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A mixed-mode ginger and turmeric solar dryer: design, simulation, biochemical and performance analysis

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ABSTRACT

Postharvest loss of vegetables and fruits is higher in developing countries due to the lack of post-processing equipment. Although the production of ginger and turmeric is high in Nepal, farmers practices open sun drying, which leads to poor quality, and the products do not get to the market at reasonable prices. In this study, a simple, easy to assemble and disassemble mixed-mode solar dryer has been designed, fabricated, and biochemical and performance analyses were done. The dryer was designed considering the solar irradiation, sunshine hours, latitude of the location, locally available materials, moisture content (MC) of the product, and drying capacity. The Computational Fluid Dynamics (CFD) analysis was performed using ANSYS Fluent simulation software to predict the dryer's temperature and air flow behavior. The experiment was carried out in November in the harvesting season of ginger. The dryer performance is compared with the open sun drying using ginger and turmeric. The biochemical properties such as Oleoresin and Essential oil were determined using Soxhlet and Steam distillation methods and compared with the product of open sun drying. The experiment results showed that ginger and turmeric took only about 14 sunshine hours to reach from 88% to 10-12% moisture content. The maximum collector and drying efficiency were recorded at about 45.32% and 31.364%, respectively. The temperature distribution inside the dryer obtained from the experiment correlated with the results obtained from the CFD analysis. The retention of essential oil was found more in product drying with dryer than open sun drying. Among the various drying models, Wang and Singh model was found suitable for describing the drying model. It is concluded that the designed dryer is suitable for ginger and turmeric drying into a safe moisture level, ensuring product quality.

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1. Introduction

In developing countries, the food loss is significant; about 20-40% of agricultural products are being lost due to managerial and technical limitations of post-harvesting techniques such as storage, transportation, processing, packaging, and marketing [1]. For example, postharvest losses in fruit and vegetables in Nepal are estimated at 20 to 50% [2]. However, this loss can be minimized by proper management of postharvest techniques like cold storage, drying, material handling, transportation, processing, cooling facilities, infrastructure, packaging, marketing system, etc. [3,4].

The drying technique is one of the effective methods of eliminating the problems of postharvest losses [5]. Mainly, it is done for the safe storage of storing crops by reducing the water activities that lead to an increase in self-life of product. Renewable energy, such as solar energy, can be effectively used for drying agricultural products, which is eco-friendly and has fewer environmental consequences. Solar drying can be an encouraging substitute for open-air drying and is expected to play a more vital role in most developing countries due to the availability of a high level of solar radiation all over the year. The national average solar insolation of Nepal is recorded as 4.66 kWh/m^2/day [6], with the energy generation capacity of 57,519 GWh [7]. With an appropriate solar dryer design, solar energy can efficiently be utilized for crop drying [8].

In this study, Ginger and Turmeric are chosen for the experiment due to the ginger and turmeric pocket zone is near the experimental location. So, it is readily available in the market, and study would be helpful for the farmers growing in the area. Ginger (*Zingiber officinale*) and Turmeric (*Curcuma longa*) are rhizomatous plants; their derivative products are widely used for food additives and folk medicines [9]. The fresh rhizome of ginger and turmeric is dried to prepare its derivatives such as ginger pickle, powder, and extractives such as ginger and turmeric oil. In 2019, Nepal is the fourth largest ginger producer and exporter after China, India, and Nigeria [10]. In 2018/19, it was cultivated in an area of 22,132 hectares (ha) and produced about 284,427 metric tons (t)[10]. However, due to Nepal's shortfall of suitable postharvest management techniques, fresh ginger is primarily exported in India (about 70% of the total production) [1,11].

On the other hand, the production of turmeric requires less investment, water, and fertilizer and has low pest/disease infestation. For the hilly region of Nepal, it is considered a good cash crop [12]. In the fiscal year 2018/19, it was cultivated in 10,160 Ha and produced 98,904 metric tons in Nepal[10]. However, farmers still depend upon open sun drying and low-efficiency dryer for drying, which is used for making various derivatives products. The intervention of an efficient dryer would allow farmers to get market of their fresh product in production season and derivative products during the offseason. Promoting such infrastructures and applied research plays a vital role to make food self-sufficient, and helps to meet the sustainable development goals (SDG) target, especially SDG 2 [13].

Many studies related to the solar dryer have been conducted globally on various agricultural products for seeking the appropriate dryer with greater drying efficiency. The design, fabrication, and testing of the mixed-mode dryer [8] with their modifications on various agricultural products such as grapes [14], grains [15], red peppers [16], Okra slices [17], tomatoes [18], etc. have been demonstrated in many studies. Studies have shown that the mixed-mode dryer needs very little time to reach the products' safe moisture level without compromising quality. However, very little literature has been reported regarding the drying of the ginger [19,20] and turmeric [21–23] in the mixed-mode and other dryer types for determining the best-fitted drying models and product qualities. In Nepal's context, little literature has been reported on the application of the dryer in the prospect of the rural areas [24,25] by taking the different types of dryer such as solar cabinets, tunnel, rack dryers, etc. These studies have shown that the modifications help in improving performance and have suggested testing of the modified dryer.

Although some of the studies are reported in Nepal to determine the drying performance, no such literature has been found that studied the performance of mixed-mode ginger and turmeric dryer. In addition, also drying temperature prediction with its distribution on drying chamber and airflow pattern have not much reported before.

To fulfill this gap, in this study, we have designed and fabricated a mixed-mode solar dryer, and performance analysis was conducted on ginger and turmeric drying. In addition, biochemical analysis was also investigated to evaluate ginger and turmeric's biochemical properties (essential oil and oleoresin). Further, we have done computational fluid dynamics (CFD) analysis to observe the temperature profile inside the dryer.

2. Methodology

2.1 Governing Equations and Drying models

2.1.1 The governing equation used in CFD analysis

The governing equations which are to be solved in differential form for a 3-dimensional case are as follows:

a) The Continuity equation, which represents the conservation of mas

$$\frac{\partial\rho}{\partial t}+\nabla(\rho\vec{u})=0 \qquad (1)$$

Here, $\vec{u}$ and ρ represent the fluid velocity and density of air, respectively.

b) The Navier-Stokes equation, which represents the conservation of momentum [26]:

$$\frac{\partial}{\partial t}(\rho\vec{u})+\nabla.(\rho\vec{u}\vec{u})=-\nabla P+\nabla\bar{\bar{\tau}}+\rho\vec{g}+S_m \qquad (2)$$

Here, $\bar{\bar{\tau}}$ and S_m represent Reynold's shear stress tensor and the source term for momentum, respectively.

c) The energy equation [27]:

$$\frac{\partial}{\partial t}(\rho E)+\nabla.\left(\vec{u}(\rho E+P)\right)=\nabla.(-\vec{q}+\bar{\bar{\tau}}.\vec{u})+S_h \qquad (3)$$

Here, S_h, $\vec{q}$ and E represent the heat source team, the flux vector (positive inward) and the total energy (sum of internal and kinetic energy), respectively.

