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Techno-economic Analysis of Inclined Solar Dryer for Carrot (*Daucus carota L.*) Drying

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Abstract: Solar dryers' performance evaluation and economic analysis for drying perishable agricultural produces was undertaken. The dryer was fabricated using locally available materials, e.g., galvanized iron sheet, mild steel angle, glass, and stainless steel wire mesh. The provision of tilting the dryer helps to receive maximum solar radiation round the year thus, captures more solar radiation than that of a horizontal plane. The drying trial for dehydrating carrot (*Daucus carota* L.) was conducted in this dryer in February 2019. During the performance evaluation, the maximum stagnation temperature inside the drying chamber was observed 68°C, and on loading with 8 kg carrot, it reduced to 58°C, while the outside ambient temperature was 37°C on a clear sky day (from 08:00 h to 18:00 h) in February 2019. During the drying process, the moisture content of the carrot was reduced from 74% (wet basis) to about 13% within three days. The efficiency of the dryer was found to be 17.57%. The economic evaluation of the solar dryer revealed that the high value of IRR (84.4%) and low value of the payback period (1.42 years) make the dryer unit very cost-efficient. The economic indicator cost-benefit ratio was found to be 2.09, which shows the potential of using solar dryers in place of conventional dryers. The economic attributes, namely net present worth (Rs. 41830) and the system's annuity (Rs. 5635) revealed its economic viability. Inclined solar dryers in remote locations/rural areas can be a useful solar gadget in reducing post-harvest losses and carbon emissions in the arid region of Rajasthan.

Key words: Inclined solar dyer, economic analysis, carrot.

Vegetables are highly perishable and available in plenty at particular times of the year. In the peak season, the selling price decreases, leading to heavy losses to the grower. During the season, the supply of fruit and vegetable increases, leading to spoilage. Drying may not only preserve it for use in the off-season but also fetch higher prices. Carrot (*Daucus carota* L.) is one of the important root vegetable crops and is highly nutritious as it contains an appreciable amount of vitamins B1, B2, B6, and B12 besides being rich in β-carotene. It also has many essential minerals. β-Carotene is a precursor of vitamin A and is reported to prevent cancer (Ong and Chutil, 1983), its maximum retention is of utmost importance for preserving the product's attractive appearance and dietary value. Carrots have a moisture content of 80-90% (wb) at harvest time (Kalra *et al.*, 1987). They are seasonal and highly susceptible to moisture loss leading to wilting and loss of fresh appeal.

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Drying is an important task related to agriculture in rural areas and is practiced to increase storability and reduce food product losses (Poonia *et al.*, 2018 a,b; Poonia *et al.*, 2022). Most farmers rely on farming only and cannot afford costly devices. The open sun drying process was still used in many countries, but the major problem of this method is defiled the product and non-uniform drying. Solar or electric drying in forced convection mode is the best solution to meet this problem. Mechanical or electric drying is mainly used for industrial purposes but in the Thar desert of India, small and marginal farmers cannot afford this hi-tech facility. India occupies a better position regarding solar energy potential. The arid region is blessed with renewable energy sources like solar energy, wind power, and biogas. The average value of solar energy in arid region of India varies from 5.8 to 6.3 kWh m^{-2} day^{-1}. (Poonia *et al.*, 2020).

Solar dryers can substitute sun-drying because of low operational cost (Purohit *et al.*, 2006; Poonia *et al.*, 2017; Poonia *et al.*, 2018 a,b; Poonia *et al.*, 2022). The solar dryer is very profitable, eco-friendly, and cost-effective for rural people. It can be used in place of sun-drying to ensure the quality product (Sharma *et al.*, 2009). Several research studies show that the solar-based drying system is the best option compared to open drying for the dried food produced (Mahapatra and Imre, 1990; Sodha and Chandra, 1994; Ekechukwu and Norton, 1999; Hossain *et al.*, 2005).

