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Techno-economic evaluation of forced convection solar photovoltaic dryer for drying date palm (*Phoenix dactylifera L.*) fruit

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ABSTRACT

The drying experiment for dehydrating date palm (Phoenix dactylifera L.) fruits was carried out in this dryer (developed by CAZRI, Jodhpur) in the month of June, 2020. During the testing, the maximum average stagnation temperature in the drying chamber was found as 70°C and when loaded with 20 kg date palm it reduced to 64°C, when outside ambient temperature was observed as 39.5°C on a clear day (from 08:00 hr to 18:00 hr). During the drying trial, moisture content of date palm fruits got reduced from 65% (wet basis) to about 26% in 6 days by dryer, whereas in the open sun drying it is taken 8 days. The temperature gradient of the drying chamber got reduced from 6-8°C to 2-3°C in the system provided with pre-heater, which resulted in uniform drying. The effective moisture diffusivity was 4.34×10^{-9} $m^2.s^{-1}$*, and the efficiency of the dryer was 16.1 per cent. The developed hybrid forced convection drying system produced better quality products in shorter time by the efficient use of solar energy. The economic evaluation of the hybrid forced convection solar dryer indicated high value of IRR (57.4 percent) and low value of payback period (2.10 years), suggesting the dryer to be cost efficient. The winnower was used for winnowing the 200-300 kg grains from threshed material in a day in the absence of natural wind. The winnower was also used for separating grains from straw to enhance the utility throughout the year.*

Keywords: *Date palm drying, PV Winnower, hybrid solar dryer, economic, evaluation*

INTRODUCTION

Date palm (Phoenix dactylifera L.) is one of the oldest domesticated fruit crops and is considered as one of the world's first cultivated fruit trees. It is one of the most important fruit crops which can grow in hot arid regions of the world and only crop able to withstand high temperature and low humid conditions at bearing stage. Date fruit is a high-energy food (300 calories/100 g) owing to high sugar content, a good source of iron, calcium, potassium, and iodine, as well as low in fats (Uchoi et al., 2020). The major problem with the dates produced in this region is that the maturation stage of dates coincides with the onset of monsoon in the month of June. The exposure of date fruits to rain results in fruit rot and spoilage which makes the fruits unable to consume as fresh dates. Therefore, dates are harvested prematurely before the onset of monsoon to prevent spoilage and marketed. Hence, processing of these immature dates into value-added products could improve the marketability (Sagarika et al., 2019). Conventional drying methods cause many adverse effects in plant materials, such as shrinkage, discoloration, and oxidation of vitamins etc. Drying is the important tasks related to agriculture in rural areas. Drying is practiced to enhance the storage life, minimize losses during storage and reduce transportation costs of agricultural products (Poonia et al., 2018 a,b). In India, 70% people depend on agricultural practices and of this most farmers are subsistence farmers and affording hi-tech facilities and equipment is a major problem. Direct sun drying method has been practiced since ancient time and it is still being widely used in developing countries. Although this method of drying is cheap, yet it is associated with the problems like, contamination as well as uneven drying. In order to overcome these disadvantages, the drying process can be replaced with solar drying or industrial drying methods such as hot air. In order to overcome these disadvantages, drying process can be replaced with solar energy or industrial drying method as hot air drying. Mechanical drying is mainly used in industrialized countries as an alternative to sun drying, and is not applicable to small farms in India. This is due to its high investment and operating costs. India is blessed with abundant solar energy. During the winter season from November to February months,

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most of the Indian stations receive 4.0 $kWhm^{-2}day^{-1}$ to 6.3 $kWhm^{-2}day^{-1}$ solar irradiance, while in summer season it ranges from 5.0 $kWhm^{-2}day^{-1}$ to 7.4 $kWhm^{-2}day^{-1}$. The arid and semi-arid regions of the country receive higher radiation of 6.0-7.4 $kWhm^{-2}day^{-1}$ mean annual daily solar radiation having 8.9 average sunshine hours a day at Jodhpur, India (Poonia *et al.,* 2020).

