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Design of Fruits Solar Energy Dryer under Climatic Condition in Jordan

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Abstract

In this paper, a new design of a natural convection solar dryer used to dry fruits is presented; taking into account the local climatic conditions prevailed in Jordan during summer season. The dryer will have a capacity of 100 kg of sliced apples and the simulation is based on mass and heat balances. It is deemed that such new design will be able to reduce the original moisture content, of the final product, to 10% within two days. The special tailored program could be used to calculate drying parameters for similar products under different climatic conditions. The next step will be focused on constructing the solar dryer in order to conduct actual experiments in the field.

Keywords

Solar Dryer, Fruits Drying, Convection, Design, Radiation

1. Introduction

During the long past history, several thousand years ago, solar energy was used to dry main food products, such as fruit, vegetables, meat and fish, in order to be preserved for later use. Although new technologies, such as cold storage, brought changed techniques, but still solar drying is used in different parts of the world, including the Middle East Region, due to the increasing demand for healthy and low-cost natural foods. Equally important is the new trend for green economies and sustainable development.

Drying of agricultural products, e.g. fruits, vegetables, grain, etc., is one of the oldest forms of known food preservation methods, the idea of drying is to provide longtime storage without degradation. The process involves the slow removal of the majority of water contained in the fruit or vegetable so that the moisture contents of the product is below 15%. Dryers have been developed and used to dry agricultural products in order to improve their shelf life [1]. Most of these dryers use an expensive source of energy such as electricity [2]. Projects of such nature have not been adopted by small farms either because the final design and data collection procedures are frequently inappropriate or the cost has remained inaccessible and the subsequent transfer of technology from a researcher to an end user has been anything but effective [3].

According to sources of the Ministry of Agriculture, the total cultivated area with apple trees and its annual production, in Jordan, is about 54148 Dunums (*i.e.* 54148×10^3 m^2), and 5500 tons, respectively [4]. Apples are popular fruits in the world market because of their unique and attractive flavor, color and nutritional value. During the harvest season there is a large quantity of this fruit and it has a relatively low price. Drying might be an interesting method in order to keep the price of this fruit in the accessible range and prevent fresh fruit deterioration. There is a spoilage of fruits and vegetables that could be preserved using drying techniques in Jordan. Large quantities of small apples that are not demanded in the market could be used in solar energy drying. It is therefore, envisaged that the design of a simple solar dryer could contribute greatly to solving this problem.

Main factors affecting food dryers are: i) solar radiation and ii) relative humidity. Drying time is also affected by type of food and its water content, and thickness of slices. Generally speaking very wet foods like mango, pineapple and tomato will take two full days of solar heated drying. Some like apple, coconut, potato, onion etc. can be done in one day. Leafy products like herbs take only part of a day. It is important t note that excessive heat should be avoided in order to produce a high-quality product, since high heat rates may cause product degradation. Drying time can be shortened either by raising the product temperature or treat the product. In the 1st method moisture is vaporized, while at the same time the humid air is constantly being removed. In the 2nd method, the product is treated to be dried so that the moisture barriers, such as dense hydrophobic skin layers or long water migration paths, will be minimized.

In the open literature, there are mainly three types of solar dryers:

1. The absorption or hot box type dryers in which the product is directly heated by sun.

2. The convection dryer in which the product is exposed to warm air which is heated by means of a solar absorber.

3. Dryers combining the principles of the above two, where the product is exposed to the sun and a stream of pre-heated air simultaneously.

Also solar dryers are usually classified according to the mode of air flow into natural convection and forced convection dryers. There is no need for a fan to pump air in the dryer in the natural convection. Therefore, research efforts will be focused on designing the solar dryer. The use of solar technology has been often suggested for the dried fruit industry for both reasons of reducing the energy cost and economically speeding the drying process to improve the final product quality in the terms of color and flavor. The solar energy can be economically used for drying only if the purpose can be coordinated with specific characteristics of solar radiation which are that the incident radiation energy must be considerably higher than the world average 3.82 kW/m^2day, and high number of sunny days per year [5]. In Jordan, the calculated average radiation intensity is 5.5 kW/m^2day and there are 330 sunny days yearly [6] [7] [8]. For this reason economic use of solar energy could be achieved in Jordan. It is important to govern the investment costs in matching of the drying process and the specific characteristics of solar energy, flat plate collectors are considered to be cheap with also producing moderate temperature medium (usually under 70˚C) and their efficiency improves with a decrease in operation temperature, so dryers with flat plate collectors can be used for drying agricultural products.

