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Research article

Novel design and performance evaluation of an indirectly forced convection desiccant integrated solar dryer for drying tomatoes in Pakistan

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ABSTRACT

The process of drying agricultural products for food preservation is a difficult task that requires a significant amount of energy. The increasing cost and depletion of fossil fuels have led to the development of a food dryer that utilizes renewable energy sources. This research paper proposes the design and performance evaluation of an indirectly forced convection desiccant integrated solar dryer (IFCDISD) at the Solar Energy Research Lab at USPCAS-E, NUST Pakistan. Tomatoes were chosen as the test product due to their importance and widespread consumption. The drying process involves slicing the tomatoes and placing them on the IFCDISD rack, where a desiccant called calcium chloride ($CaCl_2$) is integrated into the dryer. The experiments were conducted during both sunshine (SS) hours and Off-sunshine (OSS) hours. The IFCDISD operates using sunlight during SS hours and utilizes the absorbed heat of $CaCl_2$ in OSS hours via a forced DC brushless fan powered by battery charged thro solar panel. The tomatoes were weighed before and after each drying mode, and the moisture removal was calculated. The results show that the dryer efficiency was 50.14 % on day 1, 66 % on day 2, and an overall efficiency of 58.07 %. The moisture content removal was 42.858 % on day 1, 22.9979 % on day 2, and an overall moisture content removal of 58.07 %. Moreover, the payback period is 5.1396 and the carbon mitigation was recorded as 2.0335, and the earned carbon credit was recorded as 11559.6.

1. Introduction

Food preservation was practiced in almost every culture and civilization since a long time ago and ancient man had to use nature's resources to survive [1]. They put seal flesh on the ice in cold climates to freeze while they exposed food to the sun to dry it during hot

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Nomenclature

Abbreviations

CSD	Controlled Sun Drying
$CaCl_2$	Calcium Chloride
CFD	Computational Fluid Dynamics
DC	Direct Current
DS	Drying system
DSD	Direct Solar Dryer
DNI	Direct normal irradiation
DHI	Diffuse horizontal irradiance
E	Total energy utilization
GHI	Global horizontal irradiance
ISD	Indirect Solar Dryer
IFCDISD	Indirectly forced convection desiccant integrated solar dryer
0SD	Open Sun Drying
0SS	Off-Sunshine Hours
O	Overall uncertainty
SS	Sunshine Hours
SEC	Specific energy consumption
TES	Thermal Energy Storage
$LiCl_2$	Lithium Chloride
PV	Photo voltaic
Pb	Payback period
p	Parameters

Subscripts

C_{ccd}	Capital Cost of the Drying System
E_m	Embodied energy of an industrial system
T1	Absorber temperature
T2	Glass temperature
T3	Collector outlet temperature
T4	Bottom tray temperature
T5	Upper tray temperature
T6	Upper tray temperature
T7	Upper tray temperature
T8	Desiccant bed temperature
M_L	Moisture loss
$M_{initial}$	Initial mass of product
M_{final}	Final mass of product
%MC	Moisture content
x_n	Level of uncertainty
η_t	Thermal efficiency of dryer
η_d	Drying efficiency
v	Volumetric flow rate of air (m^3/s)
ρ	The air density (kg/m^3)
C_p	The specific heat of air at constant pressure
A_c	The total cross-sectional area of the solar drier in (m^2)
I_c	Total solar intensity (W/m^2) measured by pyranometer
Q_E	The total thermal energy gained
Q_i	The total incident thermal energy

climates because the food naturally starts to spoil as soon as it is harvested [2]. Moreover, the ancient food was dried directly from the sun and breeze. More evidence of the former cultures has been found, each would have approaches and materials that would replicate their sources of sustenance, such as domestic animals and fish etc [3,4]. Vegetables & Fruits have also been preserved thro drying since ancient periods [5]. In the Middle Ages the home was purposefully constructed in a way that they are utilized to dry vegetables, fruits, and herbs, where there was insignificant direct sunshine [6].

Previous studies have demonstrated that drying is a labour-intensive process that requires intricate mechanisms of mass & heat transport among the drying medium & the product. Numerous approaches for the preservation of food were reported in previous literature; Sun-drying, Oven-drying, Dehydrator, Microwave drying, Air-drying, etc [7,8]. According to the research that has been done thus far on solar drying, it is essential to create naive, affordable, and applicable solar dryers to meet the rising need for food preservation, particularly in developing nations like Pakistan [9–11]. Solar energy is a gift from God to our country in which almost 300 out of 365 days we receive a tremendous amount of solar radiation [12,13].

The drying system (DS) is distributed into 2 categorises founded on how much solar energy is utilized. One of them is open sun drying (OSD) Meanwhile, the other one is controlled solar drying (CSD). i). In OSD the items to be dehydrated are dispersed out on the land or in mats, slim layers on trays, as well as concrete floors, uncovering the foodstuff to open air & sunlight. They are mostly rack-type reported in the literature [14,15]. The wet foodstuffs to be dried are kept in series/parallel tracks in this technique. Conversely, groundbreaking new dryers with controllable drying constraints presented in the literature are CSD [16]. The CSD can be further classified into Direct solar dryer (DSD) & Indirect solar dryer (ISD). In the DSD, transparent glasses are utilized to carry radiation from the sun directly to the foodstuffs [8,17]. Losses of Convective need to be reduced in these dryers, permitting the drying compartment temperature to be improved. Solar cabinet dryers, Glass-roof solar, and green-house dryers are illustrations of DSD [18]. As a substitute for heating the material to be dehydrated straightforwardly, ISD heats the entering air. Succeeding channel throughout the material to be dehydrated, this hot air frequently discharges through a chimney & rises uphill, transportation any moistness that was discharged from the material with it. The literature recognizes two kinds of ISD: (a) Forced convective type and (b) Natural convection type [19]. However, in the proposed research we have performed experimental Performance Evaluation of an IFCDISD for Drying Tomatoes in Pakistan.

