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Drying kinetics, quality assessment and socio environmental evaluation of solar dried underutilized arid vegetable Cucumis callosus

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ABSTRACT

A natural convection solar tunnel dryer of capacity 100 kg was used to analyse the drying kinetics of naturally grown arid vegetable kachri (*Cucumis callosus*). The moisture reduction was found from 86.10 % to 7.02 % (on wet basis) in two solar days (15 hours). Solar drying curves were estimated using six different drying kinetic models and were compared based on their modeling efficiency. The statistical analysis revealed that Page and Midilli kinetic drying models accurately estimated solar drying characteristics of kachri with a modeling efficiency of 0.971 as compared to other models. Nutritional, microbial, and organoleptic analysis showed that dried kachri product was nutritionally healthy for human consumption. A significant ($p<0.01$) relationship was found between rehydration characteristics and rehydration time. Techno-economic indicators show that the drying system was economically feasible and could recover investment in 8.70 months. The net carbon dioxide mitigation potential was found 77.05 tons over the lifespan of the dryer.

1. Introduction

The western part of India is one of the largest subtropical deserts in the world. The vegetable cultivation area and production are limited to areas which have assured irrigation facilities. However, vegetable cultivation is negligible under irrigated and non-irrigated, covering most of the desert area. These arid and semi-arid agro-climatic conditions favour traditionally grown of several vegetables such as kachri (*Cucumis Callosus*), mateera (*Citrullus Lanatus*), phoot kakri (*Cucumis Melovar Momordica*), ker (*Capparis Decidua*), sangria (*Prosopis Cineraria*), clusterbean (*Cyamopsis Tetragonoloba*) etc. [1]. Kachri (Cucumis Callosus) is a wild variety of cucumbers and its belongs to Cucurbita cease family [2].

Kachri has short-hairy stems, monoecious, long spreading hairs on the ovary, yellow flowers, 4.5-6 cm long fruit with a 50-200 g weight, and egg and elliptic fruit shape. It has yellow, light green, or cream uniform colour with orange and dark green spots, large seed cavity, and its initially bitter but at ripening, it turns into sweetnes [3]. It is the natural earth food growing wild, and rich in carbohydrates, protein, and minerals for people living in the harsh arid regions. The indigenous people of rural arid regions still gather kachri in limited amounts. However, increased urbanization has negatively impacted the eating habits of local communities and the ecosystems in which their native foods grow, making vegetables like kachri increasingly rare [4]. The ground powder of dried kachri can be preserved for a few months and the whole dried kachri can be persist for a few months.

Furthermore, some have a fantastic flavor and taste and make delicacies at home. In the desert regions of north-western India, dried kachri is one of the important components of the delicious dish known as PANCHKUTA (Kachri, Gunda, Kumti, Ker and Sangari) [5]. The fruit is better at unripe condition, pungent and appetizer. The dehydrated kachri is tonic, refrigerant, coughcide, gastric stimulant, vermicide, laxative, diuretic, and suppurative [1]. It is useful in cough, digestion, coryza, piles, facial paralysis, bile obesity, and constipational troubles [5]. Regular use of dehydrated kachri powder help to cure minor skin diseases like bed sores, manifestation, lice, boils, earache, itching, prickly heat, and so on [6].

In a hostile environment where vegetable crop diversification is difficult, the kachri crop provides a source of income [7]. However, the kachri fruit is only available for a very short duration, and fresh produce has a short self-life, so it becomes almost unfit for human consumption within a week of harvest. In this way, only a small portion of the entire product of kachri is used profitably during the short availability period. The remaining product spoils due to over ripeness or lack of knowledge of various processing strategies. Due to glut and its perishable behaviour during harvesting period, post-harvest losses range from 30-40 %, lowering the fruits market value [8]. Drying the kachri can be a useful way to avoid post-harvest losses while also providing high returns to growers and allowing the fruit to be available during the off-season [9]. Limited literatures are available on the value addition of kachri.

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Nomenclature

T_a	Ambient temperature (°C)
E_{ta}	Annual thermal energy output of the dryer
AOAC	Association of Analytical Communities
BCR	Benefit cost ratio
B_t	Benefit in each year
R^2	Coefficient of determination
ΔE	Colour index
C_t	Cost in each year
Df	Degree of freedom
I	Discount rate (%)
Dm	Dry matter
E_m	Embodied energy (kWh)
EPBT	Energy payback time
E_e	Energy required for drying (J)
M_e	Equilibrium moisture content
$MR_{exp,i}$	Experimental moisture ratio (dimensionless)
M_o	Initial moisture content
IRR	Internal rate of return (%)
N_{sys}	Life span of dryer (years)
W_t	Mass of sample at time t
T_m	Mean temperature of dryer (°C)
$MR_{exp,mean,i}$	Mean value of the experimental moisture ratio (dimensionless)
EF	Modeling efficiency
M_t	Moisture content at time, t
MR	Moisture ratio (dimensionless)
NPW	Net present worth (USD)
PBP	Payback period (years)
L_a	Poor domestic appliances losses (%)
$MR_{pre,i}$	Predicated moisture ratio (dimensionless)
P	Probability value
RMSE	Root mean square error
STD	Solar tunnel dryer
SS	Sum of square
E_{tb}	Thermal energy output per batch (kWh)
N_b	Total number of batch per year
L_{td}	Transmission and distribution losses (%)
a_w	Water activity
W_d	Weight of dried sample
Wb	Wet basis
χ^2	Chi-square
λ_w	Latent heat of evaporation (kJ/kg)

A comprehensive study on drying characteristics, rehydration properties, mathematical modeling, statistical analysis, quality evaluation, and the techno-economic of such an underutilized arid fruit i.e., kachri are presented in this paper.

2. Materials and methods

2.1. Experimental setup

The solar tunnel dryer (STD) used for drying kachri slices consisted of a 200 μm UV-stabilized polyethylene sheet in semi-cylindrical shape and the orientation was south facing. The total collector area was 5 m length, 3.45 m width and 1.9 m height. The air flowed into the tunnel dryer through a rectangular opening of 20×20 cm. Fig. 1 illustrates a schematic diagram of the solar tunnel dryer used in the present study. The solar dryer was not shaded during the drying time from 09:00 a.m. to 05:30 p.m. The other technical specifications of the STD are presented in Table 1.

Table 1
Detailed technical specifications of STD.

Particulars	Specifications
Length of STD, m	5
Width of STD, m	3.75
Height of STD	1.9
Number of trolleys	2
Number of Chimney	2
Diameter of Chimney, m	0.20
Height of Chimney, m	0.45
Plastic cover, uv stabilized	200 μm
Covering material area, m^2	38.65
Fresh air vent area, m^2	0.04
Door	1.75×0.75 m

2.2. Experimental procedure

Fully ripe and fresh kachri were procured from a local market of Barmer, Rajasthan (India). The row freshly harvested kachri was manually sorted and was firm, brownish-yellow, mature in nature. Kachri were washed thoroughly and manually cut into 8 ± 0.1 mm thick slices. The kachri slices were then distributed evenly on the tray inside the STD. Fig. 2 illustrates the complete process for kachri processing. The weight loss of the kachri slices was measured constantly at 30 minute intervals until the moisture content of the kachri remained constant, which was considered as dynamic equilibrium.

