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Design and Development of Domestic Solar Dryer with Comparative Analysis of Nutritional Aspect of Dried Raisins

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Abstract: Solar dryer technology is simple and can be implemented by households and small communities due to its simplicity. The suitable design of the absorber/collector is very vital for any solar drying system as the collector efficiency plays a key role in determining the overall system drying efficiency. To study the practical applicability of a developed solar dryer, grapes were dried in the drying chamber of a designed and developed solar dryer and for comparison, in open sunlight. Faster drying was noted for the grapes dried in the unit. The study on nutritional aspects indicated that solar drying process retained the major nutritional components like total sugars, total proteins and total lipids in raisins. The comparison between the solar dried raisins and open sun dried ones showed a higher ash content of 2.71% with solar dried ones and 1.95% in case of open sun dried raisins. The quantity of MUFA content was also affected by the varying drying practices implemented with 10.95% and 7.12% MUFA in solar dried and open sun dried raisins respectively. The drying technique also affects the bacterial load on raisins as observed in our current study with negligible bacterial growth on on solar dried raisins compared to open dried ones.
Keywords: Solar dryer; Collector efficiency; Energy balance; Prediction & experimental validation; Raisins; Nutritional aspects.

1. Introduction

A lot of locally produced household food products which require sun-drying in course of their preparation are dried in open sun and quite often under unhygienic conditions. This may cause the food products to be of poor quality, having lesser shelf life and in addition there might be the risk of contamination. Additionally, the procedure is time consuming, drying may not be consistent, and the area requirement is large. The produce is furthermore at risk to re-absorption of moisture, which reduces its value. The nutritional content and bacteriological load on raisins are highly dependent upon the processing environment and techniques involved which can be determined through various analytical techniques [1; 2]. Researchers also studied the nutritional parameters comparing organic and conventional grapes with respect to fertilizer and pesticide treatment [3].

Solar dryer technology is a simple one and can be attuned by households due to its uncomplicatedness. A solar dryer considered in this work is a cabinet type covered unit consisting of two parts- the absorber/collector and the drying chamber. The proper design of the absorber/collector is the most important factor for any solar drying system as the collector efficiency plays a major role in determining the overall system drying efficiency. Although, forced convection requires extra electrical energy, it is preferred over natural convection in order to obtain a better control of the drying process. Lot of research and experiments have been done on solar drying using natural convection [4;5] and forced convection [6], but there has been very little work on domestic-type solar dryers which can be directly implemented in households. Janjai et al. (2006) had designed a multi-shelf natural circulation domestic solar dryer which could be used in rural and remote areas [7]. Solar concave concentrator was used for drying of tomatoes by Ringeisen et al. (2014) [8]. Solar dryers must be properly designed in order to meet particular drying requirements of specific products and to give satisfactory performance. Basic parameters such as dimensions, temperature, relative humidity, air flow rate and the characteristics of products to be dried have to be considered for designing the system. In practice, dried grapes are commonly known as raisins and make up a large quantity of the dried fruits produced today. All over the world the annual average production of raisins is about 500 000 tons. Harvesting time is an important factor in selecting a grape because the primary production of raisins is by open sun drying [9].

2. Materials and methods

2.1. Design of the domestic dryer

Most of the food products that are used in their powdered form in kitchens, e.g. red chillies, turmeric, garlic, ginger, mango powder, coriander, onion, fenugreek leaves etc., are used in small quantities of the order of a few kilograms per year. Keeping these requirements in view, the area of the collector was determined for a load of 0.5 kg from initial moisture of 80% to 10% post drying basis within the peak solar insolation period of 11:00 AM to 4:00 PM. Reflectors made of anodized aluminium were considered to be installed at the collector end to enhance the solar radiation falling on the collector surface.

