Influences of a novel cylindrical solar dryer on farmer’s income and its impact on environment

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Abstract
Poor grain drying facilities, along with the burden of drying cost, bound the farmers to market their produce soon after harvest. Thus, this research paper intends to study the influences of a novel cylindrical solar-assisted dryer on farmers’ income and its impact on the environment. The paper also presents the design and fabrication of a drying system for maize cobs using non-conventional solar energy. The performance of the solar-assisted drying system was also investigated for drying of yellow dent maize cobs. As a very energy-intensive post-harvest process, drying consumes a lot of electricity, which is usually provided by conventional energy. Here, solar dryers are the perfect solution in terms of efficiency, uniform drying of agricultural food products, less drying time, increased marketability of agricultural products, and reducing the load on farmer’s pocket for drying. With a high internal rate of return of 66 percent, the designed dryer proved to be technically and economically viable. Compared to open sun drying, the solar drying system produced better quality and drying time results. Compared to other models, the Midilli model fits the experimental maize drying data better, with a coefficient of determination of $R^2 = 0.89729$. Energy analysis inferred savings of 1352.97 kWh electrical energy and 128.18 liters of diesel fuel plus a reduction of 1.22 t CO₂ per annum can be achieved by using this dryer.

Keywords Cylindrical solar dryer · Maize · Performance evaluation · Economic evaluation · Mathematical modeling · Carbon footprint

Symbols and Abbreviations
- $T_2$ safe drying temperatures
- $t_d$ expected drying time
- $M$ dryer capacity per batch
- $C_p$ specific heat of product maize
- $\lambda$ latent heat of vaporization
- $I_t$ solar insolation, kw/h/m² day
- $H_{R_1}$ humidity ratio at the starting, kg/kg dry air
- $H_{R_2}$ humidity ratio at the end, kg/kg dry air
- $g$ gravity, m/s²
- $\rho_i$ density of inlet air
- $X_t$ the amount of moisture at any given time $t$
- $X_o$ initial moisture content
- $\eta_{ed}$ efficiency of electrically operated dryer
- $\eta_{dd}$ efficiency of diesel-operated dryer
- Wb weight basis
- M/s messers
- SWG standard wire gauge
- H.R. high resistance
- PV photovoltaic
- D.C. direct current
- G.I. galvanized iron
- USD United States dollar
- M.C. moisture content
- $\rho_e$ density of exit air
- Wb wet basis
- $E_Y$ carbon emissions, t/year
- $K$, $a$, $b$, $n$ drying constants
- $\eta_{dd}$ efficiency of diesel-operated dryer

Introduction
Solar drying has long been one of the most fundamental, energy-efficient, cost-effective, and environmentally beneficial methods for preserving agricultural products (Sharma et al. 2019; Rathore et al. 2018). The potential of...
the solar drying process to minimize waste, increase shelf-life of products, and improve the product quality with all its nutrients intact add on to the pros of being a renewable source. Because drying is necessary for efficient grain storage, this food preservation method helps reduce the cost of packaging, storage, and transportation by significantly reducing product weight and volume (Vijayavenkataraman et al. 2012). Renewable energy sources are ideal for energy conservation, as they conserve energy while maintaining the product’s natural flavor (Sharma et al. 2020a; More et al. 2021). The majority of agricultural items are dried at temperatures between 45 and 60 °C (Sharma et al. 2018).

For efficient drying of agricultural food products, the best and affordable means is using the sun’s energy, which provides the temperature in the required range and does not compromise in the quality of the dried product. Solar energy can be utilized to heat air to the temperature range required for drying agricultural products efficiently and affordably without compromising the end product’s quality (Sharma et al. 2020b). India’s average solar radiation accessible is 5 kW/m²/day for 250–300 days per year with around 8–10 h of sunshine (Rathore and Sankhla 2020). This opens up many possibilities for using solar energy to dry agricultural products.

Maize is one of the most significant cereal crops globally, ranking third in terms of area and production in India after rice and wheat. The importance of maize lies in its wide variety of uses. Most of the maize crop produced is dried for its utilization all year round as a poultry feed and for human consumption in the form of maize flour, maize dalia, and other value-added products, and only about a quarter of the maize produced is consumed directly (Murdia et al. 2016).