In previous literature, various authors proposed different DS with different analyses. In Ref. [20] experiments were performed to study the drying capabilities of two new materials used as thermal storage for drying agricultural products. The results indicate that employing limestone as a thermal storage material yields superior performance compared to the dryer utilizing beach sand for this purpose. The drying efficiency was increased by 1.55 % by using limestone instead of beach sand. Authors in Ref. [21] also proposed the modified indirect SD with amalgamated thermal storage material with a detailed experimental model for drying dhokla. In Ref. [22], a series of comprehensive experiments were accompanied to examine the impact of utilizing a winnower cum dryer in contrast to an open dryer for drying date palms, a process typically carried out using forced dryers. R, Mani [23] conducted experiments with a solid desiccant made of 10 % cement, 60 % bentonite, 20 % vermiculite, and 10 % calcium chloride, combined with a paraffin wax latent heat storage medium. The results strongly support the effectiveness of this desiccant in solar drying processes. A different method was proposed using a polymer desiccant with a solar flat plate collector. This collector was optimized with copper, black chrome coating, and corrugated fins to cut system losses. This setup performed exceptionally well [24,25]. In Ref. [26] another DS was designed which consisted of a desiccant bed, collector, and drying chamber, the simulations were carried out with the help of computational field dynamics (CFD) software, The study concluded that the CFD model successfully provided air at the necessary temperature to sustain solar drying processes. In Ref. [27], a DSD was constructed, incorporating an Indirect Forced Convection SD linked to a PV/T collector. This collector served a dual role, generating heated air and electrical power to facilitate air circulation within the solar dryer. The experimental findings were further validated through simulation using CFD software, allowing a comparison between the experimental and simulated outcomes. In Ref. [28], comprehensive experiments were conducted to investigate the performance constraints & drying features of muskmelon pieces in two configurations of the indirect forced Convective Solar Dryer. The drying efficiency, average collector, & moisture withdrawal rate were calculated and compared for both cases including and excluding thermal energy accommodation [29,30].

A lot of problems associated with DS were solved in the existing literature review. The literature review on solar drying methods offers valuable insights into diverse techniques and materials; however, the existing studies lack comprehensive comparative analyses among different methods, limiting the identification of the most efficient approach. Moreover, there's a need for broader experimentation encompassing various materials or hybrid systems to ensure adaptability across diverse climatic conditions and agricultural products. Standardizing metrics, conducting long-term studies for sustainability assessment, and incorporating detailed economic analyses would further enrich the literature, providing a more holistic understanding and guiding the development of more effective, economically viable solar drying systems.

Our work addresses significant limitations in current drying methods by presenting an innovative approach: an indirectly forced convection desiccant integrated solar dryer. This research responds to the pressing need for energy-efficient food preservation techniques amid escalating fossil fuel prices and depletion concerns. Our experimental setup, developed at the Solar Energy Research Lab, NUST, Pakistan, specifically focuses on drying tomatoes which is a staple in daily consumption. The IFCDISD utilizes calcium chloride ($CaCl_2$) as a desiccant, integrated into the dryer to facilitate the drying process. Notably, our experiments span both SS and OSS hours, leveraging absorbed heat from $CaCl_2$ through a solar panel-operated forced fan during OSS hours. Detailed measurements of tomato weight pre- and post-drying, along with moisture removal calculations, demonstrate promising outcomes. Our findings reveal a substantial 56 % moisture removal after two days, achieving an overall dryer efficiency of 58.07 %. These results underscore our novel approach's efficacy in enhancing drying efficiency using renewable energy resources.

The chief value additions of the proposed research are as follows.

1. New and simple experimental design for the drying mechanism of tomatoes, while it is experimentally capable of drying all-agricultural products.
2. The proposed IFCDISD is capable to deal with SS and OSS hours with the help of low-cost $CaCl_2$ desiccant, and solar facility.
3. The proposed methodology is environment-friendly due to solar panel utilization with carbon mitigation of 2.0335 and earned carbon credit of 11559.6.
4. The proposed IFCDISD is very efficient compared to most of the existing agricultural product drying systems.

The remaining of the research article is prearranged as follows; section 2 description of the solar dryer the IFCDISD. The experimental procedure is explained in section 3. Section 4 performs the detailed performance analysis of proposed IFCDISD. Results and discussions are revealed in section 5. Lastly, the paper was concluded with some future suggestions in section 6.

2. Description of solar dryer (IFCDISD)

An IFCDISD is a type of dryer that utilized solar energy to remove water content from materials. This type of dryer is especially appropriate for drying agricultural crops, such as fruits, grains, and vegetables. The experimental setup of the proposed reserch work has been manufactured with the help of locally available resources present in the Solar Energy Research Lab, Advance Energy Materials Lab, and thermal shed at USPCAS-E, NUST, Pakistan. The experimental setup of proposed IFCDISD is portrayed in Fig. 1. The IFCDISD comprised of a drying chamber, solar flat plate air collector, Direct current (DC) brushless fan motor, parabolic reflector, solar panel, solar charge controller, and battery [31–34]. These major and key components utilized in the experimental setup of the proposed IFCDISD have as explained one-by-one as follows.

Solar flat plate collectors are used to collect useful heat energy from the sun, and they are beneficial for various applications. In applications related to solar agricultural products drying these are more effective in giving temperature complexity and proved to me more techno economic as compared to concentrated collectors. A simple solar collector contains an absorber plate that is coated black to absorb the maximum amount of sunlight and transfer it to a working fluid. It is advisable to use a duct for air circulation. In the case of forced circulation drying applications, airflow through the collector is achieved by fans or a blower. Our setup entailed a flat plate measuring (100 × 50), featuring a black-painted 50 mm copper sheet as the absorber plate to effectively absorb arriving solar radiation. Moreover, to minimize upward heat losses parallel to the absorber surface, a 5 mm thick plain glass served as the transparent cover. Locally sourced materials were utilized for constructing the collector frame, while aluminium foil acted as insulation for the back and side portions. Details of the Single Glazed Solar Flat Plate Air Collector are mentioned in Table 1.