Solar drying has been identified as a promising alternative to sun drying for drying of fruit and vegetables in developing countries because of its minimal operational cost in terms of fuel cost (Poonia *et al.,* 2017, 2018 a, b). Recently Poonia *et al.* (2018 a, b) developed a hybrid photovoltaic-thermal forced convection solar dryer for drying of Indian Jujube (*Zizyphus mauritiana*) and reported that the average thermal efficiency of solar energy utilization under forced convection mode was higher (16.7%) than that of natural convection solar dryer (15.6%). Hence the present study was initiated. Actual installation of the photovoltaic thermal hybrid solar dryer with winnower is (Fig. 1.).

Fig. 1: PVT hybrid solar dryer with winnower installed at CAZRI solar yard

MATERIALS AND METHODS

The on-field experiments at the ICAR-Central Arid Zone Research Institute, Jodhpur, India (26°18′N and 73°04′E) were performed during 13-18th June 2020 in clear sky condition. Date palm (20 kg) fresh fruit was procured for the drying experiment during June 2020 from horticulture block of CAZRI, Jodhpur. Experiments were done between 8:00 hr and 18:00 hr using 20 kg of date palm, which was divided and equally distributed on left and right side trays. In these experiments, the hourly total solar radiation intensity (G_s) on a horizontal surface was measured using a thermopile pyranometer. DTM-100 thermometer with point contact thermocouples (accuracy 0.1°C) was used to measure the temperatures inside the dryer. Ambient air temperature was measured using a mercury thermometer (accuracy 0.1°C) placed in an ambient chamber. Moisture content of the sample was determined according to AOAC (2000).

The drying rate was calculated by using the equation of Poonia *et al.* (2018 a, b). Moisture ratio (MR) of date palm fruit was calculated using the following equations:

$$MR = \frac{M - M_e}{M_0 - M_e} \qquad (1)$$

Where, M = Moisture content of sample at a given time, M_0= Initial moisture content of sample, M_e= Equilibrium moisture content of sample, kg water. kg^{-1} solids

Effective moisture diffusivity is defined by Fick's second law (Poonia *et al.,* 2018 a):

$$MR = \frac{M - M_e}{M_0 - M_e} = \frac{8}{\pi^2} \sum_{n=1}^{\infty} \frac{1}{n^2} \exp\left(- \frac{n^2 \pi^2 D_{eff}\, t}{4r^2} \right) \quad (2)$$

here,

D_{eff} = Effective diffusivity coefficient, $m^2.s^{-1}$, r = Half thickness of sample, m, n = Positive integer, and t = Drying time, s.

For long drying times (setting n = 1), Poonia *et al.,* (2018 a, b) demonstrated that the Eq. (2) could be further simplified to a straight-line equation and can be expressed in a logarithmic form by taking the natural logarithm of both sides.

$$\ln(MR) = \ln\left(\frac{8}{\pi^2}\right) - \left(\frac{\pi^2 D_{eff}\, t}{4r^2}\right) \text{------------------ } (3)$$

Effective moisture diffusivity was calculated using the method of slopes. It is typically determined by plotting experimental drying data in terms of ln(MR) versus time. From Eq. (3), a plot of linear regression of ln(MR) versus drying time gives a straight line with a slope given as below:

$$\text{slope} = \left(\frac{\pi^2 D_{eff}}{4r^2}\right) \text{---------------- } (4)$$

The effective moisture diffusion coefficient (D_{eff}) was then calculated according to the slope of the line obtained by the linear fitting. Thermal Efficiency (η) was worked out using the relation developed by (Poonia *et al.,* 2017, 2018a):

Economic analysis of PV hybrid solar dryer

Economic analysis of the dryer was carried out by computing five economic attributes, namely, net present value (NPV), pay-back period (PBP), benefit-cost ratio (BCR), annuity (A) and internal rate of return (IRR) determined for judging the economic viability of the dryer. Net Present Value (NPV) value of solar devices was worked out using equation of Singh *et al.,* (2020). The Benefit-Cost ratio was expressed as the ratio of sum total of initial cost and net present value to the initial cost. Annuity (A) of the project indicates the average net annual returns. This term can be given as,

$$A = \frac{NPV}{\sum_{t=1\, to\, n} \left(\frac{1}{1+a}\right)^n} \text{----------} (5)$$

