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Enhancing post-harvest sustainability in temperate crops through smart IoT-integrated indirect solar dryer

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Post-harvest losses of fruits and vegetables, largely due to their high moisture content, pose a significant challenge in agriculture. Traditional drying methods, such as direct sun exposure, often result in contamination, quality degradation, and inefficient drying. This study presents the design and development of a smart IoT-enabled indirect solar dryer that not only automates the drying process but also introduces a crop-specific control system, allowing users to input precise temperature settings based on the type of crop. This capability ensures optimal drying conditions tailored to individual produce, enhancing nutritional preservation and reducing over-drying risks. The system integrates real-time cloud-based monitoring via IoT, enabling remote supervision and data analytics for temperature and airflow control. Experimental results demonstrate the system's effectiveness, achieving an average airflow of 3.0 m/s, an average solar collector temperature of 57 °C, and a stable 45 °C in the drying chamber. Compared to traditional dryers, this setup significantly reduces drying time, minimizes contamination risks, and offers higher precision and flexibility. These advancements contribute to improved scalability, sustainability, and usability in post-harvest management, especially for small and medium-scale farmers.

Keywords Indirect solar dryers, Internet of things, Smart sensors, Crop health, Smart agriculture

Post-harvest losses in agriculture, particularly in fruits and vegetables, remain a persistent global challenge, with losses estimated to be as high as 30–40% in developing countries. These losses are largely attributed to inadequate drying and storage practices. Traditional drying methods such as open sun drying, are still commonly used by farmers, especially in rural and hilly regions. However, these methods pose several challenges[1–3]: prolonged drying times, susceptibility to microbial contamination, weather dependence, and quality degradation due to direct exposure to solar radiation. The number of connected devices grows by the day. Figure 1 represents the global status of connected and non-connected devices from 2010 to 2025[3]. The IoT deals with and has uses in almost every field. Figure 2 illustrates the applications of the IoT in various domains.

To address these issues, solar drying has gained popularity as an eco-friendly alternative. Nevertheless, many solar dryers in use are manually operated and lack the precision needed to control critical drying parameters like temperature and airflow, which are essential for preserving the nutritional and commercial value of the produce[4,5].

In this context, the integration of Internet of Things (IoT) technologies into solar dryers offers a promising solution. IoT-based automation enables real-time monitoring and dynamic control of drying parameters, ensuring optimal conditions tailored to each crop's specific requirements[6,7]. Sensors can detect temperature and humidity, while microcontrollers can regulate fans and heating systems to maintain ideal drying environments.

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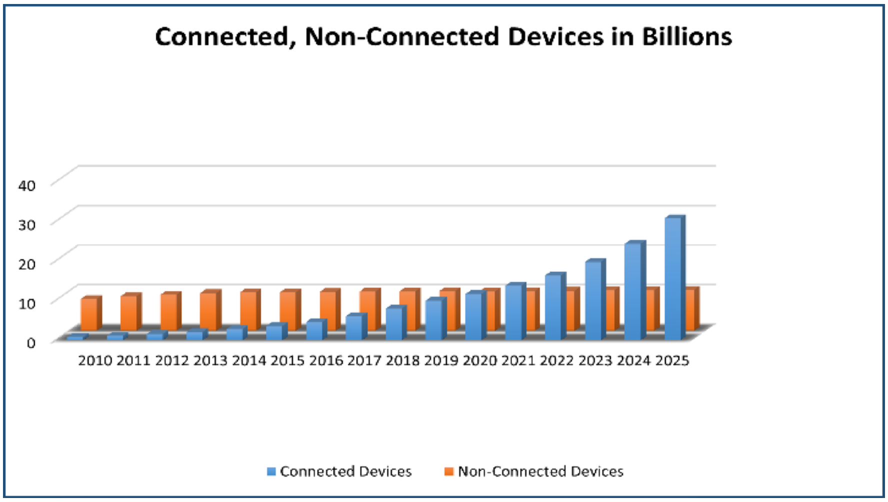

Fig. 1. Number of IoT vs. non-IoT systems throughout world[3].

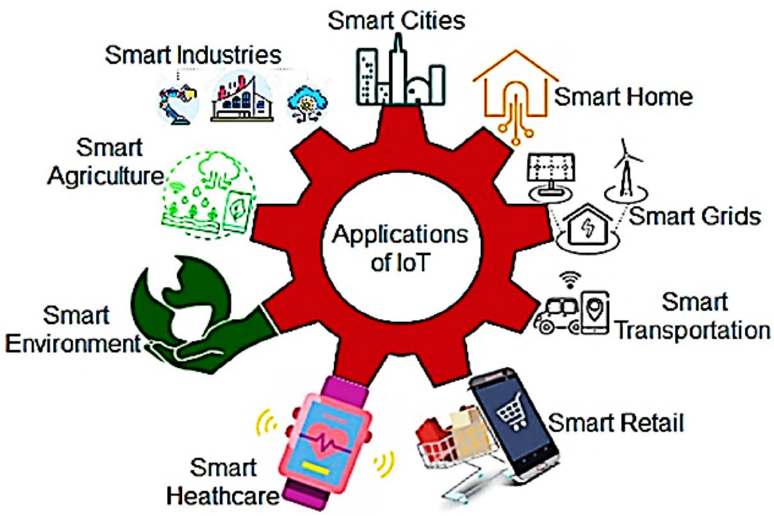

Fig. 2. Application of Internet of Things.

Additionally, cloud-based platforms allow for data logging, remote access, and performance analytics, enhancing decision-making and operational efficiency.

These features contribute to the good-quality solutions provided to users at a reasonable cost.