2.3. Drying kinetics

The moisture content of kachri sample was calculated on a wet basis (wb) using equation (1):

$$\text{Moisture content (\% wb)} = \frac{W - W_d}{W} \times 100 \tag{1}$$

Where W and W_d are the weight of the original and dried sample, respectively.

The drying rate of the sample was determined using equation (2):

$$DR = \frac{W - W_t}{\Delta t \times w} \tag{2}$$

Where DR is the drying rate at time t (kg water/kg dry solid), W and W_t are the mass of the sample at initial and time t, respectively, and w is the bone dry material.

2.4. Mathematical modeling

The moisture content was expressed as a percent wet basis and the converted to kg water per kg original material. The moisture ratio (MR) was expressed as:

$$MR = \frac{M_t - M_e}{M_o - M_e} \tag{3}$$

Where M_e, M_o and M_t are the moisture content (% wb) at equilibrium, initial and time t, respectively.

However, the relative humidity of the drying air fluctuated continuously during the solar drying process, determining the equilibrium moisture content is challenging [10]. Therefore, the moisture ratio can simplify to:

$$MR = \frac{M_t}{M_o} \tag{4}$$

The experimental drying data for kachri was fitted using six semi-empirical and empirical models presented in Table 2.

The drying rate constants (k) and empirical constants of different drying models were determined by non-linear regression analysis of Microsoft Excel (2016 version). In addition, the coefficient of determination (R^2) [11], modeling efficiency (EF), reduced chi-square (χ^2) and root mean square error (RMSE) [10] were used to assess and compare

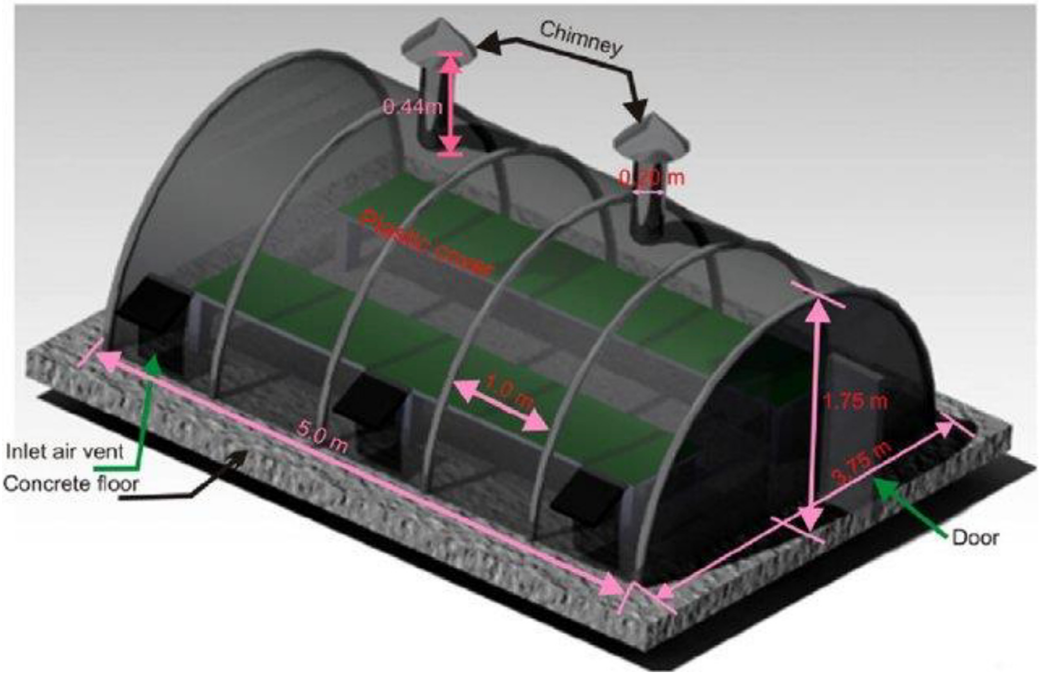


Fig. 1. Solar tunnel dryer.

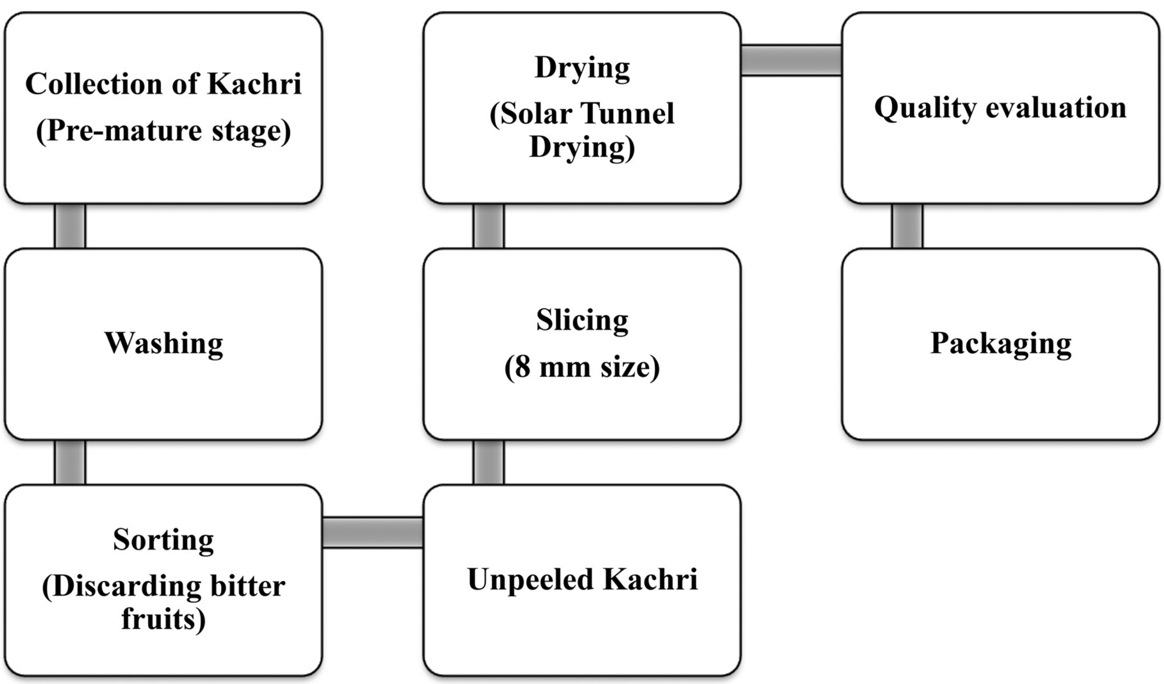


Fig. 2. Flow process of kachri processing.