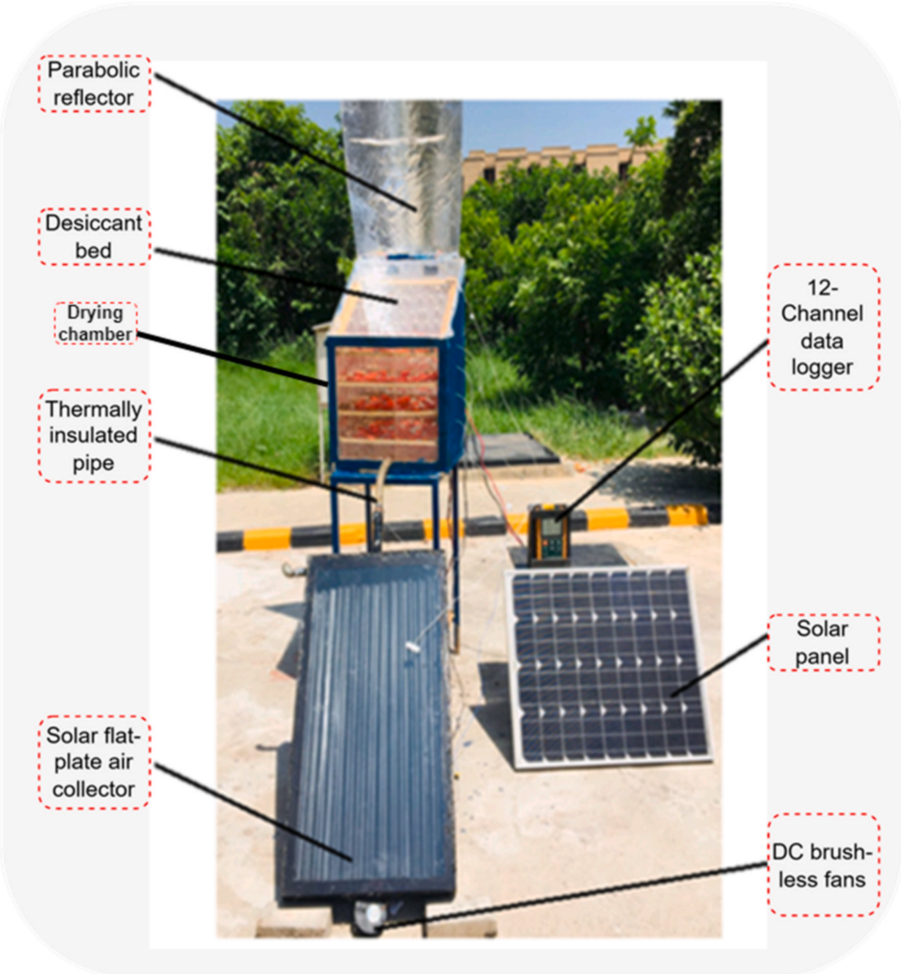

Fig. 1. Illustrative view of the experimental arrangement of proposed IFCDISD.

To make our system renewable we come up with the idea to use solar panels during the SS hours. The detail of photo voltaic (PV) Module is mentioned in Table 2. To increase solar reflection, a parabolic reflector is placed above the drying chamber supported with the help of screws. The IFCDISD is directly operated by sunlight during SS hours while in the OSS hours, the IFCDISD can use the battery to continue operation. A solar charge controller was utilized to retain the battery from overcharging and to regulate the current and voltage at the solar panel to the battery. The battery which was charged with the help of a panel to be used in the OSS hours was obtainable from the Technology Centre Lab at USPCASE, NUST. The details of the battery used are listed in Table 3, whereas the particulars of the solar charge controller are mentioned in Table 4.

The drying chamber which is the supreme essential part of the IFCDISD is constructed from a locally available resource like wood. The sizes of the drying chamber are (0.48 m × 0.48 m × 0.55 m) having a roof with a slope of 30°. The roof was used as a desiccant bed on which desiccants were placed which helps in drying during OSS hours. The desiccant bed was positioned at the uppermost of the drying chamber to hold the desiccants. The inner walls were covered with aluminum foil to increase reflection. The drying chamber was in a position to hold 4 trays of fabricated firm wire mesh with dimensions (0.47 m × 0.47 m). The shelves were retained on a wooden frame fixed on the inner walls of the wooden box and were 100 mm apart. The drying chamber also consisted of two DC Brushless fan motors of 12 V powered through the solar panel to pull ambient air over the desiccant bed to continue drying throughout OSS hours. During the SS hours, plywood was positioned at the base of the bed so that moist air coming from the drying chamber would not relate with the desiccants. During OSS hours plywood was positioned at the top of the desiccant bed to avoid heat losses through the upper surface. Another addition introduced to the drying chamber is the parabolic reflector to upsurge the intensity of incident solar radiation. Details of the Drying Chamber are mentioned in Table 5.

The temperature is being measured with a 12-channel thermocouple data logger having model TM-500 provided by the Solar Energy Research Lab at the USPCAS-E, NUST, Islamabad. All temperatures were recorded every 30-min intervals and they were saved. Copper thermocouples were placed at eight different positions to measure temperatures: Absorber temperature (T1), Glass temperature (T2), Collector outlet temperature (T3), Bottom tray 1 temperature (T4), Upper tray 2 temperature (T5), Upper tray 3 temperature (T6), Upper tray 4 temperature (T7), Desiccant bed temperature (T8).

3. Experimental procedure

The experimental procedure involved a comprehensive approach to investigate the drying efficacy of tomatoes using an IFCDISD, emphasizing meticulous monitoring, careful methodology, and multi-stage evaluations. Initially, a solar-regenerated calcium chloride-based desiccant was prepared in the Advance Energy Materials Lab at USPCAS-E, NUST, Pakistan, comprising a constituent of 10 % CaCl2, 10 % cement, 20 % vermiculite, 60 % bentonite, and requisite water content. This desiccant, moulded into cylindrical shapes, underwent pressing and subsequent drying in an oven at 200 °C for 24 h. The resulting desiccant pellets, totalling 0.5 kg, were utilized in the subsequent experiments conducted over a two-day period. Fig. 2 shows the desiccants made in a lab Fig. 2(a) part shows the desiccants placed on the desiccant Bed while Fig. 2(b) depicts the pictorial view of prepared desiccants.

The IFCDISD, fabricated in the Solar Energy Research Lab, comprised a solar flat plate air collector linked to a drying chamber equipped with four trays for holding the tomatoes. The experimental protocol involved slicing tomatoes, loading them onto the trays, and integrating the $CaCl_2$ desiccant into the dryer for moisture removal. Two distinct phases were considered: SS hours and OSS hours. During SS hours, direct solar drying was conducted, leveraging the absorbed solar heat within the drying chamber. Monitoring and data collection played a pivotal role in the experiments. Temperature and humidity were tracked using specialized equipment, including a 12-channel thermocouple data logger and a temperature/humidity sensor. Measurements were recorded every 30 min throughout the SS and OSS hours, providing insight into temperature changes and ambient conditions during the drying process. The tomatoes' initial mass was weighed using an electric balance, allowing for accurate assessments of moisture removal and drying efficiency. As the experiments transitioned into OSS hours, alterations were made to sustain the drying process. Desiccants, previously charged with solar energy during SS hours, were utilized alongside fans to maintain airflow within the drying chamber. This facilitated moisture absorption from the surrounding air, aiding in the continued drying process despite reduced solar radiation.