It is necessary for any technology/system/ enterprise to work out its economic viability so that the technology users may use it to earn higher profits. For example, the dryer protects from dust, dirt, rain, and insects and ensures better quality than open sun drying. However, the solar dryer is capital-intensive in terms of initial investment and operating cost compared to the traditional open sun drying (Barnwal and Tiwari, 2008). The techno-economic analysis of typical solar dryers with different energy sources has been reported by Sodha *et al.* (1991), who found that the plastic solar collectors of life 5-10 years are the cheapest among all the energy systems. A hybrid PV/T integrated greenhouse dryer has been used to dry grapes under the forced mode of operation. The system payback period is about 1.25 years, with an initial investment of Rs. 27,400. The cost of drying the grapes is Rs. 4.52 per kg (Barnwal and Tiwari, 2008). The potential for solar drying of selected cash crops, namely tobacco, tea, coffee, grapes raisin, small cardamom, chilli, coriander seeds, ginger, turmeric, black pepper, and onion flakes, etc. Indian conditions have been estimated along with CO_2 emissions mitigation (Kumar and Kandpal, 2005). With this in view, an inclined solar dryer was designed and developed at ICAR-Central Arid Zone Research Institute, Jodhpur, to dry perishable agricultural produces. The provision of tilting the dryer helps to receive maximum solar radiation round the year at Jodhpur, India. The optimally inclined surface receives 22.8% more solar radiation than the horizontal surface. Therefore, an optimally tilted solar dryer has been used for this study. An attempt was made to evaluate the drying characteristics of carrots for describing the thin-layer drying process for solar drying of carrots. Furthermore, economic analyses of the inclined solar dryer were carried out to assess the real-time possibilities for its use.

Materials and Methods

Principle of inclined solar dryer

The solar dryer is based on the principle of flat plate solar collector and green house effect. The solar radiation falls on the transparent glass sheet, enters the collector, and gets converted into long-wave thermal radiations, which are not transparent to the glass surface. Thus, these get trapped inside and increase the inside temperature to a great extent. However, the tilt of the dryer has to be set according to the seasonal variation of tilt angle, which is given as,

$$\text{Declination angle} = 23.45\left[360\left(\frac{284+n}{365}\right)\right] \quad ...(1)$$

where n = number of day of the year, January 1, the first day of the year.

Tilt angle = latitude ± declination angle.

The tilt remains equal to latitude (26.18° for Jodhpur) on March 21 and September 23. The average tilt angle for twelve months are given in Table 1.

Performance of the natural convection solar dryer is very good during the summer, but it is very poor during winter in northern parts of India and takes longer time for dehydration of fruits and vegetables because its absorbing surface is horizontal and so receive much less radiation compared to the optimally inclined surface. Solar radiation received at Jodhpur on horizontal and optimally inclined surfaces is shown in Table 2. From Table 2, it is clear that solar radiation received on an inclined surface is 69.36% more than a horizontal surface during December, and an inclined surface

Table 1. Average tilt angle for different months of the year

S. No.	Day of month	Tilt angle
1.	January 15	48.45
2.	February 15	39.80
3.	March 16	28.60
4.	April 15	16.77
5.	May 15	7.39
6.	June 14	2.87
7.	July 14	4.66
8.	August 13	10.85
9.	September 12	21.96
10.	October 12	33.9
11.	November 11	44.09
12.	December 11	48.15

Table 2. Mean daily solar radiation (kWh m^{-2} day^{-1}) on horizontal and optimally inclined surfaces at Jodhpur

Month	Solar radiation (kWh m^{-2} day^{-1})		
	Horizontal surface	Inclined surface	Increase over horizontal surface (%)
January	4.61	7.25	57.23
February	5.44	7.68	41.07
March	6.39	7.27	13.74
April	7.08	7.23	2.04
May	7.39	7.39	0.00
June	6.92	6.92	0.00
July	5.86	5.86	0.00
August	5.42	5.46	0.87
September	5.97	6.41	7.39
October	5.69	7.24	27.07
November	4.81	7.42	54.33
December	4.33	7.34	69.36
Mean	5.83	6.96	22.76

receives 43.8% and 22.76% more radiation than a horizontal surface during the winter season (October-March) and round the year, respectively. Therefore, an optimally tilted solar dryer has been used for this study. The tilt of the solar dryer is adjusted once in a fortnight as per the elevation of the sun.