Maize must be dried for 10–15 days (if open sun drying is done) after harvesting to lower moisture levels to 13–14 percent. Produce prices will be lower if the moisture content is higher (Bhardwaj et al. 2019). Currently, a substantial portion of maize production in India is sun dried which is accompanied by various problems of drying like much time taking process, uneven drying, deterioration in product quality, exposure to dust and pests, and improper drying practices reduce the quality of grains (Patel et al. 2013). Field dried maize cobs still need drying to an ideal moisture content for storage or further processing, and it is very difficult to reduce its moisture content after field drying and also requires much energy (Abate et al. 2015).

The design and development of the cylindrical and portable solar dryer is to meet these drying requirements and is a step toward improvement in drying practices.

Bola et al. (2013) suggested various parameters for a batch in-bin maize drier on a modest scale with a total cost of 375 USD. Abed (2009) designed and developed a maize drying system using solar energy with a V-groove collector and observed high energy gain at an angle tilt of 45°. Asemu et al. 2020 studied the drying characteristics of maize grain in a solar bubble dryer using statistical models. It was found that about 24 h were required to dry maize grains from 29 to 13% (wb) in a thin layer and 39 h were required to dry maize grains for the same reduction in moisture content in a thick layer at 30 °C temperature inside the dryer. Using a thin-layer drying model, the results showed better with the diffusion approach. Ntwali et al. (2021) assessed the performance of an inflatable solar dryer for maize and found that direct sun drying reduced aflatoxin concentration from 569.6 to 345.5 g kg⁻¹ while drying with an inflatable solar dryer reduced the same to 299.2 μg kg⁻¹. Sanghi et al. (2018) ran a CFD simulation of maize drying in a solar dryer with natural convection. The model simulated the dryer’s performance with 32% less moisture removal in overcast weather conditions as compared to the simulated fair-weather condition case. Thus, a significant amount of effort has been done to the drying of agricultural products, but still, there is a research gap in studying the influences of solar drying on farmer’s income and its impact on the environment. The proposed design of a solar dryer is an attempt toward this. The novelty of the dryer lies in the material used for its fabrication. A polycarbonate sheet of 6-mm thickness was used. The air gap in between the polycarbonate sheet acts as an insulator for heat, thereby reducing heat losses from within the dryer. Also, maize drying in this way increases its grind ability so that it can be easily used to make value-added items like soups, corn puddings, and popcorn.

The portable cylindrical solar drier was created with smallholder farmers in mind, allowing them to confidently, conveniently, and affordably dry any agricultural product to a long-term storage moisture content regardless of weather circumstances. The dryer prototype is being tested for drying maize cobs on-farm to reduce post-harvest losses for farmers and thereby boost their income.

Methodological framework

The dryer prototype is being tested for drying maize cobs on-farm, with the goal of reducing post-harvest losses for farmers and thereby boosting their income. The materials used for the fabrication of the solar drying system are reasonable and easily obtainable in the local market. The experiment was performed in the month of May by drying maize cobs in the designed solar drying system and in open sun drying for comparison of the drying results.

Specifications of the designed system

The proposed structure comprises of a cylindrical drying bin, a Flat plate collector (FPC), a PV-powered DC fan of 1.5 W, a PV panel of 10Wp, an insulated duct, and a
chimney. A flat plate collector (FPC) is used for heating of air. The drying chamber is then supplied with hot air via an insulated duct. The drying chamber is made in a cylindrical shape to ensure uniform drying of the product. The drying chamber is made of a translucent multiwall polycarbonate sheet (MWPC) which has high heat retention and thermal insulating properties with good solar gain as compared to the material used for dryer construction in the existing solar dryers. The MWPC sheet provides the advantage of itself acting as a solar collector. Furthermore, the dryer is fabricated in such a way that only 3/4th area is covered by MWPC sheet absorbing solar radiations from the south as well as east and west side and 1/4th area is insulated to prevent radiation loss from its north side. A PV-powered DC fan is installed at the bottom of the drying chamber to efficiently circulate the incoming hot air at a steady speed within the drying chamber as needed and eliminate the humidity. An exhaust vent in the form of the chimney is attached to remove the moist air from the drying bin. The product to be dried is placed in two fixed circular wire mesh trays in the drying chamber. The wheels attached provides portability to the whole system so that it can be easily installed on the farms also.