The design parameters for 0.5 kg load were computed from the following relationships [10]:

Collector efficiency, η_c, is defined as the ratio of heat received by the drying air to the insolation on the absorber surface, and is calculated from the Eq. (1):

$$\eta_c = \dot{M}_a(T_{co} - T_{am})C_p \,/\, A_c I_c \tag{1}$$

where $\dot{M}_a$ is the mass flow rate of air required for drying, T_{co} is the collector outlet temperature, T_{am} is the ambient air temperature, C_p is the specific heat of air, A_c is the collector area and I_c is the average solar radiation incident on the collector.

System drying efficiency, η_d, is defined as the ratio of the energy utilized to evaporate the moisture to the energy supplied to the collector and can be calculated from:

$$\eta_d = D h_{fg}/A_c I_c \tag{2}$$

where D is the drying rate and h_{fg} is the latent heat of vaporisation of air.

Amount of moisture, M_w, to be removed is given by:

$$M_w = M_p(M_i - M_f)/(100 - M_f) \tag{3}$$

where M_p is the initial mass of product to be dried; M_i is the initial moisture content and M_f is the final moisture content.

The quantity of heat, Q, required to evaporate the moisture is:

$$Q = M_w h_{fg} \eta_d/\eta_c \tag{4}$$

The collector area, A_c, can be calculated from:

$$A_c = Q/t_d I_c \eta_c \tag{5}$$

where t_d is the total drying time and Q/t_d is the hourly heat requirement.

Mass flow rate of air, $\dot{M}_a$, needed for drying is calculated using:

$$\dot{M}_a = \eta_c A_c I_c/(T_{co} - T_{am})C_p \tag{6}$$

Volumetric air flow rate inside the collector, $\dot{V}_a$, is given by:

$$\dot{V}_a = \dot{M}_a/\rho_i \tag{7}$$

where ρ_i is the density of air at the collector outlet.

The area of the air vent, A_v, is calculated from the following expression:

$$A_v = \dot{M}_a/\rho_o W_{inlet} \tag{8}$$

where, W_{inlet} is the wind speed at collector inlet and ρ_o is the density of the ambient air.

With air density at 0 °C = 1.29 kg m^{-3}, the air density, ρ, at any temperature, T, may be calculated using the expression:

$$\rho = (1.29)(273)/(273 + T) = 353/(273 + T) \tag{9}$$

The width of the air vent, W_v, is given by:

$$W_v = A_v/L_v \tag{10}$$

where L_v, the length of air vent.

The pressure difference, ΔP, across the collector is determined by:

$$\Delta P = g(\rho_o - \rho_i)H \tag{11}$$

where H is the pressure head (height of the hot air column from the base of the collector to the point of air discharge from the collector) and g is taken as 9.81m s^{-2}.

Velocity of air draft in the collector, W_{draft}, is given by:

$$W_{draft} = (2\Delta P/((\lambda L\rho_i/D_{hd}) + \rho_i\sum\xi))^{0.5} \tag{12}$$

where λ is Darcy-Weisbach friction coefficient, $\sum\xi$ is the minor loss coefficient and D_{hd} is the equivalent diameter of the duct through which the air passes through the collector which is given by the expression:

$$D_{hd} = 2W\delta_{pc}/(W + \delta_{pc}) \tag{13}$$

where δ_{pc} is the spacing between the absorber plate and cover and W is the width of the collector.

The assumptions and the results are provided in Table 1.

Table 1a. Constants used for design

With reflectors	
M_f	10%
M_i	80%
η_d	15%
η_c	30%
I_c	1250 W m^{-2}
T_{am}	30 °C
T_{co}	70°C
λ , Darcy-Weisbach coefficient	0.1
$\sum\xi$, Minor loss coefficient	1
t_d	5 h

