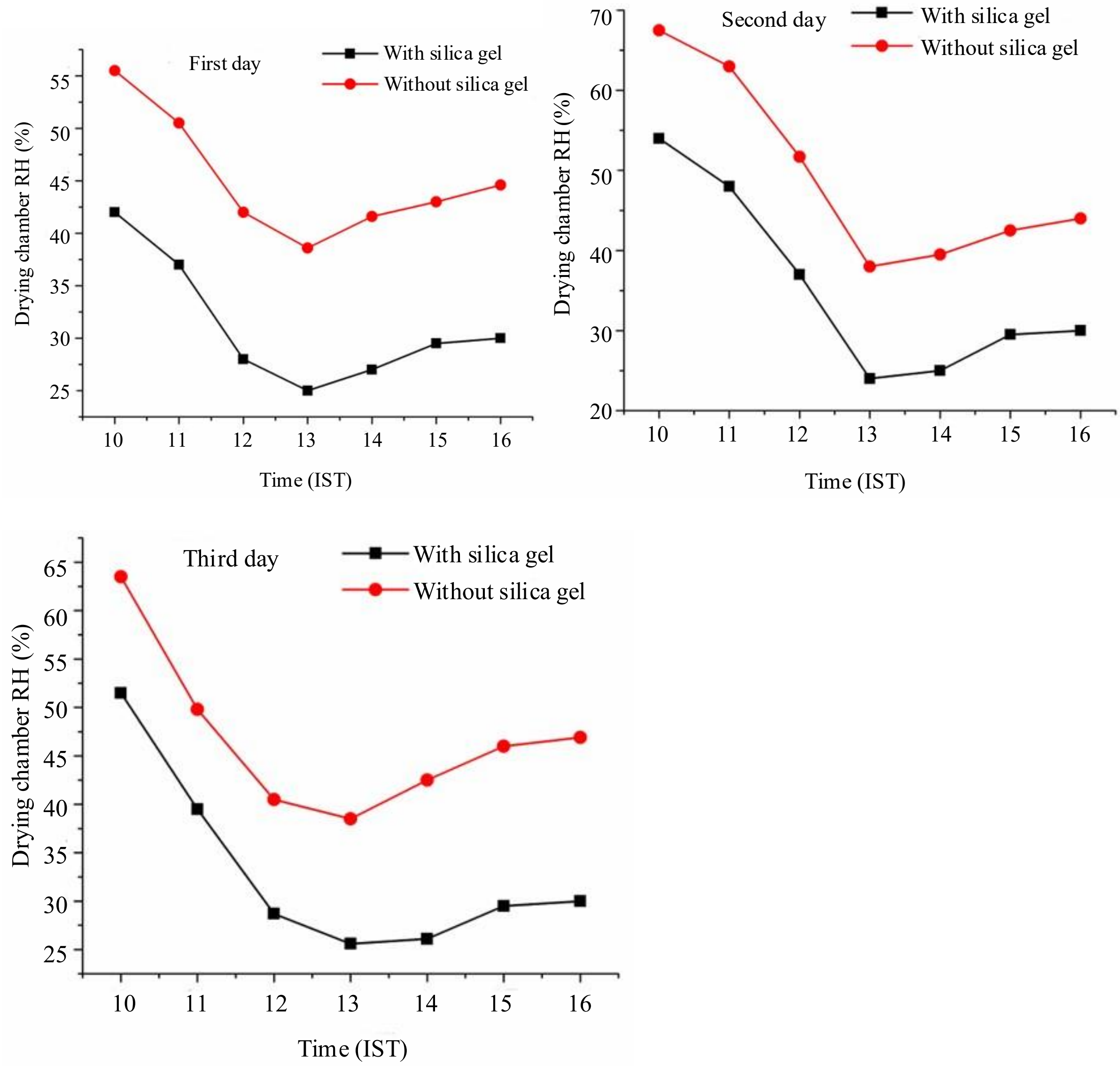

Figure 8. Relative humidity variation with and without using silica gel.

Figure 9. Apple slices before and after drying.