Using the oven method at 110 °C for 24 h, the initial moisture content of maize cobs was assessed (Singh and Gaur 2020). The moisture content of 28 percent (wb) was used as a reference. A solarimeter was used to measure the overall solar irradiance falling on a plane surface (uncertainty: ±0.5%, make: M/s. Surya Solar Systems, Ahmedabad). The measurement of all the trays, ambient air temperature, inlet temperature of dryer, and exit air temperature was done using dataTaker DT82E (uncertainty: 0.7 percent, make: Thermo Fisher Scientific Australia Pvt. Ltd, Australia) with a range of temperature -45 to 70 °C. An electronic balance was used to measure weight (make: Adair Dutt and Co. Pvt. Ltd.).

Table 1 lists the dryer’s design constraints, and Fig. 1 depicts the suggested design of a cylindrical shallow bed solar dryer.

Table 1 Considerations used for the design of solar drying system

| S. no. | Parameters                        | Specifications                  |
|--------|-----------------------------------|---------------------------------|
| 1.     | Drying material                   | Maize cobs (Zea mays)           |
| 2.     | Variety                           | Yellow dent maize               |
| 3.     | Density of product used for drying| 671 kg/m³                       |
| 4.     | Moisture content of product at the time of harvest | 28% (wb)                    |
| 5.     | Anticipated moisture content after drying of the product | 13% (wb)                    |
| 6.     | Average temperature of ambient air (Ta) | 27 °C                          |
| 7.     | Loading rate (Lr)                 | 50 kg per batch                 |
| 8.     | Drying temperature (Td)           | 60 °C                           |
| 9.     | Relative humidity (RH)            | 50%                             |
| 10.    | Wind velocity (Vw)                | 0.25–0.3 m/s                    |
| 11.    | Collector tilt angle              | 27°                             |

The dimensions of the proposed cylindrical dryer are mentioned in Table 2 below.

Main components of the developed system

The portable shallow bed solar drying system consists of following the components:

1. FPC solar collector

A flat plate solar collector is used to heat air by using solar energy. The schematic diagram of the flat plate collector is provided in Fig. 2 below.

Glass wool insulation

2. Drying chamber

The collector is situated alongside the drying chamber, which is where the product is dried. The hot air in the drying bin soaks up moisture from the product and exhausts it to the surrounding area via forced convection. Two trays were placed in this chamber for placing of product for drying. The drying chamber is in a cylindrical shape with a diameter of 1.12 m. The height of the bin is 1 m. The three-fourth surface area of the cylinder is covered with a UV polycarbonate sheet of 6-mm thickness.

Polygal multiwall polycarbonate sheet

It is a translucent sheet made of a special engineered thermoplastic that has excellent mechanical, optical, and thermal qualities. This material’s versatility allows it to be used in a variety of engineering applications. A 6-mm thickness sheet having a weight of 1300 g/m² is used.
The bin had a circular inlet vent made of insulated G.I. sheet material with a 75-mm diameter for the input of hot air from the collector. The drying bin has a slight cone-shaped top covering and a cylindrical outlet vent for the chimney, both made of G.I. sheet. An insulated gate is constructed (1 m × 0.80 m) to load wet product and unload dried product out from the drying chamber. One-fourth surface area of the cylinder is made insulated with thermocol sheet (north side from front view) and covered on the inner side with G.I. sheet and outer side with polycarbonate sheet to prevent heat loss. H.R. thermal sheet was used to make the gate airtight. The drying chamber’s bottom is provided with a small PV-operated DC fan of 12 V to extract hot air from the flat plate collector at more speed through forced convection mode. This fan can be made off if much heat is not required in the drying chamber and the heat through the transparent polycarbonate walls is sufficient enough to dry the product to the desired level.

**Drying characteristics of maize drying**

The drying characteristics of dehusked and silk removed dent maize cobs dried in a solar-assisted bin type drying system in terms of moisture removal (percent wb), drying rate (g/h-g of bone-dry matter), and moisture ratio were calculated and correlated with the findings of drying under the open sun.
Zero-load testing and complete-load testing

The product’s drying rate and the dryer’s drying efficiency determine the thermal evaluation of the proposed system. The drying system’s performance was assessed using both zero-load and complete-load testing. The temperature profile was evaluated using a no-load test, which comprised the air temperature inside the drying bin, ambient temperature, air inlet-outlet temperature, and solar insolation. The evaluation of the solar drying system in fully loaded condition was done by loading the dryer to its maximum designed capacity and then obtaining the temperature profile for it by placing the sensors at various points of the drying system (same as in the no-load test)