Table 1b. Calculated design values for M_p= 0.5 kg

With reflectors	
M_w (Eq. 3)	0.39 kg
Q (Eq. 4)	1755. 44 kJ
A_c (Eq. 5)	0.26 m^2
$\dot{M}_a$ (Eq. 6)	8.78 kg h^{-1}
ρ_o (Eq. 9)	1.17 kg m^{-3}
ρ_i (Eq. 9)	1.03 kg m^{-3}
$\dot{V}_a$ (Eq. 7)	8.53 m^3 h^{-1}
A_v (Eq. 8)	0.004 m^2
W_v (Eq. 10)	0.07 m
ΔP (Eq. 11)	0.3 Pa
W_{draft} (Eq. 12)	0.66 m s^{-1}

Table 1c. Calculated M_p value for system without reflectors with A_c= 0.26 m^2

Without reflectors	
M_p	0.36 kg

2.2. Experimental setup, measurement procedure and nutritional analysis of the dried grapes

The design was done considering that reflectors were present. The area obtained for an insolation of 1250 W m^{-2} for the 5 h period was 0.26 m^2. Using the same procedure, calculations were done for a system without reflectors. It was found that the load for drying was reduced by 38.9% for the same η_c. The construction was done based on the designed collector/absorber area. The constructed solar dryer had the absorber/collector of dimensions 0.5m × 0.55m. The collector/absorber consisted of a glass layer of 0.01m thickness as the cover and an absorber plate made of blackened aluminium sheet of thickness 0.001m at the bottom. The distance between the plate and the glass was 0.093m. Insulation of 0.02m was provided at the bottom. The entire collector/absorber was in a casing made of waterproof plywood of 0.006 m at the bottom and 0.008m at the sides. A vent with dimensions 0.065m x 0.06m was present at the entrance of the collector fitted with a pipe of diameter 0.015m to allow air to enter. The collector was mounted at an angle of 24.6° with respect to horizontal. Forced draft at the entrance of the collector and induced draft at the end of the drying chamber were achieved by placing fans at both the ends of the system. The fans were controlled by a 10W PV panel via a small battery to deliver constant power throughout the operation. The drying chamber had the same dimensions as the collector and the material to be dried could be placed in the chamber using a perforated tray. The experiment was done for a period of 7h (10:00 AM to 5:00 PM) without 0.5 kg grapes as load in the drying chamber. Temperature T_{co} was measured using J type thermocouple. T_{am} and W_{sam} were measured using a thermo anemometer (CET- 6T8B) and I_c during the operation period of drying system was measured using an Eppley PSP pyranometer. The photograph of the solar dryer is shown in Figure. 1.

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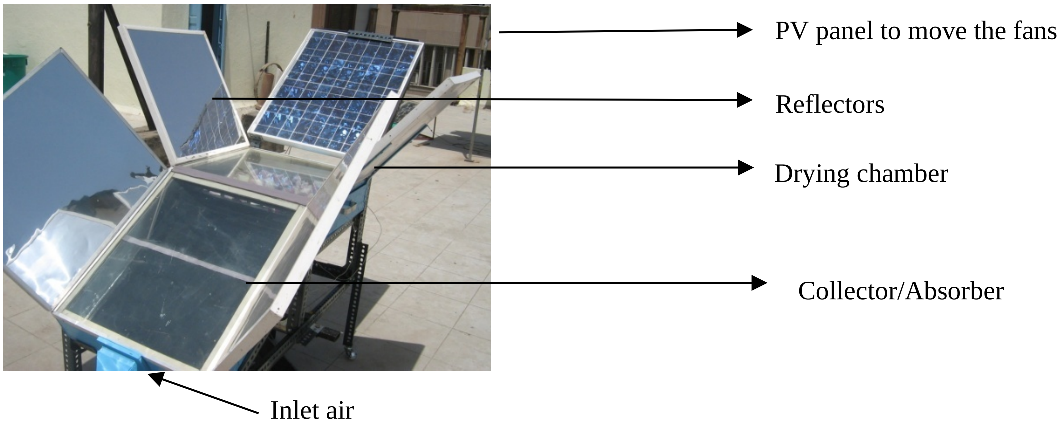

Figure. 1. Solar dryer under study

The readings were taken for every half hour interval. Drying experiment was done in a typical sunny day in the month of April. The moisture content of a grape was calculated based on the initial and the final weight of a sample kept in an oven at 65 ˚C and the bone dry weight was computed by difference. All the required data were measured at half hour intervals. The amount of moisture removed during this time interval was computed based on the difference in weights of a single grape piece gravimetrically. 0.5 kg of grapes were also kept for open sun drying in a tray beside the solar dryer in order to compare the results (Figure. 2).

