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APPLIED SOLAR ENERGY

Experimental investigation of modified indirect solar dryer with integrated thermal storage material for drying of dhekia (*Diplazium esculentum*) fern

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Abstract

Food product drying is a crucial stage in the preservation of crops and agricultural by-products that are used as raw materials for numerous end applications. The novelty of the study is the application of a phase change material in a solar dryer to improve the effectiveness of drying and reducing the overall drying period for drying while retaining/improving the quality parameters of the dried dhekia (*Diplazium esculentum*). The modified indirect thermal storage integrated solar dryer made up of a single-pass solar collector is attached with the drying chamber of 16.5 kg capacity. A thermal energy storage system prepared with paraffin wax embedded inside the drying cabinet was used. The proposed solar dryer has a thermal efficiency that is $11 \pm 0.2\%$ greater than the conventionally constructed solar dryer and reduces drying time by $40 \pm 2.1\%$. Drying kinetic analysis of dhekia was performed, and two new drying kinetic models were proposed to predict moisture ratio. From statistical analysis, it was found that the chi square value and root mean square error value fits well for the proposed models. The anti-oxidant, total phenolic content, and total flavonoid content values of samples dried in solar dryer exhibit better results compared to fresh, tray dried, and open sun-dried samples. The developed dryer shows better results in saving drying time and quality of the product. Due to its affordability and long-term solution for drying fresh farm goods, this dryer can be very helpful to small-scale farmers.

Keywords Thermal storage integrated solar dryer · Exergy analysis · Drying kinetics · Quality analysis

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Abbreviations, symbols, and nomenclature

A	Area (m^2)
C_v	Air volume heat capacity (J/kg K)
C_p	Heat capacity of dry air (J/kg K)
Ex_{eff}	Exergy efficiency (kW)
Ex_{in}	Input exergy (kW)
Ex_{loss}	Exergy loss (kW)
F	Mass flow rate of dry air (kg/s)
H	Percent humidity
h_c	Convective heat transfer coefficient (W/(m^2 K)
T	Temperature (°C)
V_d	Volume of the dry air in dryer (m^3)
W	Weight (g)
Rh	Relative humidity
Sh	Specific humidity
h_{ai}	Enthalpy
MC	Moisture content

$P_{vap,t}$ The partial vapor pressure of water in a mixture at a given temperature
$P_{svap,t}$ Saturated vapour pressure water in the mixture at a given temperature
TES Thermal energy storage

Subsections

A Ambient
b Absorbing plate
ca Circulating air
d Drying chamber
m Mass
i Inlet air
o Outlet air
p′ Product drying
g Glass cover
PCM Phase changing material
pw Paraffin wax
s Dried sample
su Thermal storage unit

Greek symbols

β Collector length, m
δ Thickness, m
ρ Dry air density, kg/m^2
η Efficiency

Introduction

The intake of edible ferns has increased significantly in everyday routine due to its wide range of beneficial properties. Dhekia (*Diplazium esculentum*), a wild edible rhizomatous fern from Athyriaceae family, is possibly the most consumed fern among tribal communities of Northeastern India. In a variety of local cuisines, the tender young shoots are used in stir-fries and salads (Junejo et al. 2018; Archana et al. 2012). Dhekia is the name locally used to refer *Diplazium esculentum* fiddleheads in Assam, Northeastern Region (NER) of India (Saikia et al. 2022a, b; Srivastava and Rao 2019). The fern is said to have a variety of therapeutic benefits like antioxidant, anti-inflammatory, anticarcinogenic, and hepatoprotective properties, as well as anti-diabetic and wound healing properties some of which have been scientifically proven (Koniyo et al. 2021). Wild leafy vegetables like *Colocasia esculenta (L) Schott* (family: Araceae), *Derringia amaranthoides (Lamk) Merr* (family: Amaranthaceae), and *Talinum triangulare (Jacq.) Willd* (family: Portulacaceae) are still underutilized due to a lack of awareness and engagement of technology aspects for their proper utilization (Nakhuru et al. 2021). Dhekia's significant nutrient composition makes it a good choice for inclusion in food or nutritional supplement programs. Due to their high moisture level, most cash crops are highly perishable and cannot be preserved beyond their harvesting season. As a result, to extend the life of self-storage, drying is required (Nayak et al. 2018).

The process of reducing moisture in any substance until it reaches an acceptable moisture content level is termed as drying. It is a complicated process that involves uneven heat and mass transfer, along with physical and chemical transformations that may affect product quality (Arunsandeep et al. 2018). Sun drying has been used as a method of food preservation since ancient time. Unfortunately, it has various drawbacks, such as being subjected to rainfall and air, besides being contaminated and powdered by bugs or other creatures, leading in losses and produce of low-quality products (Vijayan et al. 2016).

Solar energy is ideal for drying of agricultural produce owing to its long-term sustainability especially for remote regions where power is limited or inconsistent (Lakshmi et al. 2018). Because of superior control over the quality of dried items, solar drying is preferable to traditional sun drying. In indirect solar dryers, solar radiation is employed to heat the air, thereby absorbing moisture from the materials being dried. An indirect solar dryer with good design does have a significant drying rate and produces excellent products. Development of such a dryer will cost more compared to regular solar dryers, but will cost less than electricity-powered convective dryers (El-Sebaii and Shalaby 2017).

Depending on continuous solar energy is not possible because of non-uniformity of solar radiation, and thus, surplus solar energy should be saved and used during evening hours adopting collecting approaches. Widely used sensible heat storage materials (SHM) include gravel, concrete, fire bricks, and calcareous stones. The high density and temperature variations of SHM make them unsuitable for use in solar dryers. Since, latent heat storage materials are commonly available and economical; they may be employed to store thermal energy efficiently (Sharma et al. 2009). In addition, latent heat storage materials have a wide range of applications in solar dryers for agro-product drying. The widely used storage material is paraffin wax; however, wax has a low thermal conductivity which is further resolved by employing wax in aluminum tubes (Krishnan and Sivaraman 2017). While drying of several food samples in a solar dryer employing phase changing material (PCM) as a storage medium, the drying chamber temperature was reported to reach 20–50% higher temperature than the ambient temperature. Also, at a constant airflow of 0.6 m/s, the PCM-assisted solar dryer is reported to discharge 23% higher time (Agarwal and Sarviya 2016). One study found that while drying of sliced black turmeric in a forced convection solar dryer (assisted with PCM), the drying time was shortened by 60 to 70 percent particularly in comparison to open sun drying (OSD) (Lakshmi et al. 2018).

Exergy study of a solar dryer offers extensive data on how thermal energy is used within the dryer and estimates the heat that is not used. A number of different approaches on the energetic and exergetic evaluations of solar drying of various farm produce were conducted, such as star fruit (Kondareddy et al. 2022), elephant apple (Kondareddy et al. 2022), rosemary leaves (Karami et al. 2021), valerian rhizomes (Bhardwaj et al. 2021), black pepper (Lakshmi et al. 2021), blood fruit (Kondareddy et al. 2021), stevia leaves (Lakshmi et al. 2019), black turmeric (Lakshmi et al. 2018), ghost chilli pepper and ginger (Rabha et al. 2017), Jackfruit leather (Chowdhury et al. 2011), and mulberry (Akbulut and Durmuş, 2010).

To acquire specific variables that affect the dried material, the drying kinetics must be carried out. The drying parameters, the type of solar dryers used, and the physical characteristics of the food samples all have an impact on the drying kinetics. It helps researchers find the best drying operational settings and situational factors. Previous studies offered different empirical models to select the most convenient model for specific food products such as two-term exponential (Krishnan et al. 2020; Özdemir and Devres 1999), modified page (White et al. 1981), Wang and Singh (Kaleta and Górnicki 2010), and Weibull (Puente-Díaz et al. 2013) methods. However, most exergetic analyses have focused on the drying of fresh produce, but so far, no extensive experimental study on drying of dhekia is reported. Therefore, the present study is focused on dhekia dried in a modified indirect thermal storage integrated solar dryer (SD^{TS}) and exploring its drying behavior and kinetics.

The current research is focused on developing an economical thermal storage integrated solar dryer for drying seamlessly. Integration of thermal storage helps uniform drying of dhekia over sun drying. Furthermore, a comparison of the quality of dhekia (in terms of nutritional analysis, bioactive compounds, and rehydration study) dried in modified indirect thermal storage integrated solar dryer (SD^{TS}), open sun drying (OSD), and tray drying (TD) was performed.

