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Drying kinetics, thermal and morphological analysis of starchy food material: Experimental investigation through an induced type solar dryer

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ABSTRACT

Solar drying is a green and clean energy-based technique for food preservation. In this study, drying kinetics and thermal, and morphological analyses of food material have been investigated. A mathematical model has also been studied and modified to validate experimental findings. An induced-type solar dryer setup has been fabricated and experiments have been conducted with potatoes as food samples. The weight loss and temperature variations were monitored in all three types of food samples. The average drying efficiency of the dryer has been found as 20.3 %. Scanning electron microscopy analysis has also been done to examine the surface morphology of the solar-dried food samples. The spherical-shaped sample has shown interesting results and they have the quality to attain maximum temperature due to the small surface area among all three shapes. The fabricated experimental setup has an initial cost and better payback period of \$ 205.78 and 1.50 yr respectively.

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1. Introduction

Solar energy is a renewable energy source on this planet and it is used in the drying of food and vegetables, desalination of water, electricity production, etc. In developing countries, the solar dryer is a good option to reduce the moisture in crops and vegetables to improve the quality of the dried product (Arun et al., 2020; Olaoye et al., 2023; Venkatachary et al., 2020). Solar drying provides uniform heating i.e. no hotspot condition is present in the dried food product (Essalhi et al., 2018; Seo et al., 2014). There is no fuel requirement, low capital investment, low maintenance cost, and it is independent of specialist man power during the solar drying process (Chen et al., 2020; Reyes et al., 2019).

The food preservation can be done by the evaporation of the moisture. Drying of the food material is a traditional preservation method and it enhances the shelf life of the stored agro- based food materials (Huang et al., 2021; Rony et al., 2019; Vilela et al., 2017). Drying can be done by microwave heating, conventional drying, freeze-drying, and solar

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drying (Badaoui et al., 2019). Microwave is a very rapid drying method but it provides non-uniform heating (An-nori et al., 2020; Jia et al., 2003). Therefore, sometimes this heating method can spoil the quality and taste of the food product (Duan et al., 2011). Other drying methods such as conventional drying and freeze-drying cannot be used for drying the heat-sensitive food products (Cheng et al., 2019; Singh et al., 2020a, 2022).

An induced type solar dryer is used for moisture evaporation from the heat sensitive food materials because these types of food materials can be decolorized and lost their nutritive value in direct sunlight (Aydin et al., 2019; Kumar et al., 2022; Mohana et al., 2020). The collector of the dryer absorbs the global radiation and transfers the heat to the air present in the duct of the collector. This warm air lifts upward due to low density and passes through the drying chamber and heat the food sample, which is already placed in the load tray (Manrique et al., 2020; Srivastava and Shukla, 2017). This type of solar dryer is significantly used in all seasons i.e. winter, summer, and the rainy season (Mahapatra and Tripathy, 2019; Sharma et al., 2021).

Potato (*Solanum tuberosum*) is a well-known crop. It is the world's fourth largest crop after wheat, rice, and maize. It is a rich source of starch, vitamins, and other useful nutrients (Su et al., 2016). In India, potato is the king of vegetables and majority of the Indian consumes it in processed form. In the processing of the potato, it is important to preserve the nutritional values (Tagnamas et al., 2021). Many researchers have focused on the processing of the potato to examine the drying kinetics (Pu et al., 2017; Singh et al., 2023). They have also developed one dimensional diffusion model of a potato slab to understand the drying characteristics and thermo-physical properties (Darvishi, 2012; Jia et al., 2003).

Mathematical modeling has been introduced by the authors to understand the behavior of the dried product in terms of drying characteristics (Dhalsamant et al., 2018, 2017). Temperature is another parameter to maintain the texture and taste of the food material (Hamdi et al., 2018; Lim et al., 2020). Some authors have studied the drying characteristics of heat-sensitive food material such as strawberries (Acar et al., 2016; Doymaz, 2012). They have considered samples having thin layer and conduct forced drying experiments with indirect type solar dryer (Bi et al., 2022; Kiburi et al., 2020). Few authors have performed experimentation with an indirect type solar dryer, hybrid solar dryer, and mechanical tray dryer to estimate the drying parameters of the apple, watermelon, and asparagus roots. Asparagus is a useful remedy for treatment in jaundice and diabetes (Bala et al., 2010; Lingayat et al., 2020). Some researchers have modified the indirect type solar dryer, used for drying the bitter gourd slices. They have done parametric study of the developed hybrid solar dryer based on drying rate, energy efficiency, and drying air properties. They have also performed exergy and environmental analysis of the modified solar dryer (Singh et al., 2021, 2020b; Vijayan et al., 2020).

The novelty of this work is that we have represented a modified mathematical model for the shape-based analysis of potato samples. The developed shape-based mathematical model is helpful for food-producing industries to understand the drying kinetics and thermal behavior of different food materials such as vegetables, cereals, crops, etc with drying time. We have also performed experimental work to validate the developed model.

The objectives of this study are:

- (i) To develop a mathematical model for shape based food sample.
- (ii) Fabrication of induced type solar dryer.
- (iii) Performance investigation of the fabricated dryer.
- (iv) Morphological analysis of the samples.
- (v) To check the consistency of the mathematical model with experimental findings.

2. Materials and methods

2.1. Food material collection and pre-treatment

Potato is easily available in the market throughout the year and for this study, it is buy from the local vegetable market of Lucknow, UP, India. Then the potato has been pre-treated in the laboratory. Firstly, washing of potato in running water and peeled-off to remove the outer layer and dust. Now it has been cut into required shapes i.e. slab, cylindrical, and spherical. The thickness and diameter of all three food samples (potato) have been measured with the help of digital vernier calipers.

2.2. Experimental setup and measuring instruments

An induced type solar dryer with 10 kg capacity has been assembled on the rooftop of the Institute of Engineering and Technology, Lucknow (26°5/N latitude, 80°56/E longitude, 128 m above the sea level).

A pictorial view and layout of the experimental setup has been shown in Fig. 1a. The dryer mainly consists of drying chamber (0.608 × 1.219 m), solar collector (1.158 × 0.579 m), load trays, and exhaust fan. A solar collector is made by integrating glass and a metallic sheet. The solar collector has been fully insulated to prevent heat loss. A drying chamber is a main part of the dryer because it transfers the heat from the collector to load trays. Load trays have been attached inside the drying chamber to place the sample. An exhaust fan has been mounted on the top of the solar dryer to balance the airflow in the drying chamber. This fan has been fully operated by solar-generated electricity.