The total energy is given by:

$$E=h-\frac{P}{\rho}+\frac{u^2}{2} \qquad (4)$$

Where h is the sensible enthalpy of the air

d) In the flow field, the presence of porous media is presented by the Eq. (5) - (8) through the source terms. In the momentum equation, the source term is composed of viscous losses and inertial losses. In the ANSYS Fluent, this is written as:

$$\frac{\partial P}{\partial z}=-\frac{\mu}{\alpha}u_z+C\frac{1}{2}\rho{u_z}^2 \qquad (5)$$

Here, $(\frac{1}{\alpha})$ and C represents the viscous loss coefficient and the inertial loss coefficient, respectively. The equation can be applied similarly along x and y directions. Ergun developed an equation for packed beds which has been applied successfully to grain beds [28].

$$\frac{P}{L}=\frac{150\mu(1-\varepsilon^2)}{d^2{}_p\varepsilon^3}u+\frac{1.75\rho(1-\varepsilon)}{d_p(\varepsilon)^3}u^2 \qquad (6)$$

From Eq. (7) and the inertial and viscous loss coefficient were computed

$$\alpha=\frac{d^2{}_p\varepsilon^3}{150(1-\varepsilon^2)} \qquad (7)$$

$$C=\frac{3.5\,\rho(1-\varepsilon)}{d_p\varepsilon^3} \qquad (8)$$

2.1.2 Data Calculation & Analysis

The thermal efficiency of the collector (η_c) was determined from Eq. (9) and the graph of collector efficiency was plotted on an hourly basis [29].

$$\eta_c=\frac{\rho V\Delta T C_p}{A_c I_c} \qquad (9)$$

Where, ρ is the density of air (kg/m^3) = 1.225 kg/m^3, I_c Is the solar radiation on the collector (Primary), ΔT is the temperature elevation, C_p is the specific heat capacity of air at constant pressure (kJ/kg/K).

The dryer efficiency (n_d) was determined using Eq. (10) [29].

$$n_d=\frac{M_w h_w}{AIt} \qquad (10)$$

Where, A is the collector area (secondary and Primary), h_w is the latent heat of vaporization of water, M_w is mass of water removed, I is solar radiation incident on the collector of dryer, and t is drying time.

2.1.3 Drying models

The experimental data of ginger and turmeric drying were used to develop the drying model [30]. The moisture ratio (MR) is determined using Eq. (11).

$$MR=\frac{M_t-M_e}{M_0-M_e} \qquad (11)$$

Where, M_0 is initial in dry basis and M_e is the equilibrium moisture content of the sample and M_t is MC on a dry basis at a time (t). During the drying process, continuous fluctuation in temperature, relative humidity, and velocity of the drying air was observed. Therefore, a simplified form of moisture ratio, MR = M_t /M_0 is selected for the dimensionless parameter.

The procedures for thin-layer drying are typically used for evaluating and characterizing the drying parameters. The empirical models demonstrate the relationship between drying time and moisture content using regression analysis. Full-scale experiments are not feasible for various products. Hence, these models are needed for simulation by using the drying model to predict the drying rate [20]. A total of 15 most used thin-layer drying models were fitted with experiment results in this study to find the best model for describing the ginger drying process (Table 1).

Table 1: Drying models used for the study to find out best-fitted model

SN	Name of models	Model equations	References
1	Lewis	MR = exp (-kt)	[31]
2	Page	MR = exp (-kt^n)	[32]
3	Modified Page	MR = exp (-(kt)^n)	[33]
4	Henderson and Pabis	MR = a exp (-kt)	[34]
5	Logarithmic model	MR = a exp (-kt) + c	[35]
6	Two-term	MR = a exp (-k1t) + b exp (-k2t)	[36]
7	Wang and Singh	MR = 1 + at + bt^2	[37]
8	Modified Henderson and Pabis	MR = a exp (-kt) + b exp (-gt) + c exp (-ht)	[38]
9	Verma et al.	MR = a exp (-kt) + (1-a) exp (-gt)	[39]
10	Midilli and Kucuk	MR = a exp (-kt^n) + bt	[40]
11	Diffusion approach	MR = a exp (-kt) + (1-a) exp (-kbt)	[41]
12	Two-term exponential	MR = a exp (-kt) + (1-a) exp (-kat)	[42]
13	Simplified Fick's diffusion equation	MR = a exp (-c(t/L^2))	[43]
14	Modified Page equation-II	MR = exp (-k(t/L^2)^n)	[41]
15	Gaussian model	MR = a exp (-(t-b)^2/ (2c^2))	[44]

2.2 Design of dryer

In this study, a mixed-mode solar dryer was designed as per the parameters such as solar radiation, sunshine hours, efficient tilt angle, etc. The optimum tilt angle for maximization of solar insolation on an annual basis is 30° [45], which is also the angle near the latitude of Dharan (26.7944° N, 87.2817° E), Nepal. The annual average solar radiation of Dharan was found to be 3.68 kWh/m^2/day [46], average solar radiation to the surface is 525.12 $\mathrm{w/m^2}$, and the average sunshine hour is 7 hours/day.

The average ambient temperature of Dharan during the daytime is about 30℃. The various researches found that the average collector efficiency of aluminum corrugated collectors was about 30% [47]. The requirement of exhaust air temperature from the collector is 50-55℃, which is used for safe drying of ginger and turmeric [48,49].