Design of solar dryer

An inclined solar dryer was designed and fabricated at ICAR-Central Arid Zone Research Institute, Jodhpur, India. The solar dryer (1280 mm x 980 mm) based on the natural convection operation principle mainly consists of a rectangular box made of galvanized steel sheet (22 gauge) with two drying trays. A glass roof (area of collector 1.25 m^2) made of clear window glass (4 mm thick) is provided at the top of the box, and a layer of dried pearl millet stems insulation is provided at the base (Fig. 1). The dimension of two drying trays made of stainless steel angle frame and stainless steel wire mesh was (950 mm x 600 mm). The drying material can be kept on two trays and can be

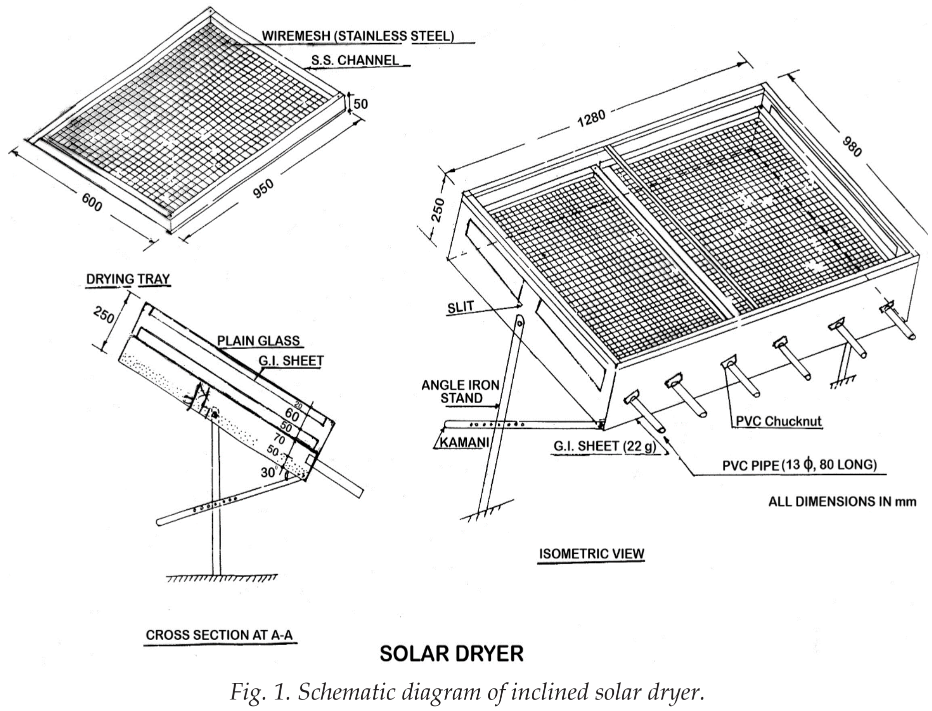

Fig. 1. Schematic diagram of inclined solar dryer.

Fig. 2. Inclined solar dryer installed at CAZRI solar yard.

placed on an angle iron frame in the dryer through an openable door provided on the rear side of the dryer. Five partitions are also provided in each tray so that the vegetables can be stacked even on the inclined plane. Six plastic pipes are fixed in the front wall of the dryer just below the trays to introduce fresh air at the base. Two tapered slits are made on the dryer's side walls to escape the hot moist air from the drying chamber. An overhang over these slits protects the material from rain and wire mesh in these slits safeguards against flies and squirrels. An adjustable iron angle stand is provided to keep the dryer at optimum tilt in accordance with latitude and season of operation. The material can be loaded in drying trays to a maximum depth of 5 cm in this dryer. The actual installation of the optimally tilted solar dryer is shown in Fig. 2.

