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EVALUATION OF DIFFERENT SOLAR DRYERS AND ITS APPLICATIONS IN JEW'S MALLOW DRYING

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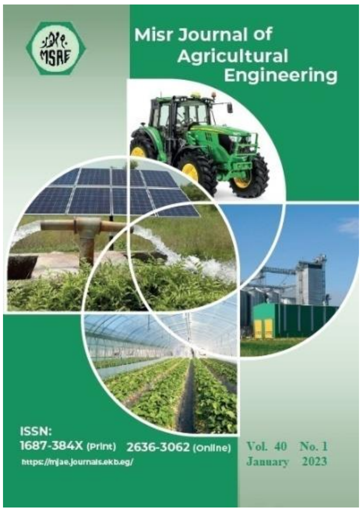


Keywords:
Solar dryer; Greenhouse dryer; Thermal efficiency; Jew's mallow; Drying rate.

ABSTRACT

The shortages in conventional fuels along with the continuous rise in their prices have led to an increased emphasis on using solar energy as an alternative source of energy. Thereto, the objective of this study was to evaluate the thermal efficiency of three different types of greenhouse solar dryers and test their performance in Corchorus olitarius drying. Three different greenhouses namely Quonset, Gable-even span and Gothic arch were constructed and tested without load under different air flow rates (0.38, 0.57 and 0.855 kg s^{-1}). The appropriate air flow rate which gives higher thermal efficiency was then applied to investigate the performance of the constructed dryers for drying the fresh Jew's mallow. The results indicated that the thermal efficiency of the dryers increased when the air flow rate decreased. The Quonset dryer reported a higher value of thermal efficiency of 58.48% under the lower air flow rate of 0.38 kg s^{-1}. Consequently, the Quonset dryer showed higher moisture removal of the Jew's mallow during drying. After 16 hours of drying, the moisture content of Jew's mallow decreased from initial moisture of 13.29 (kg water/kg dry matter) to less than 0.5 (kg water/kg dry matter). Meanwhile, the moisture content of the Jew's mallow samples in ambient air was still higher than 1.2 (kg water/kg dry matter) after the same drying time. These results emphasize the importance of using solar dryers, especially the Quonset greenhouse dryer, for the fast and safe drying process of agricultural products.

1. INTRODUCTION

Jew's mallow (*Corchorus olitarius L.*) (Arabic *Mulukhiyah*) is an important vegetable crop in Egypt. Fresh or dried leaves of Jew's mallow have a wide use and are great demand for national and international markets **(Youssef *et al.*, 2014)**. Fresh leaves and tender shoots are essential parts (**Phuwapraisirisan *et al.*, 2009**). The leaves are nutritious, rich in beta-carotene, chlorophylls, minerals, phenolics, protein, vitamins, folate, fatty acids and dietary fiber. The health benefits have been reported in antitumor promotion (**Furumoto *et al.*, 2002**), antioxidant properties, antibacterial activity (**Zakaria *et al.*, 2006**), managing diabetes and hypertension (**Oboh *et al.*, 2012**). Jew's mallow is perishable and drying is necessary and commonly used to preserve it (**Famurewa and Akinmuyisitan, 2014**). However, the literature is scarce on the drying kinetics of Jew's mallow, especially in greenhouse solar dryers and more studies are required in this field.

Solar energy is considered to be an important alternative source of the conventional energy and it is relatively preferred to other sources because it is free, abundant, inexhaustible and non-pollutant in nature compared with higher prices and shortage of fossil fuels **(Basunia and Abe, 2001; Santos et al., 2005**). The conventional sun drying technique for agricultural products is still used by farmers in most developing countries such as Egypt **(Kishk *et al.*, 2018; 2019)**. However, the contamination with foreign particles and insects are some problems associated with this method **(Sallam *et al.*, 2015**; **Sreekumar *et al.*, 2008**). Besides being time and labor-intensive method, uncontrolled sun drying is usually accompanied with flavor and color changes, nutritional degradation and reduction of functionality (**Rabha *et al.*, 2017**). To overcome previous problems, solar drying method could be used to dry agriculture products instead of traditional sun drying method as the drying process takes place in enclosed structures (**El-Sebaii *et al.*, 2002**). Solar drying as a mean of food preservation has been considered one of the most promising venues for utilization of solar energy (**Sekyere *et al.*, 2016**). The use of solar dryers significantly reduces drying time and prevents mass losses as well as product quality can be improved compared to traditional sun drying methods **(ElGamal *et al.*, 2013; 2021)**. Utilization of solar energy as a reliable energy source to dry foods in Egypt has a great potential, as, the annual daily average solar radiation on a horizontal plane in Egypt is 8 $kWm^{-2}day^{-1}$ and the measured annual average daily sunshine duration is approximately 11 h **(El-Beltagy *et al.*, 2007)**.