The mass of the ginger or turmeric was 5 kg for drying in the dryer, and the initial moisture content was taken as 90% (wet basis). The sunshine hour was considered as 7 hours per day and required the final moisture content to be 10%. Water amount to be removed from fresh ginger/ turmeric product [50].

$$\mathrm{M_{rem}} = \frac{\mathrm{M(\ Initial\ moisture\ (\%) - final\ moisture\ (\%)}}{\mathrm{100 - final\ moisture(\%)}} \quad (12)$$

By using Eq. (12), the mass of water to be removed was 4.44 Kg, and the amount of heat needed to remove the mass of water is given by Eq. (13) [51].

$$\mathrm{Q_{remove}} = \mathrm{M_{remover}}(\mathrm{H_{fg}} + \mathrm{H_f}) \qquad (13)$$

At, 50 degrees Celsius (assuming temperature inside the dryer), specific enthalpy of water at latent heat of evaporation (H_{fg}) is 2357.6 kJ/kg and Enthalpy of water (H_f) was taken as 4.18 kJ/kg. Hence, by using Eq. (13), the amount of heat required to remove water was determined as 10,391.832 kJ/kg. Hence, considering 7 sunshine hours, the rate of energy required was determined as 412.37 W. The primary collector's absorber was considered a corrugated black painted aluminum foil with absorptivity (α) 0.9. The total amount of useful heat provided by the collector [52] was determined by Eq. (14)

$$Qu=Ac[It(<\tau.\alpha>) -UL(Tc-Ta)]\ FR \qquad (14)$$

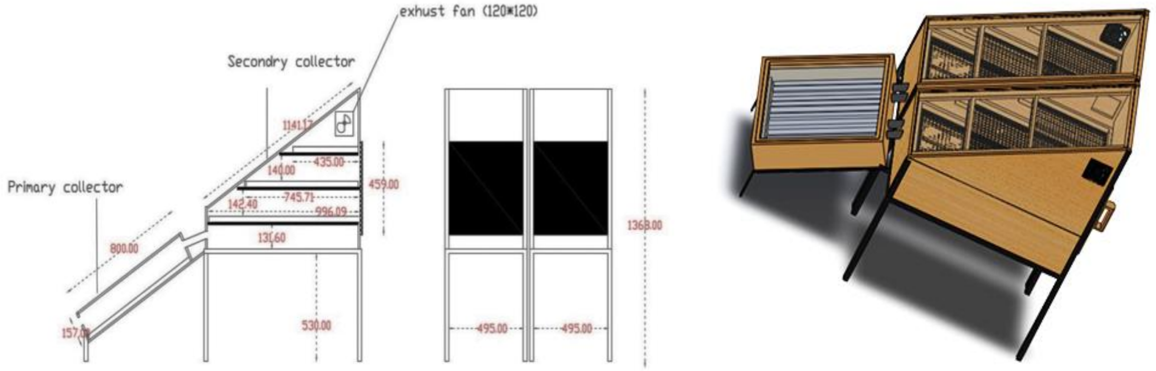
Where Fr is the heat removal factor which was considered as 0.9, and the overall heat transfer loss coefficient was taken as 5 W/m^2.°C. The plain window glass was taken with the transmissivity of 0.9, and Ac is the area of the collector that is exposed to direct sunlight of solar. The $<\tau.\alpha>$ was determined by Eq. (15) by taking the diffuse reflectance of glass cover as 0.16.

$$<\tau.\alpha>= \left(\frac{\tau\times\alpha}{1-(1-\alpha)\rho}\right) \qquad (15)$$

Using the obtained value of <τ.α> as 0.823 from Eq. (15), the collector area was determined as 1.2920 m^2.

By considering the required collector area *and* the maximum utilization of solar radiation, the collector was split as a primary collector (corrugated aluminum) and secondary collector, the wall of the drying cabinet, to form a mixed-mode solar dryer. So, it would also overcome the hourly variation of solar radiation and temperature.

The dimension of the primary collector is $800 \times 620 \times 150$ mm^3, and secondary collector on each module is $1{,}140 \times 496$ mm^2 *and* then to maintain the capacity of the dryer 5-10kg, the single solar collector connected with the two easily detachable cabinets having different tray dimensions supporting the inclination of a glass of cabinet 30° with horizontal. Exhaust fans of 12 volts 0.32A were placed on each side of the drying cabinet and were operated by a solar panel. The exhaust fan placed on its side helped to make the force circulation of air so that the drying efficiency would be maximized. The trays were placed in such a way that the products absorbed heat directly and took heated air from the collector. The drawing of the dryer and each component detail is shown in Fig. 1 and Table 2 respectively.



(a) (b)

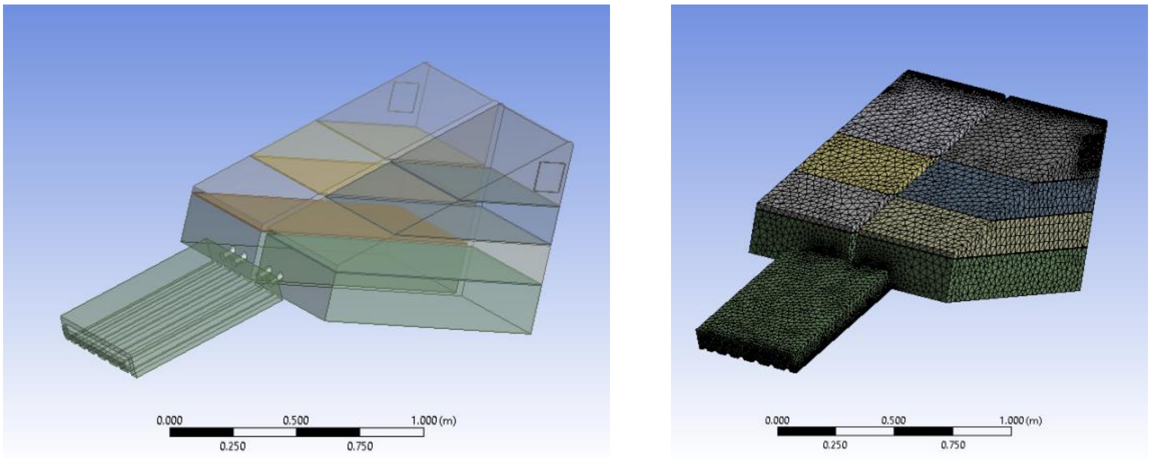
Fig. 1: (a) Sectional front view and back view of the mixed-mode solar dryer including all dimension of components in mm and (b) 3D view of the dryer created by using SOLIDWORK software for depicting each component of dryer

Table 2: Details of dryer components including their technical specifications

S.N	Descriptions	Remarks (mm)
1.	The dimension of the collector box	$800 \times 620 \times 150$
2.	Collector plate area	740×590
3.	The thickness of the Aluminum plate	1.2
4.	Absorber surface	Corrugated black
5.	Insulation thickness	25
6.	Raised of drying cabinet from Ground surface	530
7.	Spacing of trays	140
8.	The dimension of trays.	
	Tray 3	$962 \times 465 \times 30$
	Tray 2	$745 \times 465 \times 30$
	Tray 1	$435 \times 465 \times 30$
9.	The thickness of the glazing surface	10
10.	Dimension of door	459×497
11.	Number of the fan on each end of the module	2
12.	Inlet of the collector	500×45
13.	The diameter of 4 pipes for of air flowing (PVC)	38.1