The infrared thermometer, digital balance, solar power meter, and vernier calipers have been used to monitor different parameters. By using an infrared thermometer (ACETEQ, MT-4, India with ±1% error), the temperature of drying chamber,

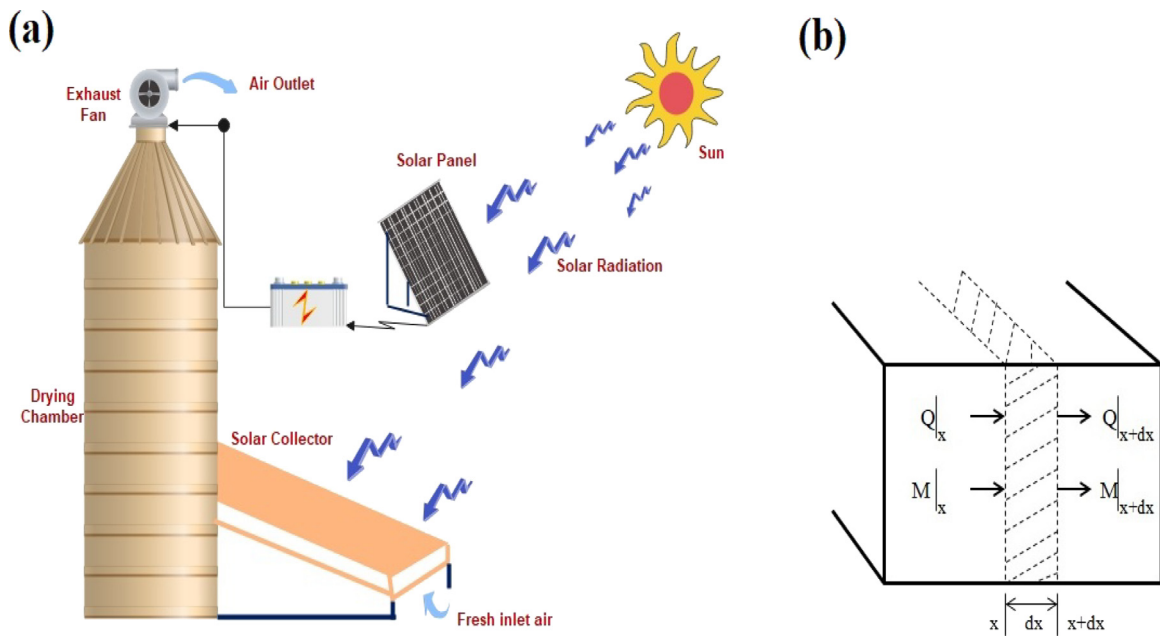


Fig. 1. (a) Schematic diagram of an induced type solar dryer, (b) A control volume element of food material with thickness dx .

solar collector, and samples have been monitored. The quantity of solar radiation has been measured by a solar power meter (TENMARS, TM-206, China with $\pm 5\%$ error). The loss in weight of the samples before and after drying has been monitored by using electronic digital balance (Citizen, CY-220, India with $\pm 0.5\%$ error). To measure the length and diameter of all the three food samples, a vernier caliper (PRECISION, MEASURING with $\pm 4.5\%$ error) instrument has been used.

2.3. Experimental procedure

The pre-treated sample has been initially weighed by using digital balance. The different shaped samples get placed on the load tray in the drying chamber and the initial temperature of all the samples has been recorded by using an infrared thermometer. During the drying process, the temperature and weight of all three types of samples have been monitored on hourly basis. The process has been repeated until food samples attained the equilibrium condition. Simultaneously, the value of solar radiation have also monitored during the drying process with the help of a solar power meter. All experiments have been done in triplicate.

2.4. Heat and mass transfer-based mathematical modeling of a solar-dried food sample

A control volume of the sample with thickness dx is considered to better insight of thermal and drying characteristics of the food sample as shown in Fig. 1b. This study is helpful to give the idea about the heat transfer and moisture evaporation mechanism within the food material (Cevoli et al., 2020; Darvishi, 2013).

For modeling, some assumptions have been taken as follows:

- (i) The fabricated solar dryer is fully insulated.
- (ii) The pressure is considered as constant.
- (iii) All physical, thermodynamic and atmospheric conditions of air are constant.
- (iv) Initially, temperature and moisture content in the food material is uniform.

By considering the Law of conservation of energy within the control volume element, Fourier law of heat conduction is applied to get the following equation (Eqs. (1) to (3)) (Cevoli et al., 2020; Darvishi, 2013);

$$\rho C_p \frac{\partial T}{\partial t} = K \frac{\partial^2 T}{\partial x^2} + Q_{solar} \quad (1)$$

Here, Q_{solar} is the radiant energy can be expressed as;

$$Q_{solar} = \alpha (A) q_i \quad (2)$$

and

$$q_i = \frac{q_h}{\cos \theta} \quad (3)$$

Now, for moisture evaporation analysis, by applying the law of conservation of mass (Fick's second law of diffusion) (Eqs. (4) and (5)) (Darvishi, 2013; Zou and Li, 2020);

$$\frac{\partial M}{\partial t} = D_{eff} \frac{\partial^2 M}{\partial x^2} \quad (4)$$

Here, effective diffusivity can be calculated as;

$$D_{eff} = 1.29 \times 10^{-6} \exp\left(-\frac{0.0725}{M_0}\right) \exp\left(\frac{-2044}{T_0}\right) \quad (5)$$

Model Eqs. (1) & (4) are second order PDE (Partial Differential Equations) consisting of two dependent variables as t and x . Initial and boundary conditions for these systems of equations (Eqs. (6) to (11)) are as follows (Jia et al., 2003):

Initial conditions;

At time $t = 0$ and $0 < x < H$;

$$T = T_0 \quad (6)$$

and

$$M = M_0 \quad (7)$$

Boundary Conditions

At time $t > 0$ and $x = 0$;

$$\frac{\partial T}{\partial x} = 0 \quad (8)$$

and

$$\frac{\partial M}{\partial x} = 0 \quad (9)$$

At time $t > 0$ and $x = H$;

$$\frac{\partial T}{\partial t} = \frac{1}{dx \rho C_p} \left[-K \left(\frac{\partial T}{\partial x} \right) + dx Q_{solar} \right] \quad (10)$$

and

$$\frac{\partial M}{\partial x} = \frac{1}{dx} \left[-D_{eff} \left(\frac{\partial M}{\partial x} \right) - J_m \right] \quad (11)$$

The thermo-physical properties of the potato such as density (ρ), thermal conductivity (K), specific heat (C_p), and mass flux (J_m) have been calculated by using initial conditions of the food sample (Cevoli et al., 2020; Darvishi, 2013; Duan et al., 2011).