Data analysis

For the estimation of solar drying curves, five independent mathematical models were applied, namely the Midilli model, Page model, Newton model, Henderson and Pabis model, and Modified page model. The root mean square error (RMSE) (Mewa et al. 2019) and the coefficient of determination ($R^2$) (Chicco et al. 2021) were calculated using regression analysis. These were employed for the comparison of models and for the selection of the model of best fit. Regression analysis was carried out using Microsoft Excel (2019 version) software for estimating the drying curves between moisture ratios and drying time. The root mean square error (RMSE) represents the difference between the expected and experimental results. $R^2$-square shows how much data is scattered around the fitted regression line. The model with the best fit is considered to have the highest $R^2$-square and lowest RMSE values (Kumar and Saha 2021). The parameters were determined by using the following Eqs. (1) and (2):

$$R^2 = 1 - \left( \frac{\sum_{i=1}^{N} (MR_{exp,i} - MR_{pre,i})^2}{\sum_{i=1}^{N} (MR_{i,exp,mean} - MR_{exp,i})^2} \right)$$ (1)

### Table 2: Dimensions of the cylindrical solar dryer

| S. no. | Parts of the developed system | Dimensions | Material used for construction |
|-------|-------------------------------|------------|--------------------------------|
| 1.    | Drying bin                    | Ht. of base cylinder: 1 m Dia. of base cylinder: 1.12 m Vol. of base cylinder: 0.99 m$^3$ Ht. of base cone: 0.1 m Dia. of top cone: 1.12 m Vol. of base cone: 0.033 m$^3$ Total vol. of drying chamber = Vol. of cylinder + vol. of cone = 1.023 m$^3$ | Multiwall polycarbonate sheet of thickness 6 mm. (covering only 3/4th surface area of cylinder) |
| 2.    | Insulation for door           | Thickness: 0.2 m Area: 1 m $\times$ 0.8 m | Inner sheet: G.I Center: thermocol Outer sheet: MWPC |
| 3.    | Insulation for the bottom of the drying chamber | Thickness: 0.2 m Area: 1 m$^2$ | Inner sheet: aluminum Center: thermocol Outer sheet: G.I |
| 4.    | Wire mesh trays               | Dia.: 1.12 m Depth: 0.18 m Perforation size: 20 $\times$ 20 m$^2$ | M.S. 14 gauze |
| 5.    | Chimney                       | Ht.: 0.457 m Dia.: 0.205 m Outlet vent area: 0.785 $\times$ (0.203)$^2$ m$^2$ | G.I. sheet |
| 6.    | Flat plate collector          | Ht.: 1.76 m Width: 1.15 m Area: 2.02 m$^2$ | Absorber: aluminum (0.05-cm thick) Receiver: glass (0.5-cm thick) |
| 7.    | Insulated connecting duct     | Length: 0.408 m Inlet vent area: 0.785 $\times$ (0.075)$^2$ m$^2$ | Inner sheet: aluminum Center: thermocol Outer sheet: G.I. sheet |
where $MR_{\text{exp},i}$ is the experimental moisture ratio, $MR_{\text{pre},i}$ is the predicted dimensionless moisture ratio, $MR_{\text{exp,mean},i}$ is the mean value of the experimental moisture ratio, $N$ is the number of observation, and $n$ is the number of constants.

**CO₂ emission estimation**

The use of fossil fuels is a major cause of the emission of CO₂ in the atmosphere. Thus, the electricity generated from non-conventional sources is a major contributor toward global warming. Moreover, energy consumption is a major contributor to the carbon footprint. One of the ways by which one can protect our environment is by reducing its carbon footprints. The solution to this biggest problem which our world is facing today is switching to a renewable source of energy. Solar energy has the potential to generate power with zero emissions. Equation (3) can be used to calculate CO₂ emission reduction (EY) (Ganesan et al. 2015).

$$E_Y = AES \times E.F.\times \text{E.F.}$$

where AES is the annual energy saving for electricity, E.F. is the emission factor for electricity (MWh/year) 0.9.