Materials and methods

Materials

Dhekia was procured from Kokrajhar's local market (Assam, India). They were graded based on their size and color. For the drying study, dark green fiddleheads with more foliage were selected. For determining the moisture content (MC) of fresh samples, dhekia was dehydrated in a hot air oven for 3 hours at 105 °C (AOAC 1984). Wet basis moisture content (MC) of newly collected dhekia fern was found to be 80.6 ± 1.22%.

Solar dryer design

The designed SD^{TS} is depicted schematically in Fig. 1. The experimental set up consists of four major components: (i) solar air collector, (ii) drying chamber (with two drying trays), (iii) PCM thermal storage unit for storing the solar energy throughout daytime so as to utilize it after sunset, and (iv) controller section chamber where all the control equipment was placed.

Solar collector design

The solar collector is made up of a finned absorber (painted in black), a transparent glass, insulation, and a frame. Fresh air was routed through air duct under the absorber, which was formed of aluminum sheet. The detailed measurement specification of SD^{TS} was shown in Fig. 1. The primary collector is 152.4 cm in length, 80 cm in breadth, and 10 cm in height. The basic structure includes galvanized iron (GI) sheets with a thickness of 2 mm and iron bars to support the collector. The base plate and a rectangular partition in the collecting chamber were made of 0.5-mm-thick aluminum sheet. An optimal air gap between the glass and base plate is 150 mm. To increase thermal efficiency, ambient air was drawn into the collector and routed along the zig-zag channel (Saikia et al. 2022a, b). A flange section was supplied at the collector's top end (air output) to attach the flexible connector with nuts and bolts. The polystyrene of 2-cm thickness with thermal conductivity of 0.033 W/(mK) was used as a sealing material to make the air duct thermal leak-proof. Wire mesh was installed on the collector's input side to keep insects out of the dryer. Since the collector was intended for adjustable inclination, a flexible connector built of special fiber-reinforced plastic material is provided to connect the collecting chamber to the thermal storage and plenum chamber (Pangavhane et al. 2002). To increase the connector's durability, two layers of fiber-reinforced plastic material were attached among two rectangular cross-sectional ducts with outer flanges made for connectors' inlet and outlet ends. The collector tilt angle is 21° toward the south from the horizontal stage to receive the optimal reception of solar radiation.

To obtain the optimal hot air flow rate of 0.65 m/s to the storage unit and dryer, a tiny fan (12 V blower fan) was installed in the solar collector's outer duct. A lightweight EE671 air velocity probe with pre-installed cable was used to measure the airflow velocity in the collector. Two resistance temperature (RTD) sensors were placed both inlet (to measure ambinet temeperature) and outlet of the collector, respectively (Fig. 2). The ACE 2007, 24 V DC data acquisition system is a Wi-Fi current module (24 V DC Wi-Fi DAQ) that is capable of taking four analog inputs and control up to two actuators/analog output. The analog input–output current range is from 4 to 20 mA.

Energy storage unit

Dryers utilizing heat storage substances are especially beneficial for drying fresh farm produce at relatively stable

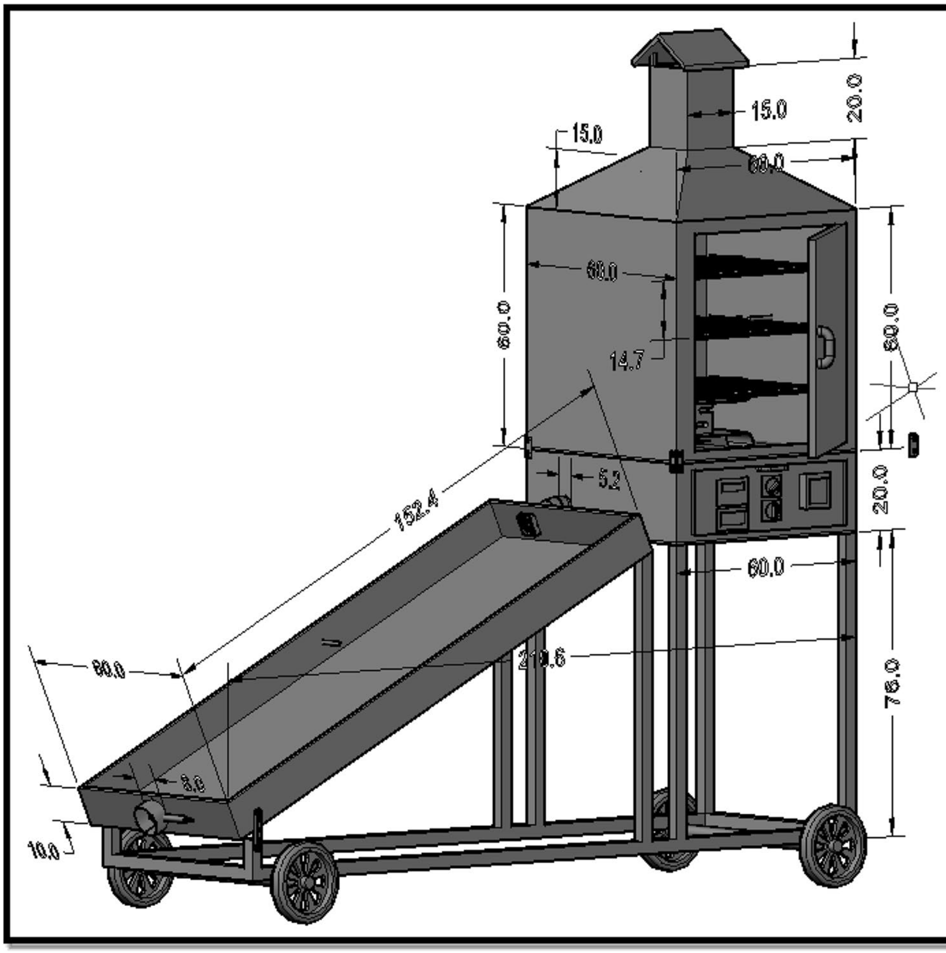

Fig. 1 Schematic (with details specifications) of thermal storage integrated solar dryer (SD^{TS})

temperatures of around 40–60 °C. Paraffin (P48-50) is a phase-changing material that absorbs latent heat in its crystalline form (Saikia et al. 2022a, b; Mugi and Chandramohan 2021; Kondareddy et al. 2020). The paraffin wax accumulates heat throughout the day and releases it at night. It plays an important role toward energy sustainability by limiting the existing demand on the energy supply.

The wax used in this system has melting point of 58–60 °C, heat of fusion of 180 kJ/kg, thermal conductivity of 0.59 W/m K, volume expansion of 8–9%, and density of 900 kg/m^3 with specific heat of 2.45 kJ/kg K. In this study, the thermal storage unit was attached just below the drying unit (60 cm width and 20 cm height) where paraffin wax is packed in 110 aluminum tubes (2-inch size with each capacity of 50 ml). Two RTD sensors were installed to monitor the temperature of the thermal storage unit and to record data.

Drying unit

The drying unit consists of three perforated stainless steel trays, each having a load capacity of 5.5 kg, with a vertical space of 15 cm separating three successive trays (Fig. 2). The hot humid air that was discharged during drying is vented outside via an air duct that was installed on top of the drying chamber measuring 20 cm in height and 15 cm in width. For measuring the weight of the dhekia sample, a load cell of range 0–20 kg with analog signal output 4–20 mA connected with a 24v SV8 digital meter was used. Humidity cum temperature transmitter (MASIBUS HT7S11; 0–100% RH; 0–50 °C) was fitted at the top the plenum chamber. Figure 2 depicts the various components of the designed SD^{TS} dryer.