There are two main types of solar drying namely direct and indirect solar drying. In the direct solar drying, the drying process can be performed directly using greenhouse dryers in which the air temperature increased inside the greenhouse and dried the product. In the indirect solar drying, the air heated using solar air heaters then the heated air transferred to a cabinet contains the product to be dried. The greenhouse dryer minimizes the shortcomings of the cabinet dryer such as capacity of full load operation, expenditure, and moisture condensation under the glass surface **(Kumar *et al.*, 2014)**. Studying the possibility of using the greenhouse as a solar dryer for some agricultural crops under Egyptian climatic conditions has been investigated by many investigators **(Radwan, 2002; Abu-Habaga *et al.*, 2010; Abdellatif *et al.*, 2010; Kishk *et al.*, 2018)**. **Radwan (2002)** evaluated a greenhouse solar dryer for drying fresh grapes compared with natural sun drying. The results showed that, the greenhouse dryer was able to dry grape samples in 36 hours compared with 54 hours for the open sun drying method. Quality evaluation tests of the dried product showed that Vitamin C content was the only chemical component that significantly decreased, the reduction rate was higher for open sun drying compared with solar drying. On the other hand, an improvement in rehydration ratio and raisins color was observed for solar drying compared with open sun drying. **Jain and Tiwari (2004)** determined the convective mass transfer coefficient and rate of moisture removal from cabbage and peas under open sun and greenhouse drying. The convective mass transfer coefficient was found to be lower for greenhouse drying under natural convection mode as compared to open sun drying. Meanwhile, its value was doubled under the forced mode of greenhouse drying compared to the natural convection mode in the initial stage of drying. **Koyuncu (2006)** constructed two different types of natural-circulation greenhouse dryers and tested for their performance. The dryers were experimented without product and with pepper crops. The dryers were also tested with chimney constructed from a galvanized iron sheet and without chimney in order to determine the effect of the chimney on the air flows. The results of the study showed that the greenhouse dryers increased the ambient air temperature by 5-9 °C, and these dryers were 2 - 5 times more efficient than open sun dryer. The dryers with a drying air outlet chimney gives better value of air mass flow by increasing the air velocity.

Abdellatif *et al.* (2010) analyzed the thermal performance of Quonset greenhouse solar dryer for drying seedless grapes. Three identical units of Quonset greenhouse solar dryers were operated under three different mass flow rates of 0.122, 0.183, and 0.259 kg s^{-1}. The inside air temperature increased with decreasing the air flow rate. The solar dyers increased the inside air temperatures above the outside (31.6 °C) by 21.9, 12.5, and 9.4°C, at the flow rates of 0.122, 0.183, and 0.259 kg s^{-1}, respectively. The daily average overall thermal efficiency of the solar greenhouse dryer ranged from 53.19% to 61.24% under the tested air flow rates. Recently, **Kishk *et al.* (2018)** evaluated the performance of greenhouse solar dryer in drying mint plant under different operating modes. Two of the forced convection operating modes (continuous and intervals) were used and compared with the open sun drying method. The continuous forced convection mode gives the highest drying rate for mint than the interval mode and open sun drying. The drying data of solar and open sun drying of mint were fitted to ten thin layer drying models and the Modified Henderson and Pabis model satisfactorily described the drying behavior of mint with highest R^2 (0.99) and lowest mean relative error values than other models. Previous study can be found which carried out by **Radwan *et al.* (2016)** they evaluated and analyzed the thermal performance of three different geometrical shapes of greenhouse solar dryers which can be used for date drying. The tested shapes of greenhouse dryers were gable-even-span, Quonset and pyramid shape. However, the literature is scarce on the drying kinetics of Jew's mallow, especially in greenhouse solar dryers. Accordingly, the main goal of the present study was to test and evaluate the thermal performance of different greenhouse solar dryers under different air flow rates. In addition, to test its performance in drying Jew's mallow compared with the open sun drying.

2. MATERIALS AND METHODS

To achieve the objectives of this study, three different greenhouses namely Quonset, Gable-even span and Gothic arch were constructed and tested without load under different air flow rates (0.38, 0.57 and 0.855 kg s^{-1}). The appropriate air flow rate which gives higher thermal efficiency was then applied to evaluate the performance of the three dryers for drying the fresh Jew's mallow.

Greenhouses Construction

Three greenhouse dryers with different shapes namely Quonset, Gable-even span and Gothic arch were designed and constructed at the workshop of the Agricultural Engineering Department, Suez Canal University, Ismailia, Egypt. Each greenhouse dryer was established on an iron frame with base dimensions of 2.0×1.0 m and 0.95 m high with surface area 2 m^2 as shown in **Fig. (1)**. The rafters of the gable-even-span were inclined at 30° to maximize the solar radiation available inside the dryer. A drying chamber from a galvanized iron sheet with base dimension of 2×1 m and 0.25 m high was established for each dryer. A wire netting is fixed in the drying chamber at 0.15 m over the bottom of the dryer forming a plenum chamber under the wire netted floor. A door of 0.75×0.45 m was located at the front side of each dryer for loading, unloading and collecting product samples during the drying process as shown in **Fig. (1)**. The solar dryers were covered by a single layer of polyethylene sheet of 50 µm thick and effective transmittance of 91 %. To maintain the durability of the structural frame of plastic greenhouses and prevent pad side effects of wind load on the polyethylene cover, ten tensile compacted plastic wires (2 mm diameter) were tied and fixed throughout the walls. Each solar dryer was equipped with a centrifugal suction fan model (SMB-10, USA) with a power of 0.75 hp electric motor and equipped with an inverter to control the fan air flow rate. A rectangular window 0.35×0.15 m is located at the top of the opposite side of the suction fan for air intake through each dryer. This design allows the drying air to be cycled through the solar dryer and heated by solar energy. The drying air was continuously introduced from the top window of the solar dryer and left through the bottom under the drying chamber via the suction fan as shown in **Fig (1)**.

