Comparative Study for Two Types of Solar Dryers (Modified-Quonset and Lean-to) for Drying Stevia Plants (*Rebaudiana bertoni*)

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ABSTRACT

The main objectives of this research work were to design, construct, and operate two different active solar dryers (Modified-Quonset and Lean-to structural forms). Thermal performance analysis of the two solar dryers, drying characteristics of thin layer of Stevia plants, and comparing experimentally between them were also tested, examined and evaluated. Moreover, the effect of drying process on the three different physical and chemical components (pigments, primary components, and anti-oxidant) had measured before and after the drying process using the two different solar dryers. The experimental work carried out on the completed plants (comprehended stems, branches, and leaves) from 25st to 28th of September 2016. The obtained results revealed that, the completed Stevia plants dried from the initial moisture content of 73.56% w.b. to 7.55% w.b. within 36 hours with drying rate of 30.03 g/hr using the Modified-Quonset solar drier. While, using Lean-to solar drier, the initial moisture content reduced from 73.56% w.b. into 5.35% w.b. within 12 hour achieving drying rate of 90.9 g/hr. For the duration of the experimental work, the hourly average thermal efficiencies for the Modified-Quonset and Lean-to solar driers, respectively, were 59.57% and 61.91%. The diurnal average solar drying efficiencies for the two solar driers during this research work were 20.45% and 25.51%, respectively. Therefore, the drying efficiency of the Lean-to solar drier was greater than that of the Modified-Quonset solar drier by 24.74%. Results also revealed that, the quality of dried product using Lean-to solar drier is better than Modified-Quonset solar drier. The very important content in the Stevia plants as a glycoside species, is the total sugar, which on an average slightly reduced (23.35%) due to drying process using Lean-to solar driers as compared with the Modified-Quonset solar drier when the total sugar reduced by 29.44%.

INTRODUCTION

Drying process is comprised a heat and mass transfer occurrence where moisture leaves the inside of the product to be dried onto the exterior surface from which it evaporates (mass transfer). Heat energy namely transfers from the hot drying air into the exterior surface of the agricultural product. A part of the heat energy is migrated into the interior of the drying product, which proceeding raising in its temperature and vapour pressure of the agricultural product, and constituting water vapour (heat transfer). The remaining amount of heat energy is functioned in evaporation of the water from the exterior surface of the product. By virtue of this process, the moisture from the inside migrates into the outside surface in order to restore the loss of moisture occurred by evaporation. In Egypt, there is a big gap (0.843 million tons) annually occurs between the total sugar production (1.757 million tons) and the total consumption (2.6 million tons) which causing a great problem (Allam, 2007). Nowadays, great attention is concentrated upon using alternative source of sugar to close up the gap between production and consumption. Stevia plant considered as an important one of sugar crops for producing sweet diterpene glycosides that are mainly contained in its leaves. The Stevia plant has recently introduces to Egyptian agriculture sector in order to produce a natural sweetener that can cover some of the shortage of sugar production. Stevia is a genus of plants belonging to the *Asteraceae* family (sunflower). The plant Stevia (*Rebaudiana, Bertoni*) has widely been planted in different locations of the world as an alternative source of sugar. It can also uses as no caloric sugar substitutes and as natural sources of antioxidants.

Nomenclature

A_c	total surface area of the solar dryer cover, m^2.
A_d	the net surface area of the drying chamber, m^2.
Cp_a	specific heat of air, $J\,kg^{-1}\,°C^{-1}$.
C_{pp}	specific heat of Stevia plant in $J\,kg^{-1}\,°C^{-1}$
h_{fg}	latent heat of water vaporization of Stevia plant, $kJ\,kg^{-1}$
k	drying constant, s^{-1}.
M_a	ash content percentage in Stevia plant, decimal.
m_a	mass flow rate of air, $kg\,s^{-1}$.
M_c	carbohydrate content percentage in Stevia plant, decimal.
M_e	equilibrium moisture content, %.
M_f	fat content percentage in Stevia plant, decimal.
M_i	initial moisture content of Stevia plant, d. b. decimal.
M_m	moisture content of Stevia plant at interval time, w. b. decimal.
M_P	protein content percentage in Stevia plant, decimal.
M_p	mass of Stevia plants inside the solar dryer, kg
M_t	moisture content at any drying time t, %.
M_w	mass of evaporated water over any time period, $kg\,hr^{-1}$
q	solar energy available inside the solar dryer, Watt.
q_{rad}	thermal radiation loss, Watt.
q_{exch}	heat energy loss by forced air exchange, Watt.

q_l	ultimately the thermal energy losses, Watt.
q_u	useful heat energy gain, Watt.
q_{cond}	heat energy loss by conduction and convection, Watt.
q_{ev}	heat energy rate that evaporating moisture from the Stevia plants, Watt.
R	the total solar radiation flux incident on a horizontal plane inside the solar dryer.
T_{ao}	outdoor air temperature, °C.
T_{ai}	indoor air temperature, °C.
T_{bulk}	bulk temperature of Stevia plant, °C.
T_{out}	drying air temperature just leaving the solar dryer, °C.
T_{ao}	outdoor air temperature, °C.
T_{sky}	cold sky temperature, K.
U_o	overall heat transfer coefficient, $W\,m^{-2}\,°C^{-1}$.
V	rate of extracting drying air, $m^3\,s^{-1}$

Greek symbols

ρ	density of drying air, $kg\,m^{-3}$.
ε	emissivity factor of indoor substances.
τ	effective transmittance of cover for long-wave radiation.
σ	constant of Stefan-Boltzmann, $W\,m^{-2}K^{-4}$.
η_o	overall thermal efficiency , %
η_d	daily drying efficiency , %.