Table 2
Applied mathematical models to the drying curves.

Model	Model Equation	References
Newton	MR = exp(-kt)	[27]
Page	MR= exp(-kt^n)	[10,22]
Handerson and Pabis	MR = a exp[-(kt)^n]	[10]
Modified page equation	MR = exp (-k(t/l^2)^n)	[43]
Midilli	MR= aexp(-kt^n)+bt	[12,44]
Two term exponential	MR = a exp(-kt)+(1-a) exp(-kat)	[22,43]

Where t is time (min), k is the drying rate constant (min^{-1}) and a, b, l and n are empirical constants.

the statistical validity of the models. The parameters were determined as follows: Equation 5-(8).

$$R^2 = 1 - \left(\frac{\sum_{i=1}^{N} \left(MR_{exp,i} - MR_{pre,i} \right)^2}{\sum_{i=1}^{N} \left(MR_{i,\ expmean} - MR_{exp,i} \right)^2} \right) \tag{5}$$

$$\chi^2 = \frac{\sum_{i=1}^{N} \left(MR_{exp,i} - MR_{pre,i} \right)^2}{N - n} \tag{6}$$

$$RMSE=\left(\sqrt{\frac{\sum_{i=1}^{N}\left(MR_{exp,i}-MR_{pre,i}\right)^2}{N}}\right) \quad (7)$$

$$EF=\frac{\sum_{i=1}^{N}\left(MR_{exp,i}-MR_{i,\ exp\ mean}\right)^2-\sum_{i=1}^{N}\left(MR_{pre,i}-MR_{exp,i}\right)^2}{\sum_{i=1}^{N}\left(MR_{exp,i}-MR_{i,\exp mean}\right)^2} \quad (8)$$

Where $MR_{exp,i}$ and $MR_{pre,i}$ are the experimental and predicated moisture ratio, respectively, $MR_{exp,mean,i}$ is the mean value of the experimental moisture ratio, N is the number of observation and n is the number of constants.

The R^2 was one of the primary comparison criteria for selecting the best drying curves model. Therefore, the most suitable model that describes the drying behavior of kachri was chosen as the one with the highest R^2 (close to one) [12] and the EF (close to one) and the least reduced χ^2 (close to zero), and RMSE.

2.5. Quality evaluation

Quality evaluation of the dried product was evaluated for ascorbic acid, colour analysis, rehydration characteristics, water activity and ash content.

2.5.1. Ascorbic acid (vitamin C)

2, 6 dichlorophenol-indophenols titrimetric method was used to determining the vitamin C contain in kachri sample [13]. Triturated sample of 10 ± 0.1 g was weighed, filtered and diluted to a 50 mL volume. The following equation (equation 9) was used to calculate the amount of ascorbic acid.

(76d as follows: (Equation 5 m is the bone dry material.oisture lost by sample of kachri slices in particular time interval

$$Amount\ of\ ascorbic\ acid\frac{mg}{100g}sample=\frac{0.5\ mg}{V_1 ml}\times\frac{V_2\ ml}{5\ ml}\times\frac{100ml}{Wt.of\ the\ sample}\times 100 \quad (9)$$

Where V_1 and V_2 are the volume of dye consumed for the standard solution and test solution, respectively.

2.5.2. Colour analysis

Colour, which reflects sensation to the human eye, is one of the most significant attributes of product acceptance. The colour of dried kachri sample was measured in the term of lightness coefficient 'L', redness (+ a value) or greenness (- a value) coefficient 'a' and yellow (+ b value) or blue (- b value) coefficient 'b' values on Hunter scale [14].

2.5.3. Rehydration characteristics

According to Ranganna [15], there is no standard period for rehydration of dried products or food stuffs and generally varies from one product to another product. A trial run was performed for the purpose of optimizing rehydration time. Before starting the rehydration test, the temperature of hot water bath was set to 30 °C for 30 minute to maintain uniform temperature. Rehydration process was performed by submerging about 5 ± 0.1 g of solar-dried sample in 100 mL of distilled water in a glass beaker with a capacity of 250 mL. The sample was withdrawn every 10 minutes until the no mass gain by the sample, wiped with filter paper to remove any superficial water on the sample surface, and weighed. The dried kachri products rehydration properties, such as rehydration ratio and coefficient of rehydration, were then determined using the method described by Ranganna [16]:

$$Rehydration\ ratio=\frac{C}{D} \quad (10)$$

$$Coefficient\ of\ rehydration=\frac{C\times(100-A)}{\left(D-\frac{BD}{100}\right)\times 100} \quad (11)$$

Where, A = moisture content before drying, (%, wb)
B = moisture content of dried sample, (% wb)
C = drained weight of rehydrated sample, g
D = test weight of dehydrated sample, g

2.5.4. Water activity (a_w)

Water activity is a function of the water content in the food and plays a key role in the preservation of fresh, frozen and dried food [17]. Water activity was calculated using the following equation [18]:

$$a_w=\frac{\text{Vapour pressure of water exrted by food}}{\text{Saturated vapour pressure of water at the same temperature}} \quad (12)$$

2.5.5. Ash content determination

Food ash is an inorganic residue that remains after burning organic matter. Total ash estimation is an index of food refinement and a valuable parameter for assessing the nutritional value of foods [4]. The ash content of samples was determined using the following equation [19]:

$$\text{Ash}\left(\frac{g}{100}g\right)=\frac{\text{Mass of ash (g)}}{\text{Mass of sample taken (g)}}\times 100 \quad (13)$$

2.5.6. Sensory evaluation of kachri powder and rehydrated kachri

Organoleptic evaluation of food products is important to assess the customers' requirements. Therefore, organoleptic properties of kachri powder and rehydrated dried samples were carried out with the help of a panel of 25 consumer panelists, using a 9-point numerical sensory card, following standard procedure [20]. The organoleptic quality of samples was assessed, including colour, odour, taste, flavor, appearance, and overall acceptability [14]. For each property, the average of all panelists score was calculated [21].

2.6. Energy and environmental analysis

2.6.1. Thermal energy output

The thermal energy output of the dryer per batch was calculated using following equation [22]:

$$E_{tb}=\frac{E_e}{3.6\ \times 10^6} \quad (14)$$

Where, E_{tb} = thermal energy output per batch (kWh)
E_e = energy required to evaporate water from sample (J)

$$E_e=mC_p\Delta T+m\times\lambda_w \quad (15)$$

Where, m = mass of water removed, kg
C_p = specific heat of water, kJ/kg.°C
$\Delta T = T_m - T_a$
T_m = mean temperature of dryer,°C
T_a = ambient temperature,°C
λ_w = latent heat of evaporation, kJ/kg
Therefore, Annual thermal energy output of the dryer

$$\left(E_{ta}\right)=E_{tb}xN_b \quad (16)$$

Where, N_b, is the total number of batch per year and is assumed to be 60 batch per year for kachri.