In India, most farmers are still using traditional farming techniques not only for the yielding process but also in terms of post-harvest management techniques[8,9]. Farmers are still exposing their crops to direct sun radiation to dry them so they can be stored longer. But the preservation process is challenging because of the quantity of moisture content[10,11]. Which can degrade the quality of these products. Drying means preserving food, fruits, and vegetables with all nutrients and quality[12]. Drying is the process of removing moisture from crops through simultaneous heat and mass transfer. To dry vegetables and fruits safely, hot air with a temperature range varying from 40 to 75 °C is required to be maintained. The utilisation of an automated mechanism for regulating humidity and temperature significantly enhances product quality to its optimal level[13]. Indirect Dryer systems are classified into two modes concerning solar heat utilization. These modes are active and passive solar energy drying solutions. Active solar dryers provide the hybrid or forced circulation, whereas passive solar dryers naturally circulate the heat. A typical functional solar dryer contains motorized blowers/fans for properly circulating the heated air through the drying cabin. Although several dryers have been introduced for drying crops or eliminating the moisture content from the harvest. To prioritize the capabilities of one dryer over another, many multi-criteria decision-making approaches have been suggested[14,15]. Systematic learning of dryers has been studied by prominent researchers in this field[16,17]. From the background study, all these dryers are manually operated. So, there is a need for IoT-based, fully automatic solar dryers[18]. The objective of this study is to design and build an IoT-based indirect sun drier to reduce post-harvest losses in temperate fruits and vegetables.

Literature survey

Almost every industry is seeing the value of the IoT. Wherever it is implemented, it can also be helpful in agriculture. In India, most farmers are still using traditional farming techniques not only for the yielding process but also in terms of post-harvest management techniques. Farmers are still exposing their crops to direct sun radiation to dry them so that they can be stored for a longer time. But the process of preservation is arduous because of the quantity of the moisture content, which can degrade quality of these products. The drying procedure means preserving food, fruits, and vegetables for an extended period with all nutrients and quality[18]. Drying is the moisture removal process from crops, involving simultaneous heat and mass transfer. Photodetectors integrated into IoT systems[19,20] can monitor solar radiation levels during crop drying, optimizing the drying process and preserving nutritional quality. To dry vegetables and fruits safely, hot air with a temperature range varying from to is required to be maintained. When an automated mechanism is used to manage the humidity and the temperature level, quality of product increases to its best rank[13]. The IoT in the agricultural industry enhances output precision. The Internet of Things can significantly contribute to meeting global agricultural product demands. The implementation of diverse sensors, such as soil moisture, temperature, pH, and NPK sensors, enables farmers to conduct a more comprehensive analysis of their crops through detailed data specific to each crop. The information supplied by this agricultural IoT device facilitates the assessment of crop parameters and enables prolonged maintenance and storage of harvested crops.

Indirect Dryer systems are classified into two modes concerning solar heat utilization. These modes are active and passive solar energy drying solutions. Active solar dryers provide hybrid or forced circulation, whereas passive solar dryers naturally circulate the heat. A typical active solar dryer contains motorized blowers/fans for properly circulating the heated air through the drying cabin. Solar dryers can be categorised as follows. Various types of dryers are available in the agroindustry, tailored to meet specific requirements, with options differing in size and design[18].

Dryers are typically categorised according to several criteria, including solar power utilisation, air movement characteristics, air direction, type of insulation employed, and the specific products designated for the drying process.

The classification of solar dryers is illustrated in Fig. 3 mainly solar dryers are of two type: (A) passive mode and (B) active mode. These two main categories can further be categorized as illustrated in the Fig. 3. A traditional technique for preserving grains, vegetables, and fruits over extended periods is sun-drying, which utilises a free and renewable energy source[21]. This method presents several drying limitations for large-scale production, including potential damage to the crop caused by various birds, rats, and other animals. The direct

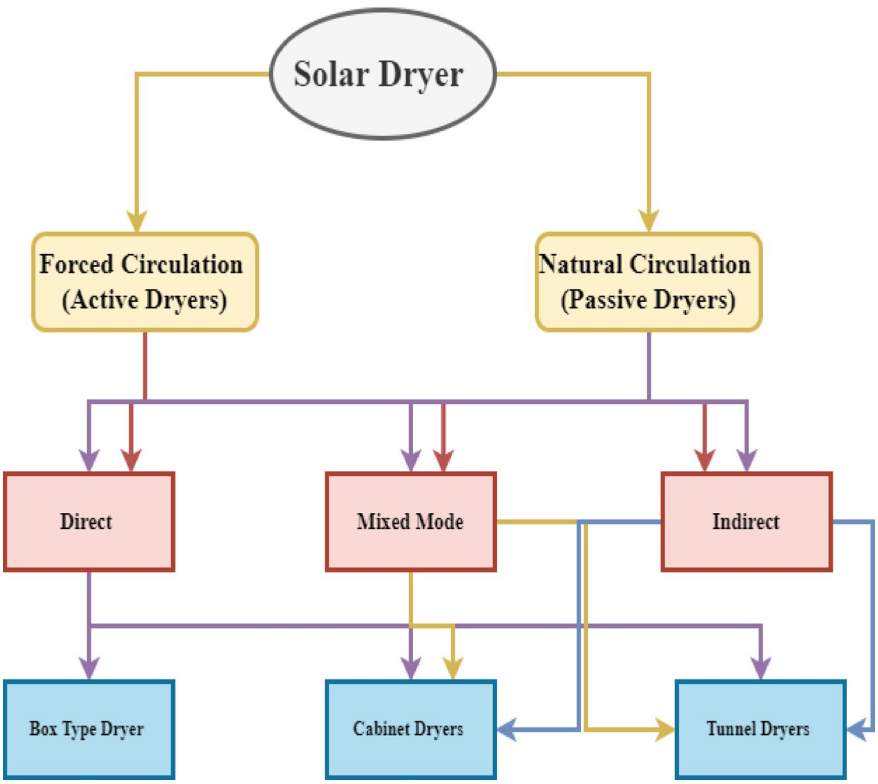

Fig. 3. Types of solar dryers: a functional and design-based classification.

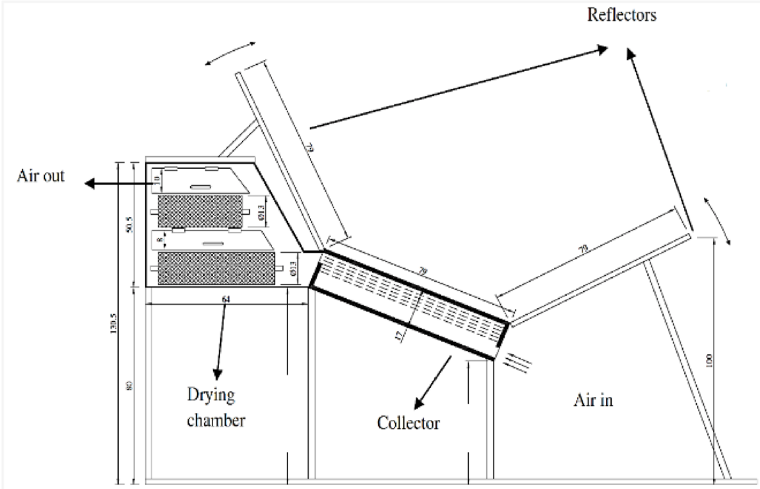

Fig. 4. Schematics indirect natural convection solar dryer[20].