2.5. Drying rate

It is the rate of heat transfer at which moisture is transferred from the sample to the environment. It is given as (Eq. (12)) (Darvishi, 2013);

$$\text{Drying rate} = \frac{M_{t+\Delta t} - M_t}{\Delta t} \quad (12)$$

2.6. Drying efficiency

Drying efficiency is generally used to examine the performance of the solar dryer in terms of energy utilization or consumption. It is calculated as the ratio of heat or energy consumed by sample to the heat or energy supplied by induced type solar dryer. It can be calculated mathematically as (Eq. (13)) (Darvishi, 2013);

$$\text{Drying efficiency} = \frac{M_w \times \lambda_w}{Q_{solar} \times t} \quad (13)$$

2.7. Economic analysis

Economic analysis is a cost-based analysis to check the economic feasibility of an experimental setup. Following equations to estimate all the costs of the fabricated solar dryer (Eqs. (14) to (25)) (Mugi and Chandramohan, 2021; Patel et al., 2021):

$$\text{Capital recovery factor (CFR)} = \frac{i(1+i)^n}{((1+i)^n - 1)} \quad (14)$$

$$\text{Annualized uniform cost (R}_1) = P \times \text{CFR} \quad (15)$$

$$\text{Shrinkage fund factor (SFF)} = \frac{i}{((1+i)^n - 1)} \quad (16)$$

$$\text{Annual salvage value (R}_2) = \text{SFF} \times P \quad (17)$$

$$\text{Annual cash flow (ACF)} = \text{Annual savings} - \text{Annual operating cost} \quad (18)$$

$$\text{Total cost (TC)} = \text{Annual operating cost} + \text{Maintenance cost} \quad (19)$$

$$\text{Annual cash benefits (CB)} = \text{Annual savings} - \text{Total cost} \quad (20)$$

$$\text{The annualized cost of dryer (ACD)} = R_1 - R_2 \quad (21)$$

$$\text{Cost of drying (C}_g) = \frac{R_1}{\text{Dried product / yr}} \quad (22)$$

$$\text{Total benefits (B)} = \text{CB} - \text{ACD} \quad (23)$$

$$\text{Benefits cost ratio (BCR)} = \frac{B}{R_1} \quad (24)$$

$$\text{Payback period} = \frac{P}{\text{CB}} \quad (25)$$

2.8. Numerical solution of the developed model

The derived equations (especially Eqs. (1) & (4)) were the second order partial differential equations with some initial and boundary conditions (Eqs. (8) & (11)). These equations can be solved by the finite difference method, and orthogonal collocation methods, but these mathematical methods are too lengthy and time taken. Therefore, these second order partial differential equations have been encoded in MATLAB software.

2.9. Simulations algorithm

A simulation algorithm is a systematic procedure to explain the experimental and modeling analysis shown in Fig. 2. In the modeling section, the heat and mass balance equations have been written along with suitable initial and boundary conditions. Some additional equations in form of drying rate, and drying efficiency have also been written. All input parameters and variables such as initial temperature, initial moisture content of the food material along with shape's thickness or diameter have been listed. On the other side, experimental work has been performed with different shaped food materials using a solar dryer. Temperature and weight loss have been monitored with drying time. The experimental data have been taken in triplicate. Now the model data has been compared with experimental data.

2.10. Surface morphological analysis

A scanning electron microscopy is a tool to examine the surface morphology or structural changes analysis of the solar-dried food samples. An SEM analyzer produced black and white images of a focused point located on the dried food sample.

2.11. Statistical analysis

After experimentation, the data of all parameters in triplicate has been fitted in ORIGIN LAB software and plotted in terms of thermal and drying characteristics with respect to shapes and drying time. The standard deviation and average value have been calculated to obtain the error and plotted simultaneously.

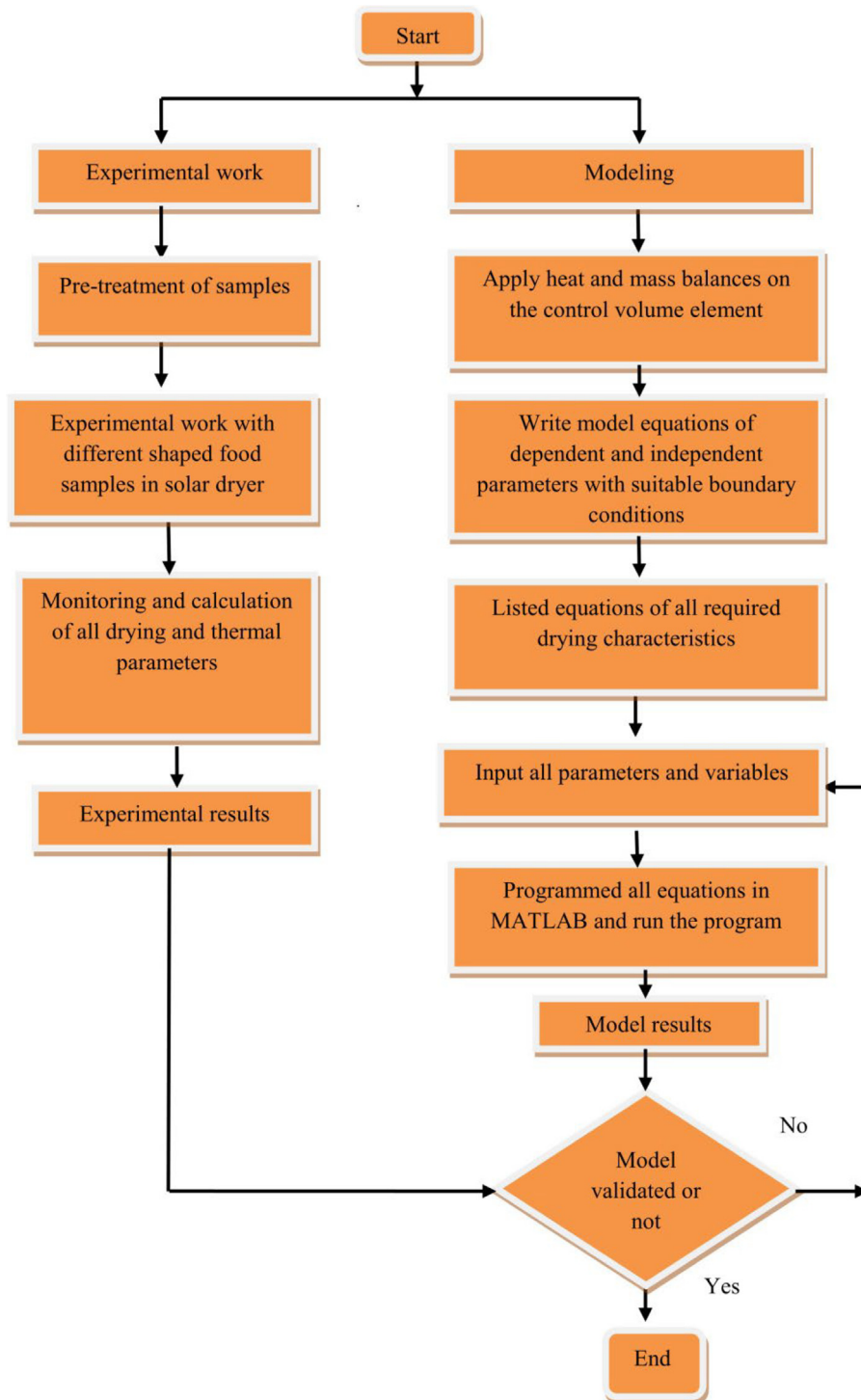


Fig. 2. A simulation algorithm of solar-dried food material.

