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Solar Drying Tomato Crop Using Two Different Architectural Configurations of Solar Driers

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ABSTRACT

This study was conducted during August 2022 to clearly elucidate and assess the best type of solar driers can be functioned in tomatoes drying and the engineering parameters that affecting the drying process. Two different architectural forms of solar- driers (lean-to and curved lean-to solar driers) are designing, constructing, and using during the experimental work. The tomato fruits handily cut into halves lengthwise and thereafter 5% sodium chloride (NaCl) was spread on the cutting part of fruits before entrance the solar driers. This manipulating process had executed in order to facilitate the up tacking of moisture from the core of fruits into the cutting part. The two solar driers have compared with the natural sun drying methods during this study. The mean initial moisture content of tomato fruits was 91.52%w.b., which reduced into 7%w.b. (±0.74 w.b.) after drying within 68 and 95 hours for the two solar driers, respectively, while it reached to 15.64%w.b. within 178 hours for the natural sun drying. The drying rates for the two solar driers, respectively, were 284.44 g/h and 205.52 g/h, while, it was 101.93 g/h, for the natural sun drying. The experimental analysis for the two solar driers and the natural sun drying revealed that, the total energy needed for drying fresh tomato fruits comprehended solar energy and electrical energy consumed by extracting fans, respectively, was 27.453, 40.457, and 22.065 kWh. As a result, the specific free water extraction rate by the three different drying systems, of 0.738, 0.503, and 0.907 kg/kWh, respectively.

***Keywords**:* Solar radiation, dehydrating, solar dehydrator.

INTRODUCTION

Tomato crop (*Solanum lycopersicum L.*) is one of the most important vegetables producing in the world. The annual total productivity of tomato fresh in 2020 yield is approximately 186,821,216 tons, while the area cultivated with tomatoes in Egypt amounted to about 406,814 feddan, with a total productivity of about 6.7 million tons (FAO, 2020). Egypt is one of most five producers of tomato crop in the world. Drying technique is among important preservation process functioned to extend shelf-time of agricultural crops as well as to facilitate the transportation, storage, and providing natural sterilisation of the dried production. However, the process of moisture extraction using various drying techniques decreases chemical changes in the dried materials by preventing microbial development and enzymatic activity. (Horuz et al., 2017). Based on the heat transfer science, drying process is included heat and mass transfer processes. A significant part of hot drying air is transferring its heat energy into the external surface of drying product that is migrated into the core of drying material. This heat energy induces in rising the core temperature of drying product and consequently evaporate water. The rest part of heat energy is used in the process of free water evaporating from a drying material's exterior surface. This process induces in migrating the free water from the core into the external surface to replenish the moisture lost by evaporation (Nikita et al., 2021). Drying appears to be the best alternative for preserving vegetables and fruits for a long time, increasing their shelf life, reducing post-harvest losses, reducing transportation weight and expense, and maintaining quality attributes. Removing moisture also reduces poor product quality due to enzyme, bacterial, yeast, and mold activities (Getahun et al., 2021).

Renewable energy has also becoming accepting as an important future source, not just for Egypt but also for the entire world. By transforming natural events into usable types of energy, renewable energy sources also provide marketable energy. Direct and indirect solar energy effects on the ground (solar radiation, wind, falling water, and various plant wastes) are using in these systems. Egypt has a huge number of renewable energy sources, particularly solar energy, with which can provide a significant portion of the country's overall thermal energy needs. It is also distinguishable. The advantages of installing and operating a renewable energy system are dividing into three categories: energy savings, employment creation, and reduced pollution (Khater et al., 2020 ; Gorjian et al., 2021).

The most common types of solar drying methods divided into two groups based on how much solar energy is used: open sun drying (OSD) and integrated solar drying. Several types of sun dryers had developed in recent decades to reduce post-harvest losses and increase agricultural product quality. Solar energy is mainly functioned to dry agricultural products. The pace of solar drying under temperature control and dehumidification ensures optimal drying and the desired end-product quality. The study of (natural or forced) air circulation strategies and heat transfer methods for passive, active, and hybrid Solar-powered dryers (Lingayat et al., 2020; Udomkun et al, 2020). Several designs of solar driers had developed to enhance their thermal performances. These designs comprehends; direct, indirect, passive, active, and greenhouse solar driers (Kumar et al., 2016; Ayua et al,. 2017;

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Hamdi et al., 2018; Wilkins et al., 2018; Lingayat et al., 2020; Gorjian et al., 2021; Buchholz, 2021).

Utilising solar energy as among the most significant sources of renewable energy was the study's primary objective for drying pre-treatment fresh fruits of tomato halves using two different architectural configurations of solar drier (lean-to and curved lean-to solar driers) and compare the obtained data with that obtained from the natural sun drying.

MATERIALS AND METHODS

Practical experiments had carried out at the Agricultural Experiments and Research Station, Faculty of Agriculture, Mansoura University, at latitude angle of 31.043ºN, longitude angle of 31.352ºE, and altitude of 6.72 m above the sea level. The lean-to solar greenhouse dryer is designing, constructing, and using in this study. The solar dryer having gross dimensions of 200 cm long, 100 cm wide with net drying surface area of 2 x10^4 cm^2. It has 80 cm high of the vertical back wall 40 cm high of the vertical front wall, 40 cm gable height, 105 cm rafter length, and total volume of 1.2 x 10^6 cm^3 as clearly revealed in Fig. (1). It was oriented in the East-West direction where the longitudinal section of the solar dryer facing south.

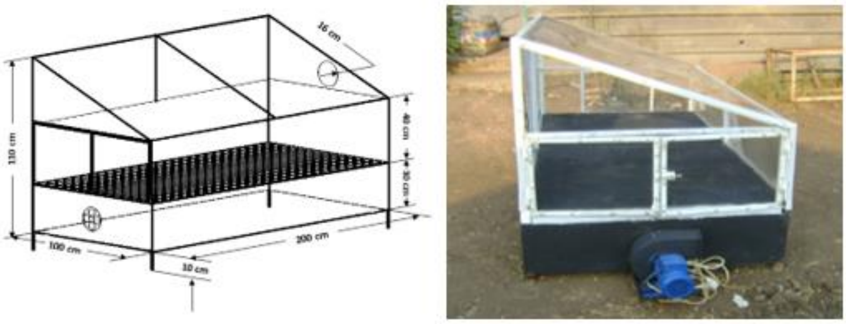


Fig. 1. Schematic diagram and the plate of lean-to solar dryer

This direction caused the inclined and vertical sections to face upward towards the sun's rays, while the northern section faced into the chilly sky and served as a solar reflector at the same time. The structural framework of the solar dryer is made of 1.27 cm diameter firm water galvanized pipes. The solar dryer's rafter is tilting with 21.9° from the horizontal plane. To augment the amount of available solar radiation inside the solar drier, the vertical back surface of solar dryer is covering with a thin layer 2.0 mm thick of nickel-chrome to function as a reflector. This solar dryer is covering with polycarbonate sheets 2 mm thick. A circular hole of 16 cm in diameter is making in the centre of the gable end of eastern section of the solar dryer to pass the outside air into the dryer. To extract the outside air into the inside solar dryer an electric centrifugal fan is placing in the corresponding location (middle of the western section of the air chamber).