Pay Back Period (PBP) was worked out as the length of time required to recover initial investment through net average annual cash inflows generated by investment. PBP was calculated by equation:

$$PBP = \frac{\log\frac{(E-M)}{a} - \left(\log\frac{(E-M)}{a} - C\right)}{\log(1+a)} \text{------------} (6)$$

Internal rate of return (IRR): At 12% interest rate, the NPV is Rs 1,13,023 and at 40% rate of interest the NPV is Rs 13,485. However, the NPV is negative at 60% interest rate (i.e. NPV = Rs –2,032). The IRR can be determined using the following relationship and taking low discount rate as 40% and higher discount rate as 60%.

$$IRR = lower\ discount\ rate + \frac{Difference\ of\ discount\ rate\ x\ NPV\ at\ lower\ discount\ rate}{(NPV\ at\ lower\ discount\ rate - NPV\ at\ higher\ discount\ rate)} \text{-----} (7)$$

RESULTS AND DISCUSSION

Performance evaluation of PV hybrid solar dryer

Performance of the system with different number of fins inside the tunnel revealed that as the numbers of fins were increased, the temperature rise of air was more but the reduction in air speed was substantial. The average air speed at the exit of the tunnel varied from 3.5 m/s to 5.5 m/s during different hours of the day without fins where as it varied from 1.2 to 2.8 m/s with fins. Under loaded conditions of date palm fruits, average temperature of air at different points *viz.* upper, middle and lower trays of the drying chamber (Fig. 2). The average drying chamber temperature in left and right side of upper trays varied from 48 to 70°C, in middle trays 45 to 67°C and in lower trays 42 to 64°C, respectively. The average ambient temperature is 39.5°C and the average solar insolation varied in the range of 430 $W.m^{-2}$ to 940 $W.m^{-2}$ in the month of June 2020. Initially, the temperature inside the dryer was lower but as the time proceeds the temperature was found to be higher between 12:00 hr to 15:00 hr. After 15:00 hr the temperature inside the dryer was found lower. During the experimental period, the temperature recorded inside the dryer was almost similar for all six days drying time. The effect of drying temperature on drying time was considerably pronounced, and is in agreement with the results for several food materials as Indian Jujube (*Zizyphus mauritiana*) (Poonia *et al,* 2018 a, b), date palm (Sagarika *et al.,* 2019) and deglet nour dates fruits (Mennouche *et al.,* 2017).

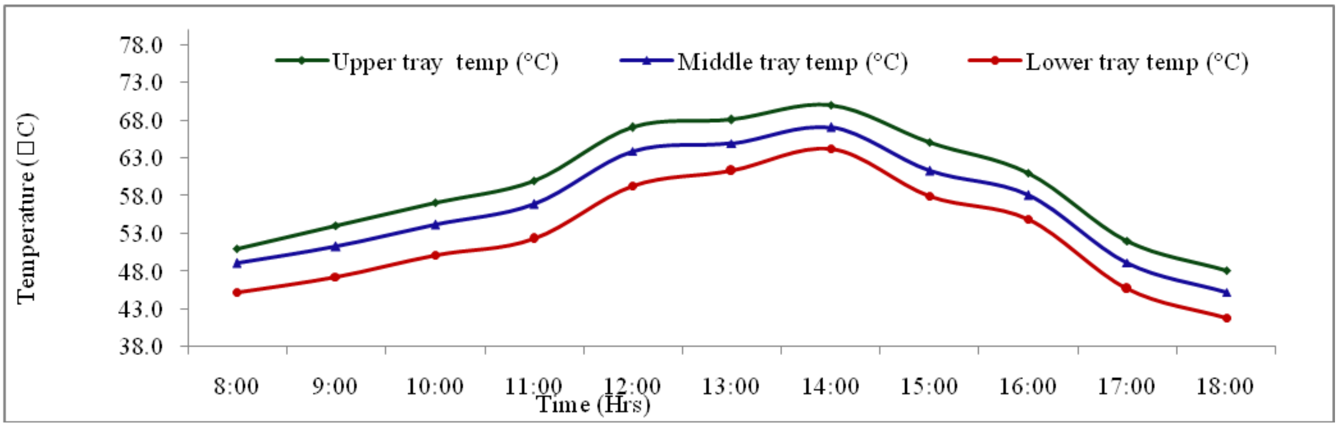

Fig. 2: Average temperature in the drying chamber at different points of PV dryer with tunnel while dehydrating date palm fruits