Drying considered as one of the most important process for postharvest handling of Stevia plants. In reality, Stevia leaves at harvesting contain moisture content of about 80% w.b. at which it must be reduced to an appropriate level for different processing (grinding and storing). The Stevia leaves with that high level of moisture content must be dried within eight hours after harvesting in order to maintain the high level of sweetness. Different drying modes of Stevia

leaves (microwave oven, electric oven, natural sun drying, and solar dryer) are mainly functioned for drying Stevia leaves. The air drying temperatures ranged between 40 and 43°C or natural sun drying at an ambient air temperature with air relative humidity lower than 60% are recommended by Hatter (2010).

The main goal of this study was to utilize the solar energy as a renewable source of energy for drying Stevia plants during September 2016. The objectives of this research work were included the following: designing and constructing two different forms of solar driers (Modified-Quonset and Lean-to structural frames), determining experimentally the drying characteristics of thin layer of Stevia leaves through studying the drying behaviour using various drying modes and solar driers, and studying the heat energy balance on each solar greenhouse drier with load.

MATERIALS AND METHODS

Materials
Solar dryers Description

Two different solar dryers (Modified-Quonset and lean-to solar dryer forms) had designed and constructed in the Department of Agricultural Engineering. They operated in the site of the station of agricultural experiments and researches (Faculty of Agriculture, University of Mansoura). The latitude and longitude angles of this station, respectively, are 31.043° N and 31.352° E, and 6.72 m mean altitude above the sea level.

Modified-Quonset solar dryer

The gross dimensions of this solar dryer type are: 2.00 m long, 1.00 m wide, 0.70 m high of vertical wall, 0.30 m high of curved end, 1.26 m long of arc, 0.70 m high of eaves, with net surface area of 2.0 m², and net volume of 1.20 m³ as revealed in Figs. (1a, b). The structural frame of this solar drier constituted of firm galvanized water pipes 12.7 mm in diameter. To maintain and increase the durability of structural frame of the solar dryer and prevent the side effects of wind load on the polycarbonate sheet, four tensile compacted plastic wires (2-mm diameter) had tied and fixed throughout the arc and vertical walls. The solar dryer is covered using polycarbonate sheet due to its high effective transmittance (about 0.9). Forced air-fan was used to extract the drying air, it has manufacturing specifications of 0.5-hp electric motor power, speed of 3000 rpm, and current of 220-v.
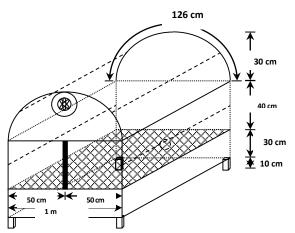

Fig. 1b. Modified-Quonset solar dryer

Solar lean-to greenhouse dryer geometric characteristic

In this study, a new concept had taken into consideration to maximize the greenhouse effect using architectural form of lean-to greenhouse dryer. The solar lean-to dryer having gross dimensions of; 2.00 m long, 1.00 m wide, 0.80 m high of vertical back wall, 0.40 m gable height, 1.05 m rafter length, 2.0 m² net drying surface area, and 1.20 m³ total volume as revealed in Fig. (2a, b). It was oriented with the East-West direction, as a result to this direction, the vertical and inclined sections orienting upward the sun's rays and the northern section orienting into the cold sky and at the same time it functioned as a solar reflector. The solar dryer structural frame also formed of firm water galvanized pipes, 12.7 mm in diameter. The rafter of the solar drier was tilted at 25°from the horizontal plane (optimum tilt angle during the experimental period) to minimize the side effects of wind load that may below over the rafter of solar dryer and to maximize the solar radiation flux incident on the rafter of dryer. To maximize the total solar radiation available inside the solar dryer through the reflected radiation from the northern wall (significant amount of solar radiation) the back surface of drier had covered with sheet of nickel-chrome 2.0 mm thick.

To facilitate and secure the exterior air pass through the solar dryer a circular hole had made in the centre of the western section of air chamber. An electrical forced air-fan was located on the opposite site (the eastern section of the solar drier gable). It has manufacturing specifications as well as that used with the other dryer. It also covered with multi-wall Polycarbonate sheets 6 mm thick. The dividing walls act as supportive structure, which provides a strong structural rigidness and flexibility of the polycarbonate sheet (Polygal, 2011). Moreover, the polycarbonate sheet has excellent thermal properties as mentioned previously. This solar dryer had located beside the Modified-Quonset dryer as shown in Fig.(3).