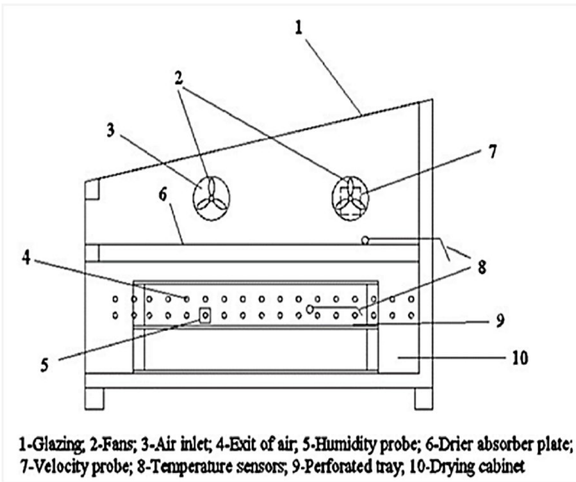

Fig. 5. Schematic representation of ISD (natural circulation)[21].

exposure to solar radiation leads to a degradation in the quality of the crops. Furthermore, contamination may arise from various factors, including rain, dirt, and dust.

Natural convection indirect type solar dryer

Traditional crop drying methods involve exposing the food products to solar radiation outdoors. This technique, known as sun drying, works well for small quantities of food. The space required for sun drying grows in proportion to the amount of food, and because the crops are exposed to the open air, it is easily contaminated. As a result, sun drying is challenging to perform with larger quantities of food because monitoring and overview become increasingly tricky as the quantity of crops increases. In contrast to sun drying, which exposes the crops directly to the sun, solar drying employs indirect solar radiation. The solar drying technique operates by harnessing solar energy to heat air within solar collectors, subsequently directing the heated air into an attached enclosure known as a drying chamber. The items designated for drying are positioned within this chamber.

The authors have created a natural circulation batch-type indirect solar dryer Fig. 4. illustrates the assembly of the fitted reflectors (north-south)[22]. The static dryer features a collector area with a loading capacity of 3.46 Kg, utilised for drying "papad," a delightful Indian wafer. This paper concludes that utilising these reflectors without any load significantly improved the efficiency of the solar collector, generally increasing it from approximately 40–58% under peak conditions on an average day. Subsequently, they reached the conclusion that modifications to this dryer are necessary, as it has the potential to induce case hardening in certain crops.

A novel type of indirect solar dryer (the natural air circulation) has been introduced by the authors with proper experiments performed on it[23]. Figure 5 shows schematics for the same; flow fans have been introduced in this type of dryer purpose of using these fans is to control the drying process similarly, they can also be used to accelerate the process. Test products were arranged under the absorbing plate to provide the prevention from the discoloration problem caused by irradiation of direct sunlight. In this paper for the experiment, the product they have used is 4Kg in weight with an initial 95% moisture content available. Bitter gourd was used as the test product. After drying it for 6 h, they have attained the target moisture content of 5% without losing the product's color. If the same amount of the bitter gourd has been dried under direct sunlight, it requires 11 h to reach the desired moisture content.

Natural Convection Solar (Indirect) Dryer, which is integrated with Bio-mass-backup heaters and collector storage, as shown in Fig. 6, was developed by[24]. The dryer can be divided into three parts to understand it's working.

1. Collector storage thermal mass.
2. Bio-mass burner having the flue gas chimney and rectangular duct.
3. Drying chamber having the chimney.

The dryer underwent testing across three parameters or modes of operation.

1. Biomass.
2. Solar.
3. Solar-biomass.

They used 12 batches of fresh pineapple, where the weight of the single batch was around 20 kg each. After performing the test procedures, they concluded that the part of absorbed heat and solar energy from the burner could be stored in the thermal mass. Furthermore, testing the dryer under mode two drying process can only be achieved on clear sunny days. The drying process can be completed in mode three, even in unwanted and unfavorable climate conditions. The moisture content of pineapple slices was reduced to 11%, resulting in a nutritious desiccated product, in this mode of operation. In the end, they reported that the dryer's efficiency was 15, 11, and 13% in solar, biomass, and solar biomass, respectively.

In 2012[25], a solar tunnel drier was conceived and constructed, capable of drying 17 kg of sliced cabbage. The dryer achieves a moisture content reduction from 95 to 9% within a span of five days. The dryer is orientated southerly and positioned at an inclination angle of 6^0C. The authors designated it as a two-pass solar tunnel drier. It may retain the heat generated using local resources. The dryer's heat storage capability can sustain a temperature of up to 5 °C even post-sunset. 12.13 kJ/m² Fig. 7 illustrates the concept of a double-pass solar tunnel dryer, together with the estimated solar radiation incident on the dryer surface. The authors ultimately determined that the dryer's overall efficiency was 17.68%. The moisture extraction efficiency was estimated at 79.15%. The airflow in the dryer was approximately $9.68\frac{m^3}{hr}$. The authors assert that drying time may be lowered by 30 to 50%, contingent upon the product.

Indirect (forced convention solar dryer).

The process diagram of the solar dryer, illustrated in Fig. 8, was developed by the authors. An experimental study was conducted on the oscillating inclined bed forced convection[26].