The second solar dryer is the curved lean-to. The gross dimensions of the solar dryer are; 200 cm long, 100 cm wide, 40 cm high on the front vertical wall, 40 cm high on the back curved end, 110 cm long of arc, with a net surface area of 2 x10^4 cm^2 and net volume of 1.33 x 10^6 cm^3 as revealed in Fig.(2). This solar dryer's structural frame is making of sturdy 1.27 cm in diameter-galvanized water pipes. It also has an air chamber formed of a firm galvanized steel sheet with the following dimensions, 200 cm long, 100 cm wide, and 30 cm deep, with a net surface area of 2 x 10^4 cm^2, and total volume of 0.6 x 10^6 cm^3. A circular hole of 16 cm in diameter is making in the centre of the eastern sector of the curved end of solar dryer to let the outside air passing through the solar dryer easily. An electric fan is also placing in the corresponding location (middle of the western sector).

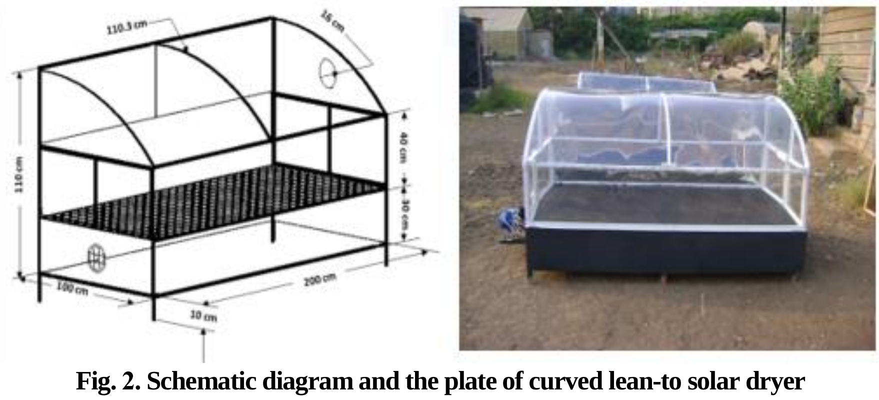


Fig. 2. Schematic diagram and the plate of curved lean-to solar dryer

The two solar dryers were adjacent situated during the experimental work (August 2022) in order to compare them and determine the best design could use in the drying process of tomatoes fresh fruits based on the properties of the drying mode of thin layer drying of tomatoes crop The two solar dryers receive the drying air from the upper sector, which descends vertically to the air chamber through the tomatoes before expelling out of the dryers

The natural sun drying is one of the simplest, oldest and easily drying methods, as it saves effort and costs. It is more profitable for farmers and traders. Therefore, some districts in Egypt have using this method of natural sun drying such as the Nubaria project for drying tomato crop and different fruits (FAO, 2019). A wooden drying tray having gross dimension of 200 cm long, 100 cm wide, and 50 cm high with a net drying surface area of 2 x 10^4 cm^2 is used during the experimental work to compare between the active solar dryer and the natural sun drying. The wooden frame is covering using galvanized wire meshwork, located beside the two active solar dryers, and functioned without cover as a natural mode of sun drying as shown in Fig. (3)

Fig. 3. Wooden frame of natural sun drying beside the two solar driers

Fresh tomatoes purchased from the local market at Mansoura city in August 2022, and sorting into the symmetry in shape and size of each fruit. The average diameter of fruits ranged from 5 cm (±0.4 cm). The tomato fruits had carefully examined to remove the impurities and rotten fruits from the fresh tomato. Thereafter, the clean operation of the selected tomato fruits has done using pure fresh water. After cutting the tomato fruits into halves lengthwise, 5% sodium chloride (NaCl) had spread on the fruits in the cutting part. The tomato halves had distributed inside the solar dryers in a consistent manner on the area designated for drying, taking into account that the skin layer is adjacent to the drying net. At that time, same amount of tomato halves had distributed on the natural solar drying tray. Total load 22 kg of fresh tomato fruits were located in each dryer (solar dryers and natural sun drying).

Several measurements had executed during the experimental work using different measuring devices. The external climatic conditions surrounding the solar dryers were, measured and recoded in the work area of the Agricultural Experiment and Research Station's project site. These measurements comprise dry-air temperature, air relative humidity, solar radiation flux incident on the horizontal surface and wind speed. These measurements were recorded using the meteorological station in the project during the experiment period from 8^{th} to 25^{th} of August 2022. During the experimental period, the drying air speed was measured twice daily at the entrance and outlet flow locations of drying air using a vane LCD Digital Anemometer (Montreal, Canada). The measurement ranged from 0 to 45 m/s, with an overall accuracy of 2%. The solar radiation flux incident on the horizontal surface outside and inside the solar dryers had measured and recorded using disk solarimeter device. The measurement was taking every one-minute and the average of five scans recorded and stored on the memory of the solarimeter device. The air temperature and air relative humidity inside the two different solar driers were measured and recorded using data–logger (Watch-Dog, 1000 series, USA).

The main objective of the drying process for any agricultural product is to increase its shelf life and ensure its continuous existence. Also, to reducing size of fresh crop in order to save transportation and storage costs, taking into account the quality of the final product. The initial moisture content of tomato fruits that used in the experimental work had measured by the experimental laboratory and its average value was about 92.5% w.b. (±1.8 w.b.). The lycopene, the ascorbic acid, the percentage of nitrogen, and the percentage of ash were also determined as some of the measurements used in measuring the quality of dried tomato fruits.

A sample of tomato fruits placed in a crucible on each of the solar dryers, as well as on a natural solar drying tray, and the readings were taking each an hour during the duration of the experimental work using an electrical digital balance with a maximum capacity of 600 g ±0.01g accuracy. The experiment continued for several days until reaching the final moisture content of 7% w.b. (±0.72) as shown in Part of the dried tomato was collecting and packed in glass jars with olive oil as a preserving and stored method. To secure supply tomatoes throughout the year, easy transportation and storage, the majority of the dried tomatoes were grinding into the final powder using an electric grinder as shown in Fig. (4). It is essentially to a large portion of the world's population and regarding as one of the basic food components could add to the vegetables during different cooking food.