The variations in moisture content (w.b.) versus drying time in PV dryer as well as open sun drying of the fruit on each day of drying is compared in Fig. 3. It can be seen that the moisture content reduced from 65% to 26% within 6 days by the solar dryer, and on the 8th day the moisture content of fruit reduced to 20%, whereas in the open sun drying it is taken 8 days to bring down moisture content 26%. The moisture content, however, reduced to 26% after 6 days of drying, and could be safely stored for further use. The final moisture content of dried date palm under different conditions ranged from 20% to 26% on wet basis. It can be observed from Fig. 3 that the drying rate was much higher in PV dryer as compared to open sun drying. This was in agreement with the result of study on drying kinetics of date palm fruits in greenhouse dryer (Sagarika *et al.,* 2019), Algerian deglet-nour dates (Mennouche *et al.,* 2017). The drying rate in the solar dryer increased sharply when the moisture content fell below 54 per cent.

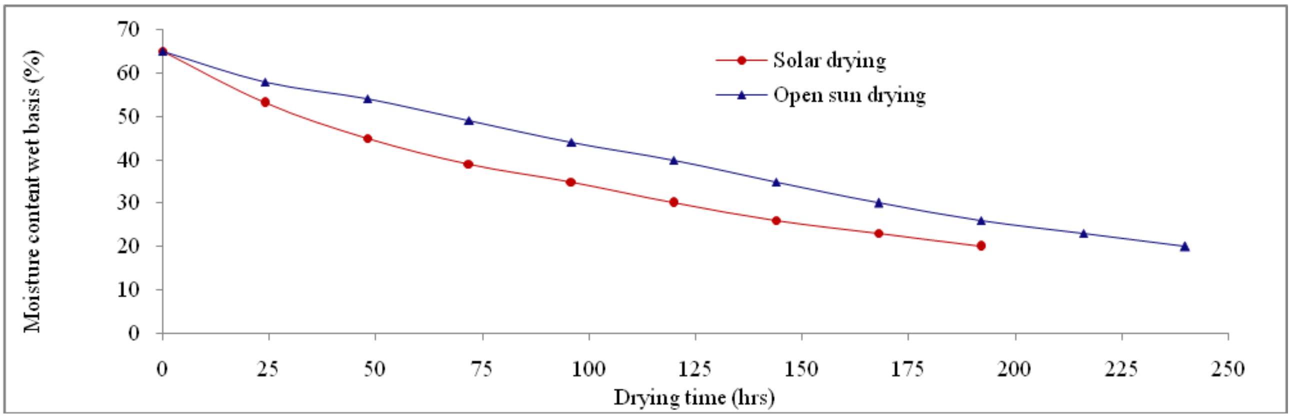

Fig. 3: Variation of moisture content of date palm during solar and open sun drying against drying time

The thermal gradient varied from 2-3□C inside the drying chamber in the beginning and then it increased to 4-6□C as drying proceed. The temperature rise is due to energy gain primarily from the pre air heater and the top plane due to high altitude of sun. The temperature difference at the top and middle trays of the bin were 6-8□C without the pre air heater whereas with pre air heater it was found to be 2-3□C initially, which also varied in different seasons for dehydrating various drying materials. Data of this experiment was found to be in accordance with the mathematical model for air heating and for predicting the temperature in the bin to a reasonable extent (Pande *et al.,* 2010). In this experiment the colour and aroma of the product was maintained.

The variation in moisture ratio with respect to drying time is shown in Fig. 4. The moisture ratio was found to be in decreasing trend for both solar drying and open sun drying (Fig. 4). The desired moisture ratio of (0.3) was achieved in a short time in solar drying as compared to open sun drying.