The meticulous data collection included recording temperature changes, fluctuations in tomato mass, and ongoing moisture

Table 1
Details of single glazed solar flat plate air collector.

Type of air collector	Nonporous conventional type
Gross dimensions	100 cm * 50 cm
Area of absorbing surface	45 cm * 90 cm
Absorber material	Steel
Number of glazing	1
Glazing material	Plain window glass
Spacing between glazing and absorber	6 cm
Back insulation	55 mm
Side insulation	40 mm
Location of the test	USPCASE NUST H-12 Islamabad
Longitude	73.0479 E
Latitude	33.6844 N
Height	507 m
Energy absorbed per/meter square	0.2

Table 2
Details of PV module.

Company	SUNTECH
Model	STP060S-12/Sb
The rated maximum power	60W/P max
The output tolerance	+_ 5 %
The current max	3.41 A
The voltage max	17.6 V
The short circuit current I_{sc}	3.84 A
The open circuit voltage	22 V
The cell temperature at nominal operating	45 +- 2C
Weight	6.2 KG
Dimensions	771*665*30
Series fuse rating	15 A
Cell Technology	Mono-Si
All technology STC	25 C
AM	1.5 A
Irradiance	1000 W/m*2

Table 3
Details of battery features.

Company	LONG
Model	WP18-12SHR
Cycle use	14.4–15 V (25C)
Standby use	13.5–13.8 (25C)
Initial current	5.4A MAX

Table 4
Details of the solar charge controller.

Company	Land Star
Model	LS1024EU
Voltage	12/24 V
Current	10 A
USB Output	5 V 1.2 A

Table 5
Details of the drying chamber.

Type of drying chamber	Indirect type with forced circulation
Dimension of the drying chamber	0.48 m × 0.48 m × 0.55 m
Number of drying trays	4 with an area of 0.47 m × 0.47 m
Material used for construction	Locally available wood
Number of parabolic reflectors	1
Air duct	Pipe connecting the air collector and drying chamber
Mode of air flow	Air flow in the upward direction through the drying material

removal throughout both SS and OSS hours. These parameters were pivotal in assessing the drying process's effectiveness and efficiency. The experiments spanned two days, with interruptions due to weather changes on the second day, culminating in comprehensive data collection for analysis. This experimental design, encompassing detailed monitoring, distinct phases, and careful adjustments throughout the drying process, aimed to assess the IFCDISD's performance in terms of moisture removal, drying efficiency, and the utilization of renewable energy resources for food preservation. The flowchart of the experimental procedure is depicted in Fig. 3.

4. Uncertainty error analysis

The study utilized different instruments to quantity numerous parameters (P), each with their own uncertainties. The uncertainties for the perceived parameters (P) can be found in Table 6. These uncertainties are important for understanding the dependability & accuracy of the experimental measurements & are necessary for precise clarification & study of the results. To determine the overall uncertainty (O) for each parameter (P), the study utilized a root-sum-square (RSS) depicted in Eq. (1) method as described by Refs. [35–37].

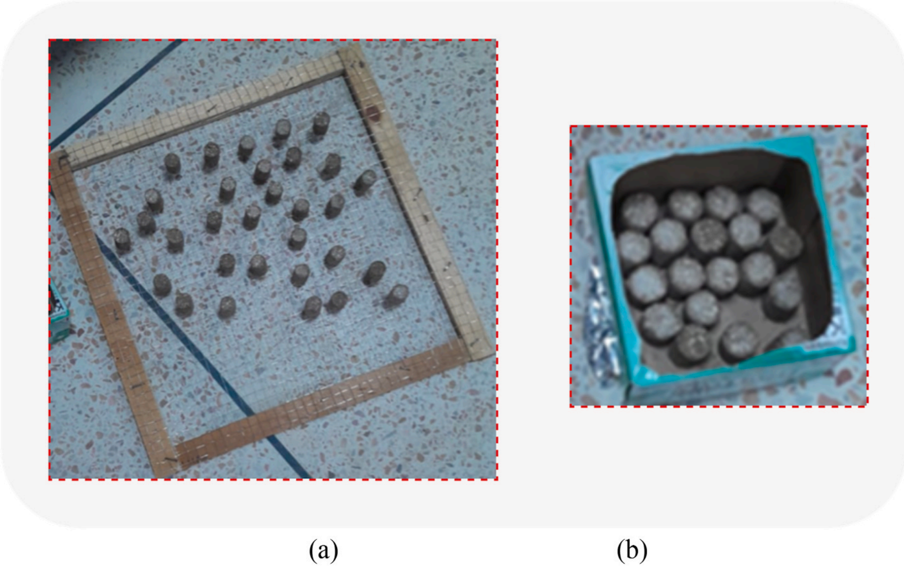

Fig. 2. (a) Desiccants placed on the desiccant Bed. (b) Pictorial view of desiccants.

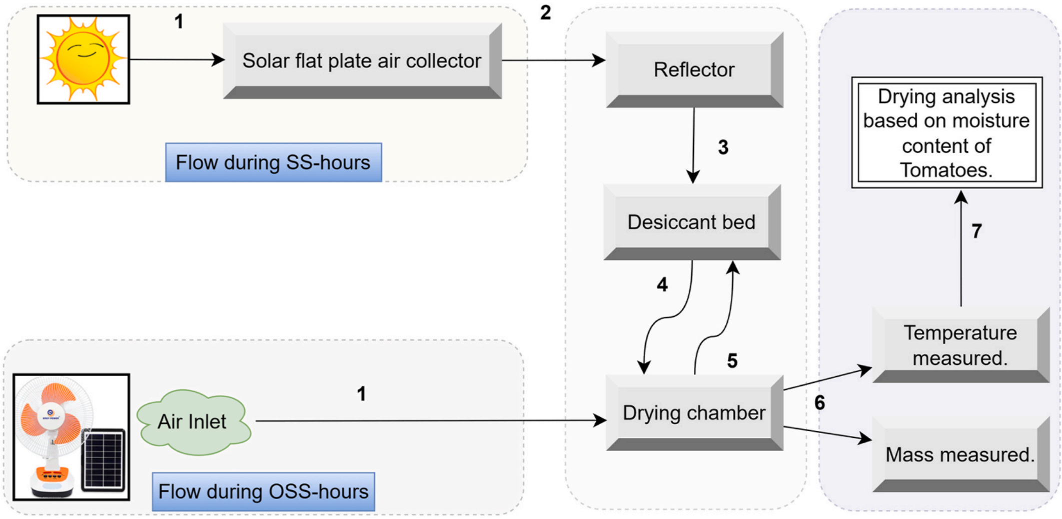

Fig. 3. Flow chart of the Experimental procedure of IFCDISD.