Table 1
ANOVA of experimental data of food sample.

Source of variation	Sum of square	Degree of freedom	Mean sum of square	F-ratio
Between samples	SSC = 0.147	DF = 2	MSC = 0.073	$F_{(2,18)} = 0.047$
Within samples	SSE = 28.074	DF = 18	MSE = 1.559	
Total	SST = 28.222	DF = 20		

2.11.1. Analysis of variance (ANOVA)

Analysis of variance is a technique to calculate the variation of experimental results between and within the samples in mathematical form. In this study, three experimental data of each sample have been examined. ANOVA parameters have been calculated by using the following equations (Eqs. (26) to (36)):

$$\text{Grand total } (T) = X_1 + X_2 + X_3 \quad (26)$$

$$\text{Correction factor} = \left(\frac{T^2}{M} \right) \quad (27)$$

$$\text{Sum of square between samples (SSC)} = \frac{(\sum X_1)^2}{n_1} + \frac{(\sum X_2)^2}{n_2} + \frac{(\sum X_3)^2}{n_3} - \frac{T^2}{M} \quad (28)$$

$$\text{Degree of freedom for SSC} = E - 1 \quad (29)$$

$$\text{Total sum of square (SST)} = \sum X_1^2 + \sum X_2^2 + \sum X_3^2 - \frac{T^2}{M} \quad (30)$$

$$\text{Degree of freedom for SST} = M - 1 \quad (31)$$

$$\text{Sum of square within sample (SSE)} = SST - SSC \quad (32)$$

$$\text{Degree of freedom for SSE} = M - E \quad (33)$$

$$\text{Mean sum of square between samples (MSC)} = \frac{SSC}{E - 1} \quad (34)$$

$$\text{Mean sum of square within sample (MSE)} = \frac{SSE}{M - E} \quad (35)$$

$$F - \text{ratio } (F) = \frac{MSC}{MSE} \quad (36)$$

where, X_1 , X_2 , and X_3 are the data values.

M is the total no. of food samples.

n_1 , n_2 , and n_3 are the no. of food samples per run.

E is the no. of experimental runs.

The analysis of variance is done by the ORIGIN LAB software and given in Table 1.

The value of F ratio is found as 0.047. This means that the difference between the sample values is deemed statistically significant.

3. Results and discussion

In this study, different shaped based modified mathematical model of a food sample has been developed. This model is used to obtain the moisture distribution, temperature distribution, drying rate of the solar-dried food material along with drying efficiency of the solar dryer. The obtained model equations are partial differential equations and solved in MATLAB environment. During the modeling and experimental work, some input parameters or variables have been monitored and calculated. The initial weights of all samples have been measured as 4.9 g with initial temperatures of 36 °C.

The initial moisture content of all pre-treated slab, cylindrical and spherical shaped food sample has been measured as 3.37, 3.32, and 3.13 g/g db respectively.

3.1. Assessment of meteorological parameters during the experimentation process

Some meteorological parameters such as solar radiation, ambient temperature, etc affect the drying process. Solar radiation is fully responsible to generate heat inside the solar collector (Patel et al., 2021). Fig. 3 represents the hourly variation in radiation and ambient temperature. The experimental work has been conducted for six hours. The beauty of our fabricated dryer is that it can work significantly in low radiation conditions also. Initially, when samples have been

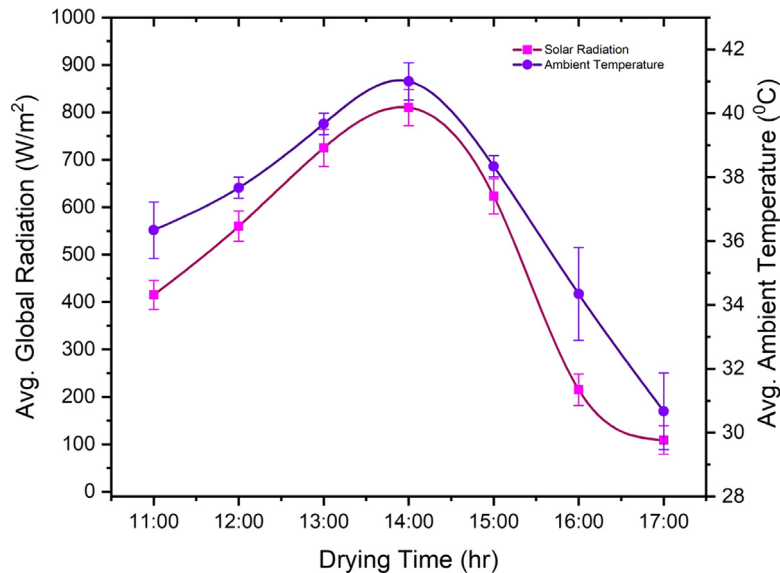


Fig. 3. Avg. global radiation and Avg. ambient temperature with time.

placed in the dryer at 11:00 AM, the value of average radiation and average ambient temperature have been found as $415 W/m^2$ and $36.3 ^{\circ}C$ respectively.

Due to weak radiation, the solar collector has been transferred a minimum amount of energy to the drying chamber. After some time, as soon as the sunshine is increased, the amount of fallen solar radiation has been increased and the collector received more amount of radiation at 14:00 as $810 W/m^2$. Similarly, maximum value of ambient temperature has been found as $41 ^{\circ}C$ at 14:00. The amount of global radiation increases or decreases according to sunshine.

3.2. Thermal variation in the food samples

The thermal variation in terms of temperature variation depends on the intensity of the solar radiation that falls on the surface of the solar collector of the dryer (Djebli et al., 2020; Simo-Tagne et al., 2019). After placing the samples inside the solar drying chamber, it transferred heat to all the samples. The temperature of the food materials is proportional to the received heat in the dryer. The temperature of all three samples has been gradually increase and reaches up to their maximum values.

Fig. 4 depicts the hourly variation in temperature of the food material. In slab-shaped food material, initially it has a temperature value as $36 ^{\circ}C$ but as soon as solar radiation increases, the slab-shaped food sample attained a maximum temperature value of $52.2 ^{\circ}C$.

In case of cylindrical and spherical-shaped food samples, it is found that cylindrical and spherical-shaped food samples attained maximum temperatures as $62.3 ^{\circ}C$ and $69.7 ^{\circ}C$ respectively. Among all shapes, the spherical shape attained maximum temperature due to the lowest surface area of the sample. The lowest surface area may cause less heat loss from the samples, while in slab shape; it has been found minimum due to large surface area.