Figure. 2. (a) Raw grapes inside the drying chamber of the solar dryer (b) Raisins inside drying chamber after day 1 (c) Raisins in open sunlight after day 6.

After successful conversion to raisins, for the bacteriological analysis , the open sun dried and solar dried raisins were kept aseptically on respective nutrient agar plates incubated at 37℃ for 24 hours in a forced convection lab incubator (Esco Isotherm forced convection laboratory incubator). The experiment was conducted in two sets to ensure the bacterial load on respective raisins. In the first set, both solar dried and open sun dried raisins were aseptically kept on nutrient agar plates respectively. In the second set raisins were soaked overnight in sterile distilled water followed by smashing before adding the sample to the nutrient agar plate on subsequent day.

2.3 Nutritional analysis of the raisin sample

2.3.1 Ash content

The ash content in raisin samples was determined according to AOAC (1984) [11]. About 5g of raisin samples were correctly weighed into the crucibles. The sample containing crucibles were kept into the muffle furnace for 5 h till it attained temperature of 500 ℃. After cooling of the furnace, crucibles were removed and weighed. The percent ash content was calculated using the following equation. (Eq. 14):

$$\% \text{ Ash} = (\text{Weight of Ash} \div \text{Weight of raisin sample}) \times 100 \tag{14}$$

2.3.2 Protein, amino acid and sugar estimation

Protein content of the raisin samples were estimated by Folin Lowry assay [12]. Amino acids content was determined by the high-performance liquid chromatography method (HPLC-Waters Alliance) using a Phenomenex C-18 column [13]. Anthrone method was used to estimate total sugar content in raisin samples.

2.3.3 Lipid and fatty acid estimation

The procedure of Folch et al. 1957 was used for the extraction of lipids from raisins [14]. Dried raisins were weighed and crushed further in mortar pestle followed. 5 ml of 2:1 chloroform: methanol mixture was added to the crushed sample and sonicated. The material obtained was centrifuged further and the supernatant was collected and dried. The dried material was weighed appropriately and lipid content was determined as follows (Eq. 15):

$$\%\text{lipid} = (\text{lipid weight} \div \text{biomass weight}) \times 100 \tag{15}$$

The sample prepared above was further transesterified and the fatty acid methyl esters prepared were determined for fatty acid analysis using Gas chromatography-mass spectrometry (GC MS) (Shimadzu-QP-2010) using BP – 20 column (30 m x 0.25 µm) [15]. Helium served as carrier gas and column oven temperature was 100 °C with 240℃ injection temperature with split injection mode and 73.0 kPa pressure. Total flow and column flow was 304.0 ml/min and 1.00 ml/min respectively. Linear velocity was 37.2 cm/sec with 3.0ml/min purge flow and 300 split ratio.

2.3.4 Mineral analysis

Mineral analysis was performed using inductively coupled plasma-optical emission spectroscopy (ICP-OES) Optima 2000 DV (Perkin Elmer) according to AOAC (1984).