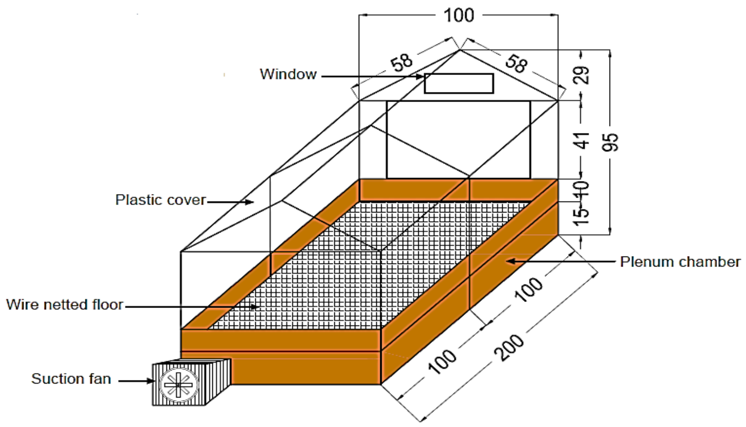


Fig. (1): Schematic diagram of the greenhouse solar dryer (Gable-even-span shape)

Experimental Setup

The constructed greenhouses were installed on the Agricultural Engineering Department building roof at Suez Canal University (latitude of 30.62^o, longitude 32.27^o and 5m above sea level). To maximize the intensity of the solar radiation, the three dryers were orientated in the East-West direction.

Fig (2): General view of the constructed greenhouse dryers

Thermal Performance of the Constructed Dryers

The solar dryers were operated under quasi steady-state conditions as an air-heating solar collector. The heat energy balance for the three studied solar dryers without load could be computed as follows:

$$Q_T = Q_U + Q_{Loss} \quad (1)$$

where, Q_T is the total solar heat energy available for the dryer (W), Q_U is the useful heat gain by the dryer (W) and Q_{Loss} is the total heat losses from the solar dryer (W).

The useful heat gain by the dryer (Q_U) could be expressed as:

$$Q_U = M_a C_p (T_{ai} - T_{amb}) \quad (2)$$

where, M_a is the mass air flow rate (kg s^{-1}), C_p is the heat capacity of the air (J kg^{-1} K^{-1}), T_{ai} and T_{amb} are the temperatures inside and outside the dryer (K), respectively.

The total heat losses from the solar dryer (Q_{Loss}) to the outside by conduction and convection, air exchange, and thermal radiation could be computed from the following formula:

$$Q_{Loss} = q_c + q_e + q_r \quad (3)$$

where, q_c, q_e and q_r are the heat losses from the solar dryer by conduction and convection, forced air exchange, and by thermal radiation (W), respectively, and can be computed as follows:

$$q_c = U_O A_c (T_{ai} - T_{amb}) \quad (4)$$

$$q_e = M_a C_p (T_{ai} - T_{aex}) \quad (5)$$

$$q_r = \varepsilon\, \tau\, \sigma A_d (T_{ai}^4 - T_{sky}^4) \quad (6)$$

$$\text{with,} \quad T_{sky} = 0.0552 (T_{amb})^{1.5} \quad (7)$$

where, U_o is the overall heat transfer coefficient (W m^{-2} K^{-1}), A_c is the total surface area of the solar dryer plastic cover (m^2), A_d is the floor surface area of the solar dryer (m^2), T_{aex} is the temperature of the air leaving the dryer (K), ε is the mean emittance factor of the inside substances τ is the average transmissivity coefficient at long-wave radiation, σ is the Stefen-Boltzmann constant (W m^{-2} K^{-4}) and T_{sky} is temperature of the sky (K).

Finally, the overall thermal efficiency (η_o) is defined as the ratio of useful heat gain over any period to the total solar energy available over the same period:

$$\eta_0 = \frac{Q_U}{Q_T} * 100,\ \% \quad (8)$$

All dryers were tested before the drying experiments to determine their thermal performance without load. To select the appropriate air flow rate, the dryers were operated for three days under different air flow rates of 0.38, 0.57 and 0.855 (kg s^{-1}), and each day the three dryers operated under one of the selected air flow rates. The air flow adjusted by controlling the blower speed from its control panel. The dryers operated for 9 hours each day from 8 AM to 5

PM and the temperature was recorded to solve the above equations. The appropriate air flow rate gives higher thermal efficiency was then applied to evaluate the performance of the three dryers for drying the fresh Jew's mallow leaves.