Experimental design

The on-field experiments at the ICAR-Central Arid Zone Research Institute, Jodhpur, India (26°18'N and 73°04'E) were performed during February 2019 in clear sky condition. Carrot (8 kg) fresh vegetables were procured for the drying experiment during February 2019. The selection of fruits was based on a visual assessment of uniformity in color and geometry. Experiments were done between 08:00 hr and 18:00 hr using 8 kg of carrot, divided and equally distributed on left and right side trays. Using a thermopile pyranometer, these experiments measured the hourly total solar radiation intensity (Gs) on a horizontal surface. DTM-100 thermometer with point contact thermocouples (accuracy 0.1°C) was used to measure the temperatures inside the dryer. The ambient air temperature was measured using a mercury thermometer (accuracy 0.1°C) placed in an ambient chamber. The moisture content of the sample was determined according to AOAC (2000). The moisture content of the drying product was measured at an interval of 60 min by taking 100 g of sample from the trays by using a digital electronic balance (Testing Instrument Pvt. Ltd., India) with an accuracy of ±0.001 g. The samples' initial and final moisture contents were determined by the drying oven method at 105°C. The difference of mass before and after drying in the oven gives the moisture content.

The initial moisture content (wet basis) of carrot was calculated using the relation,

$$M_i = \left(\frac{W_i - W_f}{W_i}\right) \times 100 \quad \text{... (2)}$$

where, M_i = Initial moisture content of sample (w.b.), %, W_i = Initial weight of sample, g and W_f = Final weight of sample, g.

Drying rate of carrot was calculated as,

$$DR = \frac{\Delta M}{\Delta t} \quad \text{... (3)}$$

where, ΔM = Loss of mass of fruit, kg water. kg^{-1} dry matter, and Δt = Interval of time, min.

Thermal efficiency (η)

The efficiency of utilization of solar energy in the solar dryer (ratio of heat used in evaporation of moisture from fruit and vegetables to the incident total solar radiation on the horizontal plane) has been worked out by using the following relation (Poonia *et al.*, 2018 a,b and Leon *et al.*, 2002),

$$\eta = \frac{ML}{A\int_0^\theta H_T d\theta} \quad \text{... (4)}$$

where A = Absorber area (m^2); H_T = Solar radiation on horizontal plane (J m^{-2} hr^{-1}); L = Latent heat of vaporization (J kg^{-1}); M = Mass of moisture evaporated from the product (kg); θ = Period of test (hr) and η = Efficiency of the solar dryer.

Results and Discussion

The experiment was conducted to study the performance of a solar drying system for dehydrating carrot in an inclined solar dryer during February 2019. For the experimental study, the dryer was kept facing due south and loaded with an equal quantity of material in two drying trays. The unit was kept at optimum tilt in accordance with latitude and season of operation. The air temperature inside the dryer at the center of the drying trays and ambient air temperature were recorded hourly from 08:00 h to 18:00 h during the drying trials. The average maximum stagnation temperature observed inside the drying chamber was 68°C and on loading eight kg of carrot, the maximum average temperature was reduced to 58°C when the outside ambient temperature was 27°C on a clear sky condition (from 8:00 hr to 18:00 hr).

The variation of the carrot's measured moisture content (wet basis) on each day of drying trials was shown in Fig. 3. It can be seen that the moisture content was reduced from about 74% to 13% within three days by the solar drying method, and on the 4th day, it came 10%, however, after three days (13% moisture content), it could be safely stored for further use. In contrast, it took six days to dehydrate the same quantity of carrot by open drying. The drying rate in the solar dryer increases sharply when the moisture content falls below 66%. The shape of the drying curve indicates a rapid moisture removal from the product at the initial stage, which later decreased with an increase in drying time. Thus the moisture ratio decreased continually with drying time. This continuous decrease in moisture ratio indicates that diffusion has governed the internal mass transfer. This was in agreement with the results of the Indian jujube (Das and Dutta, 2013; Doymaz, 2007).