**Energy analysis**

One of the important parameters used for the analysis of energy in drying is energy consumption (Lawrence et al. 2019). The energy consumption in the developed solar dryer is calculated by evaluating the total quantity of heat required for the removal of the desired moisture content. This heat output is used for calculating the heat input in an electrically...
Table 3 Designed parameters for the fabrication of a solar drying system

| S. no. | Parameters                        | Formulas used | Reference                  | Value                        | Assumptions used                                                                 |
|--------|-----------------------------------|---------------|----------------------------|-------------------------------|----------------------------------------------------------------------------------|
| 1.     | Dryer dimensions                  | Volume = base area × height | Abed (2009)                | 1-m diameter and 1-m height. (Considering two trays for loading of the product of height 0.09-m with gaps of 0.27 m for effective circulation gives a total height of the drying chamber as 1 m) | Bulk density of maize = 671 kg/m³, dryer diameter = 1 m |
| 2.     | Quantity of water to be removed, $M_R$ | $M_R = M \left[ \frac{Q_1 - Q_2}{1 - Q_2} \right]$ | Sharma et al. (2020a)       | 8.62 kg                      | $Q_1$: initial moisture content, $Q_2$: maximum desired final moisture content (13%) |
| 3.     | Total energy required, $H_r$      | $H_r = M C_p \Delta T + M_R \lambda$ | Agrawal and Sarviya (2016)  | 26028 kJ or 2366.18 kJ/h     | $\lambda = 2260$ kJ/kg, $C_p = 1.8$ kJ/kg °C                                    |
| 4.     | Collector area required, $A_c$    | $A_c = \frac{0.980}{\eta}$ | Tomar et al. (2017)         | 2.5 m²                       | $Q_r$: energy required per hour for drying of product (kJ/h), $I_p$: annual average is 6.16 kWh/m²/day for Udaipur, Raj. (India) |
| 5.     | Quantity of air required, $Q_a$   | $Q_a = \left[ \frac{M_R}{H_r - H_1} \right]$ | Hajar et al. (2017)         | 1436.6 kg                    | $\eta$: collector efficiency, % (assumed) = 25%                                  |
| 6.     | Air mass flow rate                | $Q_a$ per unit time = $\frac{M_R}{t_d}$ | Hajar, Rachid, and Najib (2017) | 0.78 kg/h or 0.00022 kg/s    | $H_r$ = 0.018 kg/kg dry air, $H_1$ = 0.024 kg/kg dry air (As determined from the psychometric chart under normal temperature and 101.325 kPa barometric pressure when the product's temperature increases to 50 °C) |
| 7.     | Design of chimney                 | $D_1 = H \times g \times (\rho_i - \rho_e)$ | Abed (2009)                 | 0.22 kg/m²/s                  | $g = 9.81$ m/s², $\rho_i = 1.14$, $\rho_e = 1.09$                               |
|        | (i) Draft produced, $D_1$        |               |                            |                               | Assumed height of the chimney $H$ is 0.457 m                                      |
|        | (ii) Actual draft, $D_2$          | Assumed as 75% of this draft. |                           |                               |                                                                                  |
|        | (iii) Velocity of exit air through the chimney, $V$ | $V = \sqrt{\frac{2 D_1^2}{\rho e}}$ |               | 0.551 m/s                    |                                                                                  |
|        | (iv) Cross-section area of chimney, $A_{ch}$ | $A_{ch} = \frac{Q}{V_o k}$ |                   | $A_{ch} = \frac{0.022}{0.55 \times 0.55} = 0.054$ m² | $Q$: flow rate through the chimney which is the average value of $V_o$ in both phases in the above equations |
|        | (v) Diameter of chimney, $D_{ch}$ | $D_{ch} = \sqrt{\frac{0.00094 \times 0.01}{3.14}}$ |       | 0.2626 m                    |                                                                                  |
and diesel-operated dryer. By considering the efficiencies of the respective conventional drying systems and heat input in them, energy savings in electrically operated drying system and diesel-operated drying system can be obtained. This shows the benefit of replacing conventional energy sources by non-conventional energy sources.

**Result and discussion**

**Design procedure**

The design was proposed according to steady flow systems with 27 °C ambient temperature (da Silva et al. 2020). Under normal temperature and 101.325 kPa barometric pressure, the original humidity ratio (Hr1) is predicted to be 0.01 kg/kg of dry air by using a psychometric chart. Asemu et al. (2020) state the most reliable drying temperature (T2) required for drying of maize is 40 °C.

The designed parameters for dryer fabrication are listed in Table 3 below.

**Thermal performance**

The data from the no-load and full-load testing were used to analyze the effectiveness of the drying process using a solar drying system.