2.6.2. Embodied energy (E_m)

The total energy required to produce any things, services, and system is referred to as embodied energy. The calculation of E_m of various materials utilized in the manufacturing of drying system is shown in Table 3.

2.6.3. Energy payback time (EPBT)

It is the number of useful life years required to pay back the same amount of energy used in the drying system manufacturing and determine as [23]:

$$EPBT=\frac{E_m}{E_{ta}} \quad (17)$$

Where, E_m = embodied energy
E_{ta} = annual energy output

Table 3
The calculation of embodied energy for STD.

S. No.	Materials	Quantity (Kg)	Coefficient of E_m (kWh/kg)	E_m (kWh)	References
i.	Polycarbonate sheet	10.50	10.197	107.07	[23]
ii.	GI Pipe	48.00	37.00	1776.00	[45]
iii.	Chimney	1.50	34.80	52.20	[45]
iv.	Wire mesh steel tray	15.00	9.67	145.05	[23]
v.	Hinges	0.10	55.28	5.528	[22]
vi.	Stopper	0.05	55.28	2.764	[22]
vii.	Handle	0.10	55.28	5.528	[22]
viii.	Screws	0.10	55.28	5.528	[22]
Total embodied energy(kWh)				2099.67	

2.6.4. CO_2 emission

The carbon dioxide emission per year can be calculated as [23]:

$$CO_2 \ emissions \ per \ year \ = \frac{E_m \times 0.98}{Life \ time} \tag{18}$$

2.6.5. CO_2 mitigation

The carbon dioxide mitigation is measured per kWh in order to be compared with the emissions of carbon dioxide (CO_2) from other power generation technologies.

The different energy losses by consumers using domestic appliances in consumption, transmission, and distribution of unit power. The average CO_2 equivalent intensity from coal-fired-based electricity is 0.98 kg of CO_2 per kWh, therefore the CO_2 mitigation of the system would be X as below [23]:

$$X = \frac{1}{1 - L_a} \times \frac{1}{1 - L_{td}} \times 0.98 \tag{19}$$

Where, X = the CO_2 mitigation of dryer, kg/kWh

L_a = poor domestic appliances losses (taken as 10 %)

L_{td} = transmission and distribution losses (assume 45 %)

Net mitigation over the lifespan of solar dryer = Total CO_2 mitigation – Total CO_2 emission

$$= \left[E_{ta} \times N_{sys} \times X - E_m \times 0.98\right] \tag{20}$$

Where N_{sys} is lifespan of dryer (taken 12 years).

2.7. Economic evaluation

The economic analysis of the STD for the drying of kachri was carried out by employing four different economic indicators such as Net Present Worth (NPW), Benefit Cost Ratio (BCR), Pay-Back Period (PBP), and Internal Rate of Return (IRR) [24].

2.7.1. Net present worth

Discounting can be used to determine the present values of potential future returns. Discounting is essentially a method for reducing future advantages and cost streams to their present worth. The most straight forward discounted cash flow measure of project worth is the net present worth (NPW). The net present worth can be calculated by deducting the total discounted present value of the cost stream from that of the benefit stream. The parameters considered for the calculation of NPW includes benefit in each year (B_t); cost in each year (C_t); number of years (t = 1, 2….n); life time of dryer in years (n) and discount rate in percentage (i).

The net present worth of solar drying system was calculated by following equation:

$$\mathrm{NPW} = \sum_{t=1}^{t=n} \frac{B_t - C_t}{(1+i)^t} \tag{21}$$

2.7.2. Benefit cost ratio

This is the ratio obtained when the present worth of the benefit stream is divided by the present worth of the cost stream. The project's economic cost is the sum of installation costs, operation and maintenance, and replacement costs. The formal selection criterion for the benefit cost ratio for the measure of project worth is to accept projects with a benefit cost ratio of one or greater.

The mathematical benefit-cost ratio can be expressed as:

$$Benefit \ cost \ ratio = \frac{\sum_{t=1}^{t=n} \frac{B_t}{(1+i)^t}}{\sum_{t=1}^{t=n} \frac{C_t}{(1+i)^t}} \tag{22}$$

2.7.3. Payback period

The payback period is the time from the installation of the solar tunnel dryer until the incremental production stream's net value reaches the total capital investment. It calculates the length of time needed to recover investment costs.

Payback period can be computed as follow:

$$Payback \ period = \frac{Total \ investment \ of \ the \ project}{Annual \ net \ profit} \tag{23}$$

2.7.4. Internal rate of return

Another way of using the internal cash flow to measure the worth of a project is to find the discount rate that makes the net present worth of the incremental cash flow equal to zero. This discount rate is called the internal rate of returns.

Internal rate of return is determine using following equation:

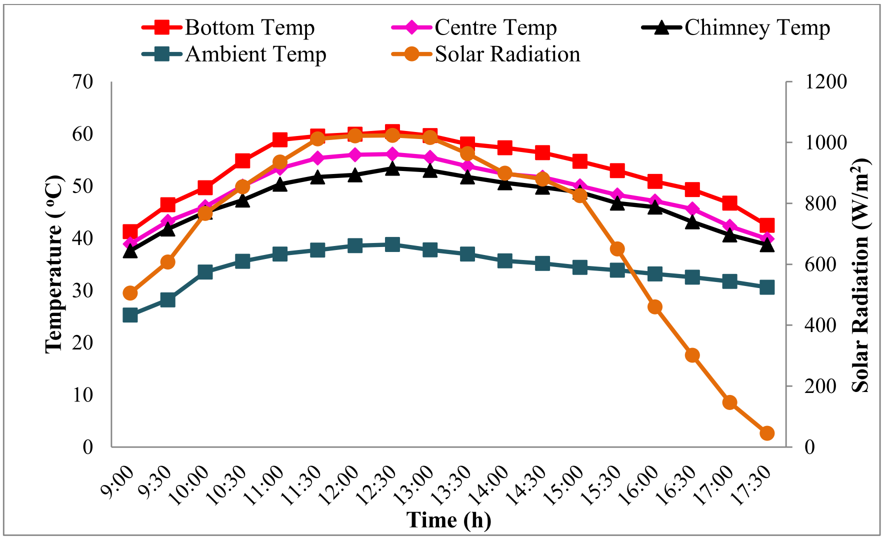
$$\sum_{t=1}^{t=n} \frac{B_t - C_t}{(1+i)^t} = 0 \tag{24}$$