The overall efficiency of the drying is affected by several factors such as drying time, climatic conditions (solar insolation and temperature), the drying characteristics of the dried materials, and structure of the drying devices, etc. The average efficiency of solar energy utilization in the solar dryer was calculated by eq. (4), and it was found that about 17.57% solar energy was utilized in this solar dryer. During the drying process, it was observed that higher efficiency was observed at the initial stage of drying. Later, this dryer efficiency was decreased due to decreased moisture content. Moreover, the efficiency at a higher drying load of 12 kg might be due to the highest drying time.

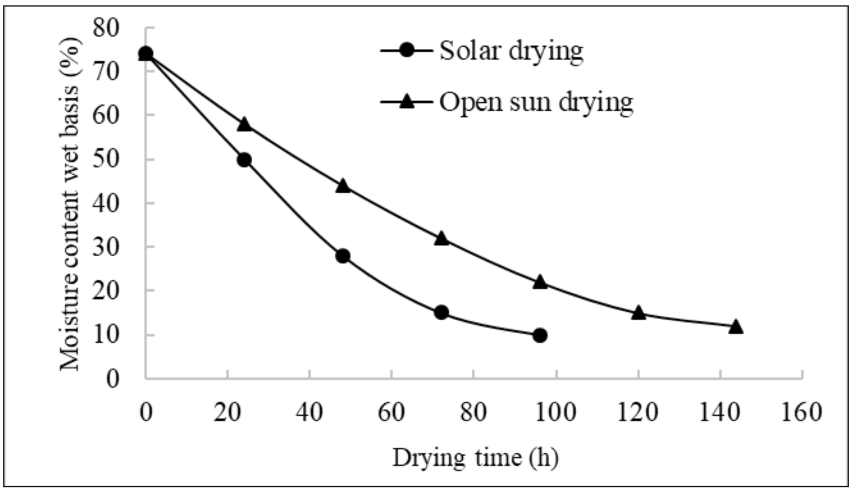

Fig. 3. Variation of moisture content of carrot during solar and open sun drying against drying time

Economic Analysis

The economic analysis of the present dryer was carried out by computing the life cycle cost (LCC) and life cycle benefit (LCB) of the dryer. In addition, five economic attributes, namely, benefit-cost ratio (BCR), net present worth (NPW), annuity (A), internal rate of return (IRR), and payback period (PBP), were also determined for judging the economic viability of the dryer technology.

Life cycle cost (LCC)

Life cycle cost (LCC) of the inclined solar dryer is the sum of all the costs associated with a solar drying system over its lifetime in terms of money value at the present instant of time and takes into account the time value of money (Kalogirou, 1996). The initial investment (P_i) in the dryer unit is Rs. 9000, as shown in Table 3. The annual cost of operation and maintenance (O&M), including labour is taken as Rs. 4000. The salvage value is taken as 10% of the initial investment.

Economic attributes

i. BCR, The ratio of discounted benefits to the discounted values of all costs given as LCB/LCC

ii. NPW, It is the sum of all discounted net benefits throughout the project given as LCB-LCC

iii. The annuity (A) of the project indicates the average net annual returns given as,

$$\text{(Annuity)} = \frac{NPW}{\sum_{t=1\ to\ n}\left(\frac{1+e}{1+i}\right)^{n}} = \frac{NPW\left(\frac{1+e}{1+i}-1\right)}{\left(\frac{1+e}{1+i}\right)\left[\left(\frac{1+e}{1+i}\right)^{n}-1\right]}$$

iv. PBP, It is the length of time from the beginning of the project before the net benefits return the cost of capital investments (value n for LCB - LCC = 0)

v. IRR, It is that rate of interest that makes life cycle benefits and life cycle cost equal (LCB - LCC = 0)