Instruments and Data Acquisition

During the experimental work, several measurements were executed using different measurement devices. The macroclimatic conditions surrounding the solar dryers had measured and recorded at a height of 3.50 m above the ground level using weather station (Vantage Pro 2, Davis type, USA). The measurements of this station included, solar radiation flux incident on a horizontal plane in W/m², dry-bulb temperatures in degree Celsius, and air relative humidity. The microclimatic conditions of the two solar dryers were precisely measured and recorded by means of two small data-loggers (watch-Dog, USA and

Fig. 1a. Schematic diagram of the modified-Quonset solar dryer

HOBO data-logger). These measurements were implied; the solar radiation available inside the solar dryers, indoor dry-bulb air temperature, indoor air relative humidity, and the bulk temperature of Stevia plants.
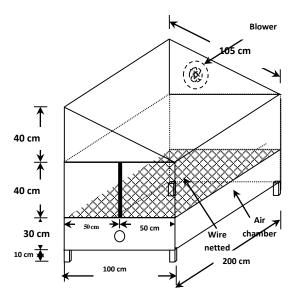

Fig. 2a. Schematic diagram of the lean-to greenhouse solar dryer

Fig. 2b. Lean-to greenhouse solar dryer.

Fig. 3. Modified-Quonset and Lean-to solar dryers used for drying Stevia plants (*Rebaudiana Bertoni*).

Mathematical Modeling

The two different solar driers (Modified-Quonset and Lean-to) had employed under quasi-steady-state circumstances as a perfect stirred solar tank. Under these conditions, the solar dryer thermal performance marked out by the heat energy balance that clarifies the distribution of solar energy flux incident and its conversion into numerous heat energy sources. These heat energies comprises; absorbed solar radiation (q), useful heat energy gain (q_u), rate of heat energy that functioned for evaporating moisture from the Stevia plants (q_{ev}), and ultimately the thermal energy losses (q_l).

Analysis of thermal performance test

The air is an ideal medium that can employees to facilitate movement of moisture from agricultural products during the drying process by using several solar dryers. As a result, the heat energy added and removed from the solar drier by moving the dying air (medium), the temperature drop between transport fluid and drying chamber can minimize to a lower level. The typical system in which solar greenhouse is used as a perfectly stirred tank (air tank), can be declared by the solar air heating system inside the dryer. The heat energy balance on the solar dryer can be determined as follows (Bargach, *et al*., 2000; ASHRAE, 2005; Duffie and Beckman, 2013):

$$q = q_u + q_{ev} + q_l \qquad (1)$$

The solar energy available inside the solar dryer (q) can be measured and computed by means of the total solar radiation flux incident on a horizontal plane inside the dryer in W m^{-2} (measured) and the net surface area of the drying chamber (A_d) in m^2 as:

$$q = R\ A_d, \qquad \text{Watt} \qquad (2)$$

The collected solar energy by the solar dryer (useful heat gained) can be represented by means of the following symbols:

$$q_u = m_a\ C_{pa}\ (T_{ai} - T_{ao}), \qquad \text{Watt} \qquad (3)$$

The heat energy used for evaporating moisture from the Stevia plants can calculate by the following equation:

$$q_{ev} = [h_{fg}\ M_w + M_p\ C_{pp}\ (T_{ai} - T_{bulk})]/3.6, \qquad \text{Watt} \quad (4)$$

The approximated latent heat of water vaporization from Stevia plant can be computed using the following equation (Gallaher, 1951):

$$h_{fg} = 2393.673\ (1 + 23\ e^{-0.40\ M(d.b, \%)}), \quad \text{kJ kg}^{-1} \quad (5)$$

The specific heat of Stevia plant can be determined as follows (Charm, 1971):

$$C_{pp} = 1.4224\ M_c + 1.549\ M_p + 1.675\ M_f + 0.837\ M_a + 4.187\ M_m, \quad \text{kJ kg}^{-1}\ ^{\circ}\text{C}^{-1} \quad (6)$$

The total heat energy lost from the solar dryer into the surrounding environment outside the dryer is mainly pointed out by three different modes of heat transfers which comprise; heat energy loss by conduction and convection, heat energy loss by forced air exchange, and thermal radiation loss. The total heat energy losses can be calculated as:

$$q_l = q_{cond} + q_{exch} + q_{rad}, \text{Watt} \qquad (7)$$

It is not required to individually assess the conductive and convective heat losses from the solar dryers due to the overall heat transfer coefficient represented both modes. The conductive and convective heat losses from the greenhouse solar dryer were computed using the following formula:

$$q_{cond} = A_c\ U_o\ (T_{ai} - T_{ao}), \text{Watt} \qquad (8)$$

The loss of heat energy by forced air exchange (q_{exch}) between the indoor and outdoor of solar dryer was calculated using the following formula:

$$q_{exch} = V\ \rho\ C_{pa}\ (T_{ai} - T_{out}), \text{Watt} \qquad (9)$$

The thermal radiation heat energy loss from indoor substances into the cold sky was estimated using the following relationship:

$$q_{rad} = \varepsilon\ \tau\ \sigma\ A_f\ \left(T_{ai}^4 - T_{sky}^4\right), \qquad \text{Watt} \qquad (10)$$

$$T_{sky} = 0.0552 \, (T_{ao})^{1.5}, \quad \text{K} \quad (11)$$

The thermal performance of the two solar dryer types had substantially specified by the overall thermal efficiency. The overall thermal efficiency (η_o) was precisely preceded by dividing the collected solar energy by the solar dryer and the actual solar energy available inside the dryer.