Experimental procedure

The tests started at 8 a.m. in the developed dryer. To attain stable equilibrium, the setup was run for an hour without load. After reaching a steady condition, the product was placed into the dryer. The SD^{TS} was located in front of the PG Boy's Hostel, CIT Kokrajhar, Assam, India, at 90°18′ east and 26°28′ north. The drying tests were performed in a fully sunny day during the final week of March 2021. Using a four-channel k-type thermocouple, input and output temperature of solar collector, and the drying chamber, was monitored during the experiments. Based on the measured temperatures of air (in wet basis and dry basis; sample data are calculated to the moisture condition of the fern after

Fig. 2 Different parts of the SD^{TS} (loaded condition)

1. Main switch
2. RTD for Soler collector
3. RDT inside the thermal storage unit
4. RDT just below the inlet of the solar dryer
5. RTD with pt100 (PTC) sensor placed inside the drying chamber
6. RTD with pt100 for ambient temperature
7. Load cell for the weight of the food sample
8. SV8 Digital display show weight reading
9. MASIBUS HT7S11 Humidity cum temperature transmitter
10. EE671 Air flow sensor with air inlet
11. UNI 901 Solid state relay
12. ACE 2007 Wi-Fi data acquisition systems
13. Multispan Ms-1208 8 Channel Scanner
14. Thermal storage chamber with several number of Paraffin wax container tube
15. Fan for controlling the airflow
16. Food sample tray
17. Power supply 24v DC
18. Fuzzy control VI running form remote location.
19. PTC heating element

Table 1 Psychrometric correlations for energy and exergy analysis

Term	Symbol	Formula
Relative humidity	Rh	$Rh = \frac{P_{vap,t}}{P_{svap,t}}$
Specific humidity	Sh	$Sh = 0.622\frac{Pvap,t}{P-Pvap,t}$
Enthalpy	h_{ai}	$h_{ai} = Cp_{ai}T_{ai} + Wh_{svap,t}$

being allowed to air-dry at room condition humidity), the different psychrometric characteristics of air (enthalpy, relative humidity and specific humidity) were evaluated and listed in Table 1. A pyranometer (LPPYRA10, Delta ohm) was used for recording solar insolation on the collector's surface. The flow rate of air at the solar collector intake was measured using an anemometer make Metravi AVM-10 (model), and the accuracy is ± 0.065 m/s). A data logger was employed to store and record all readings periodically using all of the thermocouples and the pyranometer. The collected results were then used for analysis of energy and exergy. In addition, with the thermal storage integrated solar dryer (SD^{TS}), drying experiments were carried out with sun drying (OSD) and tray drying (TD), respectively. A detailed flowchart of experiments has been presented in Fig. 3.

Mathematical model of developed SD^{TS}

Mathematical model for the dryer was developed by taking the collector and drying chamber into consideration

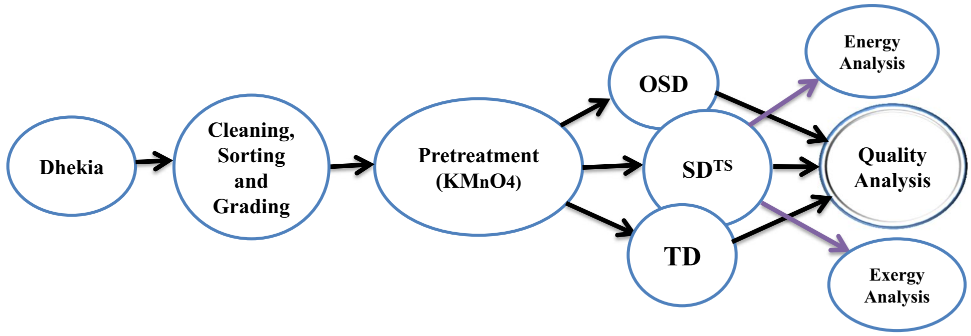

Fig. 3 Dhekia fern flowchart for various drying approaches

(Vásquez et al. 2019). As shown in the collector schematic in Fig. 4, the dynamic characteristics of glass cover temperature T_g, absorber plate temp (at the base) T_b, and circulating air temp T_{ca} were used to examine the heat transfer within the collector. The dynamics of the circulating air in collector T_{ca} were by convective heat transfer between glass surface to air and bottom absorbing plate to air. The collector's inner area is $A_{(b,g)}$, and the collector's length from air intake to the outlet is x, which is designated by a longitudinal length of dx. The collector's energy balance equation was represented in Eq. (1).

$$\rho_{ca}A_g\delta_{sp}C_{ca}\frac{\partial T_{ca,x}}{\partial t}+\beta F_{ca}C_{ca}\frac{\partial T_{ca}}{\partial x}=A_g h_{c,gca}\left(T_g-T_{ca}\right)+A_{b,g}h_{c,bca}\left(T_b-T_{ca}\right) \quad (1)$$

Equation (2) depicts the dynamic functioning of the thermal storage unit, which is regulated by variables such as circulating air temperature T_{ca}, glass cover temperature T_g, and paraffin wax temperature T_w. The temperature of the circulating air inside the thermal storage was taken into account in this equation using position index x, when x is unity, the $T_{(ca,0)}$ is equal to T_a. The temperature of the circulating air inside the storage unit was determined using Eq. (2) and $h_{c,pwf}$ is the coefficient of convective heat transfer from wax to the circulating air. Cylindrical tubes were filled with 100 g of paraffin wax.

$$\rho_{ca}A_g\delta_{su}C_{ca}\frac{\partial T_{ca,x}}{\partial t}=F_{ca}C_{ca}\left(T_{ca,0}-T_{ca,x}\right)+A_g h_{c,gca}\left(T_g-T_{ca,x}\right)+ A_{b,su}h_{c,bca}\left(T_b-T_{ca,x}\right)+A_w h_{c,pwf}\left(T_{pw,x}-T_{ca,x}\right) \quad (2)$$

The drying chamber's mathematical model explains the dynamics with known parameters values like inlet and outlet temperatures and humidity in the drying chamber (T_{di} ,T_{do}, H_{di}, $H_{do,}$ respectively). The ideal drying chamber circulating air velocity is V_d, $T_{p'}$ is the dried dhekia temperature, and the coefficient of convective heat transfer to the dhekia form circulating hot air was $h_{(c,pf)}$ in the chamber, were all taken into consideration in Eq. (2) (Saikia et al. 2022a, b).

The temperature at drying chamber outlet was determined with the following equation (3) (Sami et al. 2011).

$$\rho_d V_d\left(C_d+C_v H_{do}\right)\frac{dT_{di}}{dt}=F\left(C_d+C_v H_{di}\right)T_{do} -F\left(C_d+C_v H_{do}\right)T_{di}+A_p h_{c,pf}\left(T_{di}-T_{p'}\right) \quad (3)$$

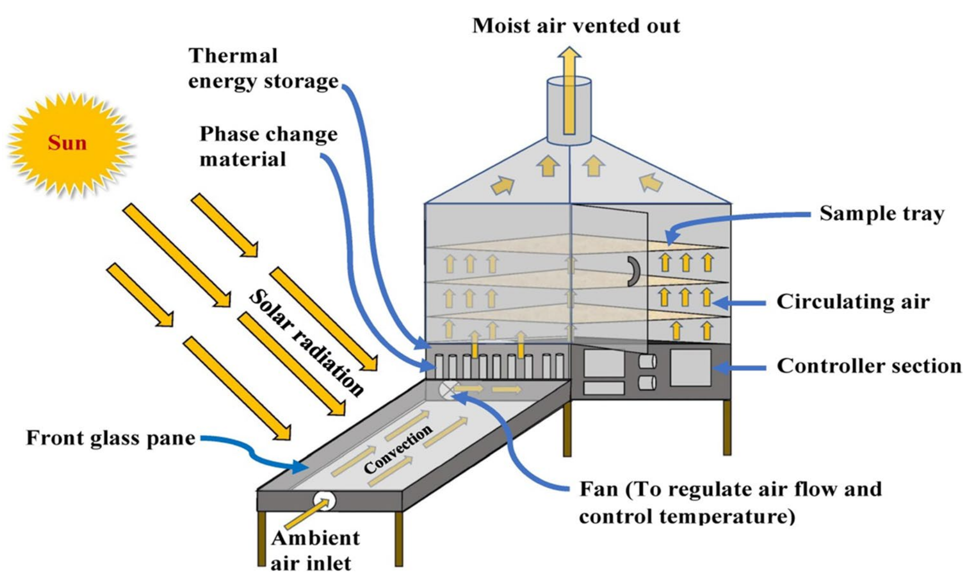

Fig. 4 Diagram of energy flow and heat transfer from the collector to the plenum chamber

The temperature in the drying chamber was determined using both experimental and simulated data (Zoukit et al. 2019).

SD^{TS} energy analysis

The moisture from the fresh product is reduced during the solar drying process by using thermal energy supplied by the solar thermal collector. The collector functions as a heat exchanger absorbs solar energy and transferred this energy to the working fluid (ambient air). Equations (4), (5), and (6) were used to determine the amount of energy necessary to remove moisture from dhekia in the proposed SD^{TS}. The mass balance of air in the drying chamber is calculated using Eq. (4).

$$\Sigma m_{ai} = \Sigma m_{ao} \tag{4}$$

The moisture mass balance while drying is expressed in Eq. (5).

$$\Sigma (m_{wi} + m_{m}) = \Sigma m_{wo} \tag{5}$$

The ambient air was considered to be similar to the air entering the solar collector. The difference in the amount of radiation received and the amount of thermal energy dissipated by the collector was used to quantify the energy utilized.