Determination of LCC

Economics of the inclined solar dryer was calculated through life cycle cost (LCC) analysis. Let P_i is the initial investment (Rs.), P_w is operational and maintenance expenses including replacement costs for damaged components (Rs.), n is the life of the dryer (Year), P_w (SV) is the salvage value of the dryer at the end of the life (Rs.). The procedure of life

Table 3. Cost estimates of inclined solar dryer

Item with specification	Quantity	Unit cost (Rs.)	Amount (Rs.)
G.I. Sheet (22 gauge) 2.20 x 1.500	3.36 sqm	744/ sqm	2500
Plain glass (1.28 x 0.980 m)	1.25 sqm	480/ sqm	600
M.S. angle (37 x 37 x 6 mm)	4.65 sqm	54/ sqm	250
Kamani (25 mm wide x 3 mm thick)	1.12 m	134/ m	150
PVC chuck nut	6 Nos.	8/No.	50
PVC pipe (13 mm ϕ) 6 x 0.800	4.8 m	26/ m	125
Insulation (pearl millet stem) 1.28 x 0.98 x 0.050	0.0627 cum		
Aluminium angle (25 mm x 25 mm)	4.52 m	28/ m	125
Wooden batten (0.025 x 0.025 x 0.980 x 2)	0.00122 cum		
Drying tray			
(i) S.S. channel (50 mm x 50 mm) – 3.1 x 2	6.2 m	234/ m	1450
(ii) Wire mesh (stainless steel) (1.10 x 0.60) x 2	1.32 sqm	2257/ sqm	2980
(iii) Hinges (100 mm long)	10 Nos.	12/No.	125
Black board paint	1.5 lit.	100/lit.	150
Zinc Chromate Primer	1.0 lit.	200/lit.	200
Synthetic Enamel paint	1.0 lit.	240/lit.	240
Rubber gasket (25 mm x 3 mm)	4.52 m	12/m	55
Total			9000

cycle cost estimation as adopted by (Barnwal and Tiwari, 2008; Poonia *et al.*, 2018 a,b and Poonia *et al.*, 2020), the LCC is given as,

(i) LCC (Unit) = Initial cost of unit (P_i) + P_w (O & M Costs including labour)– P_w (SV) ... (5)

$$= P_i + P_w \frac{X(1-X^n)}{1-X} - SV(1+i)^{-n}$$

$$= 9000 + 4000 + \frac{X(1-X^n)}{1-X} - 900(1+i)^{-n}$$

$$= 9000 + 4000 \frac{0.945(1-0.945^{10})}{1-0.945} - 900\ (1+0.1)^{-10}$$

$$\text{where, } X = \frac{1+e}{1-i} = \frac{1+0.04}{1+0.1}$$

where, e = annual escalation in cost (in fraction); *i* = interest or discount rate (in fraction)

Life cycle benefits (LCB)

The values of R (annual benefit) is obtained by using the dryer ten trials each for ber, seedless lasoda/gonda. The quantity of ber dried was about 120 kg costing about Rs. 2400. The dried ber was about 40 kg, which accrued about Rs. 6000 @ Rs. 150/kg. The ensuring benefit of Rs. 3600. Similarly, thirty trials of seedless lasoda/gonda dried about 120 kg gonda, which ensured Rs. 30/kg benefit on raw seed less gonda amount to about Rs. 3600 and remaining six-month drying trials of tomato, spinach, and carrot about 360 kg @ Rs. 10/kg. The ensuring benefit of Rs. 3600. Thus total annual benefit from the dried product was about Rs. 10800.