3.3. Moisture content analysis with drying time in food samples

The moisture content of each sample has been calculated with the help of weight loss from the sample. During the experimentation, the amount evaporates with drying time and follows falling rate period in the drying curve. After some time moisture reaches equilibrium condition in the food material, this period is well known as a constant rate period (Dhanushkodi et al., 2017). Fig. 5 represents the moisture evaporation from the different shaped solar-dried food samples.

First case depicts the moisture evaporation in the slab shape sample. Initially, the sample has enough amount of moisture as $3.37 g/g$ db. During experimentation, when the drying chamber supplied heat to the slab sample, the moisture has been evaporated with time. After some time (approximate 360 min) it attained its equilibrium state (no more moisture evaporation). Similarly, Second case depicts the moisture content in a cylindrically shaped food sample. In this case, the sample has an initial moisture content of $3.32 g/g$ db and takes 300 min to attain its equilibrium state. Third case shows that a spherical shaped sample takes only 240 min to evaporate whole moisture from the sample.

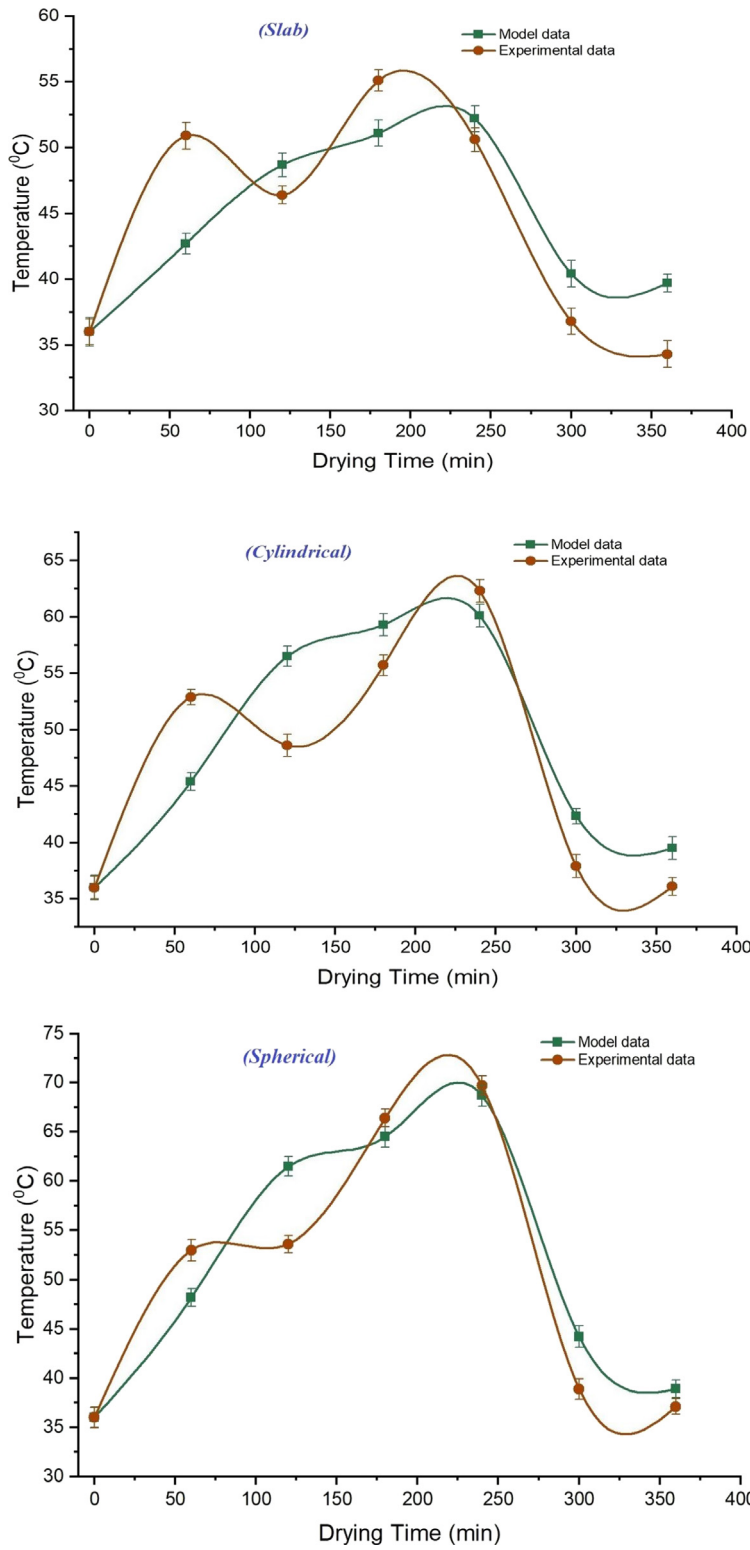


Fig. 4. Temperature variation in different shaped food samples.