Table 6
Uncertainties for different parameters.

Parameters	Uncertainty
Relative Humidity	±0.05–1%
Solar Radiation	±4–5 W/m^2
Mass	±0.01 g
Dryer Efficiency	±1.00
Moisture ratio	±0.064
Temperature	±0.05–0.1C

$$Rss = \sqrt{\left(\frac{\partial P}{\partial x_1}x_1\right)^2 + \left(\frac{\partial P}{\partial x_2}x_2\right)^2 + \ldots\ldots\ldots\ldots\ldots\ldots \left(\frac{\partial P}{\partial x_n}x_n\right)^2} \tag{1}$$

x_n refers to the level of uncertainty or error associated with each measurement of a variable.

5. Environmental analyses and economic analyses

5.1. CO_2 mitigation potential

Conducting an environmental analysis for a solar thermal system is crucial in case of solar dryer, particularly in the context of industrial appliances. The primary purpose of this research is to anticipate and mitigate the emission of greenhouse gases into the atmosphere. However, in developing countries like Pakistan the CO_2 emission is calculated by using the concept that the power produced by the grid is typically produced by the coal-based power system, thus emission of CO_2 is held as 0.98 kg/kWh [38]. The formula for emission of CO_2 is as follows.

$$CO_2\ Emission \Big/ year\ of\ Embodied\ energy\ * 0.98 \Big/ Lifetime\ of\ dryer \Big] * \left[\frac{1}{1 - Lda}\right] * \left[\frac{1}{1 - Ldt}\right] \tag{2}$$

Therefore, by following Eq. (2), the CO_2 mitigation from solar dryer is computed as.

$$CO_2\ Mitigation\ (kWh / Yr.) = \left[\frac{1}{1 - Lda}\right] * \left[\frac{1}{1 - Ldt}\right] * 0.98 \tag{3}$$

$$CO_2\ Mitigation\ Lifetime = Embodied\ energy\ *\ CO_2\ Mitigation\ (kWh / Yr.) \tag{4}$$

Total Carbon mitigation formulated in Eqs. (3) and (4) is calculated in the span of 20 years. While the net carbon mitigation is calculated using Eq. (5) as follow.

$$Net\ Carbon\ mitigation = [Annual\ energy\ output\ *\ Lifetime\ of\ dryer] - [Embodied\ Energy\ *\ CO_2\ Mitigation\ (kWh / Yr.)] \tag{5}$$

The carbon credit produced by the solar dryer is calculated using Eq. (6) as follows.

$$Carbon\ Credit\ Earned = \{Net\ CO_2\ Mitigation \times Price\ per\ ton\ of\ CO_2\ Mitigation\} \tag{6}$$

5.2. The payback time

The concept of Energy Payback Time refers to the duration required for a solar dryer to recover the energy invested in its construction [39]. Mathematically it can calculate using (7) as follow.

$$Energy\ Payback\ time = \frac{Embodied\ Energy\ (kWh)}{Annual\ Energy\ Output\ (Kwh/Yr.)} \tag{7}$$

Currently the day-to-day thermal energy output can be computed using Eqs. (8)–(12) as follows.

$$Daily\ thermal\ output = \{(Moisture\ evaporated\ per\ day)\ [kg] * Latent\ heat\ [J / kg]\}/ \tag{8}$$

$$Daily\ thermal\ output = \{1.12 * 2430000\}/3600000 \tag{9}$$

$$Daily\ thermal\ output = 0.81 kWh \tag{10}$$

The yearly energy can be computed as follows.

$$Annual\ energy\ output = No.\ of\ sunshine\ days \times Daily\ Thermal\ Output \tag{11}$$

No. of sunshine days in Islamabad = 260–280 we are taking as 270

$$Annual\ energy\ output = 2.7 \times 270 = 218.7 kWh/Yr \tag{12}$$

5.3. Payback period

This payback period is calculated by calculating annualized cost (AC) which is composed of four components named as (C_{acc}) cost each year to operate, (C_{mc}) price every single year to uphold, running electricity price to work (C_{ec}) which is zero in our case as we have charged fans with the help of renewable source like as solar panel, and annual salvage value (S_a) during drying system lifetime [40]. It is written as

$$AC = (C_{acc}) + (C_{mc}) + (C_{ec}) + (S_a) \tag{13}$$

Salvage value in Eq. (13) is the value which the constructor receives by selling his product after its product has completed its useful life or in present study lifetime of a dryer taken as 20 years. It is taken as 0 in almost all cases. Now below are two formulas as Eqs. (14) and (15) which help in calculating annualized cost AC.

$$(C_{acc}) = C_{ccd} * \{i(1+i)^n / (1+1)^n - 1\} \tag{14}$$

where the n = real interest rate, the i = Interest rate = real interest rate + rate of inflation. However, the interest rate in Pakistan = 12.15 %, and the real interest rate = 22 %. C_{acc} = 2645.56 the (C_{mc}) = Roughly 1000 Rs. By putting the values in Eq. (13).

$$AC = 2645 + 1000 + 0 - 0 = 3645 \tag{15}$$

The payback period is dependent on C_{ccd} of drying system, savings in first year and the real and interest rate in the country. It is calculated by Eq. (16) as follow.

$$P_b = \ln\{1 - C_{ccd} / S1(i-r)\} / \{ln(1+r) / (1+i)\} \qquad 16)$$

$$P_b = 5.1396 \tag{17}$$

6. Performance evaluation

The analysis concentrated on crucial aspects such as determining moisture content, assessing drying efficiency, and analysing moisture ratios. Accurate determination of moisture content was a central focus in our study, meticulously executed using well-established mathematical formulations. The methodology cantered on the initial and final weights of the tomatoes, enabling precise measurement of humidity content variations throughout the drying procedure. Additionally, the determination of drying efficiency, a key performance metric, was based on the calculated moisture content alterations.