3. Results and discussion

3.1 Grapes to Raisins in the solar dryer

The basic principle of the design of the mentioned domestic dryer is that solar radiation incident on an aperture can be intensified by reflecting and redirecting additional solar radiation using appropriately inclined reflectors. This work makes use of anodized aluminium reflectors to reflect and direct additional solar radiation into the top glass window of the inclined collector/ absorber which has an opening at the side near to the ground. Due to the inclination of the absorber/collector, the heated air enters and rises up the unit with little resistance. This air then flows across the food item placed in the drying chamber connected to the absorber/collector. The higher absolute amount of radiation incident on the collector and the enhanced heat transfer efficiency as a result of the enhanced temperature differential between the absorber surface and the ambient raises the overall efficiency of the unit. The slant collector/absorber provides additional heating to the main horizontal drying chamber by catching rays of low altitude sun in the early forenoon and late afternoon more efficiently than the main horizontal heating chamber. As observed from Figure. 3, the residual moisture content of the grapes under study decreased from 78.10 % to 9.05 % in the period of 7 hrs starting from 10:00 A.M. Both the collector /absorber and drying chamber had reflectors in V-trough alignment and as a result the drying air temperature in the collector/absorber rose to as high as 105.7 ℃. Care was taken to ensure that case hardening did not occur. Because of the attainment of such a high temperature, complete drying of the grapes was possible in 1 day. The air escaping out of the drying chamber had a maximum temperature of 80 ℃ which may be used in some other applications. The grapes which were kept in open sun for drying, continued to dry and the desired moisture level was attained on day 6 from starting of the experiment (Table 2). Similar studies on drying of grapes under open sun and solar dryer was carried out by Essalhi et al., 2018 [16].

Table 2. Weight of sample grape under open sun drying condition

Time	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00
Sample weight (g) day 1	-	3.22	3.21	3.15	3.13	3.05	3.03	2.99
Sample weight (g) day 2	2.86	2.86	2.83	2.78	2.74	2.69	2.66	2.64
Sample weight (g) day 3	2.46	2.42	2.34	2.22	2.1	2.03	1.98	1.95
Sample weight (g) day 4	1.86	1.82	1.77	1.73	1.7	1.68	1.66	1.64
Sample weight (g) day 5	1.58	1.56	1.52	1.46	1.37	1.31	1.26	1.2
Sample weight(g) day 6	1.14	1.08	1.02	0.97	0.93	0.9	0.9	0.9

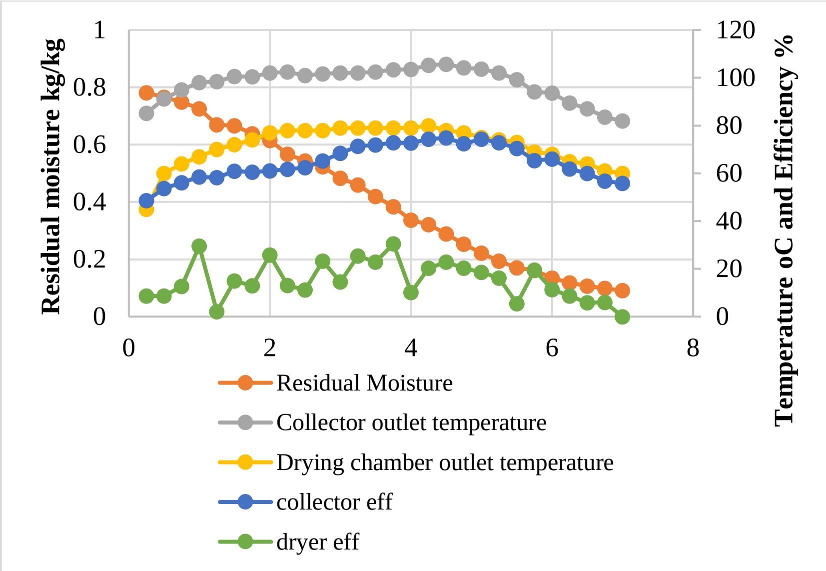

Figure. 3. Variation of solar dryer parameters with time.