Fig. 4. Dried tomato halves before and after grinding on the left hand-side, and dried halves tomato packed in jars with olive oil on the right hand-side.

Mathematical Modeling

Drying characteristics of dehydrated tomato

Experimental work executed using two different types of solar dryers based on their architectural forms, and they comparison with the natural solar drying during the summer season of 2022. The duration of the experiment was 7 days from 8/8 to 14/8, 10 days from 8/8 to 17/8, and 18 days from 8/8 to 25/8 using lean-to, curved lean-to, and natural sun drying, respectively. Moisture content (MC) had measured using a hot air oven using the following standard procedure of AOAC (2005).

$$MC, w.b = \frac{\text{weight of water removed (g)}}{\text{weight of sample (g)}} * 100 \qquad (1)$$

The drying rate (DR) represents the amount of moisture that evaporated over the drying time. It computed using the following equation (Delfiya et al., 2018).

$$DR = \frac{Mt - M_{t+\Delta t}}{\Delta t}, \quad \text{kg of water/kg of dry matter} \qquad (2)$$

Where;

Mt, is the moisture content at time t, Δt, is the time difference in hour, and $M_{t+\Delta t}$ is the moisture content at time = t+ Δt

To determine the rehydration ratio of the dried samples, five-gram dried samples had taken and soaked in water at the ratio of 1:50 (w/v) for 3 hours. After that, the rehydrates samples were taken out of the water and wiped with tissue paper to remove surface water and the weight was recorded (Lewicki, 1998).

Rehydration Ratio (RR) =

$$\frac{\text{Wr (final weight of the sample after immersing in water and drained}}{\text{Wd (weight of dry sample}} \qquad (3)$$

The energy required for drying, Q_d, is estimating using the following formula (Lingayat et al., 2020):

$$Q_d = M_a c_{pa} (T_{co} - T_f) = M_w h_{fg} \qquad (4)$$

Where;

M_a, is the mass flow rate of drying air in kg /s, C_{pa}, is the specific heat of air at mean temperature in J/kg ºC, T_{co}, is the outlet temperature in ºC, T_f , is the temperature at the exit of chamber in °C. M_w, is the mass of water extraction in kg, and, h_{fg}, is the latent heat of evaporation at mean temperature [$(T_{co}+T_f)/2$] in J/kg

The amount of water extraction (M_w) throughout the drying process is computed using the following equation:

$$M_w = M_i (M_{ci} - M_{cf}) / (100 - M_{cf}) \qquad (5)$$

Where;

m_i, is the initial mass of the product (drying load) in kg, M_{Ci} and M_{Cf}, is the initial and final moisture contents of the product, respectively.

Moisture content in the product is estimated using the following equations:

$$\textbf{Moisture content, wet basis (w.b.), } M_{ci} = \frac{(M_p - M_d)}{M_p} \qquad (6)$$

$$\textbf{Moisture content, dry basis (d.b.), } M_{ci} = \frac{(M_p - M_d)}{M_d} \qquad (7)$$

Where;

M_p, is the mass of the product before drying and, M_d, is the mass of the dried product in kg.

Analysis of thermal performance test

The experimental work had carried out under semi-constant conditions for the solar dryers. Under these conditions, the thermal performance of solar dryers is distinguishing through the thermal energy balance, which shows the distribution of solar energy and its conversion to different heat sources such as; solar radiation (q), heat energy acquisition (q_u), heat energy used to remove moisture from the product (q_{ev}), and heat energy lost (q_l). Air is entering through a circular hole with a diameter of 16 cm in the upper part of the dryer. The product (tomato fruits) had placed on the meshwork tray and the air is passing over the drying product to facilitate the movement of moisture to flow around during drying. The heat transfer process between the solar dryer and the surrounding external environment is associated with the convection, radiation and evaporation. The heat transfer process could describe by the following equation (Bargach, et al., 2000; ASHRAE, 2005; Duffie and Beckman, 2013; Çerçi and Das, 2019):

$$Q = Q_u + Q_{ev} + Q_L, \quad \text{Watt} \qquad (8)$$

Where;

Q, is the solar energy available inside the solar dryer in W, Q_u, is the heat energy collected by the solar dryer in W, Q_{ev}, is the heat energy used for evaporating moisture from the product in W, and, Q_l, is the total thermal energy losses in W. The total solar radiation incident on a horizontal plane inside the solar dryer (R) in W/m² and the net surface area of the drying tray (A_t) in m² are using to determine how much solar energy available inside the solar dryer (Q) as follows:

$$Q = R\, A_t, \quad \text{Watt} \qquad (9)$$

The heat energy acquisition (Q_u) can compute by the following formula:

$$Q_u = M_a C_{pa} (T_{ai} - T_{ao}), \quad \text{Watt} \qquad (10)$$

Where;

T_{ai} and T_{ao}, is the indoor and outdoor air temperatures in ºC, respectively. The following equation could use to calculate the amount of heat energy required to extract moisture from tomato fruits (Q_{ev}):

$$Q_{ev} = \frac{[h_{fg} M_w + M_p C_{pp} (T_{ai} - T_{bulk})]}{3600}, \quad \text{Watt} \qquad (11)$$

Where;

h_{fg}, is the latent heat of water vaporization, 2.26 x 10⁶ J /kg, M_w, is the mass of water that has evaporated over time in kg/h, C_{pp} , is the specific heat of tomato, in J /kg ºC, and, T_{bulk}, is the bulk temperature of fruits in ºC.

The specific heat of tomato fruits can be determined as follows **(Dickerson, 1969).**

$$C_p = 1.672 + 0.025\, M\, (\text{w.b.\%}), \quad \text{k J /kg °C} \qquad (12)$$

Where:

M, is the moisture content of tomatoes at interval time.

The total heat energy loss from the solar dryer to the environment outside the dryer during the drying process can be calculated using the following equation. The total heat energy loss is mainly reported by three different heat transfer processes, which include losses by convection, forced air exchange, and heat radiation losses.

$$Q_l = q_{cond} + q_{exch} + q_{rad}, \quad \text{Watt} \qquad (13)$$

It is not necessary to evaluate each mode separately as the total heat transfer coefficient represents both the conduction and convection heat losses from the solar dryers. The conductive heat loss and convection of the greenhouse solar dryer are calculated as follows:

$$q_{cond} = A_c U_o (T_{ai} - T_{ao}), \quad \text{Watt} \qquad (14)$$

Where;

A_C, is the total surface area of the solar dryer cover, in m², and, U_O, is the overall heat transfer coefficient, in W/m² ºC.