The dryer system designed & manufactured consists of:

1. Double pass flat plate collector.
2. An insulated blower with pipe connections.
3. Oscillating bed.

The double pass collector functions by heating the surrounding air, resulting in the production of hot air. The blower integrated into the system functions to circulate hot air to the bed. The dryer is capable of oscillating its

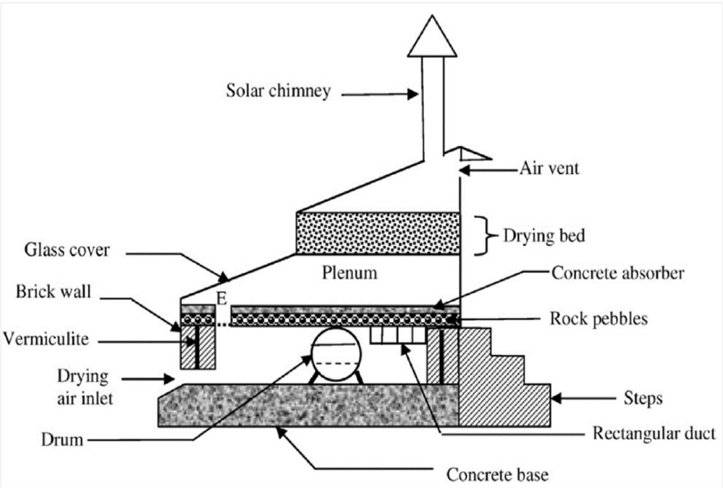

Fig. 6. Cross-sectional view of the implemented solar dryer[24].

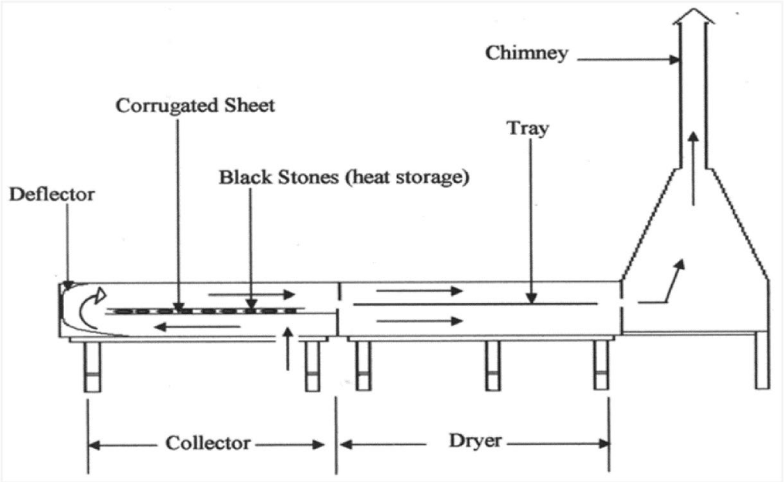

Fig. 7. Schematic of double pass solar tunnel dryer.

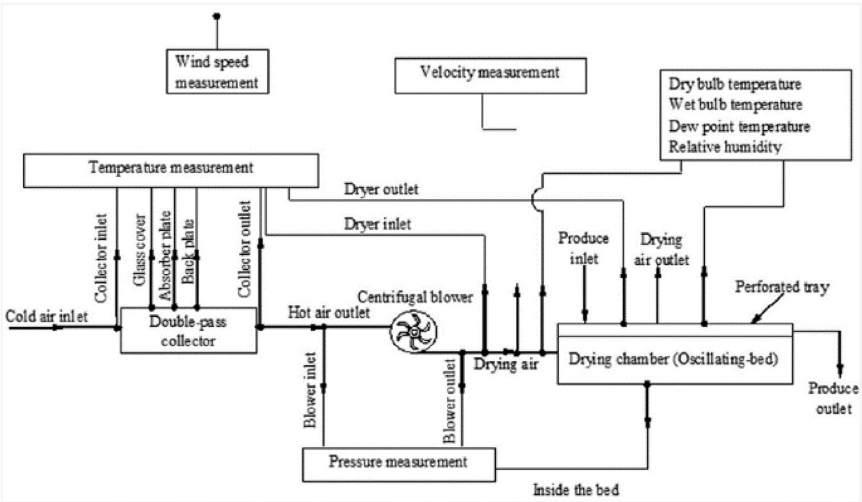

Fig. 8. Flow diagram of solar dryer[26].

bed when maintained in an inclined orientation. The authors commenced the drying process using 40 kg of sunflower seeds, which had a moisture content of 15%. The dryer feeder is calibrated to deliver a consistent mass of 2 kg of sunflower seeds to the bed tray every 30 min. The authors took observations every 30 min. Following is the observation taken by the authors.

1. Solar radiation.
2. Temperature and pressure.
3. Air properties at inlet and outlet.
4. Wind velocity.
5. Percentage of moisture content in sunflower seeds that have been dried.

The dryer experiment run-time was 8 h from 9 A.M. to 5 P.M., whereas the dryer was started 30 min before the experiment was conducted.

A system is developed and designed for the drying of hilly products[27]. The system's capacity was 25 Kg, as shown in Fig. 9. solar cell was attached to the dryer to provide enough supply for the fans. For the cloudy and rainy seasons, they have connected bulbs in the collector to heat the air artificially to maintain the temperature for the drying process. Thus, making the solar dryer for continuous operation. He adopted a methodology that started with a detailed questionnaire in the Hindi Language for the individual farmers. Then six districts of Himachal Pradesh were selected based on their Agro-climate conditions survey conducted in these six districts covering 16 blocks.

The authors conducted an analysis of the solar drying system's performance, which included an auxiliary heater for drying peas and beans[28]. The drying performance of peas and beans was compared with the natural

Fig. 9. Constructed model of the indirect solar dryer for practical use[27].

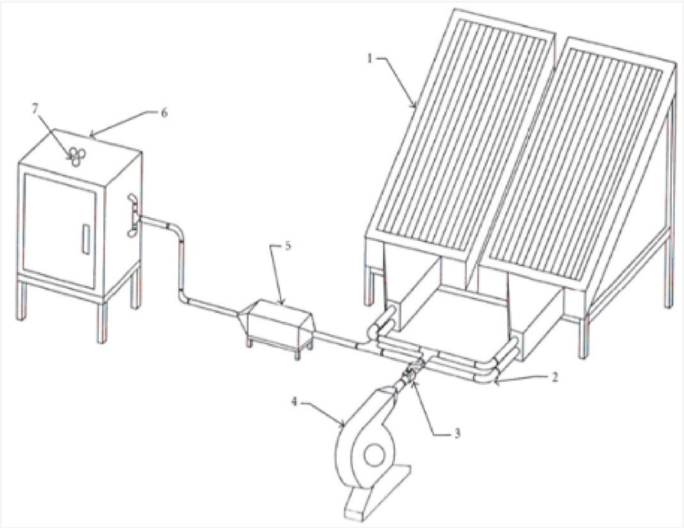

Fig. 10. Schematics of the proposed solar dryer[28].

drying process. Experiments were carried out at four distinct flow rates: 0.0383, 0.05104, 0.0638, and 0.07655. The findings indicated that the drying time for peas and beans was significantly shortened to 12 to 14 h, in contrast to the natural drying duration of 56 h. Concurrently, the combined solar dryer linked with the supplementary heater required merely 809 h for the same process. Ultimately, they determined that the auxiliary heater solar dryer demonstrated a 25% increase in efficiency when compared to the conventional solar dryer. The proposed solar dryer is illustrated in the schematics presented in Fig. 10. Observations indicated a reduction in drying time for beans by 36%, while for peas, the reduction was 33% when utilising the auxiliary heater. Concurrently, the system encountered a drawback regarding its energy consumption. The rate of energy consumption rose by 30% for beans and 22% for peas. Comparison of indirect natural convention type and forced convection type solar dryers are shown in Table 1.