Equation (6) was used to calculate the quantity of thermal heat gained by the solar collector (Fig. 5) from the atmospheric air.

$$Q_u = m_{ai} C_{p_{ai}} (T_{ao} - T_{amb}) \tag{6}$$

Equation (7) was used to estimate the quantity of heat delivered to the product within the drying chamber.

$$Q_d = m_a (h_{di} - h_{do}) \tag{7}$$

SD^{TS} exergy analysis

The quantity of energy accessible and converted into work is referred to as exergy. Exergy evaluation at the dryer inlet and exit, along with exergy loss, were obtained by second law of thermodynamics. The evaluation of exergy readings at different phases of the process is the focus of exergy analysis.

Input exergy, exergy loss (Ex_{loss}) and output exergy and exergy efficiency are estimated using Eqs. (8) and (9), respectively.

$$Ex_{loss} = Ex_{in} - Ex_{out} \tag{8}$$

$$E_{x,in} = m_{ai} C_{pai} \left[\left(T_{id} - T_{amb} \right) - T_{amb} ln \frac{T_{id}}{T_{amb}} \right] \tag{8a}$$

$$E_{x,out} = m_{ai} C_{Pai} \left[\left(T_{od} - T_{amb} \right) - T_{amb} ln \frac{T_{od}}{T_{amb}} \right] \tag{8b}$$

$$Ex_{eff} = 1 - \frac{Ex_{loss}}{Ex_{in}} \tag{9}$$

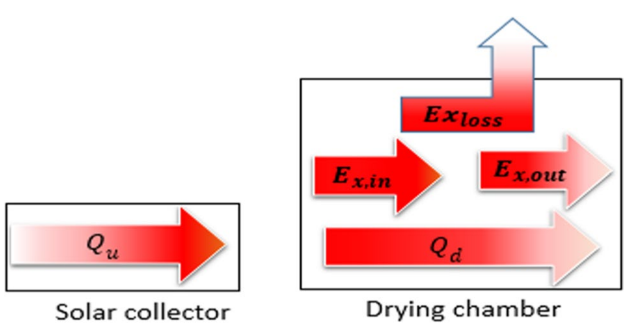

Fig. 5 Schematic diagram for flow of energy in SD^{TS}

Mathematical modeling

The moisture levels of dhekia after procuring ($M_{initial}$) and after drying (M_{final}) are calculated on a dry basis (db).

$$M_{initial} = \frac{m_{initial} - m_d}{m_d}; M_{final} = \frac{m_{sd} - m_d}{m_d}; M_{time} = \frac{m_{ts} - m_d}{m_d} \tag{10}$$

where m_d represents mass of dhekia while drying, m_{sd} represents mass of dhekia dried in SD^{TS}, and M_{time} represents the moisture level of dhekia at time ts.

Moisture ratio (MR) of dhekia was estimated using Eq. (11):

$$MR = \frac{\left(M_t - M_e\right)}{\left(M_0 - M_e\right)} \tag{11}$$

The above equation applicable for uniform relative humidity condition, in case of solar drying relative humidity fluctuates over drying time. The dimensionless MR expressed for solar drying (Eq. (12)) is as follows (Lakshmi et al. 2018):

$$MR = \frac{\left(M_t\right)}{\left(M_0\right)} \tag{12}$$

Drying is a continuous mass and heat transfer process that takes place over time. Several quasi-theoretical and empirical drying kinetics models have been proposed in the previous studies to estimate the drying behavior of agriculture products (Karthikeyan and Murugavelh 2018; Nukulwar and Tungikar 2021). The optimal drying curve equations for all cases of dhekia were found considering ten different models (Table 2). The first eight models mentioned in Table 2 are widely used in the literature on food drying using solar (Kondareddy et al. 2020; Krishnan et al. 2020; Lakshmi et al. 2019; Kumar et al. 2017). The last two models (Nos. 9 and 10) are provided for the first time in this study as proposed model 1 and proposed model 2. In all of these approaches that include drying time as a variable, the influence of drying conditions is represented by the drying constants (n and a, b, and c). The rate constant (min^{-1}) is measured by the coefficient k, while time is measured by t (min). MINITAB 20.2.0 was used for conducting regression analysis. To define finest kinetic model for drying process, R^2, χ^2, and RMSE values have been used and expressed in Eqs. (13), (14), and (15).

$$x^2 = \frac{\sum_{i=1}^{N}\left(MR_{exp,i} - MR_{pr,i}\right)^2}{N - n} \tag{13}$$

$$R^2 = 1 - \frac{\sum_{i=1}^{N}\left(MR_{exp,i} - MR_{pr,i}\right)^2}{\sum_{i=1}^{N}\left(MR_{avgpr} - MR_{exp,i}\right)^2} \tag{14}$$

$$RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(MR_{exp,i} - MR_{pr,i}\right)^2} \tag{15}$$

Quality analysis

The following processes and methods were used to determine the nutritional and biochemical characteristics of the fresh and dried samples. The tests were all performed in triplicate.

Estimation of protein

The protein analysis was carried out using the Kjeldahl method and represented as a percentage of gross nitrogen (AOAC 1984).

Table 2 Different kinetic models fitted in thin layer drying of dhekia fern

Sl. no	Model name	Model
1	Lewis	$\text{MR} = e^{(-kt)}$
2	Page	$\text{MR} = e^{(-kt^n)}$
3	Modified page model	$\text{MR} = \exp[-(kt)]^n$
4	Logarithmic model	$MR = ae^{(-kt)}$
5	Two-term exponential	$\text{MR} = \text{aexp}(-kt) + (1-a)\exp(-kt)$
6	Midilli model	$\text{MR} = \frac{M-M_e}{M_o-M_e} = a\exp^{-(kt^n)} + bt$
7	Aghabashlo model	$\text{MR} = \exp[-\frac{k_1 t}{(1+k_2 t)}]$
8	Henderson and Pabis	$\text{MR} = a\exp(-kt) + (1-a)\exp(-kt)$
9	Proposed model 1	$\text{MR} = ae^{(-kt^n)} + \text{c}$
10	Proposed model 2	$\text{MR} = 1 - \text{e}^{(-a/t) - b\ln(x) + c}$

Estimation of lipid

The Soxhlet method was used to calculate lipid content and expressed in terms of percentage (Lakshmi et al. 2018).

Estimation of ash content

The AOAC (1984) technique was used to estimate the ash content. The ash's weight was calculated as a percentage of its total weight.

Estimation of carbohydrate

Carbohydrate was estimated by hydrolysing it with sulfuric acid into simple sugars and then using the anthrone technique to demonstrate the resulting monosaccharides (Lakshmi et al. 2019).

Total phenolic content

Nayak et al. (2017) described the Folin–Ciocalteu technique for determining TPC.

Total flavonoid content

Nayak et al. (2018) proposed an approach to determine the flavonoid content of dried materials. Flavonoids for samples were measured in mg CE/ml of extract.

Antioxidant activity

Demir's approach was used for determining antioxidant activity of dried dhekia (Saikia et al. 2022b; Demir and Korukluoglu 2020).

Rehydration experiments

Rehydration studies for dried materials (OSD, TD, and SD^{TS}) were conducted in a distilled water bath at 40 °C (± 2 °C). In a 500-ml beaker, dried dhekia of 1 g was mixed to 200 ml distilled water for 5–15 min. Before weighing, the sample was carefully taken by blotting on tissue paper. The dried and rehydrated samples were weighed using a digital electronic balance with an accuracy of 0.001 g. The following equation was used to determine the rehydration ratio (R_R) (Ranganna 1986).

$$R_R = \frac{W_1}{W_2} \tag{16}$$

where W_1 is the weight of the dehydrated dhekia fern taken for rehydration, g and W_2 is the drained weight of the rehydrated dhekia fern, g.

The coefficient of rehydration was calculated using the following equation:

$$CR = \frac{W_2 \times [100 - M_1]}{[W_1 - M_f]X100} \quad (17)$$

where M_f is the moisture content of dried dhekia before rehydration, g and M_1 is the moisture content of fresh sample before drying percentage.