Drying Experiment

Fresh Jew's mallow (*Corchorus olitorius* L.) plant was purchased from the local market in Ismailia, Egypt. Green leaves were separated from the plant, washed with tap water and then drained and left to dry on a cheesecloth for 15 min at room temperature (31 ± 2°C). The moisture content of the fresh Jew's mallow leaves was immediately determined according to the **AOAC (2000)** method (number 934.01). The average initial moisture content of fresh Jew's mallow leaves was found to be 87% w.b (13.29 kg water/kg dry matter). Before the experiment, eight trays with a dimension of 0.5×0.5 m were loaded with the Jew's mallow samples. Each tray was loaded by about 800 g of fresh Jew's mallow with a distribution density of about 3.2 kg m^{-2}. The trays were placed in the middle position of each greenhouse dryer (two trays for each dryer). Then, the remained area of the greenhouse dryers was loaded with Jew’s mallow samples distributed uniformly over the surface of the perforated wire net of each dryer. The density of Jew’s mallow samples was adapted to be the same as on the trays (3.2 kg m^{-2}). For the traditional sun drying method, two trays with Jew's mallow samples were placed under the open sun. The trays were used to easily record the weight losses of samples during drying. During the experimental work, an electrical digital balance (BS-Series, China) with an accuracy of 0.001 g was used to determine the weight losses of samples during drying. The weight of the samples was recorded before conducting the drying test and each hour during the drying process. Each hour, the two trays were taken out each greenhouse dryer for weigh using the electrical digital balance and then returned to the same place inside the dryer.

Data Accusation and Measurements

The meteorological data included the solar radiation flux incident on a horizontal surface, wind speed, air temperature and the air relative humidity were obtained from the meteorological station (Vantage Pro 2, Davis, USA) which was located beside the greenhouse dryers. Relative humidity was measured using a digital thermo-hygrometer data logger (Prime Capsule/HT-165, Australia) with an accuracy of (± 1%). The air temperature inside the solar dryers was measured by k-type thermocouples. The thermocouples were connected to a data-logger system (Lab-Jack logger, USA) to display and record the data during the experimental work. The output data were recorded every ten minutes. Three thermocouples were functioned to measure the indoor air temperature for each greenhouse. The inlet and outlet air temperatures were measured using four thermocouples. The velocity of drying air was measured at the outlet using a digital anemometer (MT- 4005, Korea) with a measuring range up to 30 ms^{-1} and an accuracy of ± 0.1 ms^{-1}.

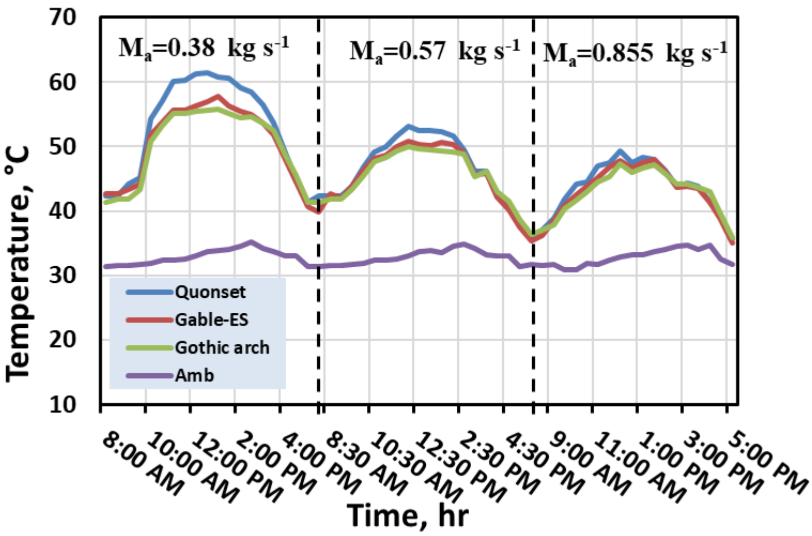
3. RESULTS AND DISSECTION

Thermal Performance of Greenhouses

To evaluate the thermal performance of the selected dyers without load, they operated under different air flow rates and the temperature recorded during the experiments and used to calculate different energies and thermal efficiency from equations 1 to 8. **Fig. (3a)** shows the recorded temperatures inside and outside the dryers under different air flow rates. It can be seen that, during the operating period (three days), the ambient air temperature ranged from 31 to 35 °C with the same range in the three days (**Fig. 3a**). Therefore, the effect of the weather fluctuations could be neglected and the differences among the three days data for the same dryer are due to the change in the airflow rate only.