In 2013 forced convection indirect solar dryer was developed in integration with the PV cells to provide the power supply for the electric fans. The system is divided into two parts[29].

1. Collector unit (heat collection is done in this unit).
2. Food dryer chamber (all products will be dried in this chamber).

Sr. No.	Dryer type	Performance	Loading capacity/sample size	Drying time range	Temperature readings
1.	Natural Convection Solar Dryer[20]	Collector Efficiency = 58%	3.46 Kg	6 h	65 to 75 °C
2.	Natural Convection Solar Dryer[21]	–	4 Kg	11 h	97.2° C
3.	Natural Convection Solar Dryer[23]	Global efficiency of the System = 17.68% Moisture extraction Efficiency = 79.15%	17 Kg	–	
4.	Natural Convection Solar Dryer[28]	System Efficiency = 78.73% Collector Efficiency = 46.4% Moisture Removal = 77.5%	10 kg	0.184 kg/Hr	58° C Max Temp. recorded for the collector, collector case, cabinet
5.	Indirect type forced convection solar dryer[25]	–	25 Kg	–	
6.	Indirect type forced convection solar dryer[29]	–	–	–	52° C
7.	Indirect type forced convection solar dryer[30]	Collector efficiency = 45%	–	14 h, tomato, 15 h-onion, 12 h- pepper, 11 h- okra and 1 h- spinach	36 °C, 52 °C, 53 °C, 40 °C
8.	Mixed-indirect type forced convection solar dryer[31]	–	25 kg	10 h	61 °C-mixed-mode 40 °C -indirect mode

Table 1. Comparison of indirect natural convention type and forced convection type solar dryers.

Fig. 11. Actual solar dryer[29].

They conducted experiments on the apples and concluded that the developed system could help dry the moisture content of most agricultural products. Electric fans were used for air circulation from the heat collector to the food drying chamber. PV cells were embedded to provide the necessary power supply to the electric fans. They compared their results with open sun drying and concluded that the system reduces time by 43.46% compared to available drying. The actual solar dryer is shown in Fig. 11.

Materials and methods

Crop drying is necessary to eliminate moisture from food grains, fruits, and vegetables. Fruits and vegetables possess a significant moisture content, which may result in infection during prolonged storage. This technique is also advantageous for the long-term preservation of agricultural products. Solar drying is among the most advantageous and effective uses in this domain. This approach assists in preventing crop contamination. The solar drying methods include direct solar drying, indirect solar dryers, and mixed-mode solar dryers. Traditional drying methods, referred to as direct solar drying, involve crops being directly exposed to solar light. Natural solar drying presents several disadvantages, including extended drying durations and susceptibility to pest infestations. Nonetheless, an indirect solar drier mitigates all the drawbacks associated with direct solar drying. Figure 12 below illustrates the block diagram for the automation of an indirect solar dryer utilising IoT devices.

A. Product drying process and its psychrometry: In the product drying process, reduction of moisture content is required up to an acceptable limit, and it is reliant on the product categories. Reducing such moisture content from fruits or vegetables up to a certain level can promote long-term preservation of the dried products[29].

The energy required for drying purposes (Q_{dp}) can be calculated as[30,31]:

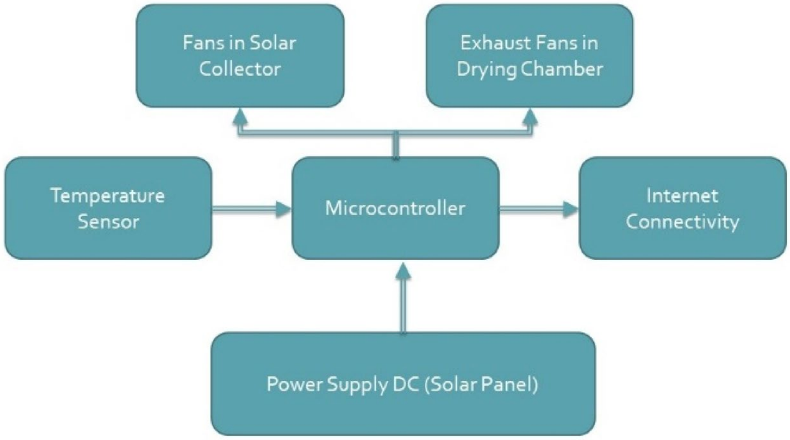

Fig. 12. Block diagram for the automation of solar dryer.

$$Q_{dp} = m_a C_p (T_{oc} - T_{fe}) = m_{wr} \quad (1)$$

Where, m_{wr} is mass (amount) of water removed in Kg, L_{wr} is the heat (latent) of water at a Average temperature $(T_{oc} + T_{fe})/2$ in J/Kg.

Amount of water-removed $(\boldsymbol{m_{wr}})$ in the drying process is given as:

$$m_{wr} = m_{ip} (MC_{ip} - MC_{fp})/(100 - MC_{fp}) \quad (2)$$

where, m_{ip} is the initial mass of the product (drying load) in Kg, MC_{ip} is the initial moisture-content of product.

MC_{fp} is the final moisture-content of product.

Moisture-content in the product undergone drying can be given as[31,32]:

a. On a wet basis, moisture-content can be calculated as:

$$MC_{ip} = (m_{ip} - m_{dp})/m_{ip} \quad (3)$$

where, m_{ip} is the initial mass of the product before drying.

b. On a dry basis, moisture-content can be calculated as:

$$MC_{ip} = (m_{ip} - m_{dp})/m_{dp} \quad (4)$$

where, m_{dp} is the mass of the dried product.