Uncertainty analysis

The devices used to assess temperature, air velocity, sun intensity, and sample weight all have their own inaccuracies, resulting in some uncertainty in the estimated parameters' readings. The efficiency of the dryer and solar heater can be estimated using the method described below (Kline and McClintock 1953). Equation (18) is used to compute the overall uncertainty in the dryer efficiency.

$$n_{IFSCD} = f(m_{w,} I, A_{s,}, t) \quad (18)$$

$$\Delta n_{IFSCD} = \pm \left[\left(\frac{\partial n}{\partial m_{\omega}} \Delta m_w \right)^2 + \left(\frac{\partial n}{\partial I} \Delta I \right)^2 + \left(\frac{\partial n}{\partial A_s} \Delta A_{s1} \right)^2 + \left(\frac{\partial n}{\partial t} \Delta t \right)^2 \right]^{\frac{1}{2}} \quad (19)$$

The maximum uncertainty was estimated to be $\pm 3.2\%$ and $\pm 1.2\%$ for the solar heater and dryer, respectively.

Statistical analysis

Following three repetitions of the drying tests and analytical investigations, the data was calculated by MS Excel and statistical software (SPSS 19.0 trial version). A one-way ANOVA test was conducted on the data, with a statistical significance value of $p < 0.05$.

Results and discussion

SD^{TS} performance characteristics

On a sunny day of 27th March 2021, the experiments were conducted. The performance parameters heat transfer fluid temperature, atmospheric temperature, and air temperature inside the drying chamber were measured and depicted in Fig. 6. From 8 a.m. to 5 p.m., solar radiation levels ranged from 300 to 950 W/m^2. A robust controller controls the airflow velocity inside drying chamber to monitor the temperature with a ± 1 °C precision range. With selected control action, the ideal range of circulating air velocity inside drying chamber has been kept at 0.5–0.7 m/s. The ambient temperature ranged from 28 to 31 °C. The temperature within the drying chamber rises from 10:00 to 14:00 h, then falls due to solar insolation depletion until 4.30 p.m., and from 4:30 p.m. to 8 p.m., thermal storage delivers 29.16% more stable process temperature in the dryer. At 20:00 h, the temperature within the solar dryer with thermal storage was 44.3 °C, while the temperature within the solar dryer without thermal storage was 32.5 °C, as shown in Fig. 6.

Energy analysis of SD^{TS}

Figure 7 shows how energy utilization as a function of drying time varies within the solar collector and drying chamber. Based on collector's inlet and outlet temperatures, the quantity of usable energy from the solar collector was calculated using Eq. (6). The amount of useable energy obtained by the collector from solar radiation ranged from 0.07 to 0.63 kW. This thermal energy was supplied to drying chamber and thermal storage. The energy supplied to the product with and without integration of PCM was depicted in Fig. 7. In comparison to a simple solar dryer without a thermal storage, the dryer equipped with a thermal storage constantly supplied heat energy to the product after sunset hours, as shown in Fig. 7.

Reflection loss accounted for around 7 percent of the input solar energy that was lost or wasted because of the glass cover. Furthermore, the glass cover absorbed 6 percent of the input energy, enabling the remaining energy to travel through the glass. Furthermore, the absorber plate reflected 5 ± 0.4 percent of the received solar radiation, while the absorber plate absorbed a large portion of the received solar radiation, around 85 percent.

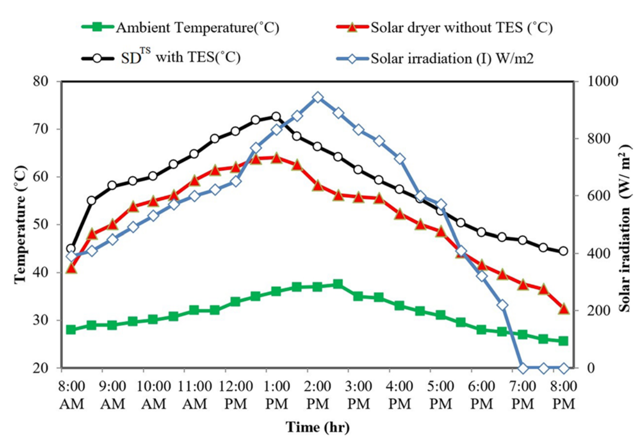

Fig. 6 Performance parameters of solar dryer with and without thermal energy storage

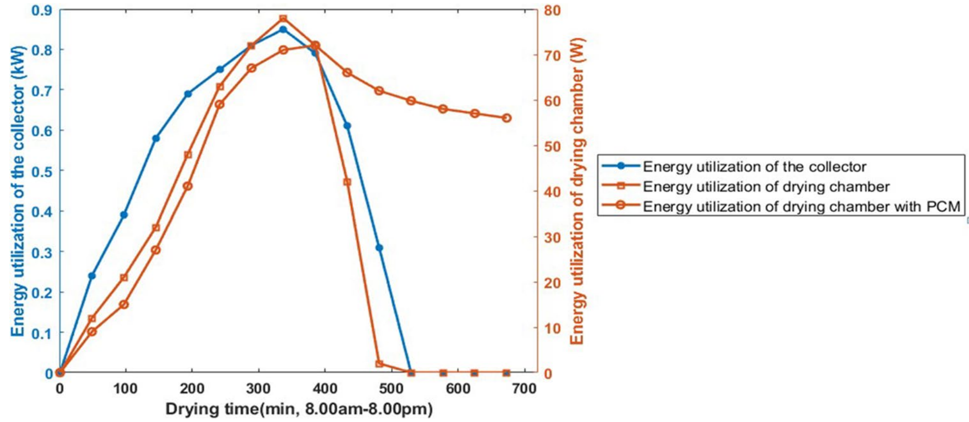

Fig. 7 Energy utilization of the SD^{TS}

Moisture content of dhekia inside the chamber decreased from 80.6 to 8.2% (wb) in 5.5 h, corresponding to energy usage ranges of 7.45–72.99 W. The rate of energy consumption varies during the day, increasing in the afternoon (about 2 PM) when the received radiation on the collector is at its peak. The temperature inside the collector fluctuated linearly with the intensity and exposure to solar radiation, since the inlet temperature is influenced by ambient temperature. In another study, Rani and Tripathy (2021) reached similar conclusions, establishing the performance evaluation of a solar concentrator with flat plate using the first and second laws of thermodynamics. This study demonstrates that solar radiation and design of the collector influence the performance of a solar collector.

Exergy analysis of SD^{TS}

Exergy analysis helps to estimate the losses occurring in the solar dryer. The usable energy delivered from collecting chamber to the drying unit is around 62.89 MJ, with 0.221 MJ energy wasted. Circulating air inside the dryer consumes 2.29 kw more energy during the drying process from 08:00 to 20:00 h with 62.8 °C average temperature and 9.4% relative humidity. The exact rate of moisture extraction throughout the drying process was 0.419 kg/kWh. Figure 8 shows the exergy analysis of SD^{TS} in respect to exergy efficiency and loss. Efficiency of the dryer from 10:00 to 17:00 h is around 66.2%.

Drying tests were conducted using three different methods, specifically OSD, TD, and SD^{TS}. The fern was dried from initial moisture content of 75.55 ± 2% to 3.80 ± 0.5% (Fig. 9). The moisture content was found to decrease gradually as the drying time increased, with SD^{TS} requiring a much shorter duration of 330 min while also maintaining its quality. Weight loss in dhekia, while drying in SD^{TS} was initially quicker owing to unbound moisture on the surface, however reduced subsequently due to internal moisture transfer from the interior to the surface, following a period of falling rate (Lakshmi et al. 2021). In the context of OSD, the drying rate was too slow on the second day, as predicted by Lakshmi et al. 2019. Rahman et al. (2016) and Zomorodian and Moradi (2010) reported comparable results while drying of mushroom and cumin using solar energy.

Evaluation of drying models

The drying parameters and R^2, χ^2, and RMSE values of dhekia fern are shown in Table 3. When the results of dhekia dried in trays were analyzed, the two-term exponential model with regard to the two variables utilized in mathematical modeling provided the best match, with the greatest R^2 (0.9991) and the lowest RMSE (0.0021). The top three models proposed model 1, proposed model 2, and two-term exponential model) actually have R^2 values that are all more than 0.999, showing that the models are perfectly matched (Table 3). Meanwhile, the proposed model 2 had the greatest R^2 (0.9996) and the lowest RMSE when the SD^{TS} drying data of the fern were investigated (0.0019). In summary, the moisture ratio is greatly overestimated by this recently suggested model.