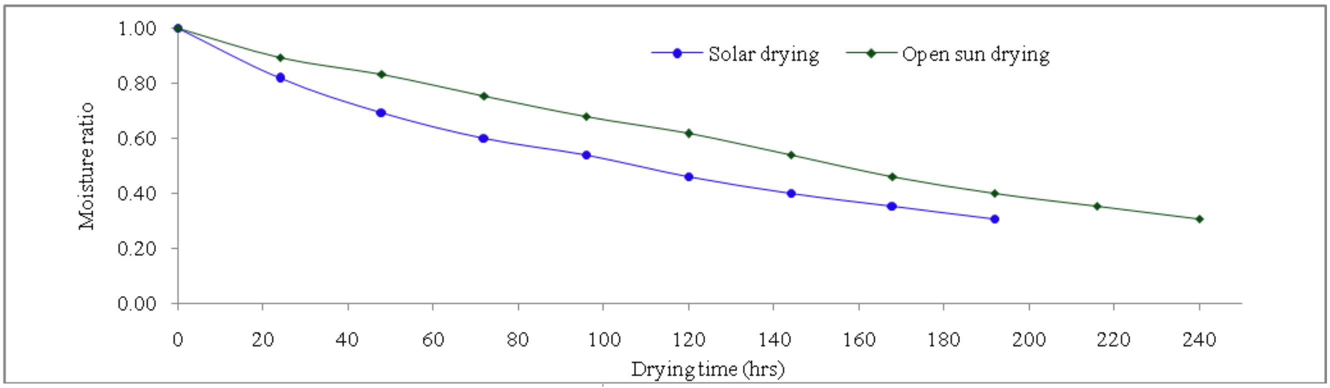

Fig. 4: Variation of moisture ratio of date palm during solar and open sun drying against drying time

Effective moisture diffusivity (D_{eff})

The effective moisture diffusion coefficient (D_{eff}) of date palm fruits in solar drying and open sun drying, ln MR was plotted against drying time (Eq. (4)) and D_{eff} was extrapolated. Plots satisfactorily describe the drying behaviour over the moisture ratio range ($0 \leq$ MR ≤ 1.0), a range that represents the bulk of the drying process, straight lines were obtained by linear regression with high correlation coefficients (r^2 = 0.990–0.9957). The effective moisture diffusivity was computed by using the graph of ln (MR) against time (Fig. 5). Moisture diffusivity of date palm fruits was 4.34×10^{-9} $m^2.s^{-1}$ at 30-65°C during the experiment for a loading rate of 20 kg in solar drying and 3.22×10^{-9} $m^2.s^{-1}$ in open sun drying. D_{eff} values mostly lie within general range of 10^{-12} to 10^{-8} $m^2.s^{-1}$ reported for most food materials (Poonia *et al.,* 2018 a, b). This was similar to the results for the thin-layer drying of date palm (from 7.53×10^{-9} to 1.11×10^{-8} $m^2.s^{-1}$) at 50–80°C and 3.34×10^{-7} for the thin-layer solar drying of Indian jujube (*Zizyphus mauritiana*) fruits at 50–70°C (Poonia *et al.,* 2018 a, b).

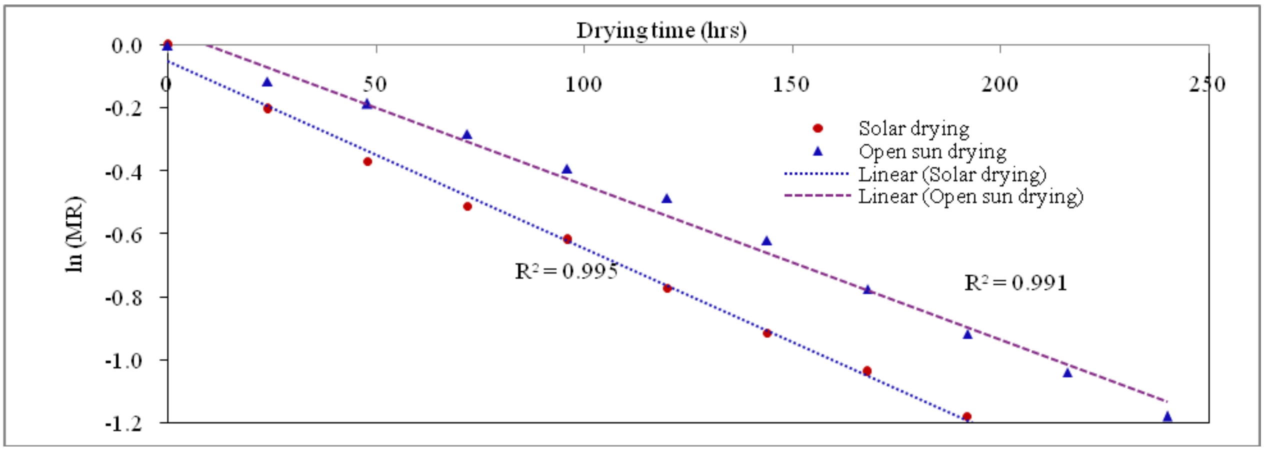

Fig. 5: ln (MR) versus drying time for drying of date palm during solar and open sun drying drying