Accordingly, the availability of solar energy and the operational marketing and economy reasons offer a good opportunity for using solar drying all over the world. A great number of successful practical applications have already been reported [9] [10] [11] [12] [13]. Solar drying is in practice since time immemorial for preservation of food and agriculture crops. This was done particularly by open sun drying under the open sky. Since traditional sun drying is a relatively slow process, considerable losses can occur. In addition, a reduction in the product quality takes place due to insect infestation, enzymatic reactions, microorganism growth, and mycotoxin development. This process has several disadvantages like spoilage of product due to adverse climatic condition like rain, wind, moist, and dust, loss of material due to birds and animals, deterioration of the material by decomposition, insect infestation and fungal growth. Solar drying can be an effective means of food preservation since the product is completely protected during drying against rain, dust, insects and animals [14]. Significant developments, during the past decade, in the area of solar crop drying were reviewed by [15], stating the fact that solar energy is considered more applicable to low-temperature in-storage drying systems and it has gained more importance work to facilitate a comparison of the financial feasibility of solar drying as against open sun drying, having presented the results of some exemplifying calculations and a brief discussion. Also they presented a comprehensive review of the fundamental principles and theories governing the drying process, along with basic definitions [16] [17]. A comprehensive review of the various designs, details of construction and operational principles of the wide variety of practically-realized designs of solar energy drying systems was presented [18]-[26]: Asys-dryers, mixed-mode solar dryers, and hybrid solar dryers [27]. Low cost drying technologies suitable for rural farming areas were presented by [28]. A brief introduction on each of the drying technology considered namely fluidized bed, spouted bed, infrared, solar, simple convective, and desiccant drying were presented followed by some technical details on their working operations. Other researchers gave a preliminary economic analysis for an indirect type solar fruit and vegetable dryer and the analysis stressed that the most significant economic parameters in the lifecycle costing of the system were the payback period and internal rate of return [29].

Many researches have focused on natural convection solar dryers which are fully described in [30] [31] [32] [33] [34]. Fruit drying and the characteristics of fruits while drying have been studied by many researchers according to [35]-[40].

In this research work, a new simple solar drying system is designed with the aim of drying 100 kgs of locally produced apple slices under the prevailing climatic conditions in Jordan. The solar dryer consists of two major sections made in one unit:

a. the flat collector upon which solar energy is incident, transmitted and absorbed to heat air which is passed by natural convection to the drying chamber;

b. the drying chamber which contains the apple slices being dried.

2. Description of the Solar Dryer That Will Be Designed for Drying

The solar dryer considered in this research paper is the shelf-type dryer with separate collector (as shown in **Figure 1**). Here the product is located on shelves inside an opaque drying chamber. Solar radiation is thus not incident directly on the crop. Preheated air warmed during its flow through a low-pressure thermos phonic solar energy air heater, is ducted to the drying chamber to dry the product. Because the products are not subjected to direct sunshine, localized heat damage, do not occur. A typical Distributed Passive Solar Energy Dryer is made up of the following basic units:

a) A Drying chamber.

b) An air-heating solar energy collector, which consists of cover plate, absorber plate and insulator (wood).

2.1. Drying Chamber

The drying chambers made of a highly polished plywood box held in place by angle irons. The material has been chosen since wood is a poor conductor of

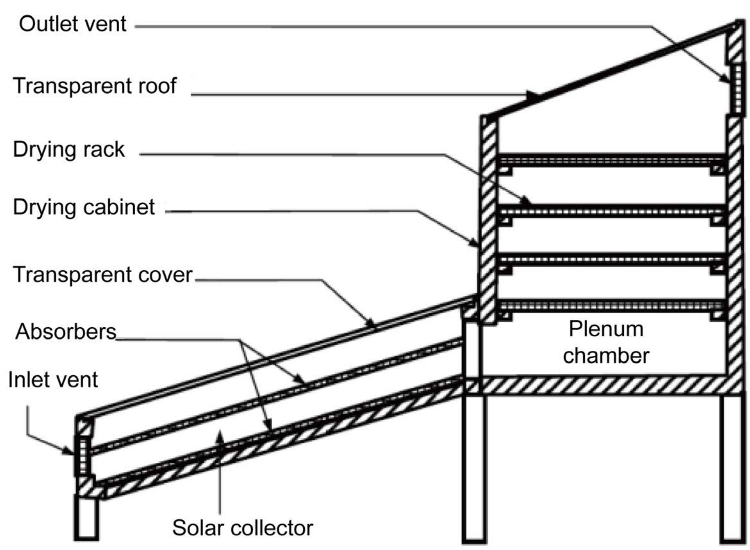

Figure 1. Sectional view of shelf-type dryer with separate collector [44].