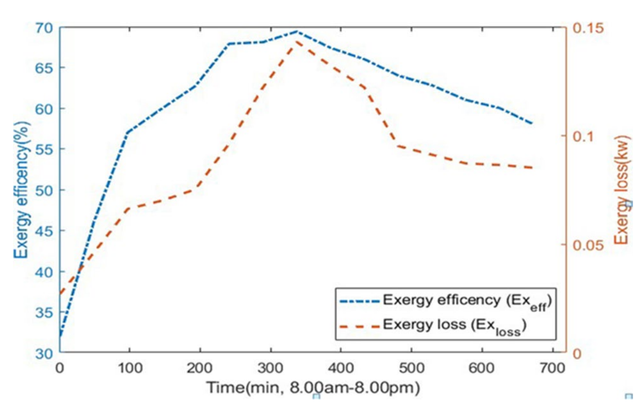

Fig. 8 Exergy efficiency and exergy loss of SD^{TS}

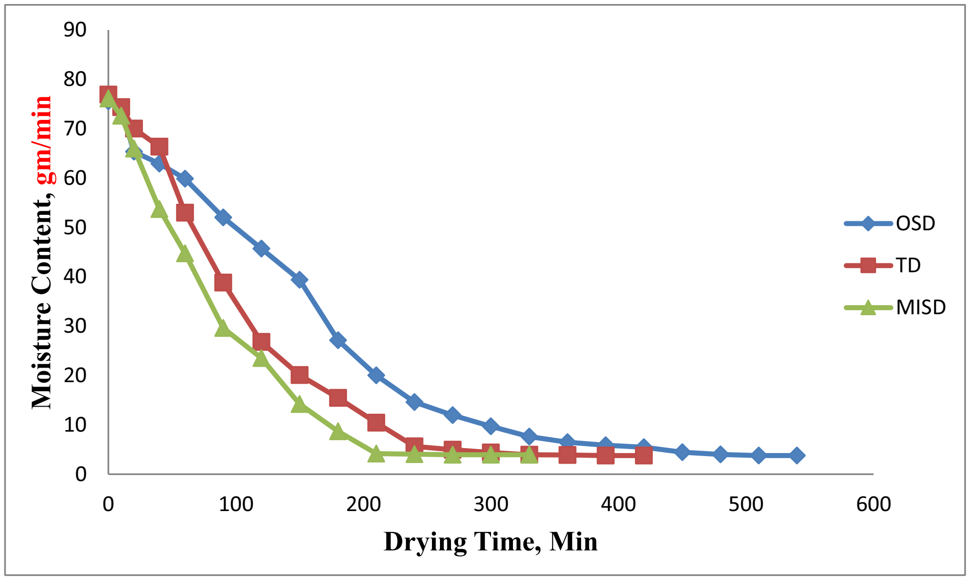

Fig. 9 Moisture content (w.b.) of dhekia dried by varying methods as a function of drying time (min)

Quality analysis of dried dhekia

Effect of different drying processes on the proximate profile

Proximate analysis was carried out for fresh, SD^{TS}, TD, and OSD dried dhekia. The dried fern's considerable drop in macronutrient content (Table 4) might be attributable to the stability of the macronutrient linkages. Because of the dryers' efficiency, the drop in protein content was found to be proportional to the amount of heat used. The observed reduction might be related to the dryers' capacity to concentrate energy, which could result in some protein denaturation in dried samples. The application of heat causes significant nutritional losses during drying, lowering the content of protein, fat, ash, and carbohydrate (Morris et al. 2004). The carbohydrate content ranged between $76.29 \pm 6.11$and 59.39 ± 5.22 with SD^{TS} dried having the highest value. The decrease in carbohydrate value after drying might be attributed to microflora using the carbon skeleton for nutrition synthesis. Carbohydrates aid fat metabolism and provide an alternative energy source for humans (Gordon 2000). The

Table 3 Comparison of the best models (top 5) for various drying processes and drying coefficients (constants)

Sl. no	Model	Drying method	Constants	R^2	RMSE
1	Modified page	OSD	$k = 0.023$, $n = 1.21$	0.9970	0.0099
		TD	$k = 0.010$, $n = 1.34$	0.9981	0.0091
		SD^{TS}	$k = 0.014$, $n = 1.29$	0.9985	0.0905
2	Two-term exponential	OSD	$a = 1.798$, $k = 0.02$	0.9965	0.0020
		TD	$\mathbf{a = 1.825, k = 0.01}$	**0.9991**	**0.0021**
		SD^{TS}	$a = 1.956$, $k = 0.02$	0.9991	0.0067
3	Midilli model	OSD	$a = 1.2036$, $k = 0.0089$ $n = 1.0589$, $b = -0.0001$	0.9992	0.0079
		TD	$a = 1.223$, $k = 0.0118$ $n = 1.1111$, $b = -0.00004$	0.9948	0.0053
		SD^{TS}	$a = 1.2369$, $k = 0.0002$ $n = 1.397$, $b = 0.00004$	0.9953	0.0024
4	Proposed model 1	OSD	$k_1 = 0.0059$, $k_2 = 0.00034$	0.9988	0.0286
		TD	$k_1 = 0.0089$, $k_2 = 0.00016$	0.9982	0.0391
		SD^{TS}	$k_1 = 0.0092$, $k_2 = -0.0003$	0.9981	0.0712
5	Proposed model 2	OSD	$a = 1.5623$, $b = 0.01355$ $n = 1.2312$, $k = 0.0076$	0.9991	0.0032
		TD	$a = 1.4567$, $b = 0.02458$ $n = 1.5698$, $k = 0.0088$	0.9992	0.0098
		$\mathbf{SD^{TS}}$	$\mathbf{a = 1.2999, b = 0.02369}$ $\mathbf{n = 1.355, k = 0.0092}$	**0.9996**	**0.0019**

Values in bold indicate best-suited model apparent rise in fat and ash content found in this study might be attributed to the elimination of moisture, which tends to raise nutrient concentrations and increased nutritional density of products, with ash being one of the nutrients. Amaranth (Amin et al. 2021) and drumstick leaves (Deepa and Kattimani 2021) were dried with similar results.

Effect of different drying processes on TPC, TFC, and antioxidant activity

Biochemical analysis was carried out on OSD, TD, and SD^{TS} samples and were evaluated for their antioxidant activities and TPC and TFC values. Fresh samples had an antioxidant activity of 25.55 ± 3.12 μ mol of TE/gm of sample. In all cases, the antioxidant activity reduced considerably, and this was also noticed during drying of turmeric slices (Lakshmi et al. 2019). As demonstrated in Fig. 10, the TPC and TFC values decreased significantly during drying. This result could be attributed to bound phenolic compounds disengaging from cellular components and releasing free phenolic compounds (Saikia et al. 2022a; Krishnan et al. 2020).

Effect of drying on rehydration characteristics of dhekia

The rehydration characteristics of dhekia fern samples were analyzed in terms of their ability to regain original shape. This characteristic is expressed in the form of rehydration ratio (RR) and coefficient of rehydration (CR) in rehydrated samples. The rehydration ratio increased as the drying air temperature decreased (Table 5). The lower rehydration ratio in case of SD^{TS} may probably be due to cellular breakdown of the fern during drying (Bishnoi et al. 2020). Rehydration ratio increased in the range of 6 to 9.5 percent with time of rehydration from 5 to 15 min for all the drying methods. A similar trend like R_R was noticed with maximum CR (0.806) for TD. Thus, it clearly indicated that drying methods affects the rehydration ratio and coefficient of rehydration.

Conclusion

The current research focused on the development of low-cost thermal storage integrated solar dryer (SD^{TS}). The following conclusions of the work has been drawn as follows:

- The temperature inside the SD^{TS} ranged from 44 to 73 °C whereas temperature in the solar dryer without thermal storage ranged from 32 to 62 °C, respectively.
- The product moisture content was reduced from 75.55 ± 2.01 percent to 3.80 ± 0.51 in 5.5 h in solar dryer with TES and in solar dryer without TES in 7.5 h drying time.
- The developed drying kinetic models suits best for dhekia dried in SD^{TS}.