Dryer overall efficiency

It was found that about 16.1% solar energy was utilized in this solar dryer. During drying process, higher efficiency was observed at initial stage of drying, while at later stage the dryer efficiency was decreased due to decrease in moisture content because initially, it is the unbound moisture that is being removed and just depends on the surface area. The result was in agreement with the previous investigations that the average thermal efficiency was 12.1% for low cost solar dryer for ber (*Zizyphus mauritiana*) fruit (Poonia *et al.,* 2017) and 16.7% for PVT hybrid solar dryer for drying of Indian jujube (Poonia *et al.,* 2018a). The overall thermal efficiency was 18.6% for the convective drying of sponge-cotton (Aissa *et al.,* 2014).

Analysis of economic viability

The annual benefit was obtained by using the dryer for drying date palm, sangri (Pods of *Prosopis cineraria*) and Lasora (*Cordia myxa*) and also labour saving in winnowing operations and also benefits gained through lightning. The benefit accrued from drying date palm and sangri was Rs 3,500/each and labour saving in winnowing amounted Rs 9,000/- and Rs 3,00/- from lighting. The benefits amounted to Rs 19,800/year, whereas present value of life cycle cost was Rs 33,089 which included initial cost and battery replacement charge, fan replacement and drying chamber replacement cost. The gross benefit of selling of the product is Rs 19,800.

The net present value (NPV) of dryer is Rs 1,13,023. Based on NPV it is concluded that the fabrication of dryer is economical as compared to solar biomass hybrid dryer (Dhanushkodi *et al.,* 2015) and PVT hybrid solar dryer (Poonia *et al.,* 2018 a, b). The value of benefit cost ratio for dryer as 4.41 by dividing life cycle benefits by life cycle cost. Equ. (5) has been used to determine the annuity of the dryer indicates the average net annual returns from dryer is Rs 14,415. The payback period is 2.10 years which is lower than the expected life of the dryer i.e. about 25 years. The values of NPW at varying discount rates are given in Table 1. From Table 1 it may be inferred that at 12% interest rate the NPV is Rs 113023/- respectively. At 40% rate of interest the NPV is Rs 13485. However, the NPV is negative at 60% interest rate (i.e. NPV = Rs –2032/-). The internal rate of return (IRR) which comes to 57.4% in the present case, which is very high for a project to be economically viable. The IRR is greater than the cost of capital. Other things being equal and using IRR as the decision criterion, the one with the highest IRR may be considered as the better choice. One reason for this conclusion is that a higher IRR indicates less risk (Singh *et al.,* 2020).

Table 1.Values of NPV for different rates of discount/interest (*i*)

NPW (Rs.)	113023	13485	-2032
Interest rate *i* (%)	12	40	60

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 2.

Table 2: Values of economic attributes

S. No.	Attributes economics	Values
1	BCR	4.41
2	NPV	113023
3	A	14415
4	IRR (per cent)	57.38
5	PBP (years)	2.10

The Moisture diffusivity was 4.34×10^{-9} $m^2.s^{-1}$, and the efficiency of the PV hybrid solar dryer was 16.1 percent. Economic evaluation of the hybrid solar dryer unit indicated high value of IRR (57.38%) and low value of payback period (2.10 year), suggesting the unit to be cost-efficient. The use of pre heating tunnel will reduce the thermal gradient and ensure uniform drying and overcome the problem of reshuffling of trays. The use of PV hybrid solar dryer considerably reduced the drying time, energy consumption and improved the quality of dried products as compared to open sun drying. The use of PV hybrid forced convection solar dryers at remote locations/rural areas can go a long way in reducing post-harvest losses as well as carbon emission.

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