$$\eta_o = \frac{q_u}{R \times A_d} \times 100, \quad \% \quad (12)$$

The main characteristics, which are used for thermal performance determination of any solar drying system, are the drying rates and the daily drying efficiency. The drying rate should be proportional to the difference in moisture content between the material to be dried (stevia plant) and the equilibrium moisture content. Drying rate may be expressed as the thin layer drying mode as follows (O'callaghan *et al.*, 1971):

$$\frac{dM}{dt} = -k \, (M_t - M_e) \quad (13)$$

Several mathematical models had proposed by many investigators in order to describe the moisture movement in various agricultural products. The process of moisture removal from the drying product may be treated similar to the convective heat loss from the hot bodies. Several investigators have been used the second law of diffusion for modeling plants drying processes considering that the surface resistance to moisture transfer is negligible as compared with the internal resistance.

The daily drying efficiency (η_d) is the ratio of energy required to evaporate the moisture from the stevia plant to the solar radiation available and received over the surface area of the drying tray. The daily average drying efficiency can be computed as follows:

$$\eta_d = \frac{Q_{ev}}{R \, A_d} \times 100, \% \quad (14)$$

RESULTS AND DISCUSSION

Because of, this natural renewable energy source of heat energy continuously changed from hour to hour and day to another depending upon the sky cover, time of the day, and the change in macroclimatic conditions, it is so difficult to control. During the experimental work, the solar driers had operated satisfactorily for about four days without malfunction. The data of outdoor and indoor solar radiations, which measured on a horizontal surface, were functioned to determine mathematically the thermal performance characteristics of solar driers and the drying process of Stevia plants. The thermal performance of solar driers comprehends heating power produced by each drier during each hour of operation, effective transmittance of drier cover, and overall thermal efficiency. The outdoor and indoor current total solar radiation monitored and measured on a horizontal surface varied from hour to hour and day to another during this experiment because of, the effect of atmospheric conditions (clearness index, water vapour, and dust) and transmission of the drier cover (polycarbonate) as listed in Table (1). Thus, the indoor monitored and measured solar radiation was always lower than that the outdoor of the dryer. The outdoor total solar radiation during the experiment ranged between 55.3 and 810.0 W m^{-2}, whilst the indoor solar radiation for Modified-Quonset and Lean-to solar dryers ranged between 18.1 and 561.3 W m^{-2} and

ranged between 35.5 and 484.1 W m^{-2}, respectively. The hourly total solar radiation incident outside the Modified-Quonset solar dryer was 548.6 W m^{-2} ($\pm$ 23.3 W m^{-2}), while that value inside the dryer was 323.2 W m^{-2}. As a result, the hourly average effective transmittance of that solar dryer cover (polycarbonate) was 0.5891.

Table 1. Hourly average solar radiation monitored and measure outside (R_o), inside the Modified-Quonset and Lean-to solar driers (R_i), and reflected from the vertical back wall (R_r), and the maximum and minimum values
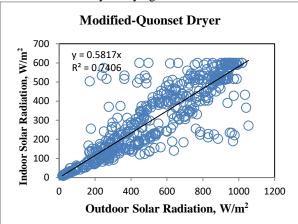
Day		Modified-Quonset Solar drier		Lean-to solar drier	
		R_o (W m^{-2})	R_i (W m^{-2})	R_i (W m^{-2})	R_r (W m^{-2})
25/09 /2016	Max.	810.0	442.0	484.1	240.6
	Min.	57.3	18.1	35.5	7.5
	Mean	477.4	279.3	361.9	95.7
	SD	± 183.1	± 72.5	± 113.5	± 41.0
26/09 /2016	Max.	760.0	441.7	483.0	139.7
	Min.	94.0	23.1	58.3	27.0
	Mean	489.6	285.8	371.1	98.2
	SD	± 168.9	± 108.2	± 104.7	± 36.2
27/09 /2016	Max.	748.0	521.2	-	-
	Min.	83.3	23.1	-	-
	Mean	598.8	353.8	-	-
	SD	± 196.8	± 90.8	-	-
28/09 /2016	Max.	658.0	561.3	-	-
	Min.	55.3	18.3	-	-
	Mean	628.7	374.1	-	-
	SD	± 210.4	± 113.4	-	-