Table 4 Proximate analysis of dhekia fern dried using various methods

Dhekia fern	Fresh	OSD	TD	SD^{TS}
Protein (%)	$11.01 \pm 0.84^{a,p}$	$7.59 \pm 0.25^{a,q}$	$8.39 \pm 0.68^{a,q}$	$9.61 \pm 0.84^{a,r}$
Fat (%)	$7.99 \pm 0.40^{b,p}$	$8.23 \pm 0.39^{a,p}$	$8.11 \pm 0.48^{a,p}$	$8.66 \pm 0.32^{a,p}$
Ash (%)	$2.49 \pm 0.37^{c,p}$	$9.99 \pm 1.11^{b,q}$	$13.25 \pm 0.98^{b,r}$	$13.25 \pm 0.96^{b,r}$
Carbohydrate (%)	$76.29 \pm 6.11^{d,p}$	$59.39 \pm 5.22^{c,q}$	$66.58 \pm 6.53^{c,r}$	$68.24 \pm 5.98^{c,r}$

Values with different letters in the same column (a–d) are significantly different ($p < 0.05$) from each other. Values with different letters in the same row (p–r) are significantly different ($p < 0.05$) from each other. Results were presented as means ± standard deviation of three replicates

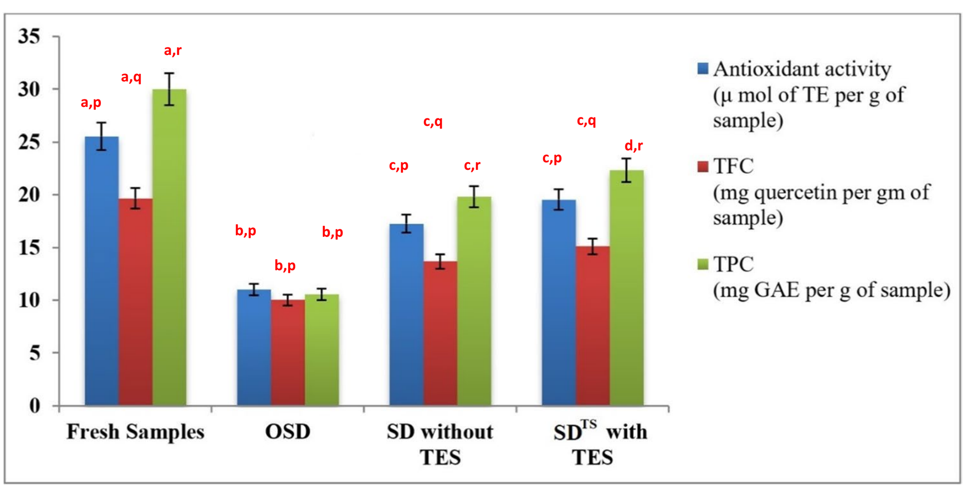

Fig. 10 TPC, TFC, and antioxidant activity as a function of drying techniques. Values with different letters in the (fresh samples to SD^{TS}) (a–c) are significantly different ($p < 0.05$) from each other. Values with different letters in the same quality parameters (column) (p–r) are significantly different ($p < 0.05$) from each other. Results were presented as means ± standard deviation of three replicates

Table 5 Experimental data on rehydration ratio

Drying methods	W_1 (g)	W_2 (g)		R_R (gm/gm)		CR	
		5 min	15 min	5 min	15 min	5 min	15 min
OSD	1	4.889	5.242	4.889	5.242	0.614	0.659
TD	1	5.318	5.766	5.318	5.766	0.744	0.806
SD^{TS}	1	5.019	5.426	5.019	5.426	0.669	0.723

- Exergy efficiency of the SD^{TS} was estimated to be ranging between 35 and 75%, respectively.
- Quality analysis was performed for fresh dhekia and dried dhekia. Antioxidant activity for the fresh samples, samples dried in SD^{TS} and OSD were 25.55, 19.55, and 10.99 μ mol of TE/gm of sample, respectively.
- Developed solar dryer with TES benefits rural community of North Eastern India.

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Author contribution Deepanka Saikia: writing original draft, review, and edit. Prakash Kumar Nayak: supervision, conceptualization, writing original draft, review, and edit. K. Radha Krishnan: supervision nd formal analysis. Rajesh Kondareddy: reviewed and edit. D.V.N. Lakshmi: review, edit, and data analysis.

Data availability The datasets generated and analyzed during this study are available from the corresponding author on reasonable request.

Declarations

Ethics approval This is not applicable.

Consent to participate Informed consent was obtained from all individual participants included in the study.

Consent to publish This is not applicable.

Competing interests The authors declare no competing interests.

References

Agarwal A, Sarviya RM (2016) An experimental investigation of shell and tube latent heat storage for solar dryer using paraffin wax as heat storage material. Eng Sci Technol, Int J 19(1):619–631. https://doi.org/10.1016/j.jestch.2015.09.014

Akbulut A, Durmuş A (2010) Energy and exergy analyses of thin layer drying of mulberry in a forced solar dryer. Energy 35(4):1754–1763. https://doi.org/10.1016/j.energy.2009.12.028

Amin SFM, Karim R, Yusof YA, Muhammad K (2021) Effects of Enzymatic Liquefaction, Drying Techniques, and Wall Materials on the Physicochemical Properties, Bioactivities, and Morphologies of Zinc-Amaranth (Amaranthus viridis L.) Powders. Inter J Food Sci. https://doi.org/10.1155/2021/1819104

AOAC (1984) Official methods of analysis. Association of Official Analytical Chemist, Washington, 12th Edn., p.1141

Archana GN, Pradeesh S, Chinmayee MD, Mini I, Swapna TS (2012) Diplazium esculentum: a wild nutrient-rich leafy vegetable from Western Ghats. InProspects in bioscience: Addressing the issues; 293–301. Springer, India, https://doi.org/10.1007/978-81-322-0810-5_35

Arunsandeep G, Lingayat A, Chandramohan VP, Raju VR, Reddy KS (2018) A numerical model for drying of spherical object in an indirect type solar dryer and estimating the drying time at different moisture level and air temperature. Int J Green Energy 15(3):189–200. https://doi.org/10.1080/15435075.2018.1433181

Bhardwaj AK, Kumar R, Kumar S, Goel B, Chauhan R (2021) Energy and exergy analyses of drying medicinal herb in a novel forced convection solar dryer integrated with SHSM and PCM. Sustain Energy Technol Assess 45:101119. https://doi.org/10.1016/j.seta.2021.101119

Bishnoi S, Chhikara N, Singhania N, Ray AB (2020) Effect of cabinet drying on nutritional quality and drying kinetics of fenugreek leaves (*Trigonella foenum-graecum L.*). J Agric Food Res 2:100072. https://doi.org/10.1016/j.jafr.2020.100072

Chowdhury MM, Bala BK, Haque MA (2011) Energy and exergy analysis of the solar drying of jackfruit leather. Biosyst Eng 110(2):222–9. https://doi.org/10.1016/j.biosystemseng.2011.08.011

Deepa J, Kattimani DR, Nithyashree K (2021) Nutritional composition of sun and shade dried form of drumstick leaves (Moringa oleifera). J Pharmacogn Phytochem 10(1):2523–2525

Demir S, Korukluoglu MA (2020) comparative study about antioxidant activity and phenolic composition of cumin (Cuminum cyminum L) and coriander (*Coriandrum sativum L.*). Indian J Tradit Knowl (IJTK) 19(2):383–93

El-Sebaii AA, Shalaby SM (2017) Experimental investigation of drying thymus cut leaves in indirect solar dryer with phase change material. J Solar Energy Eng 139(6). https://doi.org/10.1115/1.4037816

Gordon RG (2000) Criteria for choosing transparent conductors. MRS Bull 25(8):52–57

Junejo JA, Gogoi G, Islam J, Rudrapal M, Mondal P, Hazarika H, Zaman K (2018) Exploration of antioxidant, antidiabetic and hepatoprotective activity of Diplazium esculentum-a wild edible plant from North Eastern India. Future J Pharm Sci 4(1):93–101. https://doi.org/10.1016/j.fjps.2017.10.005

Kaleta A, Górnicki K (2010) Some remarks on evaluation of drying models of red beet particles. Energy Convers Manage 51(12):2967–2978. https://doi.org/10.1016/j.enconman.2010.06.040

Karami H, Kaveh M, Golpour I, Khalife E, Rusinek R, Dobrzański B, Gancarz M (2021) Thermodynamic evaluation of the forced convective hybrid-solar dryer during drying process of rosemary (*Rosmarinus officinalis L.*) leaves. Energies 14(18):5835. https://doi.org/10.3390/en14185835