In general, the initial moisture-content of the product to be dried can be approximated by using the hot air oven method. In this method, the wet product is kept at $104\,^\circ C$ for 24 h to get the required dried product.

If $\boldsymbol{m_{wr}}$ is the amount of water content removed from the product in time $(\boldsymbol{t})$ the power absorbed by the product $(\boldsymbol{q_p})$ is given as:

$$q_p = m_a C_p (T_{oc} - T_{fe})/t \quad (5)$$

Also, when the air heating process is carried in the collector, specific enthalpy of air rises from specific enthalpy at the inlet (h_{ia}) to specific enthalpy at outlet (h_{oa}): $\varphi_i = \varphi_{oc}$ (remains constant). Where, φ_i and φ_{oc} are the relative humidity ratios at the inlet and outlet of the collector, respectively.

In the drying chamber, drying air absorbs the moisture from the product and later humidity ratio changes from φ_{oc} to φ_f. Where, φ_f is the final relative humidity ratio.

The mass of air $(\boldsymbol{m_{air}})$ required for the moisture removal process can be given as:

$$m_{air} = m_{wr}/(\varphi_f - \varphi_{oc}) \quad (6)$$

If $\boldsymbol{A_c}$ is an area of the collector $(\boldsymbol{m}^2)$ and I is the intensity of solar radiation $(\boldsymbol{W}/\boldsymbol{m}^2)$, the thermal power required to heat the air from the absorber plate $(\boldsymbol{q_{ap}})$ can be given as:

$$q_{ap} = m_{air} (h_{oa} - h_{ia}) = \eta_{ce} A_c I \quad (7)$$

Where, η_{ce} is collector-efficiency.

Now, if h_{vp} is the latent heat of vaporization (KJ/Kg) and P_F is the fan power; the drying efficiency (η_{de}) can be calculated as:

a. For natural convection.

$$\eta_{de} = m_{wr}h_{vp}/A_cI \quad (8)$$

b. For forced convection.

$$\eta_{de} = m_{wr}h_{vp}/(A_cI + P_F) \quad (9)$$

Hardware Requirement: Plyboards, Glass, Aluminium Sheets, Iron Rack, Arduino Mega, DHT22/LM35 Sensor, DC fans, ESP8266 Node MCU, Solar Panel.

Software Requirements: Arduino IDE, Proteus 8.9.

Additional Tools Required: Digital Multi meter, Air Flow meter.

Energy Efficiency Calculations.

Fans used: 12 V DC fans, 15 W.

Total number of fans used: 5.

15 × 5 = 75 W.

75 × 24 = 1800 Wh = 1.8 KWh total power required by fans if they are utilized for 24 h.

Battery calculations

Ah = Wh/voltage.

1800/12 = 150 Ah.

As the lithium-ion battery DoD is 90%, we have used this battery type. Considering the DoD the actual battery capacity which is required for this setup is 150/0.9 = 167 Ah.

Solar panel calculations

The total number of fans used is 5.

Complete energy consumption of these fans in 24 h is 1800 Wh ≅ 1.8 KWh.

Considering average of 5 h/day full sunlight in India.

Panel wattage = 1800/5 = 360 W.

Taking 25% losses due to real time challenges panel wattage should be 360/0.75 = 480 W.

MPPT is 30%

Current = 600/12V = 50 A.

Results and discussion

Design of indirect solar dryer

The dryer majorly has only two chambers collector chamber and a drying chamber. For the manufacturing of solar dryers, Waterproof plywood is used for the significant structure of the collector chamber[33,34]. The insulating material has been used to prevent heat dissipation from the solar collector chamber: Figures 13 and 14 shown below show the designs of the indirect solar dryer.

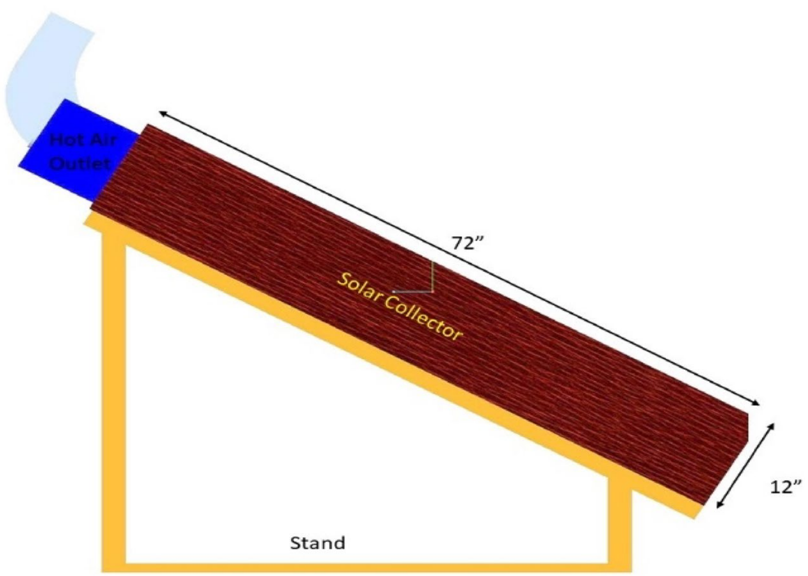

Fig. 13. Solar collector chamber.

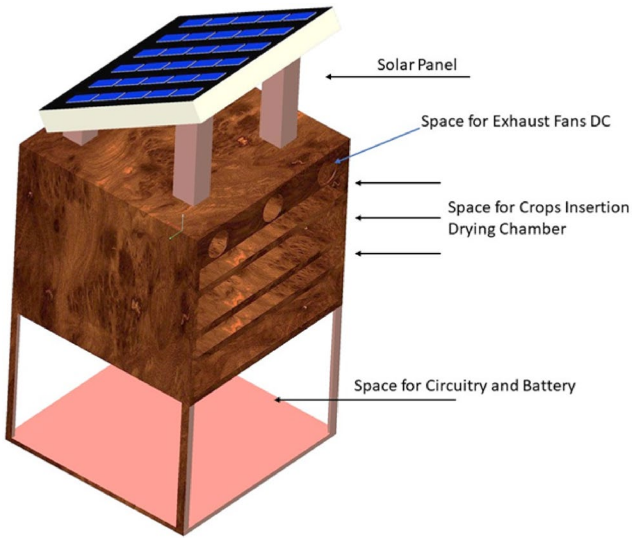

Fig. 14. Crop drying chamber.