2.3 CFD Analysis of the solar dryer

The fluid domain of the dryer was made with the support of SOLIDWORKS software and ANSYS design modular (Fig. 2). The dimensions and specifications used while making the 3D fluid domain were used according to the design. The drying bed of 5 mm was taken in each chamber for the tray. ANSYS Fluent student 2019 R3 (Academic version) was used to analyze the dryer, and meshing of the model was done according to the model's geometry. The meshing elements and nodes were 497,428 and 96,952, respectively, which were below the optimum mesh limit provided by the ANSYS Academic version. The boundary conditions (Faces), such as inlet, outlets, outlets, woods pipes, etc., were defined during the meshing. After that, fluent was opened in serial mode, and steady-state and pressure-based analysis was used. The k-epsilon (2-eqn) with a realizable standard wall function was used for the viscous model. The discrete ordinate and solar ray tracing were used in the radiation model. The latitude and longitude were selected as the location of Dharan, Nepal, with a time zone of +5.45 and the sunshine factor as 1. The analysis time was taken in the month of November 23 at 12:00 PM. Selected materials, along with their properties, are shown in Table 3.



(a) **(b)**

Fig. 2: (a) 3D model of fluid domain of the dryer including trays, collector, exhaust, PVC etc. and (b) meshing of the model with tetrahedral mesh

Table 3: Material properties of the material used in the CFD analysis of dryer [53,54]

SN	Material	Density (kg/m^3)	Specific heat capacity (J/kg-k)	Thermal conductivity (w/m^2)
1	Wood (Ply wood)	700	2310	0.173
2	Pipes	1467	840	0.17
3	Glass (Normal Window glass	2300	792	0.8
4	Ginger	410	3566.87	0.2916
5	Aluminium	2719	871.9	202.4

Similarly, the porous media was considered for the drying bed of ginger slices presented in the trays. For the bed of ginger slices, the permeability and inertial loss coefficient were determined from the Eqs. (7) and (8) by considering the volume of the void and volume of the drying bed as 0.3 and the average diameter of the slices particles as 2 cm. The value of C and ($1/\alpha$) are 4,537.037 (1/m) and 680,559.144 (1/m^2), respectively. The inlet is considered as pressure-based, and two outlets were provided with the mass flow rate of 0.0072 Kg/sec (considering the average velocity of air exhausted from the fan as 0.75 m/sec). The absorptivity of the absorber was considered as 0.95, and transitivity and absorptivity of glass were taken as 0.9 and 0.05, respectively. The solution methods used were schemes coupled with third-order MUSCL for better accuracy. The solving iteration was taken as 1000. After that, post-processing was carried out to determine the temperature and velocity distribution pattern in collector and drying chambers.

2.4 Construction of dryer

Cheap and locally available materials were used for the construction of the dryer. The dryer consists of essential parts such as a collector, drying cabinet, drying tray, and exhaust fans (Fig. 3). Collector was manufactured using a 1.2 mm corrugated aluminum sheet, painted black, mounted in the plywood box. The spacing of the corrugated sheet and glazing was 65 mm. A 1-inch angle-shaped aluminum frame gave the structural support by welding.

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Fig. 3. Experimental setup of the designed and fabricated mixed-mode solar dryer showing its components. Ginger and turmeric slices were used for the experiments

2.5 Experimental procedure

The experiments were carried out in November 2019. The slices of ginger and turmeric of 2-5mm, harvested in November from Bishnupadhuka, Dharan, were used for drying. For the experiment 2.5 kg, each of the ginger and turmeric slices was used. The drying time started from the same point. Different instruments measured different parameters of solar dryers on an hourly basis. Biochemical analysis of ginger and turmeric was done by using a soxhlet apparatus method and steam distillation method (Table 4). The fresh ginger samples were ground into a mesh using a manual blender, and 30g of the fresh ground ginger was added into a round bottom flask with water as a solvent. The quick-fit distillation apparatus was set on a thermostatic heating mantle and maintained 100℃ for ginger and turmeric. The extraction process was set for about 20-25 minutes, and the liquid collected on the beaker was separated by a liquid separating funnel [55]. The essential oil of dried ginger was also extracted as per the equivalent of fresh ginger weight at various MC.

Similarly, 10g of dried ground ginger was weighed into the thimble wetted 5 ml of the ethanol solvent before fixing the thimble 100 ml of Ethanol was poured on a round bottom flask and was fitted; the heating mantle was regulated to 78℃, which is the boiling point of Ethanol. The setup was heated for about 1-1.5hrs until the ethanol and oil solutions were dropped from the soxhlet funnel to the round bottom flask. After that, the heating mantle was turned off, and the apparatus was left to cool down. This was distilled by distillation apparatus by maintaining the temperature of 78℃ to separate the ginger and turmeric oil [55,56].

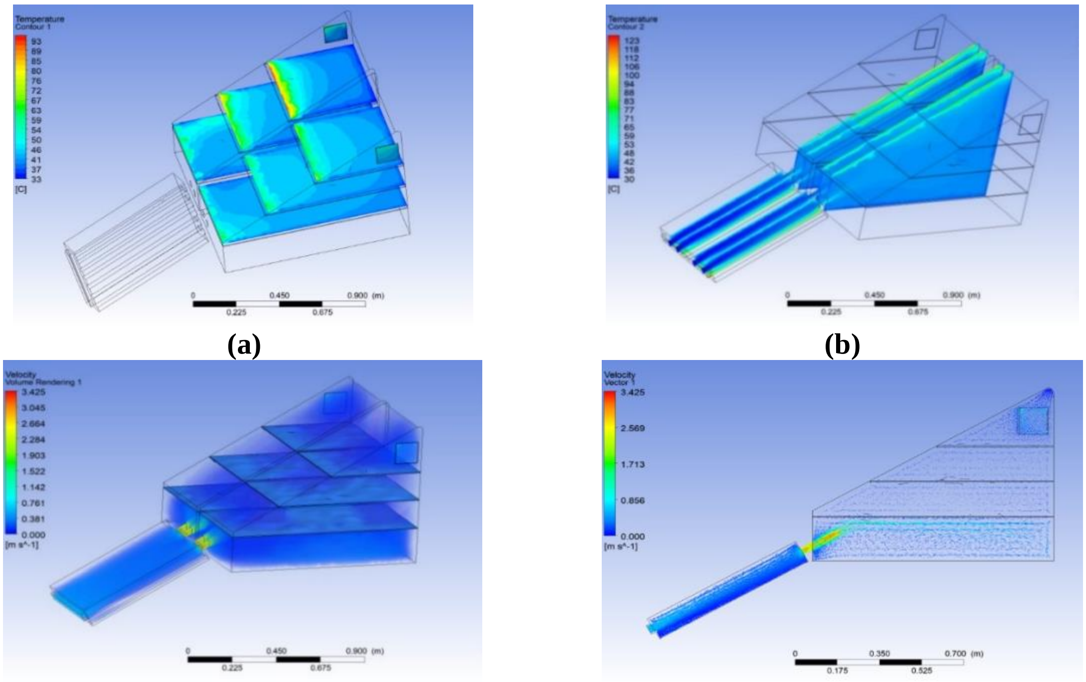
Table 4: Instruments and methods used for determining physical and biochemical parameters