3.2 Bacteriological analysis

Microbial load was determined for both solar and open sun dried raisin samples. The nutrient agar plates containing solar dried raisins indicated negligible bacterial growth whereas the open sun dried raisin containing nutrient agar plate showed higher load of bacteria. This evidently indicates that the drying in solar dryer significantly reduced the bacterial load. Solar dryer being an enclosed chamber, this is carried out in hygienic condition and has less chances of dust and other contamination problems. Several reports have indicated the relation between the condition of preparation of raisins and its quality [17, 18] In addition; various bacteria have the ability to grow in the dry environment and can survive on raisin and dry surface for months [19; 20]. Figure. 4 indicates the bacterial load on nutrient agar plates with raisin samples kept aseptically (a) Open sun dried raisin sample (b) Solar dried raisin (c) Open sun dried, soaked and smashed raisin (d) Solar dried, soaked and smashed raisin. Raisin samples soaked overnight in sterile distilled water with high water content were further smashed to release the pulp containing nutrients. They were kept aseptically on nutrient agar plates and observation after 24 hours of incubation indicated enhanced bacterial load. While raisin samples kept intact (without soaking and smashing) aseptically on nutrient agar plates showed negligible growth after 24 hours of incubation at 37 ℃.

3.3 Nutritional analysis of raisins

Solar drying process retained the amount of total sugars, total proteins and total lipids in raisins. Table 3 indicates the amount of sugar, protein, lipid in the open sun dried (OSD) and solar dried raisin (SD) samples. Saturated fatty acid content was retained in both solar dried and open sun dried raisin samples while monounsaturated fatty acids (MUFAs) content was higher (10.95%) in solar dried raisin samples than (7.12%) in open sun dried raisin samples (Table 4).

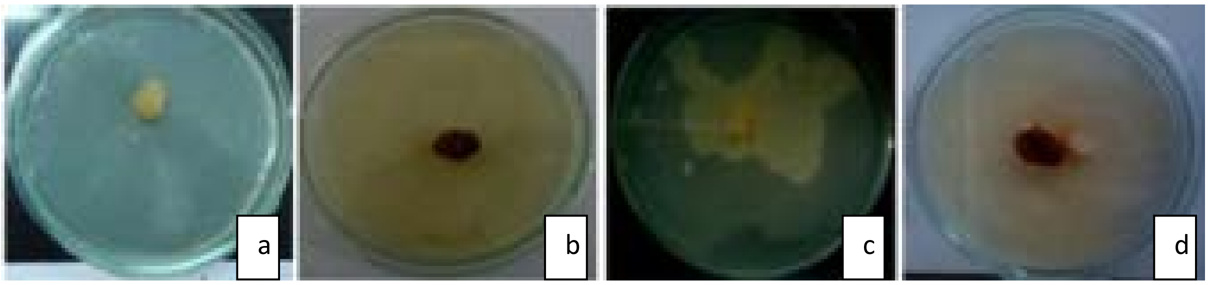

Figure. 4. Bacterial load on nutrient agar plates with raisin samples kept aseptically (a) Open sun dried raisin sample (b) Solar dried raisin sample (c) Open sun dried, soaked and smashed raisin sample (d) Solar dried, soaked and smashed raisins.

Table 3. Contents of nutrients in SD and OSD raisins

Content of nutrients	*SD	**OSD
Total Sugars (%)	70.84	70.46
Total Lipids (%)	15.43	15.74
Saturated fatty acids (%)	2.97	2.32
Monounsaturated fatty acids (%)	10.95	7.12
Polyunsaturated fatty acid (%)	86.07	90.57
Total Proteins (µg/g)	1.539	1.560

*SD: Solar dried raisins; **OSD: Open sun dried raisins

Table 4. Fatty acid profile of SD and OSD

Fatty acid	Fatty acid content (%)	
	*SD	**OSD
Saturated fatty acid		
C16:0 (palmitic acid)	1.35	1.01
C18:0 (stearic acid)	0.05	0.71
C22:0 (behenic acid)	0.57	0.60
Unsaturated fatty acid		
C18:1n9c(oleic acid methyl ester)	10.95	7.12
C18:2n6c(linoleic acid methyl ester)	0.86	0.54
C18:3n6(γ- linoleic acid methyl ester)	80.59	83.90
C18:3n3 (α- linoleic acid methyl ester)	4.62	6.13

*SD: Solar dried raisins; **OSD: Open sun dried raisins

MUFAs may benefit insulin levels and blood sugar control, which can be especially helpful in diabetes mellitus [21]. Studies show that eating foods rich in MUFAs improves blood cholesterol levels, which can decrease risk of heart disease [22].