**Temperature variation during No-load testing**

The performance of the solar dryer under no-load was evaluated to find out the maximal temperature attained inside the dryer. This was useful for predicting the effectiveness of the solar drying system for drying agricultural products.
with respect to drying under the open sun. It was evaluated by measuring solar intensity, ambient temperature, and temperature at different points inside the drying chamber. During no-load testing, the graphs representing solar radiations and temperature profiles at different locations in the drying system are depicted in Fig. 3. Since there was no load in the drying chamber, the system only served as a collector. The tests were carried out from 09:00 to 17:00 h. It was observed that the input temperature within the drying chamber was increased by an average of 49.85 °C when the drying chamber’s walls were heated. The wall is made of polycarbonate sheet, and it acted as an excellent absorber of solar radiation. Its north side insulated gate acted as a perfect insulator to heat losses from the drying chamber. The hourly collector efficiency with regard to time was used to examine the solar collector’s performance. The highest solar radiation at midday was 1116 W/m², and the solar intensity increased until 13:00 h, after which it began to decline. Likewise, the ambient temperature rises during the day and then drops slightly in the evening. Solar radiation values range from 445 to 1116 W/m², with a peak at 13:00 local time.

### Temperature variation during full-load performance

The experimental findings for full-load performance are represented by graphs shown in Fig. 4; 50-kg maize cobs were fed into the system at full capacity. The drying period was found to be roughly 2 days with 11 h of sunshine. Drying was conducted till the desired moisture content was achieved.

Based on the results obtained during the experiment, a temperature above 45 °C was recorded. The rate of weight loss on the first day was higher than on the second day of drying. During times of maximum sun exposure, a rapid rate of weight loss can be observed. Because of the rise in inlet temperature of the air, the rate of heat transfer between the drying air and the maize kernels became greater, thereby increasing the drying rate of maize. The graph showed that the rate of drying increased as the moisture content increased. The drying rate decreased as the moisture content lowered. The variation in weight of maize cobs in the solar drying system as well as drying under open sun son each day is given in Table 4. The results show high drying efficiency in the case of solar drying system as compared to drying under the open sun.

### Variation in moisture content

The moisture ratio of maize cobs varies in the dryer and during drying in the open sun, as shown in Fig. 2. The moisture content of the maize cob dropped from 28.61 percent (wb) to 12.99 percent (wb) after 11 h of drying in the solar dryer which is the required level of moisture content for safe storage of maize. Open sun drying of maize cobs, on the other hand, took 37 h to achieve the moisture content of 12.01 percent (wb) from 28.61 percent (wb), resulting in a net decrease of 8.38 percent (wb).

### Table 4 Variation in weight of maize cobs on each day

| Type of drying          | Drying day (no. of hours) | Mass of product at the start of the day (kg) | Mass of product at the end of the day (kg) | Mass of water evaporated (kg) | Average solar radiation (W/m²) | Daily drying efficiency (%) |
|-------------------------|---------------------------|---------------------------------------------|-------------------------------------------|-------------------------------|-------------------------------|-------------------------------|
| Solar drying system     | 1 (8 h)                   | 50                                          | 43.93                                     | 6.07                          | 767                           | 29.88                         |
|                         | 2 (3 h)                   | 43.93                                      | 41.98                                     | 1.95                          | 795                           | 24.69                         |
|                         | Total moisture evaporated |                                            |                                           |                               | 8.02                          |                               |
| Open sun drying         | 1 (8 h)                   | 50                                          | 46.71                                     | 3.29                          | 752                           | 19.76                         |
|                         | 2 (8 h)                   | 46.71                                      | 43.91                                     | 2.80                          | 714                           | 17.71                         |
|                         | 3 (8 h)                   | 43.91                                      | 42.50                                     | 1.41                          | 698                           | 9.13                          |
|                         | 4 (8 h)                   | 42.50                                      | 41.94                                     | 0.56                          | 771                           | 3.282                         |
|                         | 5 (5 h)                   | 41.94                                      | 41.62                                     | 0.32                          | 705                           | 2.05                          |
| Total moisture evaporated |                           |                                            |                                           |                               | 8.38                          |                               |

### Table 5 An overview of testing of solar dryer

| Initial M.C. (wb) | Final M.C. (wb) | Ambient temp. (°C) | Average dryer temp. (°C) | Drying time (h) | Collector efficiency (%) | Effectiveness factor x |
|-------------------|-----------------|--------------------|--------------------------|----------------|--------------------------|------------------------|
| 28                | 12.64           | 31.0               | 54.6                     | 11             | 60.77                    | 3.07                   |

Ratio of drying rate in a specific mode of dryer to the drying rate in open sun drying
Fig. 5 (a, b, c) Variations of moisture contents, drying rate, drying time, and moisture ratio in solar drying system and drying under the open sun.
time savings of 70.27 percent for solar drying versus open sun drying.