Items	Methods	Instrument used
	Physical Parameters	
Temperature	Direct method	Mercury and alcohol thermometer (1℃)
Humidity	Psychrometric method	Psychrometer (1%)
Velocity	Direct method	Analog Anemometer
MC	Helium moisture analyzer, setting up the program time 10 min at 120 ℃.	KERN DLB Helium moisture analyzer
Solar radiation		Pyranometer
	Biochemical Parameters	
Oleoresin	Soxhlet method	Soxhlet apparatus
Essential oil	Steam Distillation	Steam Distillator

3. Result and Discussion

3.1 Results of CFD analysis

The temperature obtained from the simulation showed that the average temperature of the tray increased from bottom to top (Table 5). The air velocity was found maximum at PVC pipe sections around 3.425 m/sec. The higher temperature of the air was reached near the collector plates (Fig. 4).



(a) **(b)**

(c) **(d)**

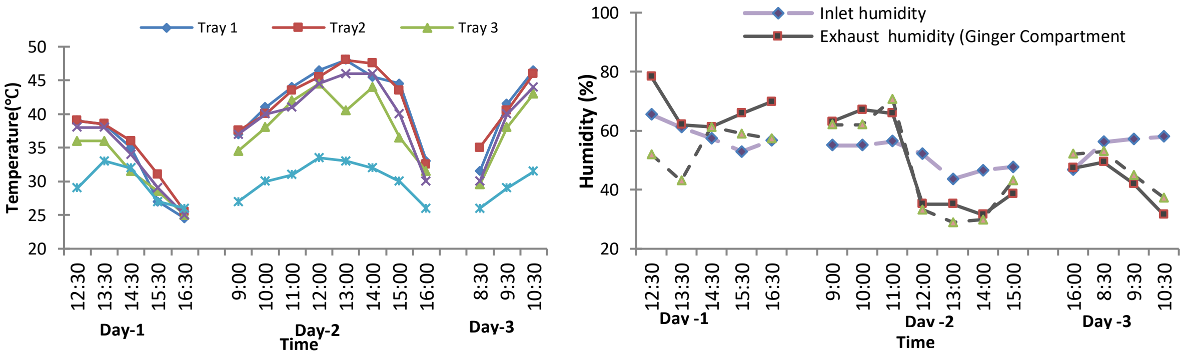
Fig. 4. CFD simulations (a) Temperature distribution contours of trays and outlet which depicts that average temperature increase from lower tray to the upper tray and temperature was maximum where the tray exposed maximum sunlight (b) Temperature distribution for vertical sections showing that temperature is increased from inlet to outlet, and (c-d) Velocity distribution and vectors in the dryer showing that the extreme velocity at the PVC section of the dryer

Table 5: CFD analysis's results which showed that the average temperature nearest to the tray increase from tray 3 to top tray 1

S.N.	Positions	Average temperature (°C)
1	Inlet temperature	30
2	Tray 1 (nearest)	44
3	Tray 2 (nearest)	42
4	Tray 3 (nearest)	40
5	Collector temperature outlet)	41
6	outlet 1	43
7	outlet 2	44

3.2 Temperature and Relative Humidity variation on the dryer

The ambient temperature rises from the collector pass through the drying cabinet and rises while reaching from tray 3 to tray 1 (Fig 5 (a)). At first, the cabinet's temperature rose to a small extent because the energy was used for the removal of moisture, not for the rise in the temperature of the cabinet. After the removal of some extent of MC, the temperature rose and reached a maximum level. The maximum rise temperature was found to be 48 ℃. The temperature difference was recorded as 10℃ at 12:30 in Day-1 and then 15 ℃ at the 13.00 and 10:30 in Day-2 and Day -3 respectively. Firstly, the exhaust air humidity was high because the MC on the product was greater. Later reduced in the moisture content of a product did not restrict to a decrease in the relative humidity (R.H.), which is clear on the graph (Fig 5 (b)).



(a) **(b)**

Fig. 5. Temperature and humidity over time (a) temperature variation curve of the different tray in the dryer showing that the temperature was supreme in upper trays than the lower one and (b) exhaust humidity curve of the different compartment shows that relative humidity from exhaust fan is affected by moisture content at the initial stage of drying.

3.3 Drying curve

The ginger and turmeric drying curve in the mixed-mode solar dryer also follows the standard food-drying curve. It took about 14 hours to reduce MC from about 88% to 10% for ginger and 85% to 12% for turmeric (Fig. 6). There is a slight difference in the uniformity of the drying curve of each tray because of the rising trend of temperature from the lower tray to the upper tray (Fig 7(a)-7(b)).