The hourly average total solar radiation incident outside the Lean-to solar dryer was 483.5 W m^{-2} ($\pm$ 8.77 W m^{-2}), while that value inside the solar drier was 366.5 W m^{-2} ($\pm$ 17.25 W m^{-2}). Consequently, the hourly average transmission of solar dryer cover (polycarbonate) was 0.7580. The Lean-to structural form covered with polycarbonate sheet transmitted solar radiation greater than the Modified-Quonset structural form, covered with the same material by 29.71%. To precisely indicating the effect of solar drier cover and the atmospheric conditions on the indoor solar radiation, the actual indoor solar radiation had plotted against the outdoor solar radiation (Fig. 4). Regression analysis showed a highly significant linear relationship between these factors. The regression formula that correlated this for the best fit was:

$$R_{i(Modified-Quonset)} = 0.5817 \, (R_o) \quad R^2 = 0.7406 \, (15)$$
$$R_{i(Lean-to)} = 0.7580 \, (R_o) \quad R^2 = 0.8656 \, (16)$$

A joined data of solar radiation into regression analysis gave a correlation coefficient of 0.8606 and 0.9304, respectively, between the indoor and outdoor solar radiation for Modified-Quonset and Lean-to solar dryers. The slope of linear formula is almost equal to the transmission of the solar drier cover. Because of, variations in the relative proportions of direct, diffuse, and ground-reflected components of the outdoor solar radiation, there were some scattering in the outdoor data as be expected, due to the atmospheric circumstances. Because of, the greenhouse effect phenomenon which continuously occurring inside the solar drier during the daylight-time, there were much heat energy accumulated during the daylight (from sunrise to sunset).

The main goal of forced and accelerated air-drying during the drying process is to transfer great part of that heat into the material being drying (Stevia plants). As a

result, the existing moisture of the drying material continuously removed and expelled out the solar dryer in a formality of water vapour. Another significant part of heat energy is from the absorption process of direct solar radiation by the drying material (Stevia plants) according to the exposed surface area, duration of drying operation, and colour of drying material. The capability of drying air to remove and expel water vapour is dependent upon the solar drier competent to raise the temperature of drying-air over the outdoor air temperature and as a result decrease the relative humidity of drying-air.
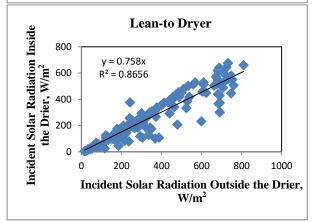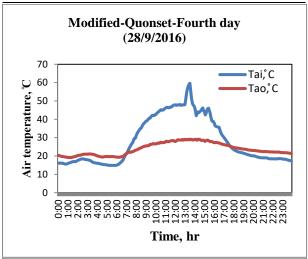

Fig. 4. Incident solar radiation inside the Modified-Quonset and Lean-to solar dryers against incident solar radiation outside the drier during the experiment

The hourly average outside air temperature, drying air temperatures inside the two solar dryers and the bulk temperature of Stevia plants during this experiment listed in Table (2). The hourly average air temperature outside the solar dryers through four days was 26.5°C, whilst, the air temperature inside the Modified-Quonset solar dryer was 38.4°C. Consequently, the solar dryer raised the drying air temperature over the outside by 11.9°C. The hourly average air temperature outside the Lean-to solar dryer through two days was 26.6°C, while, that value inside the dryer was 42.6°C. As a result, this type of solar dryer increased the drying air temperature above the outside by 16°C.

It also observed that, the bulk temperature of Stevia plants during this experiment was always lower than the drying-air temperature as listed in Table (2). The hourly average bulk temperatures of Stevia plants during this experiment inside the two solar dryers (Modified-Quonset

and Lean-to), respectively, were 31.1 and 36.2°C. Typical distributions of the air-temperatures, which monitored and measured inside and outside the two solar dryers through the fourth and the second days, are plotted in Fig. (5).

Table 2. Hourly average outside (T_{ao}) and inside (T_{ai}) air-temperatures of Stevia leaves comprising the maximum (Max.) and minimum (Min.) values each day for the two solar driers (Modified-Quonset and Lean-to)

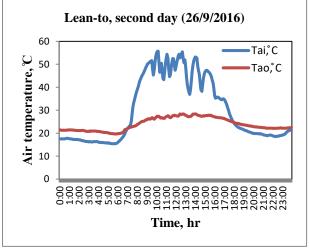| Day		Modified-Quonset Solar drier			Lean-to solar drier	
		T_{ao}, °C	T_{ai}, °C	T_{bulk}, °C	T_{ai}, °C	T_{bulk}, °C
25/09 /2016	Max.	28.6	45.0	36.7	52.6	42.2
	Min.	23.5	20.6	16.8	21.4	23.5
	Mean	26.9	36.5	29.8	42.3	35.9
	SD	± 1.5	± 7.4	± 6.0	± 9.4	± 6.5
26/09 /2016	Max.	28.0	45.3	36.9	51.2	43.0
	Min.	21.8	20.0	16.3	21.5	21.8
	Mean	26.3	36.7	29.9	42.9	36.5
	SD	± 1.9	± 7.5	± 6.1	± 9.1	± 6.9
27/09 /2016	Max.	28.0	49.1	40.0	-	-
	Min.	21.2	19.0	15.5	-	-
	Mean	26.1	39.5	32.2	-	-
	SD	± 2.1	± 9.0	± 7.3	-	-
28/09 /2016	Max.	28.9	51.1	41.6	-	-
	Min.	21.0	21.0	17.1	-	-
	Mean	26.6	40.9	32.5	-	-
	SD	± 2.5	± 9.2	± 7.5	-	-