In general, the air temperature inside the dryer decreased as the air flow rate increased. For example, the maximum temperature inside the Quonset dryer was 61.5, 53.2, and 49.3 °C at the air flow rate of 0.38, 0.57, and 0.855 kg s^{-1}, respectively. Similarly, the maximum temperature values inside the Gable-even span and Gothic arch dryers decreased from 57.8 to 48.0 °C and from 55.8 to 47.2 °C as the air flow rate increased from 0.38 to 0.855 kg s^{-1}, respectively (**Fig 3a**). This might be ascribed to the longer residence time for the air inside the greenhouse dryer at lower airflow rates (**Alta *et al.*, 2010; Kishk *et al.*, 2019, ElGamal *et al.*, 2021)**. The values of the temperature in the Quonset dryer are in agreement with reported values by **Abdellatif *et al.* (2010)** and **Kishk et al. (2018)**.

(a)



(b)

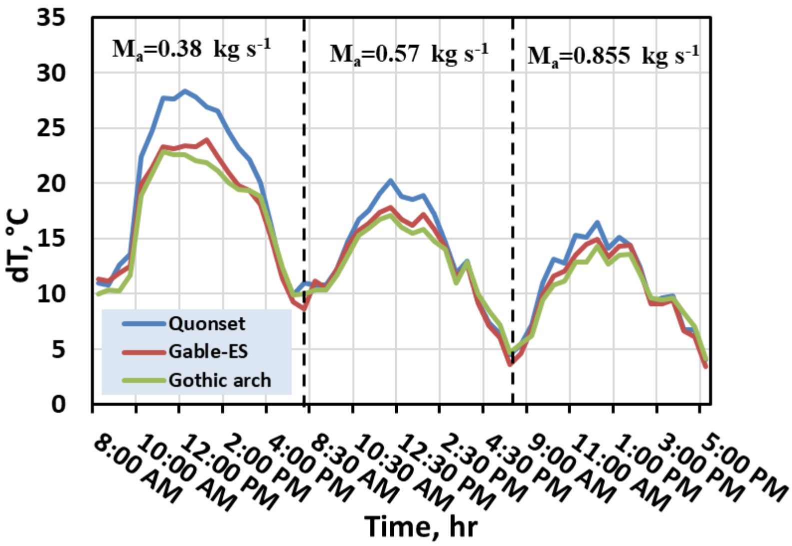


Fig. (3): Variation of air temperature inside the studied dryers at different air flow rates (0.38, 0.57, and 0.855 kg s^{-1}).

From **Fig. (3a)** it is also obvious that the Quonset dryer increased the temperature of the air more than the other dryers, despite the value of the tested airflow rate. To declare this, the difference between the air temperatures inside and outside dryer (*dT*) were calculated and presented in **Fig. (3b)**. It can be seen that, under the air flow rate of 0.38 kg s^{-1}, the maximum raise in air temperature (recorded between 12:00 PM and 1:00 PM) was 28.4 °C in the Quonset dryer. Meanwhile, the corresponding values in the Gable-even span and Gothic arch dryers were 23.9 22.8 °C, respectively. It can be expected from these results that the Quonset dryer has higher thermal efficiency than Gable-even span and Gothic arch dryers. The Quonset dryer is considered as ideal shape for greenhouse dryer as it is minimizing the side effects of wind load that may below over the rafter of solar dryer and maximizing the solar radiation flux incident on the rafter of dryer. The most important part of this study was evaluating the thermal efficiency of the selected greenhouse solar dryers under different air flow rates. **Fig. (4)** shows the hourly average thermal efficiency of the solar dryers which was calculated using equation (8) during the period from 8:00 AM to 5:00 PM at different rates of airflow. As expected from temperature data (**Fig. 3**), the Quonset dryer recorded higher thermal efficiency of 58.48% at a lower air flow rate compared with the Gable-even span and Gothic arch dryers (Fig 4). The thermal efficiency values of the Quonset dryer reported in this study are in agreement with values reported by **Abdellatif *et al.* (2010)** which ranged in his study from 53.19% to 61.24%.