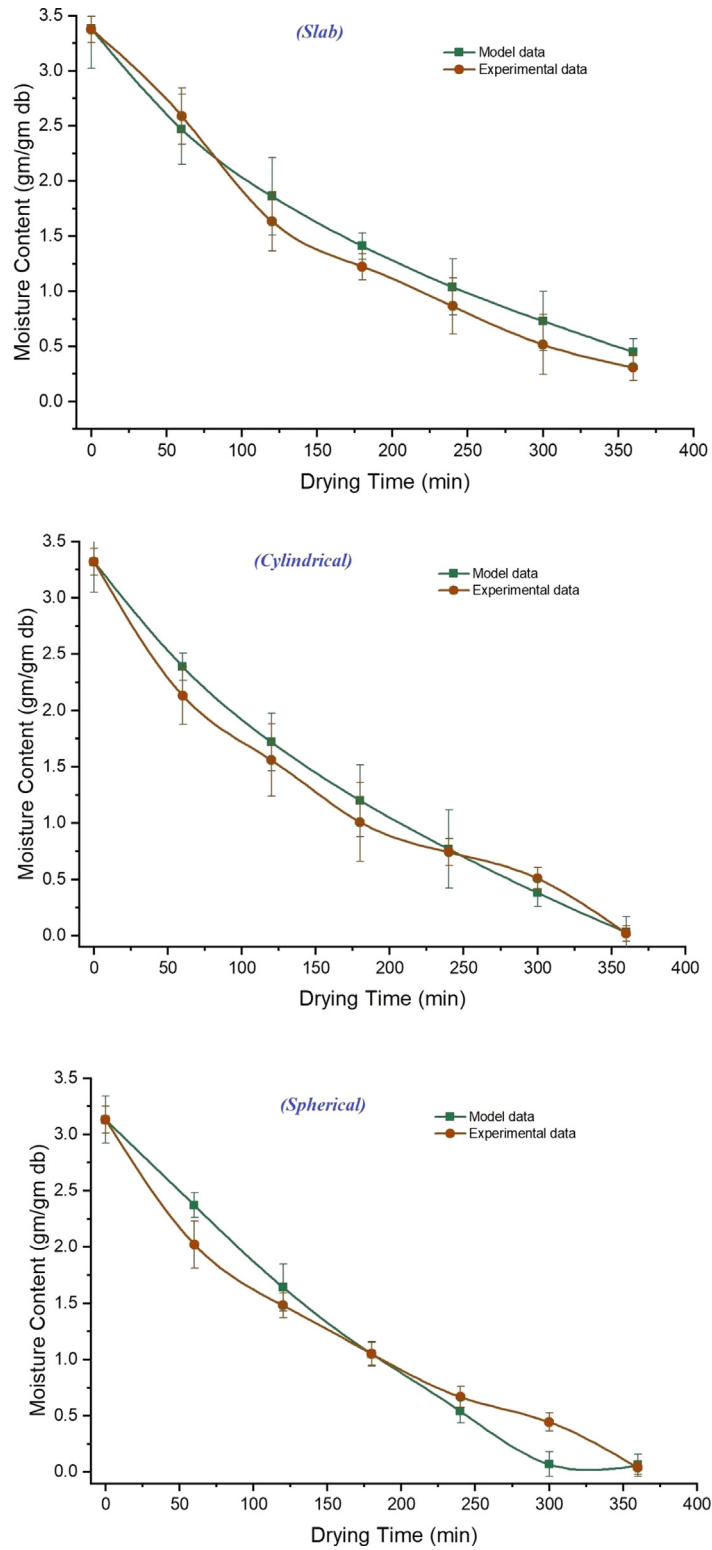


Fig. 5. Moisture evaporation in different shaped food samples.

3.4. Drying rate analysis of different shaped food material

Drying rate is the rate of moisture evaporation with time (Darvishi, 2013). Fig. 6 shows the hourly variation in the drying rate of the all three samples. In slab-shaped food sample, during the early stage of the drying process, rapid moisture transfer takes place; therefore food sample achieved higher value of drying rate as 0.014 g/g db. min. After that the drying rate decreases and attained its lower value with respect to moisture evaporation.

Similarly, Second and third cases denote the variation in drying rate of other two samples such as cylindrical and spherical-shape respectively. The higher drying rate of a cylindrical-shaped sample has been calculated as 0.011 g/g db. min, while the spherical-shaped sample has 0.007 g/g db. min.

3.5. Drying efficiency analysis of induced type solar dryer

Drying efficiency is used to examine the sustainability of an induced type solar dryer (Darvishi, 2013; Dhanushkodi et al., 2017). It is an important parameter to analyze the thermal loss from the fabricated dryer. Fig. 7 shows the hourly variations in values of drying efficiency for three different food samples. First case represents that slab samples have utilized maximum heat and gave higher efficiency at 23.2%.

Similarly, Second and third cases represent the drying efficiency values as 21.6% and 18.7% respectively. The maximum values of drying efficiencies of all three samples have been obtained at 540.99 W/m² because all three samples have utilized the enough heat for evaporation purpose. The minimum value of all three samples has been found as 5.39%, 6.46%, and 6.04% respectively at 810 W/m². The reason behind it, all types of samples have not fully utilized the supplied heat, while the heat is supplied in the maximum amount.

3.6. Surface morphology analysis of the solar- dried samples

The morphology of different shaped solar-dried potato samples has been examined by SEM graphs shown in Fig. 8. All three micrographs have been obtained at 1500 resolution. These figures have shown that the granules of the starch present in enough amount after solar drying. Due to the presence of water molecules in the pore of the samples, some fungus growth has been detected on the surface of the potato samples. First case represents the granular structure of the slab-shaped food sample. Second and third cases shows the starch structure and fungus growth in the cylindrical shaped and spherical shaped potato samples.

3.7. Economic analysis

Economic or cost analysis is the combination of different types of costs such as fabrication cost, operating and maintenance cost, annual salvage value, etc (Hassan et al., 2021; Patel et al., 2021). In this research work, an economic or cost analysis of fabricated induced type solar dryer has been performed. This setup has initial investments as \$ 205.78. The total capacity of the experimental setup is 10 kg. The experimental setup is suitable for working 200 days per year and dried 2×10^3 kg of food per year. The operating and maintenance costs have been considered as 1%. The cost analysis shown in Table 2:

The economic analysis of fabricated induced type solar dryer has been completed by calculating parameters such as annual cash flow, annual cash benefit, annual salvage value, cost of drying etc. Fabricated solar dryer has provided a significantly reduced payback period of 1.50 years. This payback period of experimental setup was found better in comparison to existing literatures (Dhanushkodi et al., 2017; Fudholi et al., 2011; Hassan et al., 2021).

3.8. Validation of the mathematical model

In this study, the modified model result data has been validated with experimental result data. Figs. 4 to 7 represents the experimental and model data of various parameters such as temperature variations, moisture evaporation, drying rate, and drying efficiency. It is clear from all the listed plots that model results profiles have been followed in good manner with experimental result profiles within 4 percent error.

4. Practical application and future research prospects

This study can be quite beneficial for domestic as well as industrial purposes. Some practical applications of this study are:

- Solar drying can replace conventional fossil fuel-based drying methods in food producer companies.
- The developed mathematical model can be used for different food materials.
- This study also suggested that spherical-shaped food samples utilized the maximum amount of energy with minimum losses. Therefore, food producer companies can produce their product in spherical shapes.
- The fabricated solar drier is economically beneficial with the initial cost of \$ 205.78. Therefore, every middle-class person can afford this fabrication cost.

The limitation of this dryer is its lower working efficiency in low radiation conditions. We will try to make significant changes in the design of the dryer to maintain its performance even in low radiation conditions.