2.8. Statistical analysis

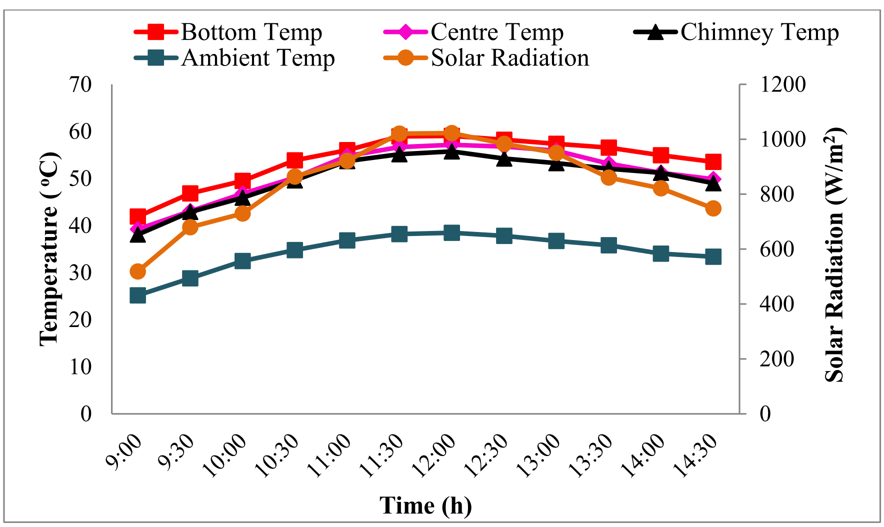
In order to assess the validity between rehydration characteristics and rehydration time, a statistical analysis was carried out using the statistical regression analysis [25].

2.9. Instrumentation

Solar radiation during the drying process was measured by a Digital Lux meter (HTC Instrument, HTCLX 101, range 1 to 200000 Lux, Accuracy ± (4.0 %+10)). The temperature of ambient air, center and bottom of drying chamber, and at the outlet of chimney was measured using a Data Taker (DT82E, Thermo Fisher Scientific Inc.), equipped with a J-type thermocouple (temperature range: -45 ^{0}C to 70 ^{0}C, % uncertainty ± 0.7 %). A digital electronic weighing balance was used to measure the weight of the sample. The initial moisture content was measured by a digital moisture analyzer (MA100, Sartorius AG). The colour of the sample was measured before and after the drying process by using a Hunter Lab Calorimeter (CFLX-45). The water activity of the samples



(a): Kachri drying during first day



(b): 2nd solar day

Fig. 3. Temperature (^{0}C) and solar radiation (W/m^2) variations over time (h).

was measured by a water activity meter (HygroLab-C1, Rotronic measurement solutions, Relative Humidity: 0-100%, Temperature: -10°C to 60°C, Accuracy at 23°C: ±1.5%rh, ±0.3K). The Muffle Furnace (Toshniwal Process Inst. Pvt. Ltd., Temperature Range: 0°C to 2000°C) was used to measure the volatile solid and Ash content of the Kachri sample. The content of ascorbic acid was determined using AOAC method No. 967.21 (2, 6 dichlorophenol–indophenols titrimetric method) (AOAC, 2000).

3. Result and discussion

3.1. Parameter of drying air

During drying experiment of kachri, the solar insolation and temperature variation with respect to time are shown in Fig. 3. Ambient air temperature during the drying period ranged from 25.26 to 38.79 °C. The kachri slices were dried in 15 hours with a maximum and average solar radiation availability of 1023 and 750 W/m^2, respectively. During the experiment, the maximum inside temperature of the solar dryer was 60.4 °C at 12:30 p.m., while the minimum temperature was 41.23 °C at 09:00 a.m. It was observed from Fig. 3 that the temperature inside the STD was lower in the morning and evening due to the minimum availability of solar radiation intensity and reached its maximum in the afternoon due to higher availability of solar radiation.

3.2. Effect of process variable on drying

The variation of moisture content (wb) of kachri slices in different trays as a function of drying time is shown in Fig. 4. Kachri slices had initial moisture content 86.10 per cent (wb) which reduced to 6.8 per cent (wb) within 15 hours (2 solar days) and followed the typical drying curve behavior. Initial stager presents a drastically decreases in moisture content and subsequently decreased drying rate with drying rate. As a result, the air's moisture carrying capacity was increased, causing a higher temperature and lower absolute humidity in the dryer compared to the ambient temperature and ambient absolute humidity. Generally, the capacity of air moisture absorption was affected by the relative humidity of the intake air in a dryer [10]. The drying rate varied from 0.00434 to 0.000114 g of water evaporated per g of dry matter and shown in Fig. 5. Which showed that, the initial four hours of the drying process graph

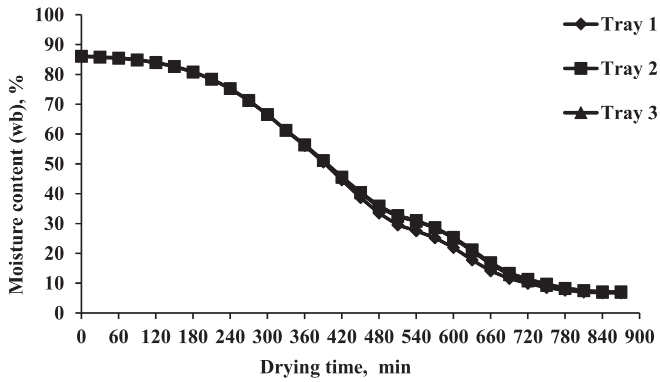


Fig. 4. Variation of moisture content (wb) of kachri with drying time.

Table 4
Estimated modeling parameters for solar drying of kachri.

Model	Model Constants		R^2	RMSE	χ^2	EF
Newton	k	0.002048	0.947	0.0557	0.0032	0.9478
Page	n	2.47529	0.971	0.0626	0.0588	0.9710
	k	2.3×10^{-7}				
Handerson and Pabis	k	0.00257	0.921	0.0912	0.0089	0.9212
	a	1.254076				
Modified page equation	n	2.667888	0.966	0.0700	0.0054	0.9656
	k	0.06124				
	l	12.9363				
Midilli	n	2.45856	0.971	0.0632	0.0046	0.9712
	k	2.3×10^{-7}				
	a	1.01236				
	b	0.00000625				
Two term exponential	k	0.0039	0.951	0.0780	0.0065	0.9512
	a	2.38202097				

remained steeper, the moisture removal rate was higher. After that, the drying rate curve was decreased up to a near-perfect horizontal line. It revealed that the drying rate decreases rapidly as the moisture content decreases and the drying time increases. Fig. 6 shows the variation of drying rate concerning moisture content (% wb). The graph showed a slight variation at the beginning of the second solar day, caused by higher solar radiation than the last drying hour of the first day. The diminishing presence of water in its free form as the moisture-food interactions get strong can be attributed to the decreases in drying rate with decreased moisture content of kachri [26]. The drying rate decreases rapidly as the moisture content decreases and the drying time increases

3.3. Mathematical modeling

Mathematical modeling is useful in the drying process, to predict the moisture content of a product [12]. Table 4 shows the results of the drying model coefficient and statistical analysis for solar drying of kachri. The values of R^2, χ2, RMSE and EF for different models range from 0.921 to 0.971, 0.0032 to 0.0588, 0.0557 to 0.0912 and 0.9212 to 0.9712, respectively. The data in Table 4 shows that, in solar tunnel drying, the R^2 for all models was higher than 0.95, except that for the Newton and Handerson and Pabis models. The models of Midilli, Page, modified Page equation, and two-term exponential were the su-