6.1. Energy analysis and drying kinetics

The Specific Energy Consumption (SEC) for each drying system is characterized as the ratio of total energy utilization (E) the amount of evaporated moisture from the tomatoes slices in each experiment (M_{evp}) measured in kilograms. It is computed in as in Eq. (18) as follows.

$$E = E_{air\_collector} + E_{DC\_fan} \tag{18}$$

where the E is the sum of solar thermal energy expected by both Single Glazed Solar Flat Plate Air Collector and drying chamber + DC brushless fan motor in watt. It is computed by the sum of both equal to $E = 0.081 + 0.6 = 0.681$ [41–43]. The expression for SEC can be formulated using Eq. (19) as follows:

$$SEC = \frac{E}{M_{evp}} \tag{19}$$

The current study extensively examined the drying kinetics and diffusional stage of solar-dried tomato slices. The analysis focused on the deviation of moisture content (M) throughout the experiments, specifically during the initial and final stages [34,44,45]. The quantity of moisture present in the products is computed using Eq. (20) as follows.

$$\%\ MC = \left(\frac{M_{initial} - M_{final}}{M_{initial}}\right) \times 100 \tag{20}$$

Moreover, the moisture loss is calculated using Eq. (21) as follows.

$$M_L = M_{final} - M_{intial} \tag{21}$$

where: $\boldsymbol{M_{initial}}$ is the initial mass of the tomatoes before drying and $\boldsymbol{M_{final}}$ is the final mass of the tomatoes after drying.

6.2. Dryer efficiency calculations

Secondly, the total thermal efficiency of IFCDISD is computed using Eq. (22) as [34,44].

$$Thermal\ Efficiency\% = \eta = \left[\frac{v\rho\Delta T C_p}{A_c I_c}\right] * 100 \tag{22}$$

Then, the drying efficiency of IFCDISD is computed using Eq. (23) as follows [45].

$$Dryer\ Efficiency\% = \eta = \left[\frac{Q_E}{Q_i}\right] \tag{23}$$

where, v is the volumetric flow rate of air (m^3/s), ρ is the air density (kg/m^3), C_p is the specific heat of air at constant pressure = 1.005 kJ/kg K^{-1}, A_c is the total cross-sectional area of the solar drier in (m^2). I_c is total solar intensity (W/m^2) measured by pyranometer.

Moreover, the Q_E and Q_i are computed using Eqs. (24) and (25) respectively as follows.

$$Q_E = mC_p\Delta T \tag{24}$$

and

$$Q_i = \frac{A_c I_c}{1000} \tag{25}$$

7. Results and discussions

A series of experiments have been conducted in our fabricated solar dryer for the drying of tomatoes in the SS and OSS hours. All temperatures in eight different locations were measured with the help of 12 channel data logger. All readings were recorded after equal intervals of 30 min throughout the experimental days. The drying experiments were carried out in 2 modes a) solar drying during SS hours and b) desiccant drying during OSS hours. The original & concluding weight of the foodstuffs was measured with the help of a Petri dish/beaker present in the Advance Energy Materials Lab. The weight measuring capacity of the beaker was 150 g, so we added the weight according to the limit of 150 g. It takes a longer time, but we try our best to meet the requirement which with the beaker can give accurate values. Now we will explain all the results in two main subsections i). Overall performance of proposed dryer, ii). Environmental and economic impacts.

7.1. Overall performance of proposed dryer

The detailed performance analysis results depiction is provided in this subsection which includes energy analytics, drying kinetics, and overall dryer efficiency. We have discussed the results one by one as follows.

7.1.1. Drying kinetics and energy analytics results

The initial weight of the tomato is 2000 g, it took 14 steps with 142.85 g loading in every single step in a beaker to mass all the tomatoes at the end of day 1 SS hours experiments started from 12:00 p.m.–5 p.m. Before experimentation, the mass of the beaker was 100.960 g while after completing 14 steps of experimentation the beaker the mass is 101.3524 g having a difference of 0.3924 g. The total moisture loss of tomatoes at the end of day 1 = 2000g–1142.8269 g = 857.1731 g. while the % Moisture content loss in tomatoes at the end of Day 1 = (2000–1142.8269)/(2000) * 100 = 42.8586 %. Moreover, the SEC computed during SS hours is 0.3696 and OSS hours is 0.5679 of day 1 using Eqs. (18) and (19) as mentioned in Tables 7 and 8. Hence, the total moisture loss of tomatoes at the end of Day 2 is 1142.8269 g–880 g = 262.8268 g. The % Moisture content loss in tomatoes at the end of Day 2 is (Initial Mass-Final Mass)/(Initial Mass) *100 = (1142.8269–880)/(1142.8269) * 100 = 22.9979 %. The total loss of moisture at the end of Experimental days reading from 10 August 2022–August 11, 2022 is 1120 g while the % M.C = (2000g–880 g)/(2000g) * 100 = 56 %. Moreover, the SEC computed during SS hours is 0.6337 and OSS hours is 0.7467 of day 1 using Eqs. (18) and (19) as mentioned in Tables 9 and 10. Fig. 4 shows the amount of moisture that is removed during day 1 and day 2 and the overall moisture removed at the end of the experiments. At the start of day 1 2000 g of tomatoes were placed in the dryer and at the end of day 1 1142.9269 g were left which were again dried the next day at the end of day 2 drying the moisture was removed and reduced to 880 g. During day 2 due to less sunshine and rain interruption, less moisture was removed as compared to day 1. But still managed to remove moisture during the off-sunshine hours due to desiccants integrated drying. The below graphs show the variations of time vs. moisture removed throughout two days of drying.