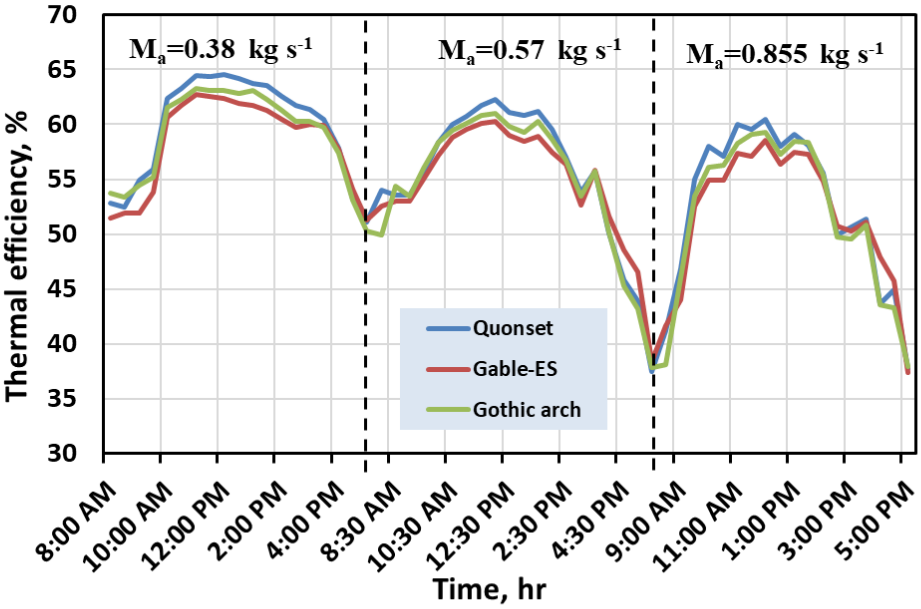


Fig 4. Thermal efficiency of studied solar dryers at different air flow rates

It can be also seen in Fig 4 that the thermal efficiency of the dryers decreased with the increase in the airflow rate. This can be explained based on the effect of the change in the airflow rate on the useful heat and heat losses from the dryers as tabulated in **Table (1)**. In general, the three studied dryers showed differences in the useful heat and heat losses at the same air flow rate. The differences in the useful heat gain and heat losses could be attributed to the effect of the geometric shapes of the three dryers and the air temperature difference between inside and outside the dryers.

Table (1): Average daily values of calculated heat energies and thermal efficiency of the studied dryers under different air flow rates.

Dryer type	M_a (kg s^{-1})	Q_u (kW h)	Q_{loss} (kW h)	Q_T (kW h)	η_0
Quonset	0.38	8.12	5.49	13.61	58.48
	0.57	8.45	6.50	14.95	55.43
	0.855	9.57	8.48	18.05	51.31
Gable-even span	0.38	6.93	5.00	11.93	57.20
	0.57	7.75	6.23	13.98	54.79
	0.855	8.84	8.24	17.08	50.52
Gothic arch	0.38	7.15	4.99	12.14	58.01
	0.57	7.88	6.21	14.09	54.96
	0.855	8.93	8.21	17.14	50.62

It can be also noted from **Table (1)** that, the daily average useful heat gain and the heat losses for the three studied solar dryers were increased as the airflow increased. On the contrary, the thermal efficiency for all dryers decreased as the air flow rate increased. This is due to fact that the heat losses increase rate was higher than the increase in the useful heat as the airflow increased. For instance, for the Quonset dryer, when the airflow rate increased from 0.38 to 0.855 kg s^{-1} the useful heat gain increased by 1.45 kWh (from 8.12 to 9.57 kWh). Meanwhile, the corresponding values of the heat losses increased by 2.99 kWh (from 5.49 to 8.48 kWh) as the airflow rate increased from 0.38 to 0.855 kg s^{-1} (see **Table (1)**). In other words, the heat losses increased two times higher than the increase in the useful heat which resulted in a decrease in the thermal efficiency at the end. The increase of the useful heat with the air flow rate can be attributed to the increase of the air mass which enters the dryer and is loaded with more energy available inside the dryer. On one hand, the increase in the heat losses with the increase of airflow can be due to the increase in air exchange by extracting fan from the minimum air flow rate to the maximum air flow rate for each solar dryer. This means that increasing the air flow rate leads to higher heat losses and the lower air flow rate recommended for the drying experiments. Also, as the Quonset dryer reported a higher thermal efficiency and higher temperatures, it is expected that the moisture removal during drying will be higher than the other studied dryers.

It can be also noted here that as the temperature not existed 61.5 °C in the studied dryers (see **Fig. (3)**), the dryers can be used safely for drying the Jew's mallow with high product quality according to **Youssef et al., (2014)** who studied the effects of hot air drying variables including air temperature (50, 60 and 70 ºC) on the quality of the dried Jew's mallow and reported that the drying at 60 showed the lowest negative effect on the leaves antioxidant activity.

Drying Behavior of Jew's Mallow

From the above results, the low air flow rate of 0.38 kg s^{-1} was selected, and the three dryers loaded with Jew's mallow were operated under this air flow rate until the plants reached the desired moisture content. The dryers operated for two dyes from 9 AM to 5 PM each day with a total drying time of 16 hours. The weight losses of Jew's mallow were recorded and the change in the moisture content and drying rate with the time was calculated. The results were compared among the three dryers and with samples dried in the ambient air as presented in **Fig. (5)** and **Table (2)**.