**Difference in drying rate**

The variation in the content of moisture in a specific interval of time was used to assess the drying rate of dent maize cobs. Water evaporation is measured in grams per hour (Agrawal and Sarviya 2016). The average rate of drying dent maize cobs in the solar-assisted dryer was found to be 0.0209 g/h-g of bone-dry matter compared to 0.0068 g/h-g of bone-dry matter in open sun drying.

**Variation of moisture ratio**

The average moisture ratio obtained for the solar-assisted dried maize cobs is 0.419, while the average moisture ratio obtained for the open sun-dried maize cobs is 0.367. The graph of moisture ratio with drying time shows moisture ratio decreases with a rise in drying time. The results obtained were similar to the results obtained by Asemu et al. (2020). An overview of the testing of the solar drying system is presented in Table 5.

The graphs representing the disparity of moisture content, drying rate, and moisture ratio with drying time are plotted for the product in both solar drying and drying under the open sun and are given in Fig. 5 below.

**Data analysis**

Regression analysis was carried out (Table 6) using Excel 2019 software for estimating the drying curves between moisture ratios and drying time. The results were found to be similar with

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**Table 6** The statistical parameters acquired to examine the fit of each model to the observed data during maize drying

| S. no. | Model name                        | Mathematical model                       | Modal constants | $R^2$   | RMSE  |
|-------|-----------------------------------|------------------------------------------|-----------------|---------|-------|
| 1     | Midilli (Agbossou et al. 2016)    | $\frac{X}{X_0} = a \times \exp(-kt^n) + bt$ | $a = 0.98985$   | 0.89729 | 0.09386 |
|       |                                   |                                          | $b = 0.00011$   |         |       |
|       |                                   |                                          | $k = 0.06632$   |         |       |
|       |                                   |                                          | $n = 1.20338$   |         |       |
| 2     | Page (Hashim et al. 2014)         | $\frac{X}{X_0} = \exp(-kt^n)$           | $k = 0.07001$   | 0.89429 | 0.09559 |
|       |                                   |                                          | $n = 1.18535$   |         |       |
| 3     | Newton (Ajala 2018)               | $\frac{X}{X_0} = \exp(-kt)$             | $k = 0.10898$   | 0.88091 | 0.09334 |
| 4     | Henderson and Pabis (Kohli et al. 2018) | $\frac{X}{X_0} = a \times \exp(-kt)$ | $a = 1.05581$   | 0.86989 | 0.10349 |
|       |                                   |                                          | $k = 0.11496$   |         |       |
| 5     | Modified page model (Asiru et al. 2013) | $\frac{X}{X_0} = \exp\left[-\left(kt\right)^n\right]$ | $k = 0.10610$   | 0.89429 | 0.09559 |
|       |                                   |                                          | $n = 1.18534$   |         |       |

$t$, drying time (h); $k$, drying rate constant (h$^{-1}$); $a$, $b$, $n$, drying constants

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**Fig. 6** Moisture ratio projected by Midilli’s model as a function of experimental moisture ratio
the results obtained from (Coradi et al. 2015; Mukwangole and Simate 2017) for drying kinetics of maize cobs. Midilli model was found to be the model of best fit with the highest R-square (coefficient of determination) values than other models and the lowest value of root mean square error (RMSE).

The graph plotted between the moisture ratio obtained from the experiment and Midilli’s model predicted moisture ratio shows the accuracy of the model with experimental data and is presented in Fig. 6.

**Techno economics of solar dryer**

The techno economics were conducted based on assumptions formed in “Inferences for techno-economic assessment” and as described by Selvanayaki and Sampathkumar (2017). The system’s net present value came out to be 1802.00 USD. Along with a benefit-cost ratio of 1.71 and payback period of 4.07, the greater the internal rate of return percentage, i.e., 66 percent, indicated a good economical return on investment. Thus, it is evident that the proposed dryer is both technically and commercially viable.

**CO₂ emission estimation**

Estimation and reduction of CO₂ emissions is a very important step toward the protection of our environment. The carbon footprint can be reduced by using renewable sources of energy instead of non-renewable fossil fuels. Solar energy has great potential to generate power with zero emissions.

Considering the quantity of one batch of product and 300 operating days of the solar dryer, the total number of batches per annum can be estimated as 150. Substituting the value of annual energy electricity savings in Eq. (1), it can be inferred that a total of 1.22 t CO₂ per annum can be reduced by using the developed dryer.