The following formula could use to determine the thermal energy lost through forced air exchange (q_{exch}) between the indoor and outdoor of the solar dryer:

$$q_{exch} = V \rho C_{pa} (T_{ai} - T_{out}), \quad \text{Watt} \qquad (15)$$

Where;

V, is the rate of extracting drying air, in m³/s, ρ, is the density of drying air in kg /m³, and, T_{out}, is the drying air temperature just leaving the solar dryer in ºC.

The following formula may use to compute the heat energy loss by thermal radiation from indoor substances to the cold sky:

$$q_{rad} = \varepsilon \tau \sigma A_d \left(T_{ai}^4 - T_{sky}^4 \right), \quad \text{Watt} \qquad (16)$$

Where;

ε, is the emissivity factor of indoor substances, τ, is the effective transmittance of cover for long-wave radiation, A_d, is the surface area of dryer in m^2, T_{sky}, is the cold sky temperature in K.

$$T_{sky} = 0.0552 \left(T_{ao} \right)^{1.5}, \qquad K \qquad (17)$$

The overall thermal efficiency had significantly influenced the thermal performance of the two different types of solar dryers. The overall thermal efficiency (η_o) is precisely computing by dividing the collected solar energy by the solar dryer and the actual solar energy available inside the dryer.

$$\eta_o = \frac{q_u}{R A_d} * 100, \qquad \% \qquad (18)$$

Drying efficiency

It is the proportion of energy supply, which is utilizing by the wet product to eliminate moisture from the product. The drying efficiency (η_d) could determine by the following two equations (Lingayat et al., 2020)

For natural sun drying:

$$\eta_d = [M_w h_{fg} / A_t R] * 100, \qquad \% \qquad (19)$$

For forced solar drying:

$$\eta_d = [M_w h_{fg} / (A_t R + p_f)] * 100, \quad \% \qquad (20)$$

Where;

P_f, is the electrical power consumed by the extracting fan in W

The daily efficiency could calculate from the following equation (Prakash and Kumar, 2014):

$$\eta_d = \frac{\text{Daily Output Energy}}{\text{Daily Input Energy}} = \frac{M_w h_{fg}}{R A_d} * 100, \quad \% \qquad (21)$$

Daily output energy of dryer, Q_d, in kWh could compute by the following:

$$Q_d = \frac{\text{Moisture evaporated (kg)} * \text{latent heat of evaporation (J/kg)}}{3.6 * 10^6} \qquad (22)$$

Evaluation of the solar drying behavior

Two thin layer models (Lewis' model and Henderson and Pabis' model) could use to adequately describing the drying behaviour (Ayensu, 1997).

Lewis's model

The exponential model Lewis model (Lewis, 1921) which assumes negligible internal resistance and zero resistance to moisture migration from beneath the material's surface, is thought to be the simplest model could explain the movement of moisture in drying products. It simply takes into account surface resistance, indicating that all resistance is concentrated in a layer at the material's surface. It can compute as follows:

$$MR = \frac{Mt - Mf}{Mi - Mf} = \exp^{(-kt)} \qquad (23)$$

Where;

MR, is the moisture ratio, M_t, is the moisture content at time t, M_i % (d.b) is the initial moisture content, M_f % (d.b) is the final moisture content, k, is the drying constant (h^{-1}), and, t, is the drying time (h).

Henderson and Pabis's model

The Henderson and Pabis model (Henderson and Pabis, 1961) is the development equation from a simple model. The difference between Henderson and the other lies in taking into account the shape of the product by adding another constant as shown in the following formula:

$$MR = \frac{Mt - Mf}{Mi - Mf} = A \exp^{(-kt)} \qquad (24)$$

Where;

A, is coefficient of Henderson and Pabis model (dimensionless)

Statistical analysis

The Excel program could use to examine statistically the experimental obtained data. Multiple regression analysis is also using to correlate the drying rate with the moisture content of tomato fruits, drying air temperature, air relative humidity, and air mass flow rate. Linear regression analysis is using to test the relationship between the characteristics of the drying air and the drying rate. The minimal level of significance is traditionally considering as a significant level of 0.05. However, where greater levels of significance are discovered, these values (P = 0.01 and P = 0.001) were included in the text.

RESULTS AND DISCUSSIONS

Agricultural production losses during the harvesting, postharvest, and marketing chains must reduce using of appropriate technology for preservation food. Drying process is a wonderful technique to preserve food, and solar dryers are an environmentally friendly solution for food preservation. They are commonly used for removing moisture from agricultural products to create a product that can be properly preserved for longer periods. There are two methods for drying tomato fruits using solar energy, either natural solar drying or the solar dryers, and this study is concentrated on these two methods. The external air temperature (T_{ao}), air relative humidity (RH_o), and the intensity of solar radiation (R_o) are the main factors that influencing the dehydration processes of tomato fruits either that utilizing the natural sun drying or the solar drying. The maximum, minimum, and hourly average values of the three main outdoor climatic factors that affecting drying process during this study are summarized and listed in Table (1).

Table 1. Measured outdoor climatic conditions during the experimental period

Value	R_o (W/m²)	RH_o (%)	T_{ao} (ºC)
Maximum SD	906.5±46.1	80.8±3.1	32.6±1.2
Minimum SD	206.6±25.3	55.6±5.3	25.2±0.7
Mean SD	612.9±27.9	64.3±3.2	30.1±0.9

The drying process of tomato fruits in this study relied on solar energy as an abundant permanent and environmentally compatible energy source needed to dry the tomato fruits or any of the agricultural products. The measured drying times for the lean-to, the curved lean-to solar driers, and the natural sun drying, respectively, were 68, 95, and 178 hours. The intensity of solar radiation inside and outside the two solar dryers had precisely measured and recoded every five minutes during the drying times. The hourly average intensity of solar radiation outside the solar driers ranged from 174.7 to 984.3 W/m² that provided hourly mean of 612.9 W/m². The outside air relative humidity during the drying process ranged between 43.2% and 85.7%, which provided hourly mean of 64.3%. During the drying process, the ambient air temperature ranged from 24.3 to 34.7 ºC, which provided an average of 30.1 ºC.

The intensity of solar radiation outside and inside the two solar dryers had precisely measured and recoded every five minutes during the drying times. These values of solar radiation are summarized and listed in Table (2).