heat and it has smooth surface finish; heat loss by radiation is minimized. To further reduce heat loss by radiation and to avoid moisture absorption by the wood, aluminum foil is wrapped on the inside of the chamber.

2.2. Cover Plate

It is transparent sheet is made of 4 mm thick glass used to cover the absorber, thereby preventing dust and rain from coming in contact with the absorber. It also retards the heat from escaping (*i.e.* forming a confinement for heated air) It is placed about 2.54 cm above the absorber.

2.3. Absorber Plate

It is a mild steel sheet with 1 mm thickness painted black to absorb the incident solar radiation transmitted by the cover thereby heating the air between it and the cover. In its plainest form, it is no more than a blackened metal plate exposed to the sun.

2.4. Insulator

It is used to minimize heat loss from the system. It is placed under the absorber plate. The insulator must be able to withstand stagnation temperature, should be fire resistant and not subject to out-going gassing; and should not be damageable by moisture or insect. Insulating materials are usually fiberglass, mineral wool, Styrofoam and urethanes, with at least 5 cm thickness (**Figure 1**).

3. Solar Dryer Design

3.1. Design Features of the Dryer

The solar dryer consists of two main sections, first section is the drying chamber which has the shape of a home cabinet and the second is the flat collector which is titled to the south, the angle of the slope of the it is 20˚ which represents the highest recorded average of solar radiation in Amman in the months of July to September as shown in **Figure 2**. It is provided with air inlet and outlet holes at the front and back, respectively. The outlet vent is at higher level. The vents have fix covers which control air inflow and outflow. The movement of air through the vents, when the dryer is placed in the path of airflow, brings about a thermo siphon effect which creates an updraft of solar heated air laden with moisture out of the drying chamber. The source of air is natural flow.

3.2. Solar Dryer Design Considerations

A solar dryer was design based on the producer described by [41] for drying dates (a cabinet type) and procedure described by [42] for drying rough rice (natural convection a mixed-mode type). The sample thickness is 3mm as recommended by [43] for solar drying of mango slice.

The following points were considered in the design of the natural convection solar dryer system:

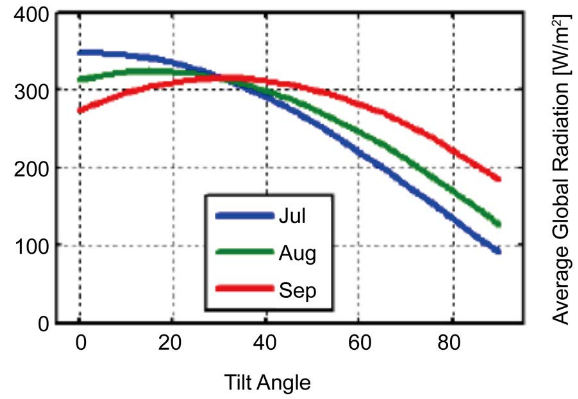

Figure 2. Monthly global radiation with tilt angle β_2 [˚] [45].

a-The amount of moisture to be removed from a given quantity of wet apple,
b-Harvesting period during which the drying is needed,
c-The daily sunshine hours for the selection of the total drying time,
d-The quantity of air needed for drying,
e-Daily solar radiation to determine energy received by the dryer per day,
f-Wind speed for the calculation of air vent dimensions.

3.3. Design Procedure

The size of the dryer was determined as a function of the drying area needed per kilogram of pulp of fruit. The drying temperature was established as a function of the maximum limit of temperature the fruit might support .

From the climatic data (Jordan metrological department, Amman, Jordan 2007) [8], the mean average day temperature in July is 32˚C and RH is 45%. From the psychometric chart the humidity ratio is 0.0137 kg H_2O/kg dry air. From the result of preliminary experiments on the crop, the optimal drying temperature was 70˚C and final moisture content of apple for storage is 10% wet basis, the corresponding relative humidity is 51% (sorption isotherms equation).