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In this experiment, 5 kg of apple slices have been taken for drying purposes. Samples of apple slices are illustrated in Figure 9 inside the drying chamber. For preprocessing, fresh apples were cleaned, peeled, and cut into consistent 3–4 mm thick slices using a stainless-steel slicer. The slices were dipped into a mixture of water and lemon juice and soaked for 30 minutes to prevent enzymatic browning. Then moisture was removed and weight of slices was noted before drying.

Performance Indicator of Solar Dryer

Atmospheric temperature of air, wind speed, humidity, solar irradiance, and mass flow rate of heated air are variables that impact dryer efficiency. Several performance indicators calculated using Eqs. 1–3 as discussed below [37].

Collector efficiency,

$$\eta c = ma \times Cp \times (Tco - Tci) / A \times IT \tag{1}$$

Drying efficiency,

$$\eta drying = mwr \times Lv / A \times IT \tag{2}$$

The variation of moisture content divided by drying time is the drying rate.

$$\text{Drying rate} = mf - mi / dt \tag{3}$$

where, *mf* and *mi* are moisture content of food products at time *t+dt* and *t* respectively. The highest value of collector, drying efficiency and drying rate are determined as 64.23%, 33.61% and 1.351 kg/h respectively using the above equations. By considering 5 hours of drying period, drying rate of hybrid solar dryer is evaluated as 1.351 kg/h whereas for natural convection and open solar drying as 0.811 kg/h and 0.579 kg/h respectively.

Arduino-Based Temperature and Humidity Monitoring System in Solar Dryer

In this study, an Arduino UNO R3 microcontroller, paired with a temperature and humidity sensor is utilized to measure environmental conditions inside the drying chamber continuously and it is represented in Figure 10. The data collected is displayed on a 16x2 LCD screen and can be used for real-time analysis, ensuring that the system operates within optimal temperature and humidity ranges for maximum energy efficiency. The solar collector was designed to concentrate solar energy for efficient heat collection, and benefits from this monitoring system by providing insights into weather conditions that directly affect heat absorption and energy production. The combination of renewable energy technology with real-time environmental monitoring paves the way for enhanced control, reliability, and scalability of solar power systems.

By incorporating feedback loops, the system could modify the thermal regulation based on sensor readings, optimizing the energy capture and preventing overheating. Furthermore, the collected data can be logged for long-term analysis, enabling predictive maintenance and performance forecasting. This allows for proactive adjustments to the system, extending its lifespan and ensuring continuous high efficiency. Overall, the integration of sensor-based monitoring with solar dryers represents a significant advancement toward more intelligent and autonomous renewable energy systems.

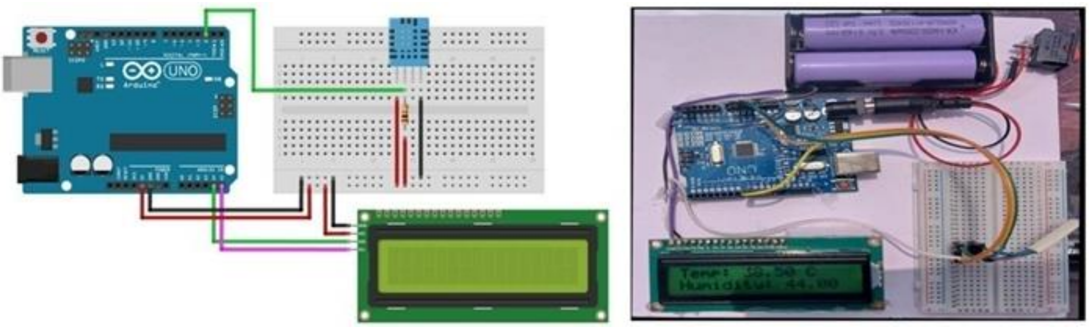

Figure 10. Arduino UNO R3 microcontroller, paired with temperature and humidity sensor.

The system monitors temperature and humidity within a drying chamber using an Arduino UNO. It provides real-time data to optimize system performance and prevent inefficiencies, utilizing a temperature and humidity sensor, an LCD display, and a battery-powered setup for portability.