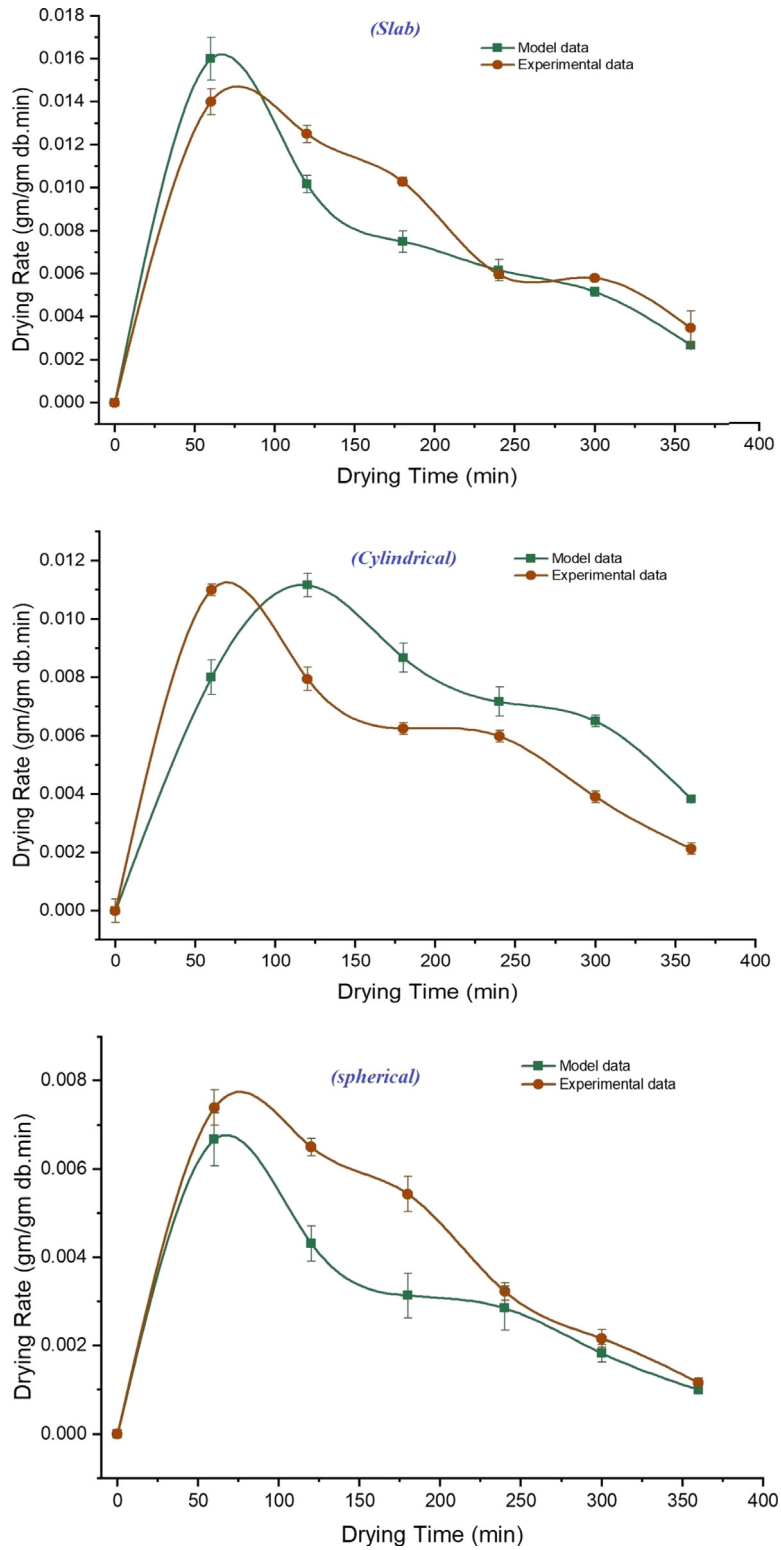


Fig. 6. Drying rate analysis in different shaped food samples.

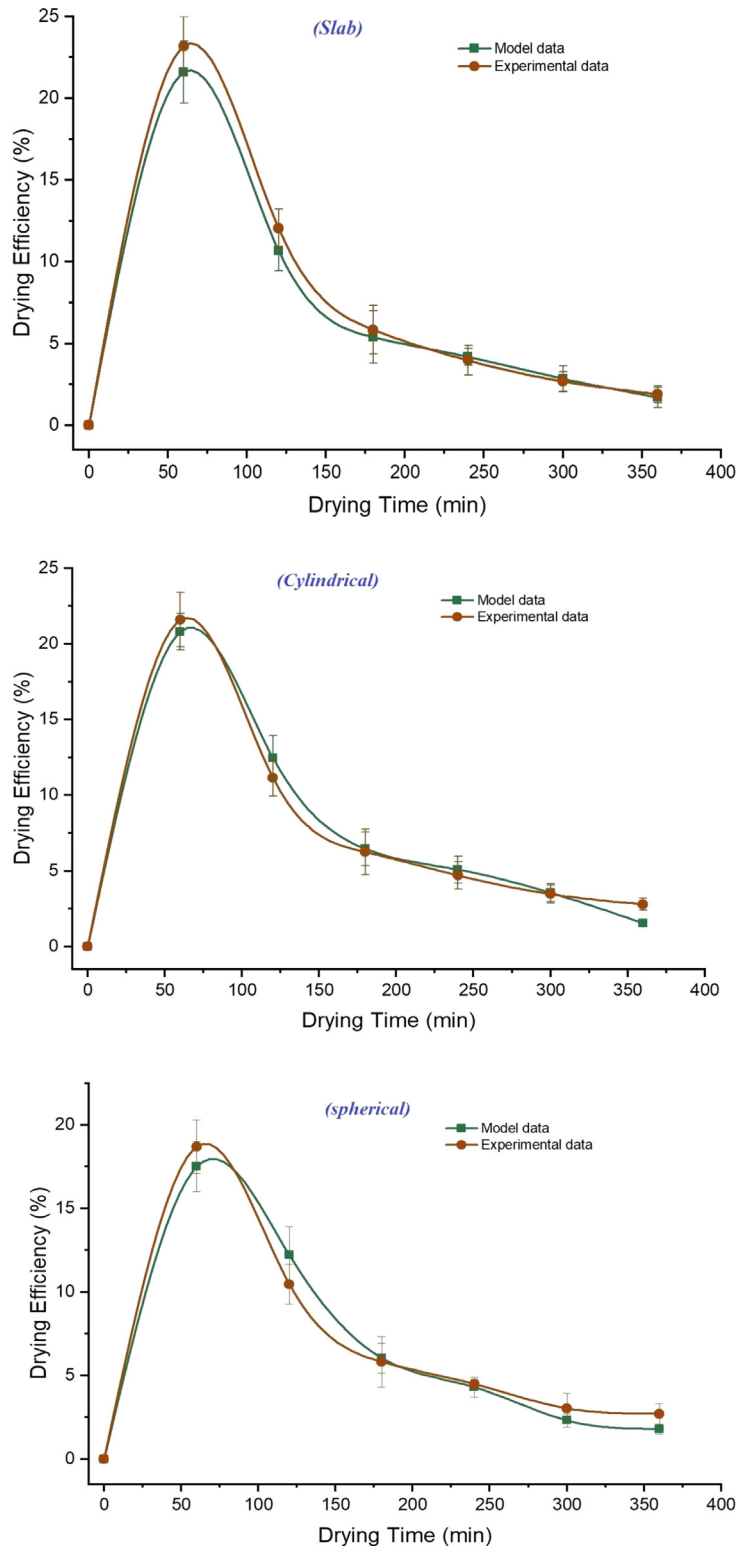
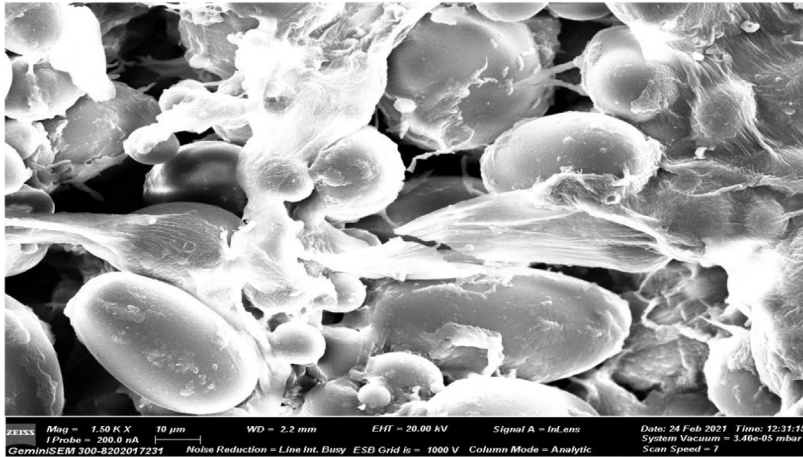
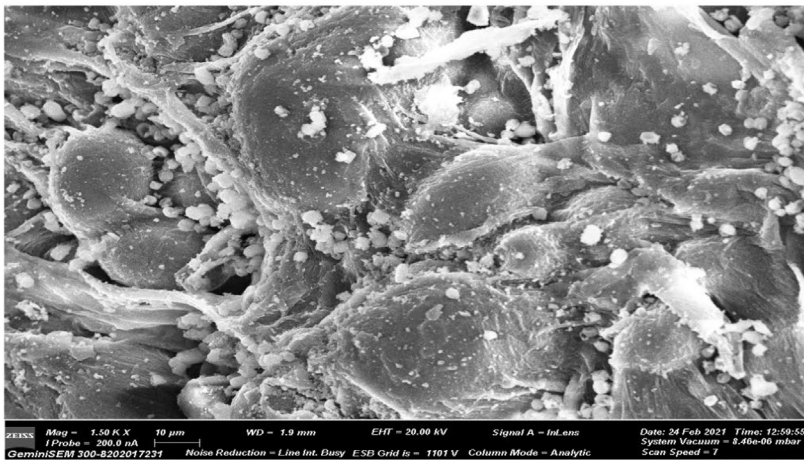