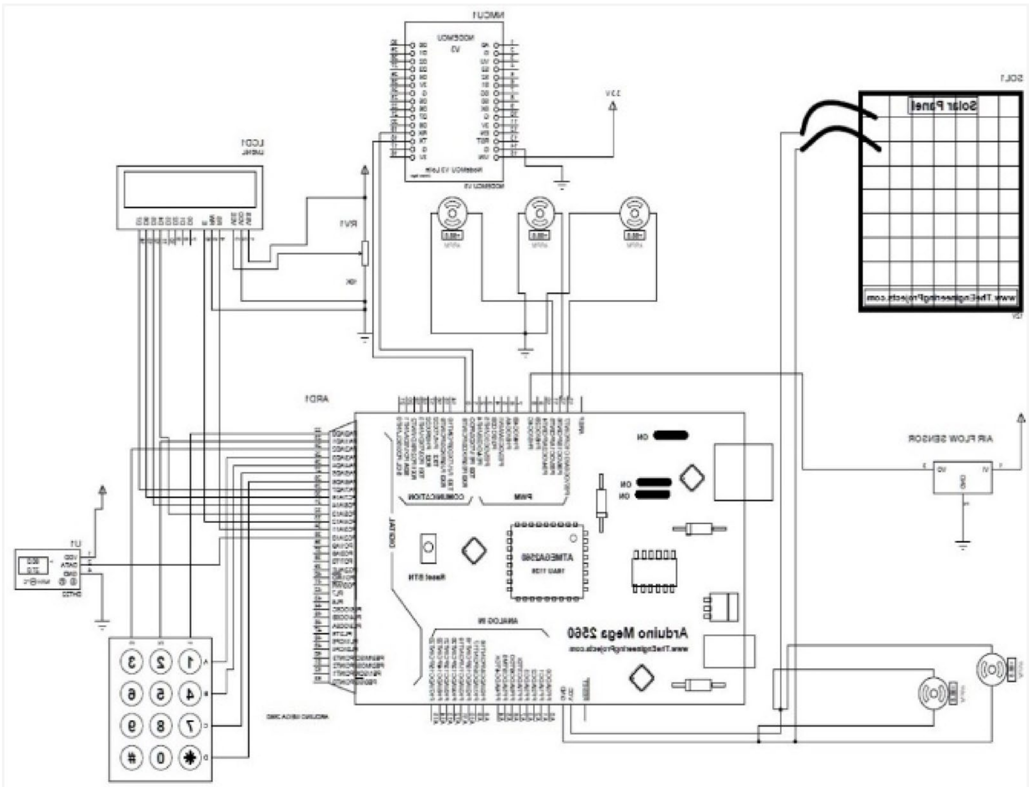

Fig. 15. Circuit of the proposed system.

Automation of solar dryer

Figure 15 presents the circuit diagram of the proposed work. A 12 V DC supply powers the circuit to fulfil the requirements of the solar supply panel introduced to the circuit. Arduino Mega2560 is the heart of the circuit. It controls all the inputs and outputs of the circuit. DHT22 sensors are used to check the crop chamber's temperature value. The observed value will be provided to the microcontroller, and accordingly, the microcontroller will control the RPM of the DC fans, which are used as the exhaust. The fans are connected with the PWM pins of Arduino, and with the help of Pulse Width Modulation (PWM), the speed of the exhaust fans will be controlled. The system provides better stability and efficiency in processing the crops inside the chamber as in previous models they only offer the maintenance of temperature within the specified range like for fruits and vegetables

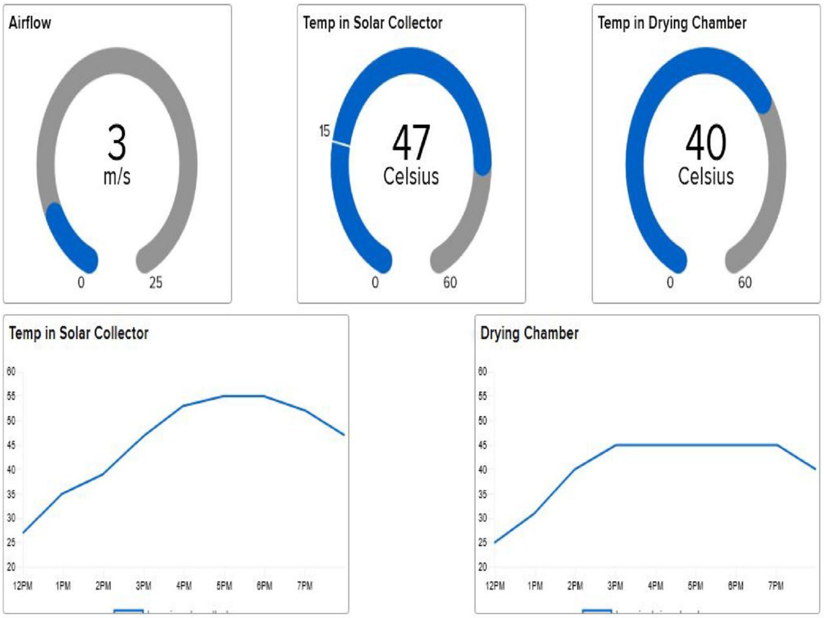

Fig. 16. Dashboard Adafruit showing values of parameters.

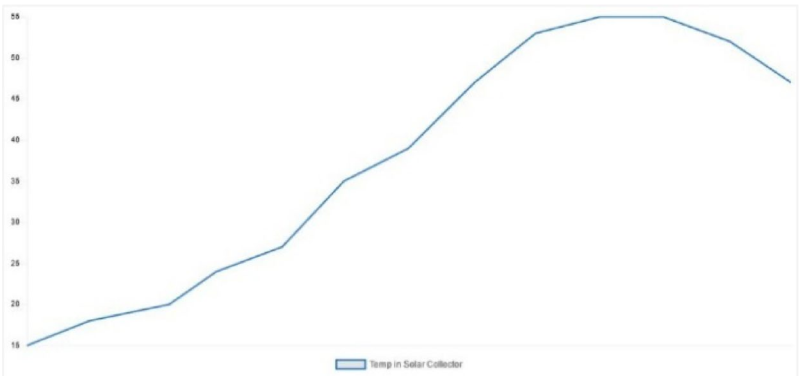

Fig. 17. Average value of temperature in solar collector.

it ranges from 40 to 75 degrees Celsius. 4 × 3 Keypad is used as the input to set the required temperature value for a particular crop. The user will be able to give the system the precise temperature value based on the crop.