The hardware components consist of Arduino UNO R3 SMD Atmega328P. The Arduino UNO R3 is the central controller, processing data from the temperature and humidity sensor and displaying it on the LCD. It uses the Atmega328P processor, ideal for this low-power, small-scale application. Temperature and Humidity Sensor (DHT22 sensor) measures both temperature and humidity. It converts environmental data into digital signals for the Arduino to process and display. The 16x2 LCD display shows real-time temperature and humidity readings. It is connected to the Arduino using the I2C interface, simplifying the wiring. The breadboard allows easy assembly, while jumper wires connect components. The switch controls power to the system. A 5V battery holder powers the system, making it portable and suitable for field use. The DHT22 sensor is connected to the Arduino's digital pin, while the LCD is connected via I2C. Power is supplied from the battery holder.

The system is assembled by connecting the components to the Arduino UNO as follows:

- *DHT22 sensor:* The 5 V and GND pins of the Arduino are connected to the VCC and GND of the sensor, respectively. The data pin is connected to Arduino digital pin 2.
- *16×2 LCD display:* Using I2C interface, the LCD's SCL and SDA pins are connected to Arduino analog pins A5 (SCL) and A4 (SDA).
- *Breadboard and jumper wires:* A breadboard is used to facilitate the connections, with jumper wires linking the components and the Arduino.
- *Switch and power supply:* A switch is connected to the power supply line, controlling the system's activation. The system is powered using a 5 V battery holder to ensure portability.

The temperature and humidity sensor (DHT22) is interfaced with the Arduino by connecting the sensor's data pin to pin 2 on the Arduino. The Arduino uses the DHT library to read digital data from the sensor. This data is then processed to obtain accurate temperature and humidity readings. The Arduino communicates with the sensor via a digital signal, which is interpreted as temperature and humidity values. The LCD screen displays the real-time readings of temperature and humidity. Using the LiquidCrystal_I2C library, the Arduino sends data to the LCD in a human-readable format. The display is updated every 2 seconds to show the current temperature (°C) and humidity (%), providing users with live environmental data.

Before using the system, calibrating the sensor ensures accurate readings. The DHT22 sensor typically provides reliable data out of the box, but it is important to verify it against known temperature and humidity values in controlled conditions. Calibration involves adjusting the sensor reading for accuracy based on reference data from a calibrated instrument. The calibration process was carried out by comparing the readings to those of a precision thermometer and hygrometer.

Once calibrated, the system was tested in various environmental conditions, including different temperature ranges and humidity levels, to ensure the sensor responds accurately. The system was tested under both controlled conditions (in a laboratory setting) and dynamic field conditions (outdoor use) to ensure its robustness and reliability. The system is powered by a 5 V battery holder, which powers both the Arduino and the sensor. To ensure efficient power usage, strategies like limiting sensor read intervals to every 2 seconds and using low-power components were employed. The Arduino's sleep modes were considered for future optimization, ensuring minimal energy consumption when the system is idle. The battery life was monitored, and the system was designed to be easily rechargeable or capable of using replaceable batteries.

CONCLUSIONS

This study presents a cost-effective hybrid solar dryer employing forced convection mode using hot air. The employment of a solid desiccant and the generation of high turbulence both enhance drying rate, collector, and drying efficiency. Both the drying chamber and collector are fabricated using aluminum material because of their good thermal conductivity property. The mean temperature within the chamber and collector is 4–6°C more when using a single glass plate on the collector than when using two glass plates. In addition, compared to natural or open solar drying, hybrid solar dryer provides a faster rate of drying and greater preservation of dried food items for extended periods. By adding auxiliary heating, the hybrid solar dryer provides more stable thermal conditions than an electric dryer, resulting in faster drying times and higher drying rates. The Arduino-based temperature and humidity sensor system offers real-time monitoring as well as provides the potential for automation and adaptive control of the drying chamber. This Arduino-based sensor system offers a cost-effective, efficient solution for improving the performance of hybrid solar dryers in diverse climates. Additionally, it facilitates flexibility to various crops and operating conditions by enabling modular integration of sensors and actuators. Furthermore, automated fan and heater operation increases energy efficiency, which is especially advantageous for hybrid solar drying systems.

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