Fig. 5. Distributions of the air-temperatures inside the two solar dryers through the fourth and the second days

The hourly average air-relative humidity inside the solar drier during the four consecutive days was 32.7%, whilst, the hourly average air-relative humidity outside the solar drier during the same period was 56.8% as listed in Table (3). Therefore, the Modified-Quonset solar drier diminished the hourly average drying air-relative humidity lower the outside air-relative humidity during the experiment by 24.1% . The hourly average air-relative humidity inside the solar drier during the two consecutive days was 28.7%, whilst, the hourly average air-relative humidity outside the Lean-to solar dryer during the same period was 55.9%. Therefore, the Lean-to solar drier reduced the hourly average drying air-relative-humidity lower the outside air-relative humidity by 27.2%.
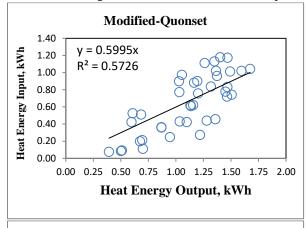
Table 3. Hourly average air-relative humidity outside (RH$_o$), inside (RH$_i$), maximum (Max.), and minimum (Min.) under the Modified-Quonset solar drier

Day		Modified-Quonset Solar drier		Lean-to solar drier
		RH$_o$ (%)	RH$_i$ (%)	RH$_i$ (%)
25/09/2016	Max.	83.9	85.6	73.9
	Min.	45.8	18.6	16.7
	Mean	53.8	34.7	29.7
	SD	± 5.65	± 19.56	± 19.96
26/09/2016	Max.	79.9	82.2	61.9
	Min.	51.3	19.6	14.1
	Mean	57.9	36.8	27.6
	SD	± 10.79	± 23.08	± 18.00
27/09/2016	Max.	75.8	75.4	
	Min.	46.5	16.0	
	Mean	55.4	28.6	
	SD	± 8.18	± 17.64	
28/09/2016	Max.	80.9	72.8	
	Min.	50.7	16.6	
	Mean	60.2	30.8	
	SD	± 9.54	± 17.02	

The hourly average solar energy available inside the Modified-Quonset drier during this experiment for the four successive days was 646.3 Watt , whilst, this value inside the Lean-to solar dryer during the two consecutive days was 926.9 watt. As the incident solar radiation inside the solar dryer is increased, the solar energy available increased. The hourly average useful heat energy acquired by the Modified-Quonset solar dryer during the same period was 386.9 Watt, while, the value of heat energy gained by the Lean-to solar dryer during the two following days was 574.0 Watt. Consequently, the Lean-to structure form solar drier increased the useful heat gain by 76.93% as compared with the Modified-Quonset structure form. The hourly average thermal efficiency for the two solar dryers was 59.57% and 61.91%, respectively. To determine and test the best model, which may be functioned to correlate between the hourly average input heat energy (q) and the hourly average output heat energy (q$_{out}$) for the two solar dryers, all the data were functioned in regression analysis (Fig. 6). Regression analysis revealed a highly significant linear relationship with (r = 0.7567 and r = 0.8924; P = 0.001). The regression equations for the best fit were:

$$q_{(Modified-Quonset)} = 0.5995 \, (q_{out}) \quad R^2 = 0.5726 \quad (17)$$

$$q_{(Lean-to)} = 0.6660 \, (q_{out}) \quad R^2 = 0.7963 \quad (18)$$

The regression formulas also clarified that, the total heat energy utilized in the Modified-Quonset solar dryer had 59.95% of the total input heat energy (incident solar radiation). Whilst, the total heat energy utilized in the Lean-to is 66.60% of the total input heat energy (incident solar radiation) and 40.05% of the total input solar radiation was lost from the Modified-Quonset solar dryer, while only 33.40% of the total input solar radiation was lost from the Lean-to solar dryer. It was observe that, the daily average solar drying efficiency for the Modified-Quonset solar dryer gradually decreased within the four successive days of drying operation. It reduced from the highest value 43.86% on the first day until reached the lowest value 10.96% at the last day. While, the daily average solar drying efficiency for the Lean-to solar dryer reduce from the highest value 44.65% on the first day until reached the lowest value 6.45% at the last day. They happened because of, the diminishing in moisture content of the Stevia plants.
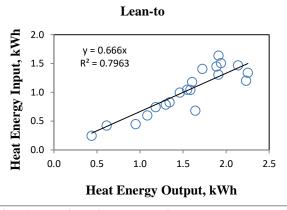

Fig. 6. Relationship between input and output heat energy under the Modified-Quonset and Lean-to solar dryers during the experiment

The initial moisture content, final moisture content, drying rate, duration of drying process of Stevia plants for the two solar dryers (Modified-Quonset and Lean-to) during the experiment briefed and listed in Table (4). The drying rate, which achieved during this experiment for the two solar dryers, respectively, was 30.03 and 90.9 g/hr. The obtained results evidently clarified that, the duration of this experiment must be carried out within three days because of, the rate moisture content had reached into the recommended level, which ranged between 8 and 12% w.b. (Muller and Heindl, 2006) and between 3 and 5% w.b. (Samsudin and Aziz, 2013).