An airflow meter is used to keep an eye on the rate of air flowing through the chamber 16 × 2 LCD so that the user can look at the provided commands.

Role of IoT

IoT is an important emerging technology. It plays a crucial role in the advancement of the indirect solar dryer. Automation of indirect solar dryers using IoT is shown in Fig. 15 in the post-harvesting technique, the temperature is the crucial factor. The drying process can only be achieved by circulating hot air through the drying chamber. The proposed system can introduce more stability and efficiency to the existing system. As the proposed method is IoT based, we have used the ESP8266 Wi-Fi Module for the same purpose. An app (IoT Solar Dryer for fruits and vegs) has been created on Adafruit. Data generated through the sensors is transmitted to the Cloud and stored. Users will be able to evaluate the data for Temperature value inside the crop chamber, Value of Airflow, and temperature of the solar collector. We have tested the proposed system with no load condition. Until now, we can check the three parameters: airflow, the average temperature in the solar collector, and the average temperature maintained in the drying chamber. Analytics from Adafruit has been shown in the Figs. 16, 17 and 18.

Output of IoT operation.

Airflow – 3.0 m/s.

Average temperature in solar collector: 57^0 in February.

Average temperature maintained in drying chamber: 45^0

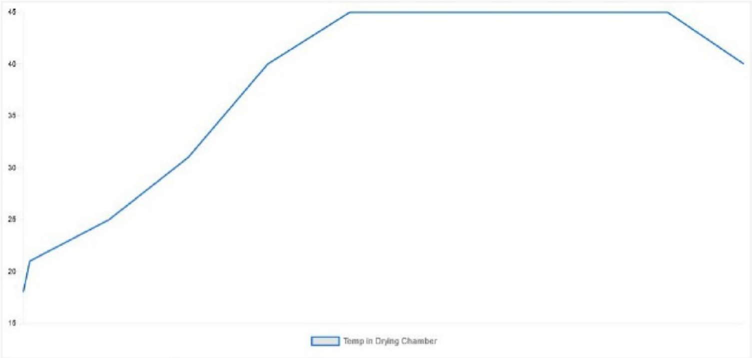

Fig. 18. Average value of temperature maintained in drying chamber.

The IoT-enabled indirect solar dryer achieved an average airflow of 3.0 m/s and temperatures of 57 °C in the solar collector and 45 °C in the drying chamber, which significantly enhance drying efficiency. The airflow ensures effective moisture removal without oversaturation, while the temperature range supports uniform drying without nutrient loss or case hardening. Compared to similar systems[23,35], which typically operate at 0.5–2.5 m/s airflow and 40–60 °C, the proposed system offers improved performance. The ability to maintain precise drying conditions through IoT automation results in shorter drying times, better product quality, and reduced contamination risks.

Despite its advantages, the use of IoT in indirect solar dryers presents several limitations. The system heavily relies on stable internet connectivity, which can be unreliable in remote agricultural areas. Limited technical expertise among users poses challenges in operation and maintenance. Additionally, power supply inconsistencies due to weather conditions can affect performance. The system's current validation is limited to no-load conditions, requiring further testing with actual crops. Data privacy concerns also arise due to cloud storage. Lastly, scalability for large-scale use remains uncertain without addressing cost and energy efficiency challenges. Results demonstrated by the IoT-integrated indirect solar dryer, potential limitations exist regarding its scalability and adoption, particularly among smallholder farmers. The initial investment in hardware components such as sensors, microcontrollers, solar panels, and backup batteries, along with the costs associated with installation and maintenance, can present economic barriers for marginal farmers. Furthermore, limited digital literacy and lack of access to reliable internet connectivity in rural areas may hinder the effective use of cloud-based monitoring and IoT functionalities. Addressing these challenges through cost optimization, capacity-building programs, and localized support infrastructure will be crucial for ensuring the widespread adoption and sustainable deployment of this technology across diverse agricultural communities.

Conclusion

The crop is still managed using traditional methods after harvest. Due to the direct exposure of crops or food products to sunlight, there is a significant risk of crop contamination. Additionally, drying crops in an open setting invites other problems, such as pests, birds, animal attacks, etc. Several solar dryers have been introduced to overcome these issues as well as to reduce the time of drying using these dryers. But these dryers come with manual working, they only provide a range of temperature for all crops, which can result in to damage the crops due receiving overheat. Whereas, in the proposed system, automation of the system has been achieved; user will set the value of temperature required to be maintained within the drying chamber. Now with the exact value of the required temperature users will be able to dry their crops more effectively. Moreover, all the data generated through different sensor embedded in the system will be stored on the cloud platform using the Internet of Things. The majority of research has focused on moving hot air from the solar collector to the drying chamber, and none of the systems have the ability to regulate the temperature.

Future-work

The current setup has been tested under no-load conditions. In the future, we plan to test it with various crops by setting fixed temperature parameters tailored to each crop. We have already collected data indicating the specific temperature requirements for individual crops, which will guide these experiments.

Data availability

The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.

Received: 16 January 2025; Accepted: 24 July 2025
Published online: 05 August 2025

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Acknowledgements
The authors acknowledge that the research Universiti Grant, Universiti Kebangsaan Malaysia, Geran Translasi: UKM-TR2024-10 conducting the research work. Moreover, this research acknowledges Princess Nourah bint Abdulrahman University Researchers Supporting Project number (PNURSP2025R10), Princess Nourah bint Abdulrahman University, Riyadh, Saudi Arabia.

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B. B. Sharma, P. Vaidya, N. Kumar, A. Tiwari made substantial contributions to design, analysis and characterization. S. Bansal, M. R. I. Faruque and K. S. Al-mugren participated in the conception, practical application and critical revision of the article for important intellectual content.

Declarations

Competing interests
The authors declare no competing interests.

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