3.4. Design Calculations

To carry out design calculations and size of the dryer, the design conditions applicable to Amman are required. The conditions and assumptions summarized in Table 1 are used for the design of the fruit (apple) dryer.

From the conditions, assumptions and relationships, the values of the design parameters were calculated. The results of calculations are summarized in Table 2.

I-Amount of moisture to be removed from a given quantity of wet apple slices to bring the moisture content to a safe storage level in a specified time:

The amount of moisture to be removed from the product, m_w, in kg was calculated using the following equation:

$$m_w = \frac{m_p\left(M_i - M_f\right)}{\left(100 - M_f\right)} \tag{1}$$

Table 1. Design conditions and assumptions.

Items	Condition or assumption
Location	Amman (latitude 32˚N)
Crop	Apple
Drying period	July to September
Variety	Kitchener
loading rate (2 days/batch)	100 kg sliced apple
Initial moisture content (moisture content at harvest)	84.89%
Final moisture content (moisture content or storage)	10% wet basis
Ambient air temperature	32˚C (Average for August)
Ambient relative humidity	45% (Average for August)
Maximum allowable temperature	70˚C
Drying time (sunshine hours)	8 hours (Average for August)
Collector efficiency	30% (Ampratwum, 1998).
Wind speed	3 m/s
Thickness of sliced apple	3 mm
Vertical distance between two adjacent trays	25 cm
Declination angle δ	12.1˚
Ratio of diffuse to direct irradiation C	0.122
Equation of time	1 min
Apparent solar irradiation A	1106.2 w/m^2
Atmospheric extinction B	0.177 m^{-1}
a_2: is the angle between the horizontal projection of the normal to the surface and the due south line measure in clock wise direction	0˚
β_2: the tiled angle of the surface is the angle between the surface and the and the horizontal	20º
α: the collector surface absorptivity	90%

where: m_p is the initial mass of product to be dried, k_g; M_i is the initial moisture content, % wet basis and M_f is the final moisture content, % wet basis.

II-Final or equilibrium relative humidity:

Final relative humidity or equilibrium relative humidity was calculated using sorption isotherms equation for mango given by Hernandez *et al.* (2000) as follows:

$$a_w = 1 - e^{\left[-e^{(0.914+0.5639\ln M)}\right]} \quad (2)$$

where:

a_w = water activity, decimal,

M = moisture content dry basis, kg water/kg dry solids.

$$a_w = \frac{ERH}{100} \quad (3)$$

Table 2. The values of the design parameters [46] [47].

Parameter	Value	Data or equation used
Initial humidity ratio, w_i	0.0137 kgH_2O/kg dry air	Tam, RHam
Initial enthalpy, h_i,	66.59 kJ/kg dry air	Tam, RHam
Equilibrium relative humidity RHf	51%	M_f and isotherms Equation (2)
Final enthalpy, h_f	101.17 kJ/kg dry air	w_i and T_f
Final humidity ratio, w_f	0.0237 kgH_2O/kg dry air	RHf and h_f
Mass of water to be evaporated, m_w	83.2 kg	Equation (1)
Average drying rate, m_{dr}	5.2 kgH_2O/hr	Equation (8)
Air flow rate, m_a	461 kg dry air/hr	Equation (9)
Volumetric airflow rate, V_a	390.68 m^3/hr	m_a, air density (ρ)
Total useful energy, E	255.307 MJ	Equation (6)
Average I_{DS}	106 W/m^2	Equation (20)
Average $I_{DN}\cos\theta$	726.8 W/m^2	Equation (21)
Average E_s	4503.9 kJ/m^2	Equation (22)
Solar collector area, A_c	18.9 m^2	Equation (23)
Vent area, A_v	0.0363 m^2	V_a, wind speed
Vent Length	4 m	
Vent Width	0.0091 m	Equation (13)

III-Quantity of heat needed to evaporate the H_2O:

The quantity of heat required to evaporate the H_2O would be:

$$Q = m_w \times h_{fg} \tag{4}$$

where:

Q = The amount of energy required for the drying process, kJ,

m_w = mass of water, k_g,

h_{fg} = latent heat of evaporation, kJ/kg H_2O.