The LCB can be given as,

$$\text{LCB} = R\frac{X(1-X^n)}{(1-X)} \quad ...\ (6)$$

where R = annual benefit (Rs.) and X = $\frac{1+e}{1+i}$

Determination of economic attributes

i. (i) BCR, The ratio of discounted benefits to the discounted values of all costs can be expressed as,

$$\text{Benefit cost ratio (BCR)} = \frac{\textit{Life cycle benefits of inclined solar dryer}}{\textit{Life cycle cost of inclined solar dryer}}$$

Benefit cost ratio (BCR) =

$$BCR = \frac{R\frac{X(1-X^n)}{(1-X)}}{P_i + P_w - P_w(SV)} = \frac{LCB}{LCC}$$

$$= \frac{80179}{38349} = 2.09$$

ii. NPW = LCB – LCC = 41830

iii. The annuity (A) of the project indicates the average net annual returns. This term can be given as,

$$\text{A (Annuity)} = \frac{NPW}{\sum_{t=1\ to 10} (X)^n} = 5635 \quad ...\ (7)$$

$$\text{where X} = \left(\frac{1+e}{1+i}\right)$$

Payback period

Pay-back period can be determined as following, -LCC + LCB = 0

$$\text{Or } 9000 + 4000 \times \frac{0.945(1-0.945^{10})}{(1-0.945)}$$

$$= 10800 \frac{0.945(1-0.945^{10})}{(1-0.945)}$$

$$\text{Or } 9000 = 6800 \frac{0.945(1-0.945^{10})}{(1-0.945)}$$

$$\text{Or } (1\text{-}0.945n) = \frac{9000\ (0.055)}{6800 \times 0.945}$$

$$\text{Or } 0.945n = 1 \frac{9000\ (0.055)}{6800 \times 0.945} = 0.923$$

Or $n \log 0.945 = \log 0.923$

$$n = \frac{\log(0.923)}{\log(0.945)}$$

n = 1.42 year

Or Pay-back period (PBP) = 1.42 year

Internal rate of return (IRR)

The values of NPW at varying discount rates are given in Table 3. From Table 3, it may be inferred that at a 10% interest rate, the NPW is Rs. 41830 respectively. At 60% rate of interest, the NPW is Rs. 3516.44. However, the NPW is negative at 90% interest rate (i.e. NPW = Rs. -804.93). The IRR can be determined using data presented in Table 4 and the following relationship,

$$\text{IRR} = \text{lower discount rate} + \frac{\textit{Difference of discount rate x NPW at lower discount rete}}{\textit{(NPW at lower discount rate – NPW at higher discount rate)}}$$

$$\text{IRR} = 60 + \frac{30 \times 3516.44}{3516.44 + 804.93} = 84.4\%$$

The internal rate of return (IRR) which comes to 84.4% in the present case, which is very high for a project to be economically viable.

Table 4. Values of NPW for different rates of discount/ interest (i)

NPW (Rs.)	41830.2	3516.44	-804.93
Interest rate *i* (%)	10	60	90

The values of five economic attributes, namely, benefit-cost ratio (BCR), net present worth (NPW), annuity (A), internal rate of return (IRR) and payback period (PBP) was presented in Table 5.

Table 5. Values of economic attributes

Attributes economics	Values
BCR	2.09
NPW	41830 Rs.
A	5635 Rs.
IRR	84.4%
PBP (years)	1.42 years

Conclusion

An optimally tilted type solar dryer can be used for the dehydration of fruits and vegetables. The initial moisture content of carrot was reduced from 74% (wet basis) to about 13% within three days. The efficiency of the inclined solar dryer was 17.57%. The farmers can dehydrate vegetables when these are available in plenty and at a low cost. Dehydrated vegetables can be sold in the off-season when prices of vegetables are high, and farmers can generate more income. The economic evaluation of the inclined solar dryer unit revealed that the high value of IRR (84.4%) and low value of the payback period (1.42 years) make the unit very cost-efficient. The use of an inclined solar dryer considerably reduces the drying time, energy consumption and improves the quality of dried products. The use of inclined dryer at remote locations/ rural areas can go a long way in reducing post-harvest losses and carbon emissions and will be a great boon for farmers in developing countries.

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