Fig. 5 depicts the variations in key parameters such as temperature from T1 to T8, relative humidity, global solar irradiation, direct normal radiation, and direct horizontal irradiation over two days of experimentation. Measurements were taken at 30-min intervals. On Day 1, during SS hours, the absorber plate temperature peaked at 68.4 °C before decreasing to 41.2 °C as solar radiation diminished. Correspondingly, the desiccant bed temperatures ranged from 71.1 °C to 41.6 °C. During OSS hours, the absorber plate temperatures ranged from 37.6 °C to 31.2 °C, while desiccant bed temperatures ranged from 36.3 °C to 32.7 °C. Experiments were conducted from 5:50 p.m. to 7:20 p.m. On Day 2, during SS hours, the absorber plate temperatures ranged from 42.8 °C to 26.6 °C, and desiccant bed temperatures varied from 40.9 °C to 26.6 °C. During OSS hours, the temperatures were lower due to weather conditions, with absorber plate temperatures ranging from 26.6 °C to 27.4 °C and desiccant bed temperatures from 26.6 °C to 28 °C. Experiments were performed from 9:50 a.m. to 4:50 p.m., with temperature measurements taken every 30 min using a 12-channel data logger. The variations in global horizontal irradiance (GHI), direct normal irradiation (DNI), & diffuse horizontal irradiance (DHI) for Day 1 ranged from maximum values of 913.6979 W/m2 (GHI), 740.2537 W/m2 (DNI), and 269.9213 W/m2 (DHI) to minimum values of 363.035 W/m2 (GHI), 42.91039 W/m2 (DNI), and 330.1161 W/m2 (DHI). Similar variations were observed for Day 2.

7.1.2. Overall dryer efficiency results

Fig. 6 depicts the dryer efficiency of both days. The overall efficiency after experiments comes down to 44 %. At the end of drying,

Table 7
Variations of mass of tomatoes and moisture loss at day 1 SS hours drying experiments.

Day	Mass of Tomatoes at 12 p.m.	Mass of tomatoes at 5 p.m.	Moisture loss from tomatoes (g)	SEC
1	2000 g	1270.2722 g	729.7278 g	0.3696

Table 8
Variations of mass of tomatoes and moisture loss at day 1 OSS hours drying experiments.

Day	Mass of tomatoes at 5:50 p.m.	Mass of tomatoes at 7:20 p.m.	Moisture loss from tomatoes (g)	SEC
1	1270.2722 g	1142.8269 g	127.4454 g	0.5679

Table 9
Variations of mass of tomatoes and moisture loss at day 2 SS hours drying experiments.

Day	Mass of Tomatoes at 9:45 a.m.	Mass of tomatoes at 04:45 p.m.	Moisture loss from tomatoes (g)	SEC
2	1142.8269 g	965.10 g	177.8269 g	0.6337

Table 10
Variations of mass of tomatoes and moisture loss at day 2 OSS hours drying experiments.

Day	Mass of tomatoes at 5:50 p.m.	Mass of tomatoes at 7:20 p.m.	Moisture loss from tomatoes (g)	SEC
2	965.10 g	880 g	85.1 g	0.7467

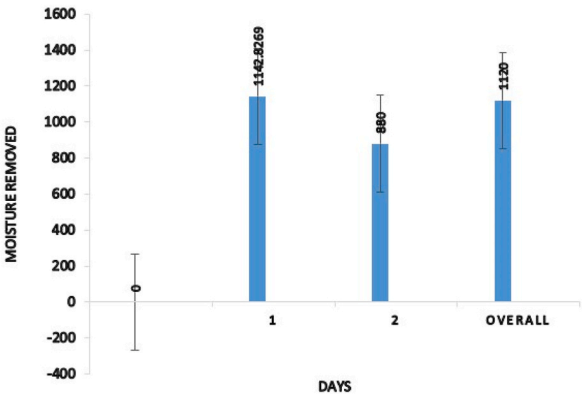

Fig. 4. Time v/s moisture removed of experiments.

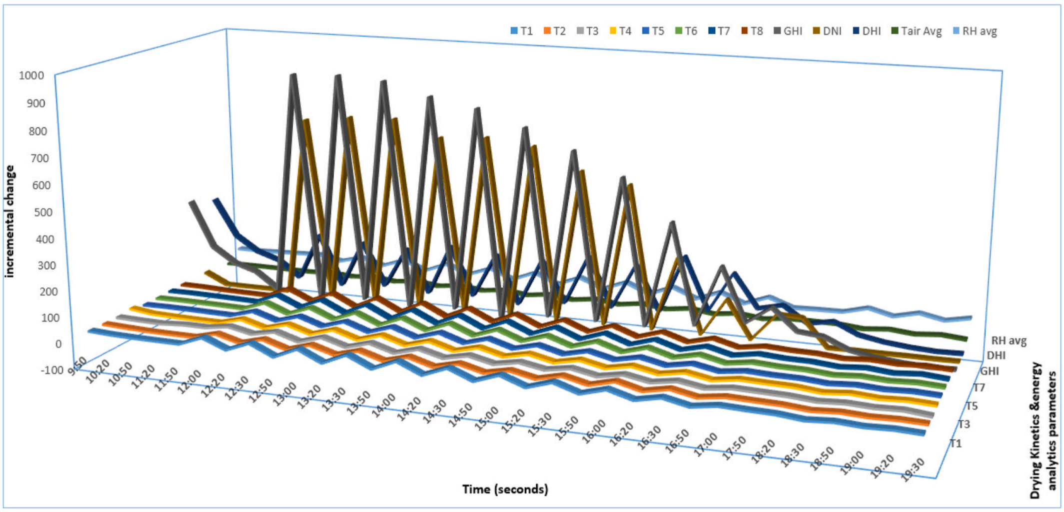

Fig. 5. Time v/s incremental changes in drying kinetics & energy analytics parameters.

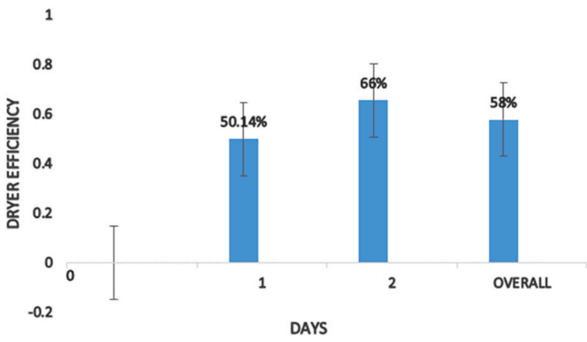

Fig. 6. Time v/s efficiency.

the experiment's moisture comes down to 880 g which was 2000g at the start of the experiments. The dryer efficiency at the end of day 1 is computed as 50.14 %. The dryer efficiency at the end of day 2 is computed as 66 %, while the overall efficiency is 58.07 %.