Table 2.Measured intensity of solar radiation outside and inside the two solar driers during the first ten days of the experiment

Value	intensity of solar radiation, (W/m^2)		
	R_o	Lean-to	Curved Lean-to
Maximum SD	928.5±51.8	918.4±19.6	902.9±49.2
Minimum SD	216.9±25.4	33.0±4.3	40.2±9.3
Mean SD	621.4±24.7	523.4±50.3	513.7±32.4

It clearly revealed that, the hourly average intensity values of solar radiation outside and inside the two solar driers, respectively, was 621.4, 523.4, and 513.7 W/m^2. As a result, the hourly average values of effective transmittance of the two solar driers (lean-to and curved lean-to) was 84.23% and 82.67%, respectively. During the experimental work, periodical changes in the intensity of solar radiation outside and inside the two solar dryers from sunrise to sunset are observing as clearly indicated in Fig. (5)

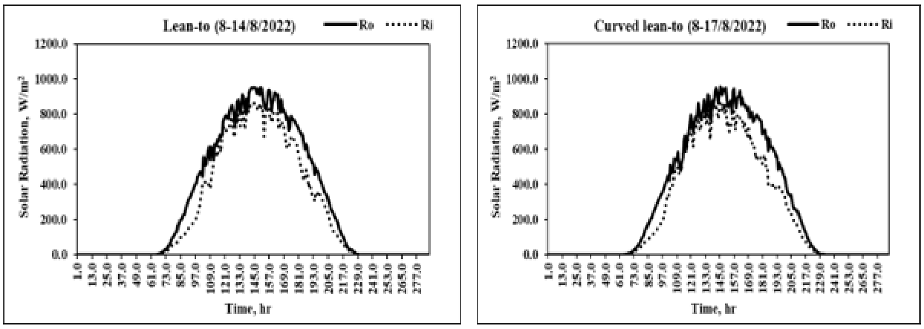


Fig. 5. Intensity of solar radiation falling inside and outside the two solar driers

To show how the polycarbonate cover of the sun dehydrator affected incident solar radiation within the two solar dehydrators, all the current data of incident solar radiation inside was plotted against the outside incident radiation to demonstrate Fig. (6). For the best fit, the following regression equations had used to determine the correlations between the incident solar radiation inside the two solar dehydrators and the outside radiation:

$$R_i \text{ (Lean-to)} = 0.8474 (R_o) \quad (25)$$

$$R_i \text{ (Curved Lean-to)} = 0.8398 (R_o) \quad (26)$$

The correlation coefficients between the incident solar radiation inside the two solar dehydrators and the outside radiation, respectively, were 0.9772 and 0.9751 (P > 0.001). The slope of each equation in the two regression equations is nearly equivalent to the effective transmittance of the solar dehydrator cover (polycarbonate sheet).

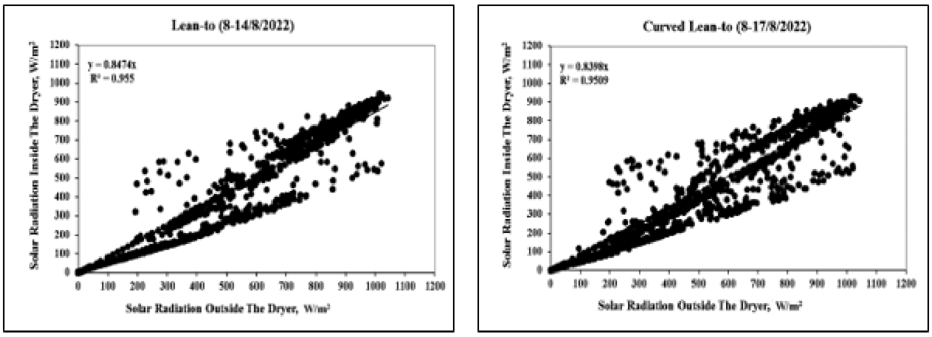


Fig. 6.Incident solar radiation inside the two solar driers versus incident solar radiation outside

Drying Air Temperature

To remove the excessive moisture from the agricultural products in the form of water vapour to the outside solar dryers during the drying process in order to approach the final moisture content (safe level), the drying air temperature is the prevalent parameter. Because of heat energy accumulated inside the two solar dryers due to the greenhouse effect, the drying air temperature rose over the outside air temperature. The space at which tomato fruits absorb direct sun radiation as it falls onto the drying tray is the source of other heat energy acquisition. This portion of the heat energy is dependent on the colour of tomato fruits, drying time, and exposure area. The overall thermal effectiveness of the solar drying equipment affects the capacity of drying air to carry water vapour by augmenting the drying air temperature and at the same time lowering its relative humidity.

Cyclic changes in the outdoor, indoor, and bulk air temperatures had observed during the experimental work, due to changes in the outdoor climatic conditions and the time of operating the extracting fan as revealed in **Fig. (7)**. The hourly average dehydrating air temperatures outside and inside the two solar driers (lean-to and curved lean-to) during the drying period (seven and ten days, respectively) were 29.7 (±2.4), 38.4 ºC (±8.4) and 39.7 ºC (±9.0), respectively. Consequently, these types of solar driers augmented the dehydrating air temperatures by 8.7 ºC and 10.0 ºC, respectively. The hourly average bulk temperatures of tomato fruits inside the two solar driers during the dehydrating period, respectively, were 40.5 (±9.9) and 39.1 ºC (±9.3). The hourly average bulk temperature of tomato fruits inside the lean-to solar dehydrator was higher than that the dehydrating air temperature by 2.1 ºC, particularly from the third day till the end of drying period, due to the absorbed sun radiation.

Whilst, the bulk temperature of tomato fruits inside the curved lean-to solar drier was on an average lower than the drying air temperature by 0.6 ºC, because of the drying period for the curved lean-to solar drier was longer than the other solar drier.