**Energy analysis**

Table 7 displays the findings of the energy study.

**Conclusions**

The accessible energy from the sun can be employed to obtain sufficient air temperature required for drying with the help of solar drying technology at almost nil fuel charges saving lots of money and quality of food products. The experiment conducted on a cylindrical and portable solar drying system revealed that the system is compatible for effectively drying of maize cobs from a moisture content of 28% (wb) to a moisture content of 13% (wb) in 11 sunshine hours as compared to open sun drying which took 37 sunshine hours for drying at the same level of moisture content. The thermal performance

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**Table 7** Energy savings per annum from the developed prototype

| S. no. | Parameters calculated                        | Formula used                                                                 | Assumptions/values used                  | Obtained values |
|-------|---------------------------------------------|------------------------------------------------------------------------------|------------------------------------------|-----------------|
| 1     | Amount of water to be removed in kg, Mᵣ    | \( Mᵣ = M \left( \frac{Q₁ - Q₂}{T₁ - T₂} \right) \)                            | \( Q₁ = 0.28 \)                            | 8.62            |
| 2     | Quantity of heat reqd. for removal of this water kJ/h, Q | \( Q = \frac{Mᵣ \times λ}{t_d} \)                                             | Latent heat of vaporization of water, \( λ = 2260 \text{ kJ/kg} \) | 1771.16        |
| 3     | Heat input in the electrically operated dryer, kJ | Heat output/\( n_{ed} \)                                                      | Efficiency of the electrical dryer is assumed as 60% | 2951.93        |
| 4     | Electricity saved per hour in the electrically operated dryer, kWh | Heat input/3600 kJ                                                           | Energy equivalent of electricity = 3.6 MJ | 0.81998        |
| 5     | Electricity saved per batch for total hours of drying, kWh | Electricity saved per hour × \( t_d \)                                         | -                                         | 9.02            |
| 6     | **Total electricity savings per year, kWh** | Electricity saved per batch for total hours of drying, kWh × 150              | Considering 300 sunny days per year and 2 days required for drying of 1 batch, total batches per year = 150 | 1352.97         |
| 7     | Heat input in diesel-operated dryer         | Heat output/\( n_{dd} \)                                                      | Efficiency of a diesel burner is assumed as 60% | 2951.933       |
| 8     | Diesel saved per batch per hour             | Heat input in diesel-operated dryer/38,000                                   | Energy equivalent of diesel = 38 MJ/lit    | 0.07768         |
| 9     | Diesel saved per batch for total drying hours in a liter | Diesel saved per batch per hour × total drying time | -                                         | 0.85451         |
| 10    | **Diesel saved per year, liter**            | Diesel saved per batch for total hours in liter × 150                        | Considering 300 sunny days per year and 2 days required for drying of 1 batch, total batches per year = 150 | 128.18          |
curves show that with the increase in solar radiation intensity, the temperature inside the solar dryer and drying rate also increases which reduces the drying time. The special feature of this solar dryer is the use of a multiwall polycarbonate sheet in the drying chamber which provides several advantages as compared to the other drying materials, such as high thermal conductivity and high solar gain.

The results of the mathematical modeling helped in the systematic understanding of the drying system, providing precision through a model of best fit out of five independent mathematical models. The developed dryer’s techno-economic metrics reveal that it is both technically and economically feasible, with just 4.07 years of payback period and a high internal rate of return (66%), indicating a favorable return on investment. There was a significant saving of 70.20% of drying time in the solar-assisted dryer than in open sun drying along with an effectiveness factor of 3.07. The developed unit for drying of maize cobs can effectively save a significant amount of 1352.97 kWh electrical units and 128.18-liter diesel fuel annually, along with a total of 1.22 t CO₂ emission reduction per year. Thus, by using solar dryers, farmers can also contribute to protecting the environment by reducing their carbon footprint. Thus, it is proposed to use this dryer on a community scale for the benefit of both farmers and the environment.

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Author contribution All authors contributed to the study’s conception and design, KS, SK, NLP: material preparation, data collection, and critical review; MRP: energy-related calculations and statistical analysis. All the authors read and approved the final manuscript.

Data availability All the relevant data is provided in the paper only.

Declarations

Ethics approval Not applicable.

Consent to participate Not applicable.

Consent for publication Consented.

Competing interests The authors declare no competing interests.

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