Fig. 7. Variation in drying efficiency of solar dryer with different shaped samples.

(slab)



(Cylindrical)



(Spherical)

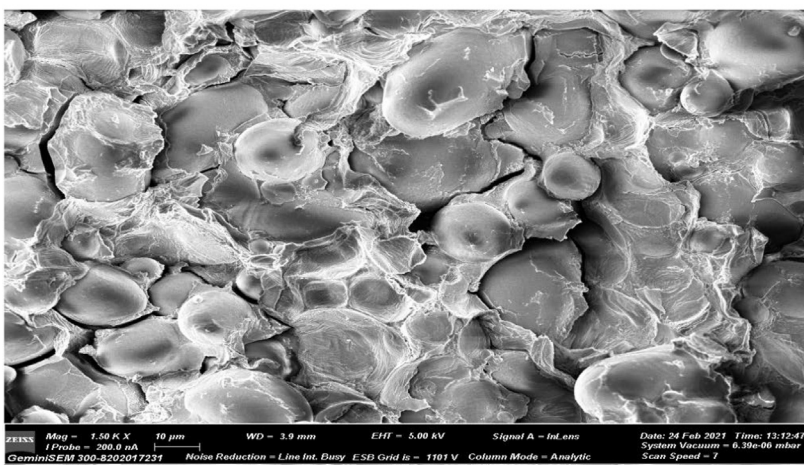


Fig. 8. Morphological analysis of different shaped samples with SEM micrographs.

Table 2
Cost analysis of induced type solar dryer.

Factor	Value		
Initial investment (P) (\$)	205.78		
Salvage value (S) (\$)	82.76		
Annual operating cost (\$)	0		
Maintenance cost (@ 1% of P) (\$)	2.01		
Total cost (\$)	2.01		
Annual interest rate (%)	8		
Annual savings (conventional energy cost) (\$)	134.36		
Annual cash flow (\$)	134.36		
Annual cash benefit (\$)	132.34		
Payback period (yr)	1.50		
Expected economic life (yr)	20	15	10
Capital recover factor (CRF)	0.101	0.116	0.149
Annualized uniform cost (R ₁) (\$)	20.96	24.04	30.67
Shrinkage fund factor (SFF)	0.021	0.036	0.069
Annual salvage value (R ₂) (\$)	4.50	7.58	14.21
Annual cost of the dryer (\$)	16.46	16.46	16.46
Cost of drying (C _g) (\$)	0.005	0.004	0.007
Total benefits (B) (\$)	116.02	116.02	116.02
Benefit cost ratio	5.535	4.825	3.783

5. Conclusions

In this study, performance investigation of an induced type solar dryer has been done by considering drying kinetics and thermal analysis. Potato is found suitable as food material for experimentation because it is rich starch source. It is found that the spherical-shaped sample has shown minimum heat loss and attained maximum temperature among various shapes. Similarly, in spherical-shaped food material, moisture removed rapidly in comparison to other samples. Solar dryer can achieve sufficient temperature in case of lower solar radiation. The mathematical model has been converged with experimental data. This solar dryer has negligible operating cost and 1.5 years payback period and found economic in comparison to other existing solar dryers. This technique can play significant role in saving energy and reduction in environmental pollution.

Nomenclature

A	Area of the sample	m ²
C _p	Specific heat capacity of the sample	kJ kg ⁻¹ K ⁻¹
D _{eff}	Effective diffusivity	m ² s ⁻¹
H	Total thickness of the sample	m
H _m	Mass transfer coefficient of vapor in the air	m ² s ⁻¹
J _m	Mass flux	gram moisture m ² s ⁻¹
K	Thermal conductivity of the sample	W m ⁻¹ K ⁻¹
M	Moisture content of the sample	gram moisture gram db ⁻¹
M ₀	Initial moisture content of the sample	gram moisture gram db ⁻¹
M _w	Mass of evaporated water	gram
M*	Equilibrium moisture content	gram moisture gram db ⁻¹
q _h	Radiation of horizontal surface	W m ⁻²
q _i	Incident radiant energy	W m ⁻²
Q _{solar}	Absorbed solar energy	W
T	Temperature of the solar dried sample	°C
T ₀	Initial temperature of the sample	°C
x	Thickness of the sample	m
Greek letters		
Δt	Drying time interval	min
λ _w	Latent heat of vaporization of water	J g ⁻¹
ρ	Density of the sample	kg m ⁻³
α	Absorptivity of solar radiation	Dimensionless
θ	Angle of incidence of solar radiation to the vertical	degrees
db	Dry basis	

CRedit authorship contribution statement

Mukul Sengar: Writing – original draft, Methodology. **Reeta Rani Singhania:** Investigation. **Deepak Singh:** Data curation. **Pradeep Kumar Mishra:** Review, Supervision. **Dhananjay Singh:** Supervising & editing, Supervision. **Manish Kumar:** Review, Supervision. **Balendu Shekher Giri:** Conceptualization.

Declaration of competing interest

The authors declare that they have no conflict of interest.

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