Table 4. Initial and final moisture contents in wet-basis, drying rate in g/hr., and drying period in hour under the Modified-Quonset and Lean-to drier during the experiment

	Modified-Quonset	Lean-to
Initial moisture content, %w.b.	73.56	73.56
Final moisture content, % w.b.	7.55	5.35
Drying rate, g/hr	30.03	90.9
Drying period, day	4	2
Drying period, h	36	12

Quality of Stevia Dried

The effect of drying process using two different solar dryers (Modified-Quonset and Lean-to solar driers) for drying Stevia plants on the total chlorophyll and carotene shown in Fig. (7). The average total chlorophyll in the fresh leaves of Stevia plant was 122.7 mg/100g, which reduced into 87.0 and 95.7 mg/100g using the Modified-Quonset and Lean-to solar driers, respectively. Consequently, the drying process reduced the total chlorophyll by 29.10% and 22.00%, respectively, while, the two different solar dryers increased the carotene content from 59.8 mg/100g to 67.8 and 69.5 mg/100g, respectively. As a result, the different drying methods increased the carotene content by 13.38% and 16.22%, respectively.

The effect of drying process on the primary components (total sugar, protein, fat, total carbohydrates fiber, and ash) using the two different dryers are shown in Fig. (8). The average total sugar in the fresh leaves of Stevia plant was 1.97 g/100g, which reduced into 1.39 and 1.51 g/100g using the two solar dryers, respectively. Consequently, the drying process reduced the total sugar by 29.44% and 23.35%, respectively. The two different dryers decreased the protein content from 14.98 g/100g into 12.76 and 13.41 mg/100g, respectively. As a result, the different drying methods diminished the protein content by 14.82% and 10.48%, respectively. The fat content increased from

2.03 g/100g to 3.18 and 3.87 g/100g, respectively. Consequently, the drying process increased the protein content by 56.65% and 90.64%, respectively. The total carbohydrates content in the fresh leaves reduced due to drying process from 67.12 g/100g to 54.01 and 54.33 g/100g drying weight, respectively. As a result, the drying process induced in reduction percentage of 19.53% and 19.06%, respectively. The fiber content in the fresh weight was 11.64 g/100g, which increased after drying process into 13.62 and 14.09 g/100g, respectively. Consequently, the fiber content increased due to drying process by 17.01% and 21.05%, respectively. The ash content in the fresh weight (prior to drying) also increased due to drying operation from 8.54 g/100g into 9.53 and 9.81 g/100g, respectively. As a result, the drying process resulting in increasing the ash content by 11.59% and 14.87%, respectively.
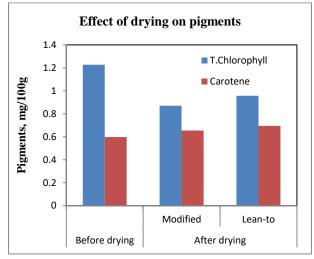

Fig. 7. Total chlorophyll and carotene contents before and after the drying process for the two different solar dryers
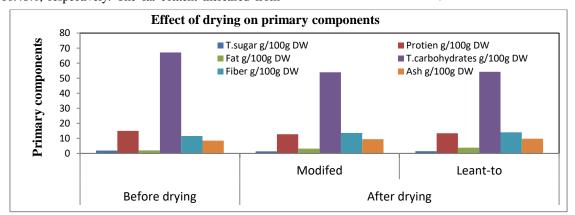

Fig. 8. Total sugar, protein, fat, total and carbohydrates, fiber, and ash contents before and after the drying process for the two different solar dryers

Ultimately, the influence of drying process on the anti-oxidant includes; the total phenol, flavonoid, and ascorbic acid in mg/g using the two different solar dryers (Modified-Quonset and Lean-to solar driers) are revealed in Fig. (9). The two different dryers increased the phenol content from 5.78 mg/g to 6.47 and 6.69 mg/g, respectively. Consequently, the drying process increased the phenol content by 11.94% and 15.74%, respectively. The flavonoid content as an anti-oxidant component in the fresh weight was 0.90 g/mg, which also increased after drying process

into 1.22 and 1.31 g/mg, respectively. As a result, the flavonoid content due to drying process increased by 35.56% and 45.56%, respectively. However, the ascorbic acid (Vitamin C) had reduced from 35.12 mg/100g to 19.95 and 23.66 mg/100g, respectively after achieved the drying process. Consequently, the drying process led to decrease the ascorbic acid by 43.19% and 32.63%, respectively.