Karthikeyan AK, Murugavelh S (2018) Thin layer drying kinetics and exergy analysis of turmeric (*Curcuma longa*) in a mixed mode forced convection solar tunnel dryer. Renew Energy 128:305–312. https://doi.org/10.1016/j.renene.2018.05.061

Kline SJ, McClintock FA (1953) Describing uncertainties in single-sample experiments. ASME Mech Eng 75:3–8

Kondareddy R, Sivakumaran N, Radhakrishnan K, Nayak PK (2020) Performance analysis of solar tunnel dryer with thermal storage and photovoltaic system for drying star fruit. InIOP Conference Series: Earth and Environmental Science; 463, 012138). IOP Publishing

Kondareddy R, Sivakumaran N, Radha Krishnan K, Nayak PK, Sahu FM, Singha S (2021) Performance evaluation and economic analysis of modified solar dryer with thermal energy storage for drying of blood fruit (*Haematocarpus validus*). J Food Process Preserv 45(9):e15653. https://doi.org/10.1111/jfpp.15653

Kondareddy R, Natarajan S, Radha Krishnan K, Saikia D, Singha S, Nayak PK (2022) Performance evaluation of modified forced convection solar dryer with energy storage unit for drying of elephant apple (Dillenia indica). J Food Process Eng 45(1):e13934. https://doi.org/10.1111/jfpe.13934

Koniyo Y, Lumenta C, Olii AH, Mantiri RO, Pasisingi N (2021) Nutrition of local wild edible fern (Diplazium esculentum) leaves. InIOP Conference Series: Earth and Environmental Science 637(1):012008. IOP Publishing, https://doi.org/10.1088/1755-1315/637/1/012008

Krishnan S, Sivaraman B (2017) Experimental investigations on thermal storage in a solar dryer. International Energy Journal 17(1):23–36

Krishnan KR, Rayaguru K, Nayak PK (2020) Ultra-sonicated vacuum drying's effect on antioxidant activity, TPC, TFC and color of elephant apple slices. Food Biosci 36:100629. https://doi.org/10.1016/j.fbio.2020.100629

Kumar S, Mahanand SS, Kumar P (2017) Mathematical modelling and experimental analysis of broccoli (*Brassica oleracea I.*) in tray dryer. J Pharmacogn Phytochem 6(6):1049–52

Lakshmi DV, Muthukumar P, Layek A, Nayak PK (2018) Drying kinetics and quality analysis of black turmeric (*Curcuma caesia*) drying in a mixed mode forced convection solar dryer integrated with thermal energy storage. Renew Energy 120:23–34. https://doi.org/10.1016/j.renene.2017.12.053

Lakshmi DV, Muthukumar P, Layek A, Nayak PK (2019) Performance analyses of mixed mode forced convection solar dryer for drying of stevia leaves. Sol Energy 188:507–518. https://doi.org/10.1016/j.solener.2019.06.009

Lakshmi DV, Muthukumar P, Nayak PK (2021) Experimental investigations on active solar dryers integrated with thermal storage for drying of black pepper. Renew Energy 167:728–739. https://doi.org/10.1016/j.renene.2020.11.144

Morris A, Barnett A, Burrows O (2004) Effect of processing on nutrient content of foods. Cajanus 37(3):160–164

Mugi VR, Chandramohan VP (2021) Energy and exergy analysis of forced and natural convection indirect solar dryers: estimation of exergy inflow, outflow, losses, exergy efficiencies and sustainability indicators from drying experiments. J Clean Prod 282:124421. https://doi.org/10.1016/j.jclepro.2020.124421

Nakhuru KS, Lokho A, Barman M, Das J, Dwivedi SK (2021) Evaluation of vitamin C of ethno-wild edible plants in Northeast India. Plant Sci Today 8(3):473–481. https://doi.org/10.14719/pst.2021.8.3.1100

Nayak PK, Rayaguru K, Radha KK (2017) Quality comparison of elephant apple juices after high pressure processing and thermal treatment. J Sci Food Agric 97(5):1404–1411. https://doi.org/10.1002/jsfa.7878

Nayak PK, Chandrasekar CM, Kesavan RK (2018) Effect of thermosonication on the quality attributes of star fruit juice. J Food Process Eng 41(7):e12857. https://doi.org/10.1111/jfpe.12857

Nukulwar MR, Tungikar VB (2021) A review on performance evaluation of solar dryer and its material for drying agricultural products. Mater Today: Proceed 46:345–349. https://doi.org/10.1016/j.matpr.2020.08.354

Özdemir M, Devres YO (1999) The thin layer drying characteristics of hazelnuts during roasting. J Food Eng 42(4):225–233. https://doi.org/10.1016/S0260-8774(99)00126-0

Pangavhane DR, Sawhney RL, Sarsavadia PN (2002) Design, development and performance testing of a new natural convection solar dryer. Energy 27(6):579–590. https://doi.org/10.1016/S0360-5442(02)00005-1

Puente-Díaz L, Ah-Hen K, Vega-Gálvez A, Lemus-Mondaca R, Scala KD (2013) Combined infrared-convective drying of murta (Ugni molinae Turcz) berries: kinetic modeling and quality assessment. Dry Technol 31(3):329–38. https://doi.org/10.1080/07373937.2012.736113

Rabha DK, Muthukumar P, Somayaji C (2017) Energy and exergy analyses of the solar drying processes of ghost chilli pepper and ginger. Renew Energy 105:764–773. https://doi.org/10.1016/j.renene.2017.01.007

Rahman MM, Mekhilef S, Saidur R, Mustayen Billah AG, Rahman SM (2016) Mathematical modelling and experimental validation of solar drying of mushrooms. Int J Green Energy 13(4):344–351. https://doi.org/10.1080/15435075.2014.952425

Ranganna S (1986) Handbook of analysis and quality control for fruit and vegetable products. Tata McGraw-Hill Education 342.

Rani P, Tripathy PP (2021) Drying characteristics, energetic and exergetic investigation during mixed-mode solar drying of pineapple slices at varied air mass flow rates. Renew Energy 167:508–519. https://doi.org/10.1016/j.renene.2020.11.107

Saikia D, Nayak PK, Krishnan KR, Kondareddy R, Lakshmi DVN (2022a) Development of indirect type solar dryer and experiments for estimation of drying parameters of dhekia (Diplazium esculentum). Mater Today: Proceed 56:774–780. https://doi.org/10.1016/j.matpr.2022.02.255

Saikia D, Nayak PK, Sivakumaranb N, Kondareddy R, Krishnan KR, Dutta J (2022) Latent heat storage system based mixed mode indirect solar dryer for drying myrobalan. J Nano-Electron Phys 14:03022-1–03022-5. https://doi.org/10.21272/jnep.14(3).03022

Sami S, Etesami N, Rahimi A (2011) Energy and exergy analysis of an indirect solar cabinet dryer based on mathematical modeling results. Energy 36(5):2847–2855. https://doi.org/10.1016/j.energy.2011.02.027

Sharma A, Tyagi VV, Chen CR, Buddhi D (2009) Review on thermal energy storage with phase change materials and applications. Renew Sustain Energy Rev 13(2):318–345. https://doi.org/10.1016/j.rser.2007.10.005

Srivastava SK, Rao JAP (2019) Diplazium esculentum (Retz.) Sw. multipurpose fern: ethno-taxonomical review. Sci Technol Dev 8(9):336–342

Vásquez J, Reyes A, Pailahueque N (2019) Modeling, simulation and experimental validation of a solar dryer for agro-products with thermal energy storage system. Renewable Energy 139:1375–1390. https://doi.org/10.1016/j.renene.2019.02.085

Vijayan S, Arjunan TV, Kumar A (2016) Mathematical modeling and performance analysis of thin layer drying of bitter gourd in sensible storage based indirect solar dryer. Innovative Food Sci Emerg Technol 36:59–67. https://doi.org/10.1016/j.ifset.2016.05.014

White GM, Ross IJ, Poneleit CG (1981) Fully-exposed drying of popcorn. Transact ASAE 24(2):466–0468. https://doi.org/10.13031/2013.34276

Zomorodian A, Moradi M (2010) Mathematical modelling of forced convection thin layer solar drying for Cuminum cyminum. J Agric Sci Technol 12(4):401–8

Zoukit A, El Ferouali H, Salhi I, Doubabi S, Abdenouri N (2019) Takagi Sugeno fuzzy modeling applied to an indirect solar dryer operated in both natural and forced convection. Renewable Energy 133:849–860. https://doi.org/10.1016/j.renene.2018.10.082