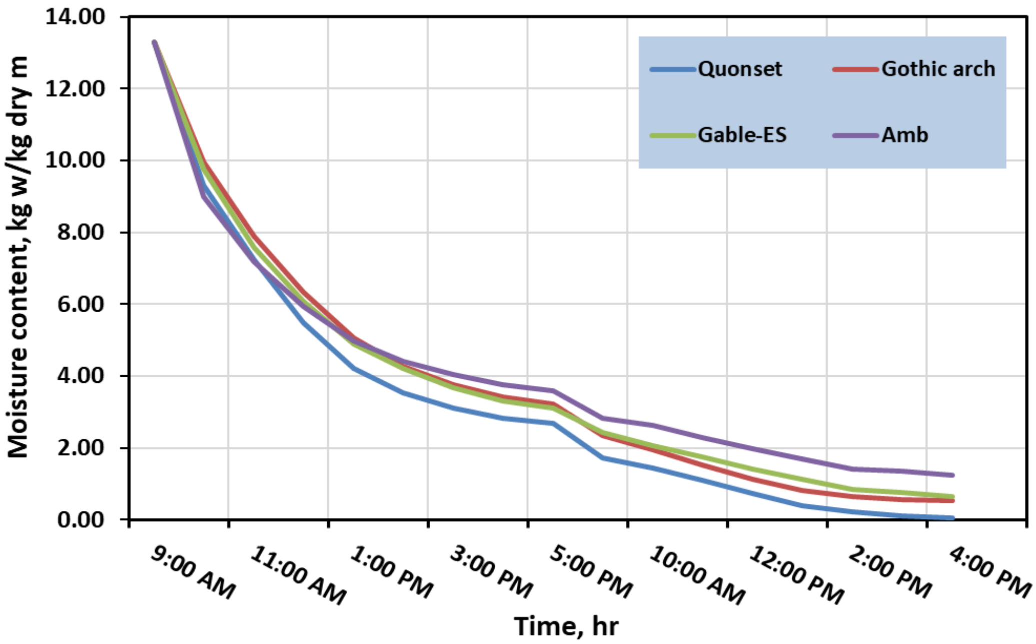


Fig. (5): Variation of moisture content of Jew's mallow with drying time.

Table (2): Moisture contents [**MC**] (kg water/kg dry matter) and drying rates [**DR**] (kg water/kg dry matter h) of Jew's mallow during drying in solar dryers.

	Drying time, h	Quonset		Gothic arch		Gable-ES		Ambient	
		MC	DR	MC	DR	MC	DR	MC	DR
First day of drying	0	13.29	-	13.29	-	13.29	-	13.29	-
	1	9.31	3.98	9.95	3.34	9.75	3.54	9.00	4.29
	2	7.24	2.07	7.88	2.07	7.56	2.19	7.17	1.83
	3	5.50	1.74	6.34	1.54	6.07	1.49	5.93	1.24
	4	4.20	1.30	5.07	1.27	4.89	1.18	4.99	0.94
	5	3.52	0.68	4.27	0.80	4.20	0.69	4.42	0.57
	6	3.10	0.42	3.75	0.52	3.67	0.53	4.04	0.38
	7	2.81	0.29	3.41	0.34	3.29	0.38	3.75	0.29
	8	**2.67**	**0.14**	**3.23**	**0.18**	**3.10**	**0.19**	**3.58**	**0.17**
Second day of drying	9	1.73	0.94	2.35	0.88	2.43	0.67	2.82	0.76
	10	1.45	0.28	1.93	0.42	2.05	0.38	2.61	0.21
	11	1.09	0.36	1.51	0.42	1.76	0.29	2.28	0.33
	12	0.72	0.37	1.13	0.38	1.40	0.36	1.98	0.30
	13	0.39	0.33	0.82	0.31	1.12	0.28	1.69	0.29
	14	0.22	0.17	0.64	0.18	0.83	0.29	1.42	0.27
	15	0.11	0.11	0.56	0.08	0.76	0.07	1.33	0.09
	16	**0.06**	**0.05**	**0.52**	**0.04**	**0.71**	**0.05**	**1.25**	**0.08**

It is clear that the drying rate of Jew's mallow in Quonset dryer was higher than the other dryers and the ambient conditions also. In the first day of drying (8 hours of drying), the moisture content of Jew's mallow decreased from initial moisture of 13.29 (kg water/kg dry matter) to about 2.67 (kg water/kg dry matter) in the Quonset dryer. Meanwhile, the moisture content of Jew's mallow was still higher than 3.1 (kg water/kg dry matter) in the other dryers and about 3.6 (kg water/kg dry matter) for the ambient drying as shown in **Table (2)**. This is due to the high temperatures and the high thermal efficiency of the Quonset dryer over the other dryers as discussed above.

From **Fig. (5)** and **Table (2)**, it can be also seen that at the beginning of drying the samples in the ambient air dried very fast and showed the same behavior as the samples in the solar dryers. This is because at the beginning of drying the free water was removed fast from the plant and the ambient air temperature and velocity were enough to remove such free water. Afterward, the bounded water in the plant cells needs more energy and power to be removed. To this end, solar dryers with forced air convection should be used. At the end of the drying period, the moisture content of Jew's mallow in the solar dryers decreased to 0.06, 0.52, and 0.71 (kg water/kg dry matter) for Quonset, Gothic arch and Gable-even span dryers, respectively. The Gothic arch dryer showed higher performance over the Gable-even span dryer and could be a second choice after the Quonset dryer for drying agricultural products. On the other hand, the moisture content of the Jew's mallow samples in ambient air was still higher than 1.25 and it may need one or more dyes to be dried to the same moisture reached by the solar dryers and this can lead to the deterioration and infection of the samples before it reaches the desired moisture.