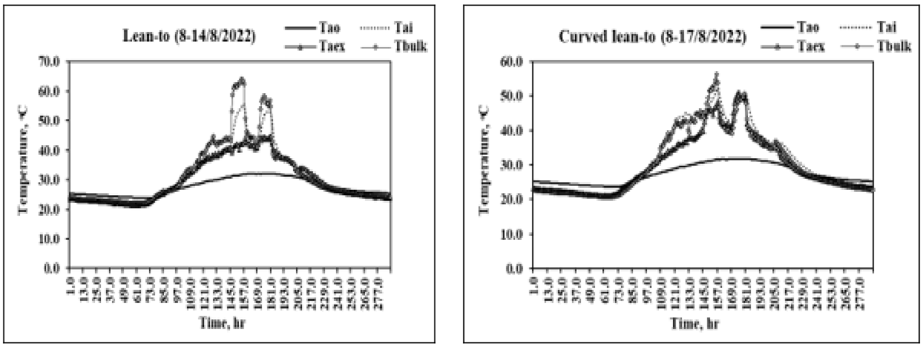


Fig. 7. Cyclic changes in outside, inside and exhausted air temperatures, and the bulk temperatures for the two solar driers

To examine and study the impact of air temperature (T_{ai}) on the bulk temperature of tomato halves (T_{bulk}) using the solar drying technique under specific circumstances during August month, the bulk temperatures of tomato halves were used as a function of air-drying temperatures as shown in Fig. (8)

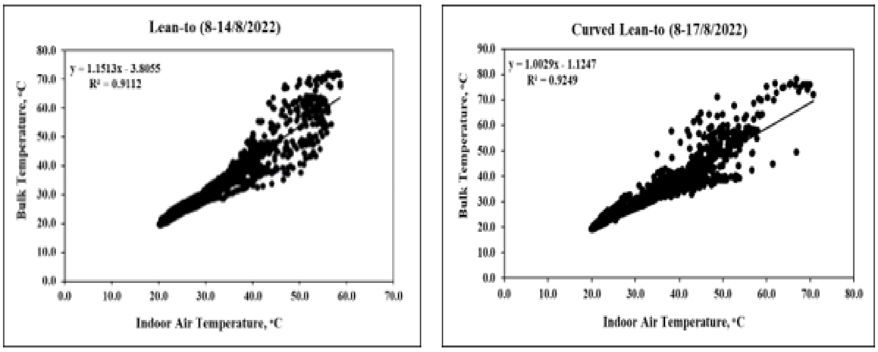


Fig. 8. Dehydrating bulk temperature versus indoor air temperature inside the two solar dehydrators.

A substantial linear association was found through regression analysis (r = 0.9546 and r = 0.9617, respectively; P ≥ 0.001). The best-fit equations between the dehydrating-air temperatures and the bulk temperature of tomato fruits were:

$$T_{bulk}\ (\text{Lean-to}) = -3.8055 + 1.1513\ (T_{ai}) \quad (27)$$

$$T_{bulk}\ (\text{Curved Lean-to}) = -1.1247 + 1.0029\ (T_{ai}) \quad (28)$$

Because of the interrupt electric fan for 2 hours during the diurnal operation hours, fluctuations of the curve had observed during the operating hours in both solar dryers.

Relative Humidity of Drying Air

One common parameter that significantly influences in the dehydrating of agricultural products is the air-relative humidity of the media of drying. It plays a significant part in the drying process due to its capacity to carry on the evaporated water from the product being drying and expel it outside the dehydrator through the exhausted air. The ability of air relative humidity to carry on evaporated water is greatly boosted as its value decreases below the moisture content of the product particularly during the daylight-time. The air-relative humidity has inversely relationship with the drying air temperature. Increase the dehydrating air capacity to carry on a larger amount of moisture that had evaporated from the product being drying causing shortening the dehydrating process time. The hourly average dehydrating-air-relative-humidity within the two solar dehydrators during the dehydration process of tomato fruits, respectively, was 38.9% (±4.0) and 36.2% (±2.9), while the relative humidity of the outside air was 64.6% (±1.1). The dehydrating-air-relative-humidity has cyclically changed from hour to hour and day to day during the experimental work for the two solar dehydrators due to the strength of incident solar radiation, dehydrating-air temperature, and air-relative-humidity outdoors. It had observed that, the dehydrating-air-relative-humidity values steadily decreased until they reached their lowest levels at and around midday (with the maximum intensity of incident solar radiation and higher dehydrating air-temperature). Thereafter, it rose gradually until it reached its greatest levels at the end of each day. According to the intensity of incident solar radiation within the two solar dehydrators and the dehydrating air temperatures, the reduction in dehydrating-air-relative-humidity varied from day-to-day.

Fig. (9) shows the cyclic changes pattern of the dehydrating-air-relative-humidity that measured and recorded within the two solar dehydrators during the ten progressing days. It is clear that, the air-relative humidity outside and within the two solar dehydrators had high values of variation from hour to hour each day at night. Thereafter, they decreased gradually with obvious changes just after sunrise until they reached the minimum values at and around noon (with the maximum intensity of incident solar radiation inside the two solar dehydrators and higher dehydrating air temperatures). The air-relative-humidity then progressively rose during the following hours, approaching the maximum value prior to sunrise. However, during the daylight-time the air relative humidity inside the two solar dehydrators was always lower than that the outside.

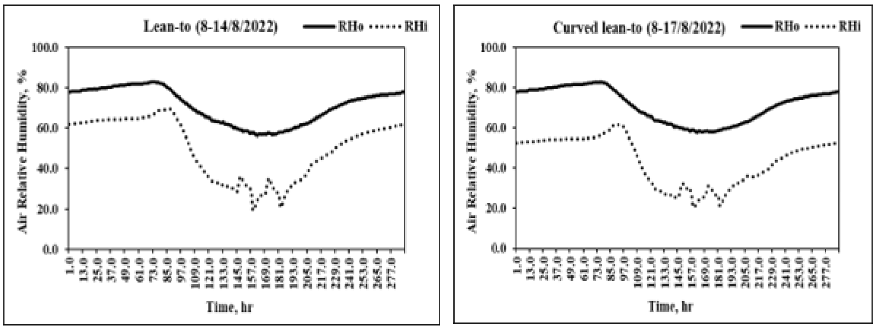


Fig. 9. cyclic changes in air relative humidity outside and inside the two solar dehydrators

Thermal Performance Analysis of Solar Dehydrators

Thermal performance analysis of solar dehydrating systems could make estimates based on either dehydrating efficiency or thermal efficiency depending on the heating power produced by the dehydrating system (dehydrating rates of the products). The mass flow rate of the dehydrating air, its specific heat, and the temperature difference between the input and outlet dehydrating air have a significant impact on the heating power produced by the solar dehydrator. The overall thermal efficiency of solar dehydrators had calculated by dividing the heating power produced by the dehydrator and the amount of solar energy available inside the dehydrator.