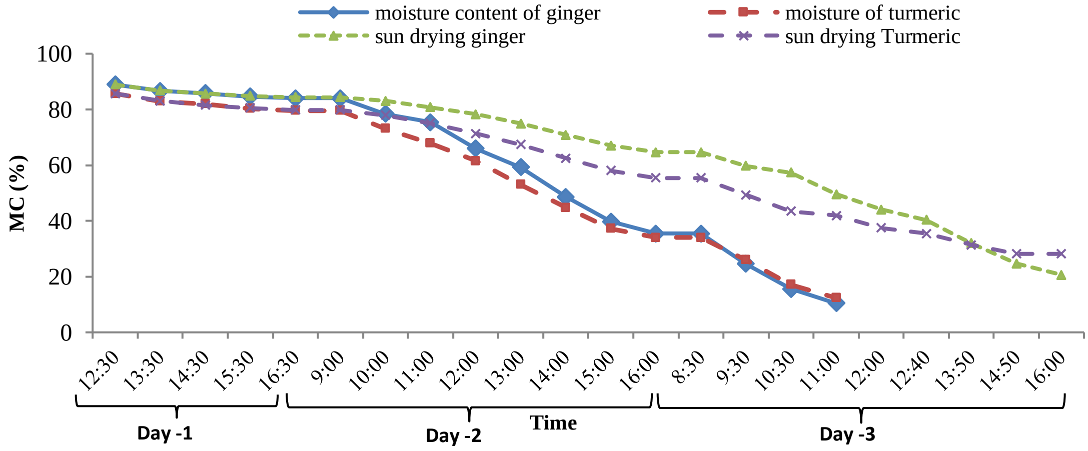
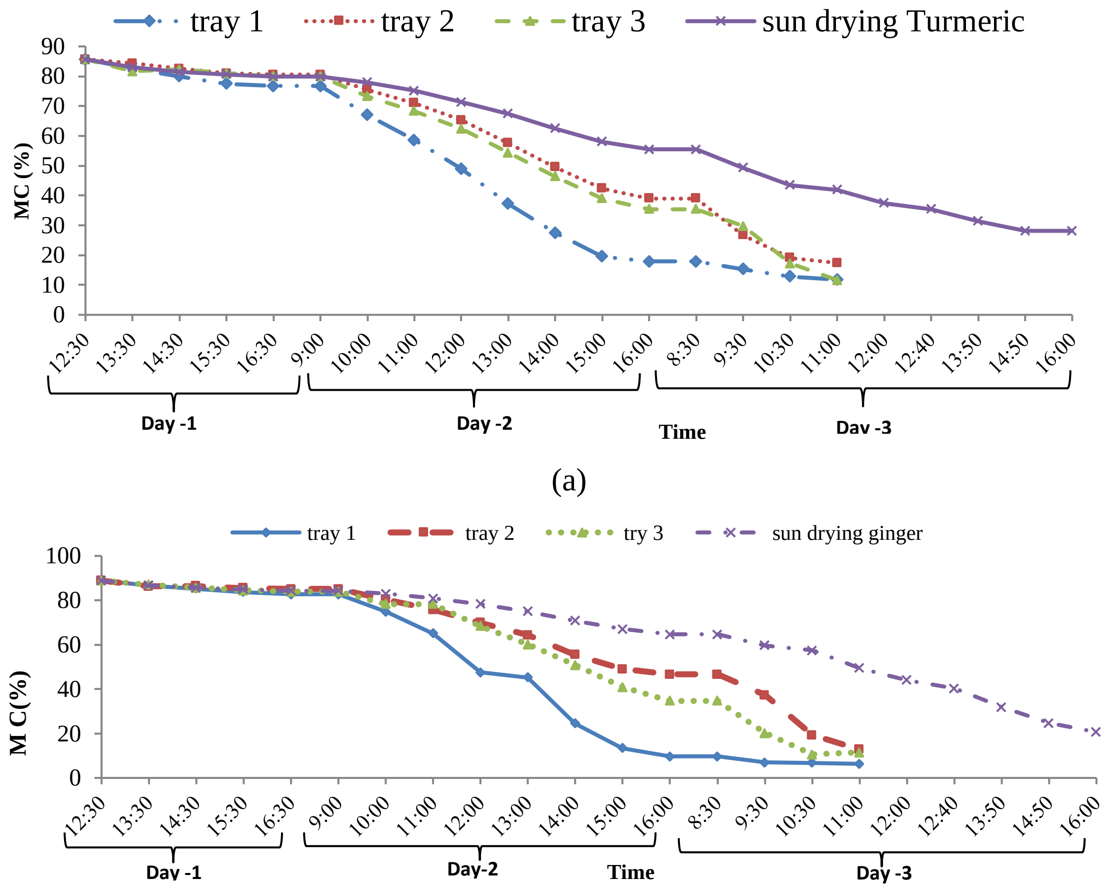


Fig. 6. Ginger and turmeric drying curve shows that the time taken by the dryer is lesser than open sun drying



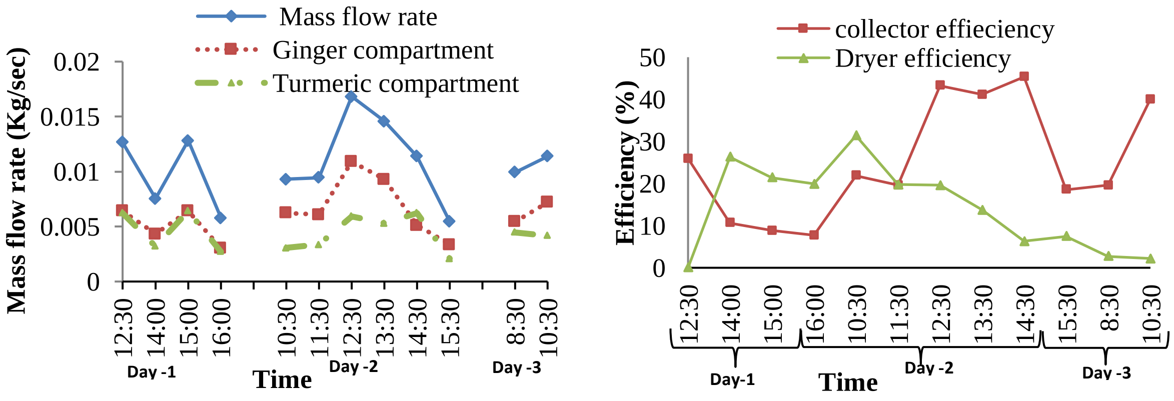
(a)

(b)

Fig. 7:(a) Variation of drying curve of turmeric on each tray and open sun drying. It shows that the drying faster in tray 1 than other one and (b) Variation of the drying curve of ginger on each tray and open sun drying. It shows that the drying faster in tray 1 than other one

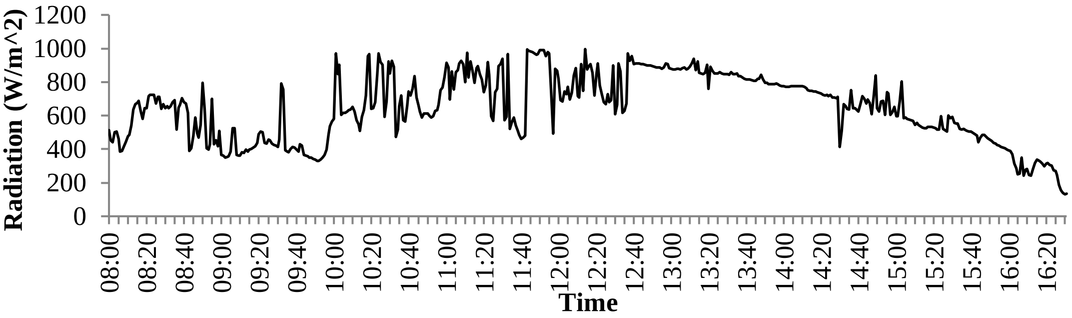
3.4 Collector and Dryer efficiency

The efficiency of the collector and dryer was determined by utilizing Eqs. (9) and (10), and the graph of collector efficiency was plotted on an hourly basis (Fig. 8(b)). For determining efficiencies, the average radiations of five minutes in each period were taken into consideration (Fig. 8(c)). The maximum collector efficiency was found at about 45.32% at 14:30. The maximum drying efficiency was recorded at approximately 26.33% at 14:00 in day -1 and 31.36% at 10:30 in Day-2 which were the initial period of the experiment in each day, and its efficiency decreased later.