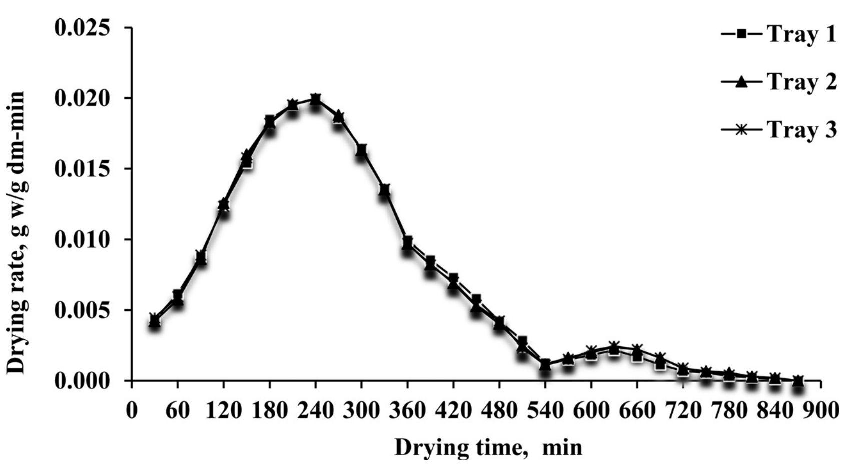


Fig. 5. Variation of drying rate of kachri with drying time.

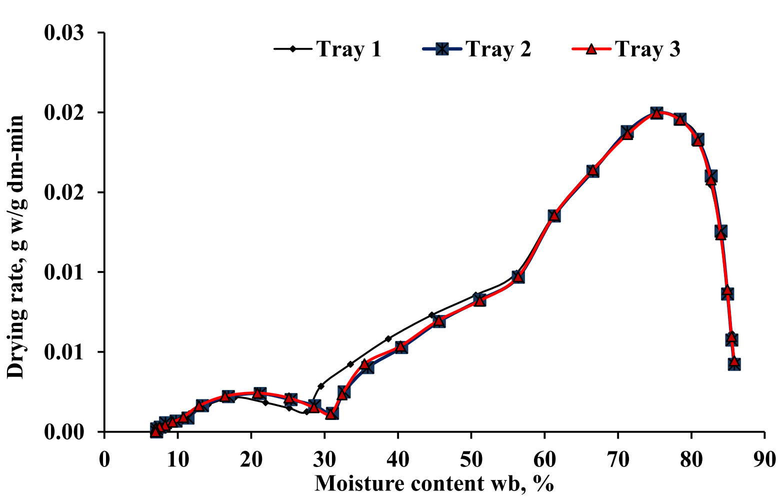
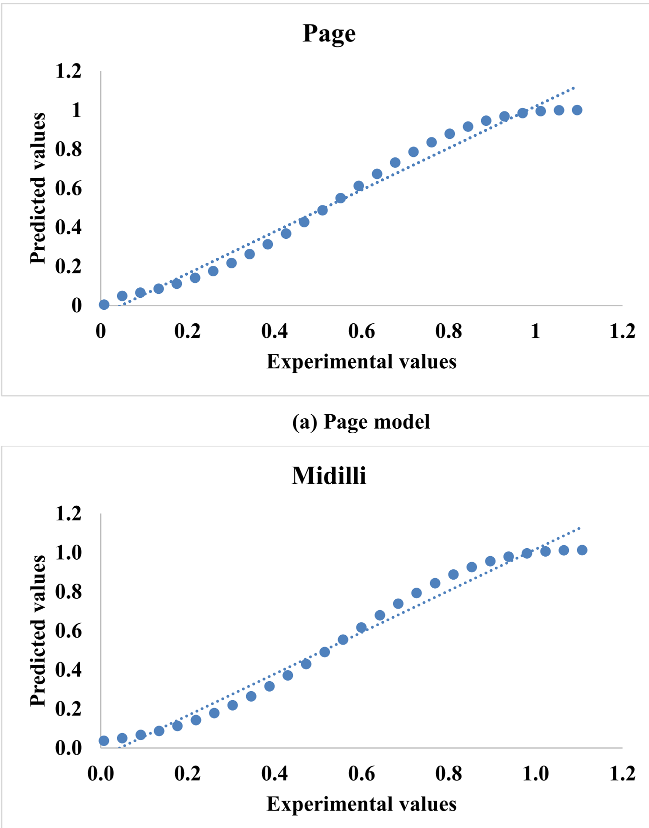


Fig. 6. Variation of drying rate of Kachri with moisture content (wb).



(a) Page model

(b) Midilli model

Fig. 7. Comparison between experimental and predicted moisture ratios for selected mathematical models for solar tunnel drying of kachri.

perior models for goodness of fit to the solar tunnel drying of kachri. According to Table 4, the midilli and page models have the highest R^2, high modeling efficiency, and the lowest value of χ^2. Consequently, it could be determined that the midilli and page models agreed with the experimental data and gave the best results for the kachri sample.

Fig. 7 shows a comparison between predicted and experimental moisture ratio values by midilli and page models. The established midilli and page models provided satisfactory agreement between predicted and experimental moisture ratios. They predicted data that was generally banded around the straight line, demonstrating the models suitability for describing drying kinetics [27–28].

3.4. Quality evaluation

3.4.1. Rehydration characteristics

The ability of a solar dried product to rehydrate is used as a quality indicator, and it can reveal chemical and physical changes caused by processing [29]. The rehydration characteristics of solar dried samples of kachri during the rehydration process versus the rehydration time of dried kachri samples are shown in Fig. 8. As seen from this Fig. 8, the rehydration ratio and coefficient of rehydration of the solar dried sample increased as rehydration time increased and structural change occurred. For every 10-minute interval, it was observed that after 70 min, no mass change was observed in the sample. The rehydration ratio and coefficient of rehydration were up to 3.88 and 0.58, respectively.

Figs. 9 and 10 show a relationship between the experimental and predicted rehydration characteristics using regression analysis for solar dried kachri. The straight line between experimental and predicted data show the observed data is suitable for describing the rehydration behavior of dried kachri.

The hypothesis for the rehydration properties of the dried kachri sample was tested using the calculated F-value, which is summarised in Tables 5 and 6. The P-value (0.0062) of the F-test is less than 0.01 and indicates that the test is significant at a 1% significance level. Based on the statistical analysis, it can be inferred that there is a significant relationship between rehydration properties and rehydration time.

3.4.2. Ascorbic acid

The amount of mean value and standard deviation of ascorbic acid in the kachri shown in Table 7. The value of ascorbic acid was found to be 0.0205 ± 0.005 and 0.0658 ± 0.006 g/100 g of fresh and dried samples, respectively. It was observed that the fresh and dried forms of kachri contain a significant quantity of ascorbic acid.