The three dehydration methods (using lean-to, curved Lean-to, and natural sun dehydrating) started at 17.00 pm on August 07, 2022, and the dehydrating process continued from 7.00 am on August 08 until it was completed. The dehydration process was interrupt at 15:00 pm on 14/08/2022 (after 68 hours), 12:00 on 17/08/2022 (after 95 hours), and 15:00 on 25/08/2022, (after 178 hrs.) for the three different methods of dehydration process, respectively. The hourly average solar energy available inside the two different solar dryers (lean-to and curved lean-to), respectively, was 1046.8 (±100.5) and 1027.4 (±64.9) Watt. This solar energy available was impacted in the useful heat energy gain, thus the amount of useful heat gain for the two different solar dehydrators was 743.2 (±110.4) and 675.8 (±40.1) Watt, respectively. Therefore, the overall thermal efficiency for the two different solar dehydrators, respectively, was 71.8% (±13.4) and 65.8% (±1.0). The hourly average useful heat energy gain for the lean-to solar dehydrator was 743.2 Watt of which 168.2 Watt had used to evaporate water from the tomato fresh yield during the drying process (68 h). As a result, the overall efficiency in evaporating water from the fresh tomato for the lean-to solar dryer was 22.63%. While the hourly average useful heat energy gain for the curved lean-to solar dehydrator was 675.8 Watt of which 138.3 Watt was used to evaporate water from the fresh yield during the drying process (95 h). Consequently, the overall efficiency in evaporating water from the fresh yield for the curved lean-to solar dryer was 20.46%.

Energy balance on tomato fruits

For forecasting and modeling reasons as well as for the proper construction of a solar dehydrator, a mathematical model of the dehydration process of tomato fruit is crucial. The dehydrating process is a complicated phenomenon that involves both mass and heat transfer. Furthermore, due to the fluctuating in weather conditions throughout the entire process, there is challenging in drying model using solar dehydrating processes. The entire heat energy balance on the product being drying can be described when the tomato fruit had exposed to the solar radiation. The input heat energy (solar energy available) during the dehydrating process of tomato crop had examined against the output heat energy (useful heat energy gain and the heat energy used in evaporating water from the crop) for the two different solar dehydrators as illustrated in Fig. (10). Regression analysis revealed a statistically significant linear relationship between these parameters (r = 0.9888 and r = 0.9979, respectively; P ≥ 0.001). The regression equations under certain conditions provided the following best fit.

$$q_{output}\ (\text{Lean-to}) = 0.7641\ (q_{input}) \quad (29)$$

$$q_{output}\ (\text{Curved Lean-to}) = 0.7043\ (q_{input}) \quad (30)$$

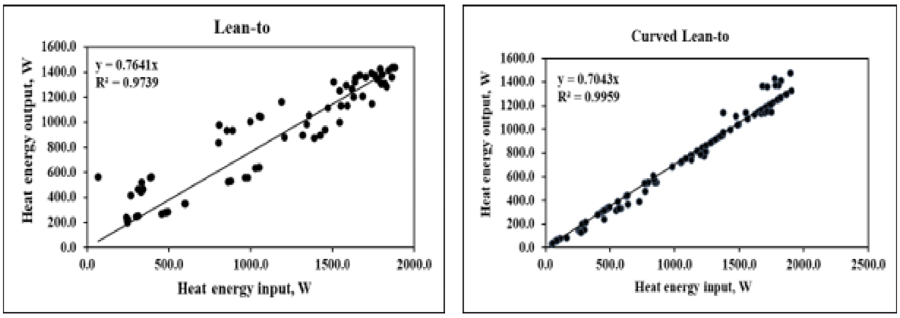


Fig. 10. Heat energy input against heat energy output for the two solar driers during the experiment.

Behaviour of tomato fruit drying

The 66 kg of pre-treated tomato fruits were divided into three equal portions each weighing 22 kg. They are dispersed throughout the three drying trays, which stand for the three various drying regimes (lean-to, curved Lean-to solar dehydrators, and natural sun drying). The tomato fruits were absorbed three components of solar radiation; beam, diffuse, and reflected radiation from the back wall. As a result, the phenomenon of greenhouse effect that occurred inside the two solar dryers caused in increasing the temperature of drying air. The initial moisture content before pre-treatment of tomato fruit ranged from 92.97 to 93.57% (w.b.) with an average initial moisture content of 92.5% w.b. (±0.77%). While, after pretreatment, it ranged from 92.63 to 90.4% w.b. with an average of 91.52 w.b. (± 0.98 w.b.). For the Lean-to, Curved Lean-to, and natural sun dehydration methods, the duration of the dehydrating process was 68, 95, and 178 hours, respectively. As a result, the lean-to solar dehydrator had taken less drying time to dehydrate tomato fruits than the curved lean-to solar dehydrator and the natural sun drying. These variances occurred because of the specific nature of geometric shape for each other and different dehydrating conditions (solar radiation intensity, dehydrating air temperature, and air relative humidity).

The total drying rate of tomato fruits using three different drying methods, respectively, was 284.44, 205.52, and 101.93 g/h. The total drying rate that attained by the lean-to solar drier was higher than that of curved lean-to solar dehydrator and natural sun drying by 38.40% and 179.05%, respectively. For the three different methods of dehydrating, the amount of tomato fruits (22 kg) that were converted into powder of dried tomato, respectively, were 1.740, 1.650, and 1.990 kg. Accordingly, 12.644, 13.333, and 11.055 kg of fresh tomato fruits are needed to produce 1-kilogram powder of dried tomato. The variations in the moisture content of tomato fruits (d. b.) with drying time for the three distinct drying procedures is illustrated in Fig. (11).

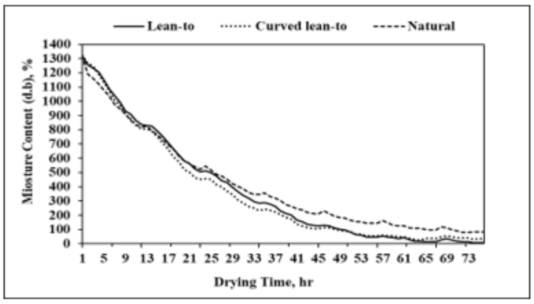


Fig 11. Changes in moisture content of tomato fruits with dehydrating time for the three different drying processes.

It was observed that, the moisture content of tomato fruits for the three drying procedures reduced steadily from their initial moisture content at the beginning of experimental work until reached their final moisture content at the end. It is evident that the moisture content of tomato fruits declined slightly at the beginning of each day, notably during the first three hours and then rapidly reduced. This occurred due to increase the amount of solar radiation falling on the upper surface of the tomato fruits. Identical behaviour was also observed prior to sunset due to the heat energy absorbed by tomato fruits. Depending on the water content of the product being dried and the intensity of incident solar radiation on the product, drying air temperature, and air relative humidity, the change rate in moisture content varied from hour to hour and day to another for the three different dehydration processes.