(a)

(b)



(c)

Fig. 8. (a) Mass flow rate of air from each compartment (b) Drying and collector efficiency showing that they are highest in mid-day and (c) Solar radiation among the three days.

3.5 Biochemical Evaluation

The essential oil content of the dried product was found less than its initial conditions. However, it was found that the retention of essential oil was higher in the mixed-mode solar dryer. It was measured 1.66 ml (at 10% MC) and 0.5 ml (at 12.33% MC) in ginger and turmeric, respectively, in mixed-mode solar drying, which is higher than that of respective open sun drying (Table 6). The oleoresin content of ginger through dryer was found similar at 10% MC to sun drying sample of MC 20.69%. The oleoresin content of the turmeric slice of the dryer of MC at 12% was also found similar to the sun drying of 28.7% MC, due to the complete drying powder was used to extract the oleoresin content of any products (Table 7).

Table 6: Essential oil determination of various samples of Ginger and Turmeric shows that essential oils are retained more in the products dried in the dryer rather than open sun products

S.N.	Sample	MC (%)	Weight of sample (g)	Essential oil (ml)	The volume of essential oil +water (ml)
			Ginger		
1	Fresh	87.75	30	2.2	84.55
2	Solar dried	10.03	Equivalent of fresh	1.66	86.55
3	Open sun-dried	20.69	Equivalent of fresh	1.5	85
			Turmeric		
1	Fresh	86	30	0.6	54
2	Solar dried	12.33	Equivalent of fresh	0.5	49
3	Open Sun dried	28.70	Equivalent of fresh	0.35	51.5

Table 7: Oleoresin extraction of various samples of Ginger and Turmeric slices which shows that there are no significant changes in oil amount of products in both type of drying methods

S.N.	Sample	MC (%)	Sample weight (g)	Oil weight (g)
		Ginger		
1	Dryer	10.33	10	0.614
2	Open Sun drying	20.69	10	0.610
		Turmeric		
1	Dryer	12.33	10	0.7134
2	Open Sun drying	28.70	10	0.7295

3.6 Drying models

Fifteen thin-layer drying models were applied to determine the model that correlates with the drying curve obtained from the experiments. The statistical data of the various models and their correlated coefficients were summarized in Table (8-9) and curves (Fig. 9-10).

3.6.1 Drying model of ginger

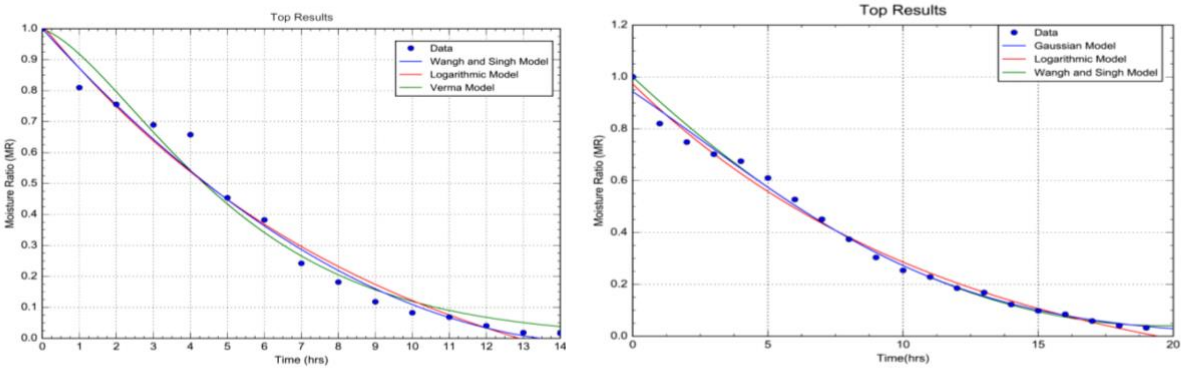
The statistical analysis found that the experimental drying curve of ginger dried in the dryer was highly correlated with the Wang and Singh model, as compared to the other models, with a high correlation coefficient of 0.992. However, it was also found that the experimental sun-drying curve of ginger was highly correlated with the Gaussian model with a higher correlation coefficient of 0.996 than other thin layer drying models. It was also clearly depicted from the top results graphs generated by curve expert professionals. Hence, Wang and Singh model and Gaussian model were used for describing the drying curves of solar-dried and sun-dried ginger slices.

The drying equation model (Gaussian Model) for ginger slice drying in the open sun

$$MR = 1.242815e^{\left(-\left(\frac{(t+7.434025)^2}{2\times 10.0005^2}\right)\right)}$$

The drying model equation (Wang and Singh Model) for ginger slices drying in the mixed-mode solar dryer.

$$MR = 1 - 0.131715t + 0.004265117t^2$$



(a) (b)

Fig. 9. Best fitted statistical analysis thin-layer drying model for ginger drying using (a) mixed-mode dryer and (b) open sun drying. Figures show that the Gaussian model and Wang and Singh model is suitable for ginger dried in the open sun and solar dryer

Table 8: Drying model for ginger (drying with dryer and open sun drying) including their model coefficients and correlation coefficient obtained from Statistical analysis using Curve expert professional