3.4.3. Colour

The colour parameters (L, a, and b) of kachri samples and total colour difference ΔE are shown in Table 7. The fresh kachri sample had a greater L value than the dried sample. This indicates that after solar drying, the brightness of the sample decreased due to long drying time, and the higher temperature in the STD caused a browning reaction [22]. The lower colour index (ΔE) shows that, the greater the

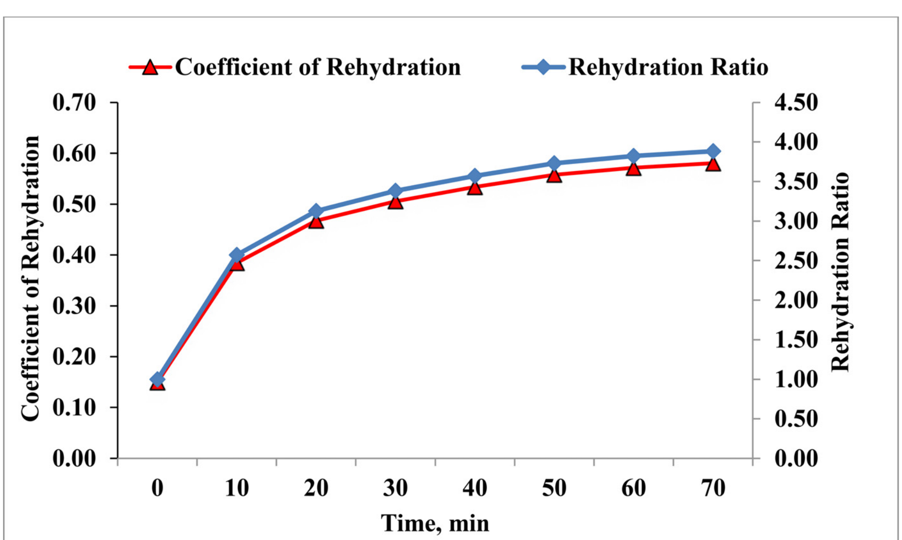


Fig. 8. Effect of process variable on rehydration curve.

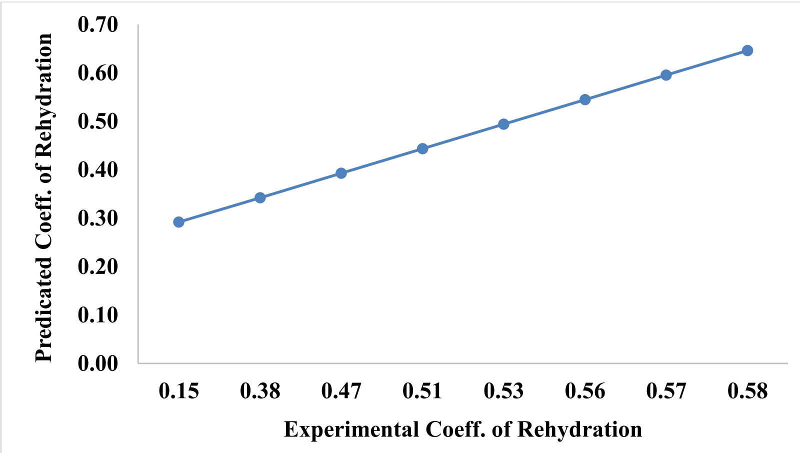


Fig. 9. Comparision of experimental and predicted value of coeff. of rehydration.

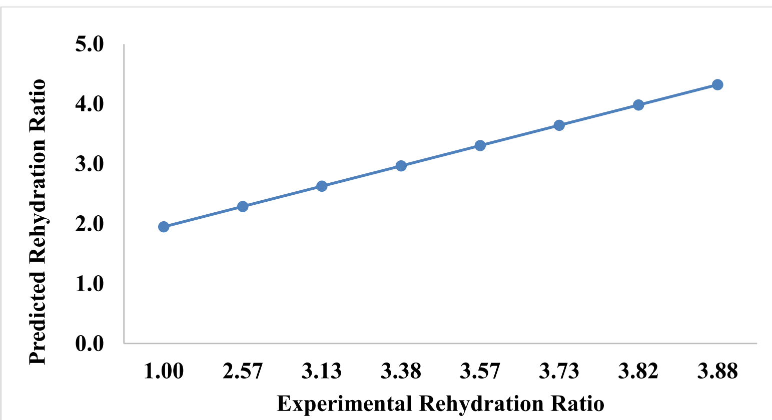


Fig. 10. Comparision of experimental and predicted value of rehydration ratio.

Table 5
Analysis of variance for rehydration ratio of kachri sample.

Source	Degree of freedom (df)	Sum of square (SS)	Mean Square (MS)	F-value	P-value
Regression	1	4.81246	4.81246	16.992	0.0062
Residual	6	1.69931	0.28322		
Total	7	6.51178			

Table 6
Analysis of variance for coefficinent of rehydration of kachri sample.

Source	Degree of freedom (df)	Sum of square (SS)	Mean Square (MS)	F-value	P-value
Regression	1	0.10756	0.10755	16.992	0.0062
Residual	6	0.03798	0.00633		
Total	7	0.14553			

Table 7
Nutritional composition of Kachri.

	Quantity (per 100 g)	
Parameter	Fresh	Dried
Moisture content (g)	86.1 ± 1.42	7.02 ± 0.54
Dry Matter (g)	13.9 ± 1.42	92.98 ± 0.54
Ascorbic Acid (g)	0.0205 ± 0.005	0.0658 ± 0.006
Ash Content (g)	2.19 ± 0.172	10.8 ± 0.213
Water Activity	0.92 ± 0.014	0.42 ± 0.019
L value	79.09 ± 1.71	75.59 ± 1.26
a value	30.14 ± 0.64	35.39 ± 0.42
b value	18.03 ± 0.55	24.19 ± 0.58
ΔE	-	11.96 ± 1.73

Result are based on mean ± standard deviation

brilliance of the dried sample, lower the changes in colour of the sample. The colour change during drying is related to its pigment (concentration/composition). The less variation in ‘a’ value (change in green to red colour), the more chlorophyll A is retained in the dried sample [30]. The increase in the ‘b’ value of the dried product indicates the change from the fresh sample’s blue colour to the dried sample’s yellow colour.

3.4.4. Ash content

The ash content of fresh and dried kachri samples was found to be 2.19 ± 0.172 g/100 g and 10.8 ± 0.213 g/100 g, respectively (Table 7). The ash content per solid content of the sample decreased after solar drying due to the leaching of soluble inorganic compounds in the rehydration water [13].