7.1.3. Efficiency comparison with existing benchmark methods

The efficiency comparison of an IFCDISD with existing benchmarks is a significant aspect to evaluate the performance of this innovative drying technology. Compared to existing benchmarks as mentioned in Table 11, this dryer demonstrates superior efficiency in terms of reducing drying time, preserving product quality, and optimizing energy consumption. Its innovative design allows for effective heat transfer, resulting in enhanced drying rates and reduced energy usage. In addition, the integration of solar energy enables significant cost savings and environmental benefits. Through a comprehensive efficiency comparison, the indirectly forced convection desiccant integrated solar dryer proves to be a highly advantageous solution for efficient and sustainable drying processes.

7.2. Cost analysis, and environmental impacts

Conducting an environmental analysis for a solar thermal system is crucial in case of solar dryer, particularly in the context of industrial purposes. The primary purpose of this research is to anticipate and mitigate the emission of greenhouse gases into the atmosphere. However, in developing countries like Pakistan the CO_2 emission is calculated by using the concept that the power produced by the grid is typically produced by the coal-based power system. Accordingly, lift time of dryer is normally taking as 20 years by the constructor while the domestic usages losses are denote as $Lda = 20$ % and the distribution & transmission losses $Ldt = 40$ %. The CO_2 Emission/year = 66.554 kg, CO_2 Mitigation = 2.0335 kWh/Yr, while the CO_2 Mitigation Lifetime = Embodied energy * CO_2 Mitigation (kWh/Yr.) = 1331.08 kg. Moreover, the Net Carbon mitigation = 3041.911163 kg and Carbon Credit Earned = 11559.6, and Energy Payback time = 2.99years as depicted Table 12. While, the energy payback time calculated from Eq. (11) by using the required embodied energy from Table 13 as follow. Fig. 7(a,b) depicts the pictorial view of tomatoes before and after drying via proposed IFCDISD.

8. Conclusion

The IFCDISD was fabricated, and experiments were conducted at the Solar Energy Research Lab, USPCAS-E, NUST, in Pakistan. The experiments were conducted during SS hours using direct sunlight and $CACL_2$ desiccants were integrated for drying during OSS hours. The DC brushless fans were used to blow ambient air into the drying chamber for $CACL_2$ desiccant drying during OSS hours. The weight of tomatoes initially placed in the drying chamber consisting of 4 trays was 2000g. After the SS hours experiments on 1st day, the tomatoes were reloaded, and their moisture was reduced and weighed as 1270.2722 g. Then, drying using $CACL_2$ desiccants during

Table 11
Efficiency comparison of an IFCDISD with existing benchmarks.

Mode of Drying	Crop/Product	Achievements/Dryer Efficiency (%)	Location	Ref
Indirect forced Convection desiccant integrated solar drying	Pineapple Green peas	43 %	India	[46]
Indirect forced Convection with Gravel packing. Chamber drying	Chilli	21 %	India	[47]
Indirect forced convection with sand packaging chamber drying	Copra	24 %	India	[48]
Mixed-mode natural convection dryer	Cassava	12.3 %	Ghana	[49]
HSD heater powered by liquefied natural gas	Sugar-palm vermicelli	13–17 %	Indonesia	[50]
Concentrating solar panels	Tomato	Drying was increased with usage of concentrators	USA	[51]
Proposed IFCDISD	**Tomato**	**58.07 %**	**Pakistan**	

Table 12
The comparison of different parameters between greenhouse dryer and present study.

Parameters	[52]	[53]	Proposed IFCDISD Study
Embodied energy	238.317	668.544	654.5802
Energy Payback time	0.588Yr	3.17	2.993Yr
CO_2 Emissions per/Yr.	24.327	36.66	66.554
CO_2 Mitigation	2.042	9.21	2.0335
CO_2 credit earned	28,600	N/A	11559.6
Payback period	2.4	3.67	5.1396

Table 13
The embodied energy values for different materials utilized in the construction of drying systems, along with their respective embodied energy coefficients.

Material	Embodied Energy coefficient (kWh/kg)	Quantity (kg)	Total embodied energy (kWh)
Wire Mesh	9.67	5	48.35
Paint	25.11	1	25.11
Copper wire used for electricity supply	19.61	0.1	1.961
Plastic components like DC fan, DC Motor, and motor casting	19.44	0.3	5.832
Fitting material			
(1) Door lock	55.28	0.2	11.056
(2) Hinges	55.28	1.5	82.92
(3) Nut Bolts	9.67	2	19.34
PV Module	60	6.2	372
Flat plate collector			
Aluminium Duct tape for insulation	55.28	0.04	2.2112
plywood	42.9	2	85.8
Total embodied energy			**=654.5802**

Fig. 7. (a) Tomatoes before drying in proposed IFCDISD. (b) Tomatoes After drying in proposed IFCDISD.

OSS hour the moisture was further reduced to 1142.869 g. The same experiment was repeated on the 2nd day, with less moisture removal due to less sunshine and rain interruption in both SS and OSS hours. However, the tomatoes were reduced to 965 g during SS hours, and after desiccant drying during OSS hours, they reached 880 g. Dryer efficiency was calculated separately for 1st day it was 50.14 % and for 2nd day it was 66 %, resulting in an overall efficiency of 58.07 %. Moisture content removed on day 1 was 42.8586 % and on day 2 was 22,9979 %, with an overall moisture content removal of 56 %. The carbon mitigation was calculated to be 2.0335 and the earned carbon credit is 11559.6.

Data availability statement

Data available on request from the authors.

CRediT authorship contribution statement

Muhammad Zeeshan: Writing – review & editing, Writing – original draft, Resources, Methodology, Formal analysis, Data curation, Conceptualization. **Iram Tufail:** Supervision, Project administration, Investigation. **Shahbaz Khan:** Visualization, Supervision, Project administration. **Ilyas Khan:** Funding acquisition, Formal analysis. **Saqib Ayuob:** Visualization, Software. **Abdullah Mohamed:** Visualization, Resources, Funding acquisition. **Sohaib Tahir Chauhdary:** Writing – review & editing, Visualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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