SN	Model name	Coefficients		R		Remarks
		Sun drying	Drying with dryer	Sun drying	Drying with dryer	
1	Lewis	k = 0.1296472	k = 0.18841	0.9877062	0.971945	
2	Henderson and Pabis	a= 1.01896, k= 0.132145	a= 1.064303, k = 0.1928872	0.9879712	0.97459	
3	Logarithmic model	a= 0.209173, k= 0.083905, c= -0.2365136	a = 1.3419, k= 0.108494, c= -0.33131	0.99556038	0.98888	
4	Two term	a= 0.510209, K1= 0.1321453, b= 0.5087503, K2= 0.1321458	-	0.987971279	-	
5	Wang and Singh	a= - 0.09744905, b= 0.0024375	a =-0.131715, b= 0.004265117	0.995175	0.9915	*Dryer*
6	Modified Henderson and Pabis	-	a= 0.4457465, k= 0.1920674, b= 0.3087505, g= 1.927013, c= 0.3087505, h= 0.1927013	-	0.97459	
7	Verma et al.	-	a= 45, k=0.349321, g= 0.356125	-	0.988542	
8	Diffusion approach	a= 1, k= 0.12964, b= 1	a= 1, k= 0.1818841, b= 1	0.9877062	0.9719448	
9	Two term exponential	a= 1.704871, k = 1.728126	a=1.918381, k= 0.2693824	0.9928356	0.987296	
10	Simplified Fick's diffusion equation	a= 1.018965, c= -0.09538507, L= 0.8495947	a = 1.064304, c= -62.0009, L= 17.92910	0.987971	0.97455926	
11	Modified Page equation-II	a = 0.9240763, k= -0.05799948, L= 1.042762, n= 1.379280	-	0.9947948	-	
12	Gaussian model	a = 1.242815, b= -7.434025, c= 10.0005	-	0.996313	-	*Sun drying*

3.6.2 Drying model of turmeric

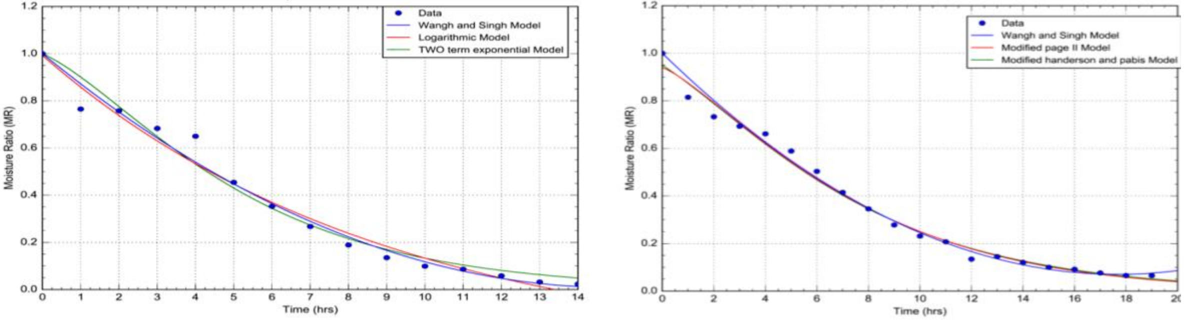
Similarly, the turmeric's sun drying and solar dried curves were also analyzed with the various thin layer drying models in curve expert professional software. It was found that the sun drying curve and dried solar curve of turmeric were highly correlated with the Wang and Singh model because they had a high correlation coefficient with Wang and Singh model as R= 0.99459559 for sun drying and R= 0.990296 for solar dried turmeric. Hence, Wang and Singh's model was suitable for describing the drying curves of turmeric generated from sun drying and drying with a designed dryer.

The drying equation model (Wang and Singh Model) for turmeric drying open sun:

$$MR = 1 - 0.105147t + 0.0029729t^2$$

The drying model equation (Wang and Singh Model) for turmeric drying in the mixed-mode solar dryer:

$$MR = 1 - 0.13253t + 0.004296t^2$$



(a) **(b)**

Fig. 10. Best fitted statistical analysis thin-layer drying model for turmeric drying using (a) mixed-mode dryer and (b) open sun drying. Figures show that the Wang and Singh model is best fitted for turmeric in both drying methods

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Table 9: Drying models for Turmeric (drying with dryer and open sun drying) including their model coefficients and correlation coefficient obtained from Statistical analysis using Curve expert professional

SN	Model name	Coefficients		R		Remarks
		Sun drying	Drying with dryer	Sun drying	Drying with dryer	
1	Lewis	K= 0.1356688	k = 0.1800525	0.9902106	0.97526	
2	Henderson and Pabis	a= 1.010587, k= 0.137134	a= 1.041562, k= 0.1872	0.99029288	0.976	
3	Logarithmic model	a= 1.09777, k= 0.1062144, c= -0.1160442	a=1.286532, k = 0.1102, c = -0.294118	0.993418	0.988	
4	Two term	-	a = 0.5011, K1= 0.18726, b= 0.54041, K2= 0.1872676	-	0.97645	
5	Wang and Singh	a= -0.105147, b= 0.0029729	a= -0.13253, b= 0.004296	0.99459559	0.990296	*Open Sun drying and Dryer*
6	Modified Henderson and Pabis	a= 2.65549, b= 0.19734, b = -0.852590, g= 0.26499, c= -0.853352, h= 0.2683422	a= 0.1738, k= 0.18720, b= 0.43383, g= 0.18772, c=0.4338, h=0.18722	0.994236665	0.9764525	
7	Diffusion approach	a= 1.000, k= 0.1356688, b= 1	a= 1,k= 0.18005, b=1	0.99021063	0.975266	
8	Two term exponential	a = 1.649675, k= 0.1753714	a = 1.84537, k= 0.257657	0.9933525	0.98636	
9	Simplified Fick's diffusion equation	a= 1.0105, c= -0.667957, L= 2.207009	a= 1.04156, c= 340.8, L= 42.6	0.990292889	0.9764525	
10	Modified Page equation-II	a= 0.93937, k= -0.95527, L= 2.7832, n = 1.2694	-	0.994565	-	

4. CONCLUSION

A simple mixed-mode solar dryer was designed and constructed successfully using locally available materials. The dryer testing was done in November using ginger and turmeric. The steady-state CFD analysis was performed using ANSYS fluent in predicting the temperature and velocity of the air inside the collector, trays, and outlet of the dryer.

The experiment's findings showed a substantial increment of the maximum temperature of around 15 ℃ in the tray of the dryer than ambient temperature. The time required for drying of the ginger and turmeric in the dryer was 14 sunshine hours from about 88% MC to 10-12% MC which was much higher than open sun drying. In addition to this, the maximum drying and collector efficiency were found to be 31.364% and 45.32%. From the result of the CFD analysis, it was found that the average temperature of the tray increased from lower trays to upper trays and maximum where trays were exposed to the sunlight, which correlates with the temperature results obtained from the experiment. The biochemical analysis performed in the essential oil and oleoresin showed that retention of the essential oil was more in the dryer product than the open sun drying product. The drying curves obtained from the dryer for ginger and turmeric were highly correlated to Wang and Singh model (R= 0.990296 for turmeric and 0.992 for ginger) compared to other drying models. Based on the finding of the experiments, it was concluded that the designed mixed-mode solar dryer has sufficient capacity to dry food items rapidly to a safe moisture level, and simultaneously, it ensures a good quality of the dried product

Conflicts of Interest

The authors have no conflicting interests – financial or otherwise.

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