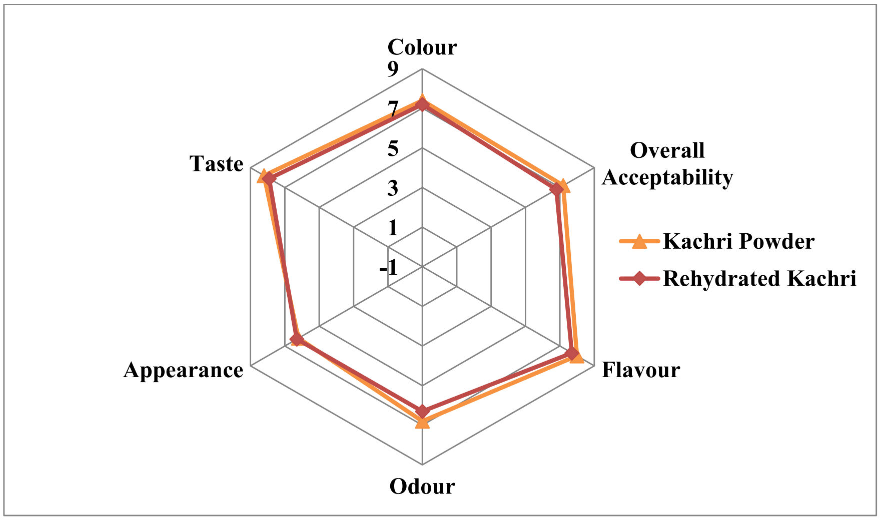


Fig. 11. Mean score of sensory evaluation of dried kachri powder and rehydrated kachri sample.

Table 8
CO_2 mitigation potential.

Embodied energy (kWh)	Annual thermal energy output (kWh)	Energy payback time (Year)	Total CO_2 emission over the life time (tons)	Total CO_2 mitigation over the life time (tons)	Net CO_2 mitigation over the life time (tons)
2099.67	3346.52	0.63	2.06	79.11	77.05

3.4.5. Water activity

The results found that, there was a clear variation in water activity between the fresh and dried kachri samples. The mean value and standard deviation of water activity of fresh and dried kachri samples were 0.92 ± 0.014 and 0.42 ± 0.019, respectively. The fresh sample had an $a_w > 0.91$; indicating that it was susceptible to oxidation, enzymatic reactions, and microbial spoilage. However, dried samples showed an $a_w < 0.42$, indicating moderately bound to water and better stable during storage. The presence of water in the dried product provides optimum conditions for the growth of microorganisms, resulting in product deterioration. As a result, the lower the product's water activity, the greater its storage potential [13].

3.4.6. Sensory evaluation

This evaluation deals with all sensory properties of samples by a panel of 25 judges and found the score ranged from 1 to 9, representing from "Dislike extremely" to "Like extremely". The mean organoleptic score of dried kachri powder prepared from dried kachri product in the present experiment and rehydrated kachri samples were given in Fig. 11. It can be inferred from that the kachri powder and rehydrated sample produced from kachri dried in a STD were accepted by the consumer panel and rated as liked very much.

3.5. Energy and environmental analysis

The Table 8 shows the CO_2 mitigation potential for drying of kachri in STD. The dryer's embodied energy and energy payback time were 2099.67 kWh and 0.63 years, respectively, which showed that the dryer was energy efficient and suitable for large-scale drying. The emission of CO_2 for the dryer's lifespan was 2.06 tons, which was very low compared to the conventional drying process [31], and this has a lower environmental impact. The net CO_2 mitigation for the drying of kachri in a STD was found to be 77.05 tons over the life time (12 years) of the dryer. The result revealed that the solar drying process used in the present study had a high potential for carbon reduction.

3.6. Economic evaluation

The assessment of techno-economics of the solar tunnel drying system for kachri was performed and presented in Table 9. The economic analysis shows that the NPW, BCR, PBP and IRR for kachri slice were 12937.47 USD, 1.49, 0.7246 years and 138 %, respectively. The indicators show that the drying of kachri economically feasible using solar tunnel drying technology for value addition and quality improvement.

3.7. Energy nexus for the solar drying

The results of this study, which focus on the energy nexus for drying arid vegetables, are critical for improving the level of human comfort and promoting sustainable development. Understanding the energy nexus in the food and drying sectors is also critical, particularly concerning their impacts on biodiversity and climate change. The demand for energy and food continues to increase due to global human population growth, increased urbanization and rural-urban migration rates, rising incomes and the desire to spend them on energy, rich and varied diets, etc. [32,33]. Consequently, a nexus approach can be used to improve energy security on a global scale [34,35]. In addition, farmers must increase their crop's shelf life by drying to preserve and store the crop for future use, which requires energy [36].

However, the high cost of fossil fuels and electricity to operate the available conventional dryers discourages many farmers in emerging economies from embarking on large-scale production for fear of crop damage due to bacterial invasions. The idea behind this project is to use solar energy to dry food instead of conventional dryers, which reduces greenhouse gas emissions into the environment and saves money. Solar drying technology reduces the over-reliance of the nexus on hydrocarbon-based fossil fuels [37] while providing a decentralized solution to the current challenges in the arid region [38]. Furthermore, reduced fossil fuel consumption may reduce the health risk of heavy metals in seafood, as fossil fuel consumption (coal combustion) has been shown to be the primary source of heavy metals in seafood [39,40]. Thus, the energy nexus approach can promote a smooth transition to

Table 9
Techno-economics analysis of STD drying system.

Sr. No.	Description	Value
i.	Initial investment (USD)	1539.65
ii.	Life of STD System (years)	12
iii.	Annual use no. of batches	60 (100 kg)
iv.	Cost of raw materials (USD yr^{-1})	@0.45 USD/kg 2694.38
v.	Repair and maintenance cost (USD yr^{-1}) *(12% of capital cost per year)*	184.76
vi.	Labour Cost: Considering one labour @ 500 USD per day for 120 days of working operation (USD yr^{-1})	769.82
vii.	Total cost (USD yr^{-1})	3648.96
viii.	Total dried product (kg yr^{-1})	900
ix.	Money value recovered from the dried Kachri	@6.42 Rs/kg 5773.67
x.	Total Net annual profit	2124.71
	Economic Indicators	
i.	Net Present worth (NPW)	12937.48 USD
ii.	Benefit cost ratio (BCR)	1.49
iii.	Pay-back period (PBP)	0.7246 years
iv.	Internal rate of return (IRR)	138%

Note: 1 USD = 77.94 Indian rupee (as on 20.06.2022).

environmentally friendly methods supporting a green economy, CO_2 mitigation, and resource efficiency [41,42].

4. Conclusion

The socio-economic status of arid-zone people can be enhanced by value addition to kachri fruits. Establishing solar tunnel dryers in arid regions could enhance the quality of dried products and increase future real farm income. The kachri were sheltered from dust, insects, and rain while drying in the solar tunnel drier. Among the applied kinetic models, the Page and Midilli kinetic models accurately depicted the solar drying behaviour of kachri. The sensory evaluation of dried kachri products showed that dried product had a good grade for human consumption and can be helpful to keep the population healthy and nutritionally secure compared to the expensive off-season vegetables. The CO_2 mitigation potential of the dryer during its lifespan was found 77.05 tons for drying of kachri.

Data availability statement

My manuscript has no associated data.

Declaration of Competing Interest

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

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