4. CONCLUSION

This paper presents the construction and thermal efficiency results of three different greenhouse solar dryers namely Quonset, Gable-even span and Gothic arch. Thermal analysis was carried out for the dryers without load under different air flow rates. The lower air flow rate of 0.38 kg s^{-1} gives higher thermal efficiency for the three studied dryers. Accordingly, this air flow rate was used for drying the fresh Jew's mallow in the solar dryers. The results can be concluded as follows:

- The air temperature inside the dryer decreased as the air flow rate increased. The air temperature inside the Quonset dryer reached higher values than in other dryers. At a lower air flow rate of 0.38 kg s^{-1}, the maximum air temperature inside the dryers was 61.5, 57.8 and 55.8°C for Quonset, the Gable-even span and Gothic arch dryer, respectively.
- The Quonset dryer showed higher thermal efficiency values than other studied dryers. As the air flow rate increased, the heat gain and heat losses for the dryers are increased and resulted in lower thermal efficiency at higher airflow rates for the three studded dryers.
- The drying rate of Jew's mallow in the Quonset dryer was higher compared to other dryers and the ambient drying. The moisture content of Jew's mallow decreased from initial moisture of 13.29 (kg water/kg dry matter) to less than 0.5 (kg water/kg dry matter) during 16 hours of drying in the solar dryers.
- Finally, the Quonset dryer is recommended to be used efficiently with lower airflow rates for drying Jew's mallow and other similar agricultural products.

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تقييم مجففات شمسية مختلفة و تطبيقاتها فى تجفيف محصول الملوخية

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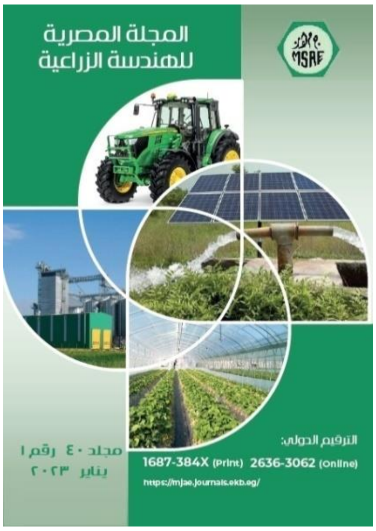

الكلمات المفتاحية:
المجففات الشمسية؛ صوب التجفيف؛ الكفاءة الحرارية؛ الملوخية؛ معدل التجفيف.

الملخص العربي

أجري هذا البحث بقسم الهندسة الزراعية - كلية الزراعة - جامعة قناة السويس بالإسماعيلية - مصر و يهدف البحث الى دراسة وتقييم ثلاثة تصميمات مختلفة من البيوت المحمية المستخدمة كمجففات شمسية وهى الشكل النصف اسطوانى و شكل العقد القوطى و الشكل الجمالونى المتناظر الإنحدار ومقارنتها بالتجفيف الشمسى التقليدى لتجفيف محصول الملوخية. تبلغ المساحة الارضية لكل مجفف ٢ م^2 وتم إستخدام طبقة واحدة من البولى ايثيلين كغطاء للمجففات الثلاثة. تم توجيه المجففات فى إتجاه شرق – غرب (المحور الطولى فى إتجاه الجنوب). وتم توصيل كل مجفف بمروحة طرد مركزى قدرة واحد حصان مزودة بجهاز تغير سرعات للتحكم فى سرعة تصرف الهواء المطلوبة. فى الجانب المقابل للمروحة يوجد شباك لدخول الهواء حيث يدخل الهواء للصوبة من أعلى ليتم تسخينة بواسطة الطاقة الشمسية ويتم سحبة من أسفل المحصول بواسطة المروحة. تم دراسة تأثير ثلاث معدلات تصرف مختلفة لهواء التجفيف (٣٨,٠- ٥٧,٠ – ٨٥٥,٠ كجم/ث). تم قياس شدة الإشعاع الشمسى ودرجة الحرارة الداخلية والخارجية وكذلك الرطوبة النسبية داخل و خارج المجفف. وتوصلت النتائج إلى:

- متوسط درجة الحرارة الداخلية للمجففات الثلاثة تقل بزيادة تصرف الهواء وبالتالى تتناسب الكفاءة الحرارية عكسياً مع تصرف الهواء.
- أعلى كفاءة حرارية كانت للمجفف الإسطوانى ٥٨,٤٨ % تحت تصرف ٣٨,٠ كجم/ث وبالتالي تم استخدام هذا التصرف لتجفيف محصول الملوخية.
- معدل تجفيف الملوخية فى الصوبه الإسطوانية أعلى من معدل التجفيف فى الصوب الأخرى وكذلك التجفيف الشمسى العادى. حيث أنه بعد ١٦ ساعة من التجفيف المتواصل للملوخية ذات المحتوى الرطوبى الابتدائي ١٣,٢٩ (كجم ماء/كجم مادة صلبه) وصل المحتوى الرطوبى النهائى فى الصوبه الاسطوانية الى ٠,٥ (كجم ماء/كجم مادة صلبه).