Mineral composition of solar dried raisin samples was higher due to higher ash content compared to open sun dried samples (Table 5). Calcium (0.065%), Potassium (0.647%), Magnesium (0.380%), Sodium (0.996%) and micronutrients like Iron, Molybdenum and Zinc were retained in solar dried raisins. The content of micro-nutrients Zinc, Iron and Molybdenum were 40 ppm, 130 ppm and 20 ppm respectively after solar drying of the grape samples while in open sun dried raisin samples, they were 30 ppm, 90 ppm, and 10 ppm respectively. Minerals and amino acids facilitate absorption of other nutrients and proteins in the body. Most of the essential amino acids were retained during the solar drying process. Magnesium was retained in comparatively higher amounts in solar dried raisin samples. Iron, an important micronutrient helps in treating anemia [23] and calcium, the main constituent of bones was also retained during solar drying process. Among micronutrients, Molybdenum and Zinc were retained in solar dried samples as compared to that of open sun dried raisin samples. Zinc contributes to healthy immune system [24].

Table 6 indicates the amino acids present in the raisin samples suggesting essential amino acids like threonine, valine, isoleucine, phenylalanine and lysine are retained in considerable amounts during solar drying. The objective in drying of the food products is substantial reduction in weight and volume, allowing the safe storage over extended period [25].

4. Conclusion

A domestic solar dryer of 0.5 kg capacity was designed and fabricated for drying of food items. Grapes were dried in the unit to form raisins in a 1 day. Similar quantity of grapes under open sun drying condition took 6 days to dry. The higher drying rate was achieved due to the attainment of higher air temperature (more than 100 ℃) in the collector/absorber due to presence of reflectors on both collector/absorber and drying chamber. Bacteriological and nutritional analysis was performed for the solar dryer based raisins and raisins obtained under open sun drying. Nutrients were retained in good amounts in the solar drying process. In addition, the percentage of MUFA in the solar dried raisin sample was higher than those dried by open sun drying. Most of the essential amino acids like threonine, valine, isoleucine, phenylalanine and lysine were present in good amounts in solar dried raisin samples as compared to open sun dried ones. Since the nutritional value of raisins obtained in the solar dryer is better, solar drying process can be used to obtain clean and hygienic food products which might fetch better market price.

Table 5. Ash content, macronutrients and micronutrients in SD & OSD raisins

Components	*SD	**OSD
Ash content		
% Ash	2.71	1.95
Macronutrients (%)		
Ca	0.065	0.056
K	0.647	0.477
Mg	0.380	0.030
Na	0.996	0.494
Micronutrients (ppm)		
Fe	130	90
Mn	nil	10
Mo	20	10
Zn	40	30

*SD: Solar dried raisins; **OSD: Open sun dried raisins

Table 6. Amino acid profile in SD & OSD

Essential amino acids (%)	*SD	**OSD
Histidine	nil	0.15
Threonine	0.028	nil
Valine	0.60	0.0135
Methionine	0.0021	0.0068
Isoleucine	0.071	0.0016
Leucine	0.17	0.67
Phenylalanine	0.74	0.21
Lysine	0.50	0.167
Nonessential amino acids (%)		
Asparagine	0.5	nil
Glutamic acid	0.69	0.17
Serine	0.15	nil
Glycine	0.44	0.91
Arginine	0.17	0.51
Alanine	0.054	0.62
Proline	0.013	0.048
Cysteine	nil	0.081
Tyrosine	nil	0.055

*SD: Solar dried raisins; **OSD: Open sun dried raisins

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