The amount needed is a function of temperature and moisture content of the crop. The latent heat of vaporization was calculated using equation given by Youcef-Ali *et al.* (2001) as follows:

$$h_{fg} = 4.186 \times 103\left(597 - 0.56\left(T_{pr}\right)\right) \tag{5}$$

where: T_{pr} = product temperature, ˚C.

Moreover, the total heat energy, E(kJ) required to evaporate water was calculated as follows:

$$E = \dot{m}\left(h_f - h_i\right)t_d \tag{6}$$

where: E = total heat energy, kJ,

$\dot{m}$ = mass flow rate of air, kg/hr,

h_f and h_i = final and initial enthalpy of drying and ambient air, respectively, kJ/kg dry air,

t_d = drying time, hrs.

The enthalpy (h) of moist air in J/kg dry air at temperature T (˚C) can be approximated as (Brooker *et al.*, 1992):

$$h = 1006.9T + w\left(2512131.0 + 1552.4T\right) \tag{7}$$

IV-Average drying rate:

Average drying rate, m_{dr}, was determined from the mass of moisture to be removed by solar heat and drying time by the following equation:

$$m_{dr} = \frac{m_w}{t_d} \tag{8}$$

The mass of air needed for drying was calculated using equation given by Sodha *et al.* (1987) as follows:

$$\dot{m} = \frac{m_{dr}}{\left(w_f - w_i\right)} \tag{9}$$

where: m_{dr} = average drying rate, kg/hr,

w_f – w_i, final and initial humidity ratio, respectively, kg H_2O/kg dry air.

The total useful heat energy required to evaporate moisture (received by drying air kJ can be calculated from the following equation:

$$E = \dot{m}\left(h_f - h_i\right)t_d \tag{10}$$

V-Air vent dimensions:

The air vent was calculated by dividing the volumetric airflow rate by wind speed:

$$A_V = \frac{V_a}{V_w} \tag{11}$$

Volumetric airflow rate, V_a was obtained by dividing ma by density of air which is 1.18 kg/m^3.

A_v is the area of the air vent, m^2, V_w is wind speed, m/s. The length of air vent, L_V, m, will be equal to the length of the dryer. The width of the air vent can be given by:

$$B_V = \frac{A_V}{L_V} \tag{12}$$

where B_V is the width of air vent, m.

VI-Solar energy calculation

The amount of solar energy on a surface is composed of direct component and a diffuse component, the direct component on a surface normal to the sun's rays depends on the time of year, time of day and the latitude of the surface as well as the atmospheric conditions.

The following equations are used to determine the parameters that are required to calculate the total solar energy flux on a surface.

-Mean Sun time (*MST*)

$$MST = LST + \left[\text{Degree East}(+)\text{or west}(-)\text{on the standard meridian}\right](4\,\text{min}) \tag{13}$$

-Local Standard time (LST)

Apparent Solar Time (AST)

$$AST = MST + \text{equation of time}\left(EOT\right) \quad (14)$$

-the altitude angle (β_1): is the angle between the sun's rays and the horizontal to the earth.

$$\text{Sin}\beta_1 = \text{Cos}L\text{Cos}\delta\text{Cos}H + \text{Sin}L\text{Sin}\delta \quad (15)$$

where,

Latitude angle (L),

-Declination angle (δ) is defined as the angle between the sun's rays and the normal to polar axis in the plane of the sun rays (−23.45 December to 23.45 in June),

-hour angle (H),

H = 0.25[number of minutes before (−) or after (+) noon AST],

-The azimuth angle (α_1): is the angle between the horizontal projection of the sun's rays and the due-south line going in the clockwise direction.

$$\text{Sin}\left(\alpha_1\right) = \frac{\text{Cos}\delta \times \text{Sin}H}{\text{Cos}\beta_1} \quad (16)$$

-Incident angle (θ): angle between sun's rays
and normal to the surface

$$\text{Cos}\theta = \text{Sin}\beta_1\text{Cos}\beta_2 + \text{Cos}\beta_1\text{Sin}\beta_2\text{Cos}\left(\alpha_1 - \alpha_2\right) \quad (17)$$

where:

α_2: the azimuth angle of the surface is the angle between the horizontal projection of the normal to the surface and the due-south line measured in a clockwise direction.