Therefore, the obtained results revealed that, the drying process using Lean-to solar dryer is better than the Modified-Quonset solar drier for drying Stevia plants.

Because of, the very important content in the Stevia plants as a glycoside species, is the total sugar, which on an average slightly reduced (23.35%) due to drying process using Lean-to solar driers as compared with the other solar dryer when the total sugar reduced by 29.44%. Furthermore, another important component in the Stevia plants is the anti-oxidant contents particularly when the dried product is used as natural drugs.
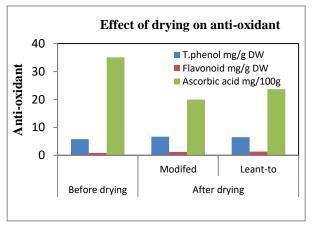

Fig. 9. Total phenol, flavonoid, ascorbic acid (Vitamin C) before and after the drying process for the two different methods of drying

CONCLUSION

This study uses two different architectural forms of solar dryers for drying Stevia plants. In the two solar dryers, the drying process is uniform and the Stevia plants dried in swirl flow media, which achieved higher air-drying temperature and lower air relative humidity. As a result, they accomplished lower moisture content in shorter time. The experiment had carried out during September 2016 at constant mass flow rate of 0.03223 kg/s. Drying proceeded successfully under the two different solar dryers where they achieved thermal efficiency of 59.57% and 61.91% and drying efficiency of 20.45% and 25.55%, respectively. The drying rate, which achieved during this experiment for the two solar dryers, respectively, was 30.03 and 90.9 g/hr. Finally, moisture contents were within acceptable limits for safe storage and processing of the dried Stevia plants.

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دراسة مقارنة لنوعين من المجففات (Modified-Quonset and Lean-to) أثناء تجفيف نباتات الاستيفيا
صلاح مصطفى عبد اللطيف ، ياسر مختار الحديدى ، غاده على مسعد و ضحى اسامه السيد
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يهدف هذا البحث إلى تصميم وتركيب وتشغيل نوعين مختلفين من المجففات الشمسية الفعالة (Modified-Quonset and Lean-to) . تم إجراء تحليل للأداء الحرارى للمجففين الشمسيين وخصائص التجفيف لطبقة رقيقة من نباتات الاستيفيا داخلها ثم مقارنتهما عملياً واختبارهم وتقييمهما. كما أنه تم قياس المكونات الفيزيائية والكيميائية الثلاثة المختلفة (الصبغات، المكونات الأولية ومضادات الأكسدة) قبل وبعد عملية التجفيف فى المجففين الشمسيين. تم استخدام نبات الاستيفيا الكامل شاملا الساق والفروع والأوراق أثناء العمل التجريبى باستخدام نوعين مختلفين من المجففات الشمسية. أجريت التجربة العملية لتجفيف نبات الاستيفيا الكامل باستخدام نوعين مختلفين من المجففات الشمسية الفعالة فى الفترة من 25 إلى 28 سبتمبر 2016. أظهرت النتائج التى تم الحصول عليها أن نباتات الاستيفيا الكاملة تم تجفيفها باستخدام المجفف الشمسى (Modified-Quonset) من نسبة رطوبة 73.56 على أساس رطب وصلت إلى 7.55 % على أساس رطب خلال 36 ساعة بمعدل تجفيف 30.03 جم/ساعة. في حين أنه باستخدام المجفف الشمسى (Lean-to) انخفضت النسبة من 73.56 % على أساس رطب إلى 5.35 % على أساس رطب خلال 12 ساعة بمعدل تجفيف يصل إلى 90.9 جم/ساعة. خلال فترة التجربة العملية كان متوسط الكفاءة الحرارية لكل ساعة للمجفف الشمسى من النوع Modified-Quonset 59.57 % وللمجفف الشمسى من النوع Lean-to 61.91 % ونتيجة لذلك كان متوسط الكفاءة الحرارية للمجفف Lean-to أعلى من المجفف Modified-Quonset بنسبة 3.93 %. كان متوسط كفاءة التجفيف الشمسى اليومية للمجفف Modified-Quonset 20.45 % وللمجفف Lean-to 25.51 % لذلك كانت كفاءة التجفيف للمجفف الشمسى Lean-to أعلى من المجفف الشمسى Modified-Quonset بنسبة 24.74 %. أظهرت النتائج التى تم الحصول عليها أن المجفف الشمسى من النوع Lean-to أفضل من المجفف الشمسى Modified-Quonset فى عملية تجفيف نبات الاستيفيا، حيث أن أهم محتوى لنبات الاستيفيا كنوع من الجليكوسيدات هو السكر والذي كان انخفاضه قليلا باستخدام المجفف Lean-to مقارنة بنسبة انخفاضه باستخدام المجفف Modified-Quonset حيث كانت نسبة الانخفاض فى Lean-to 23.35 % وفى Modified-Quonset كانت نسبة الانخفاض 29.44%.