β_2: the tiled angle of the surface is the angle between the surface and the horizontal.

The total solar energy flux (I_{tot}) on a surface of any orientation and tilt with incident angle θ is equal:

$$I_{\text{tot}} = I_{DN}\cos\theta + I_{DN} \quad \left(\text{W/m}^2\right) \quad (18)$$

where:

I_{DN}: The direct solar component, calculated from the following equation

$$I_{DN} = Ae^{-(B/\sin\beta_1)} \quad \left(\text{W/m}^2\right) \quad (19)$$

I_{DS}: The diffuse component of solar irradiation coming from the sky.

A: The apparent solar irradiation at air mass zero.

B: The atmospheric extinction coefficient.

$$I_{DS} = CI_{DN}F \quad \left(\text{W/m}^2\right) \quad (20)$$

where C is the diffuse to direct normal irradiation on a horizontal surface

F is the angle factor between the surface and the sky.

$$F = \frac{1 + \text{Cos}\beta_2}{2} \tag{21}$$

The amount of solar energy flux absorbed by a collector surface E_s during drying period per second

$$E_s = \alpha I_{\text{tot}} x t_d \ \left(\text{kJ/m}^2\right) \tag{22}$$

where α is the collector surface absorptivity, *td* is the drying period in seconds.

Area of the solar collector can be calculated using the following equation:

$$Ac = \frac{E}{E_s}\eta \tag{23}$$

where E is the total useful energy received by the drying air, kJ; E_s is the amount of solar energy flux absorbed by a collector surface, kJ/m^2 and η is the collector efficiency, 30 to 50% (Sodha *et al.*, 1987).

4. Feasibility

The solar collectors system is set to replace the electrical heater as a source of heat for the generator. A comparison between the saving of electrical power and the initial cost of the collectors is done; to determine the payback period of the solar dryer.

The approximate initial cost of the solar collector, as it is calculated above which needs two solar collectors (5 m × 1.9 m). The average price in the market is around 650 JDs. The initial cost (I.C) of two collectors will be 1300 JDs.

To calculate the saving of the solar dryer it is necessary to find the operation cost of solar dryer during the months of July to September.

According to the calculated total useful energy generated by the drying air needed to dry 100 kgs apple slices during 16 hours (2 day period) is 1099.2 kWh/month.

Table 3. Range of electricity cost in Jordan [48].

Price (JD)	Range (kWh)
0.033	1 - 160
0.072	161 - 300
0.086	301 - 500
0.114	501 - 600
0.158	601 - 750
0.188	751 - 1000
0.265	1001 - 9,999,999

From **Table 3** you can calculate the monthly cost of electricity which will approximately be 114.66 JDs (for the experiment period of 3 months it will be 114.66 × 3 = 343.98 JDs) the savings during year (YS).

The payback period (n) of the solar dryer can be calculated using the following equation:

$$I.C.\times(1+i)^n - YS\left[\frac{(1+i)^n-1}{i(1+i)^n}\right]=0 \tag{24}$$

Solving this equation for a low interest rate (i) of about 4% yields

$$1300\times(1.04)^n - YS\left[\frac{(1.04)^n-1}{0.04(1.04)^n}\right]=0 \tag{25}$$

where the payback period found using iterative methods will be around 5 years.

5. Conclusion

The high demand on fossil fuels due to increasing world population and higher standards of living is causing global environmental difficulties due to pollutant emissions as a result of combustion process of such fuels. Therefore, the whole world attention has been focused on renewable energy sources including solar, hydropower, geothermal, and wind energy as alternative energy sources to substitute for fossil fuels in some applications. Jordan enjoys high rates of solar energy, especially during summer season, when fruits are grown and products picked up by farmers. Solar drying represents a simple and low cost method to preserve fruits for off-season. In this paper, a new solar dryer is designed taking into account the local climatic conditions. The designed dryer with a collector area of 18.9 m^2 is expected to dry 100 kg of fresh apple, with moisture content from about 84.9% to less than 10% by wt., within two days under ambient conditions during the harvesting period, *i.e.* July-September. Based on the estimated costs and preliminary economic analysis, it is predicted that the payback period of such system would be around 3 - 4 years depending on the used materials and its prices in construction in the local market. It is deemed that such solar dryer will help poor farmers to secure a sustainable income due to higher selling prices of dried apples.

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