The air-dehydrating temperature and air-relative humidity, which are the two main dehydrating parameters, typically changed from hour to hour during the drying time of each day as the macroclimatic conditions are changed. This the main reason to make difficult use of any dehydrating model using solar dehydrating method. As a result, operating control of these parameters is very difficult. For ten hours each day, the solar dehydrating process run continuously, and it had only stopped when the temperature of the tomato fruits and the dehydrating air reached a stage of quasi-equilibrium. However, an attempt had made to investigate the behaviour of tomato fruits dried in a thin layer utilising solar energy by running two analytical models (Lewis and Henderson and Pabis models). To investigate the viability of combining the two models with solar dehydrating, the data on the dehydration process of tomato fruits for the distinct techniques of dehydrating were gathered and revealed in Fig. (12).

According to the regression analysis, the Lewis model could significantly applied for the dehydration process utilising solar energy under the specific circumstances. However, Henderson and Pabis model could not used for representing the behaviour of drying process of tomato fruits. The capacity of the drying model is chosen based on the highest determination coefficient and the lowest standard error values. A highly substantial exponential relationship between the moisture ratio and the dehydration time as revealed by regression analysis ($r = 0.9873$, $r = 0.9969$; $P \geq 0.001$).

The regression equations for the best fit using Lewis' model were:

For the lean-to solar dehydrator:

$$\mathbf{MR = \exp(-0.058\,t)} \qquad \mathbf{(31)}$$

For the curved lean-to solar dehydrator:

$$\mathbf{MR = \exp(-0.047\,t)} \qquad \mathbf{(32)}$$

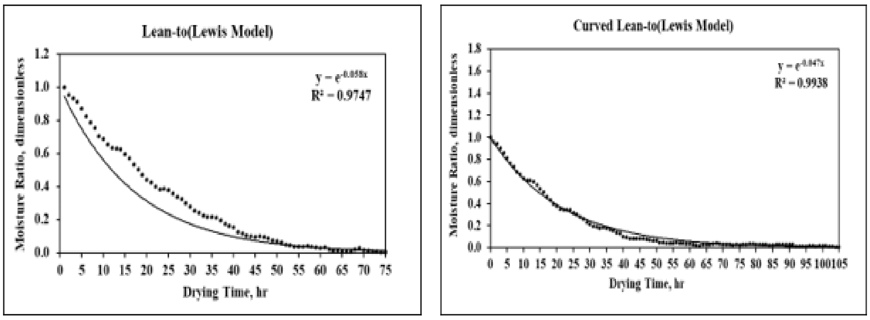


Fig. 12. Moisture ratio versus drying time for the lean-to and curved lean-to solar dryers using the Lewis model

As shown in Fig.(12) The behavior of the experimental data using the solar drying processes of tomato fruits for solar dryers was predicted by simple exponential equations, which indicates a statistically significant relationship between the measured and calculated moisture contents during the experimental work. The coefficient of determination values for the two solar dehydrators using Lewis model was $R^2 = 0.9747$ and $R^2 = 0.9938$, and the standard error values were $SE = 0.0414$ and $SE = 0.0244$, respectively. They demonstrate that, the applying of simple model (Lewis's model) produced a satisfactorily dehydrating behaviour. Lean-to and curved lean-to solar dehydrators were found to have the highest coefficient of determination value (R^2) and the lowest standard error value (SE) when utilising

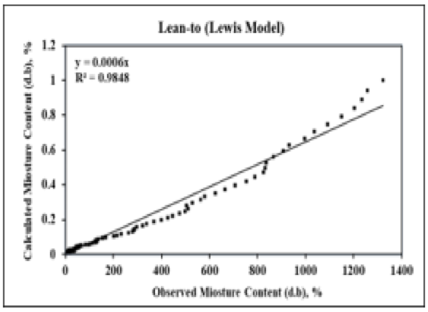
Lewis' model. As a result, the Lewis model considerably recognized by the description of solar dehydration. The relationship between observed and calculated moisture contents for the two different solar dehydrators using Lewis model are plotted in Fig. (13). The coefficient of determination between the observed and calculated of moisture content for the two different solar driers using Lewis model, respectively, was 0.9726 and 0.9910. The linear equations that correlated the observed and calculated of moisture content for the best fit were:

For the lean-to solar drier

calculated= 0.0006 Observed (33)

For the curved lean-to solar drier

calculated = 0.0008 Observed (34)



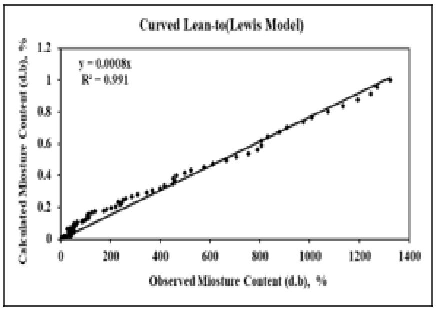


Fig. 13. Observed moisture content versus calculated moisture content using Lewis model for the Lean-to and curved lean-to solar dryer.

Energy Required for Drying Fresh Tomato Fruits

During the dehydration of fresh tomato fruits, the experimental analysis revealed that, the total amount of solar energy consumed without electrical energy values used by extracting fans for evaporating free water from the fresh fruits for the lean-to, curved lean-to solar driers, and natural sun drying, respectively, was 7.327, 10.274, and 22.065 kWh. Whilst, the total amount of energy consumed comprehended solar energy and electrical energy consumed by extracting fans for evaporating free water from the fresh fruits for the lean-to, curved lean-to solar driers, and natural sun drying was 27.453, 40.457, and 22.065 kWh, respectively, as revealed in Fig. (14).

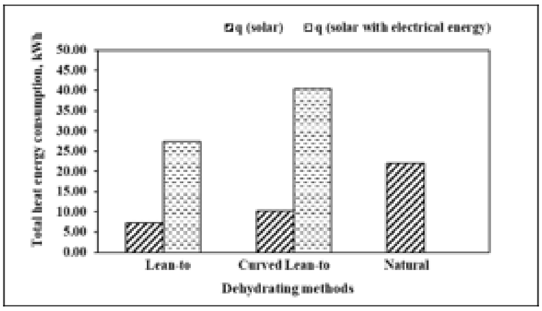


Fig. 14. Total amount of energy consumed for evaporating free water from the fresh fruits during the drying process using the three different dehydrating processes.

By the acting of this total amount of energy consumed by the three different methods of dehydrating of fresh tomato fruits, the amount of free water evaporated from the fresh fruits for the lean-to, curved lean-to solar driers, and natural sun drying, respectively, was 20.260, 20.350, and 20.010 kg. Consequently, the specific free water extraction rates from the fresh fruits without the electrical energy consumed by fans was 2.765, 1.981, and 0.907 kg/kWh, respectively. While, the specific free water extraction rates from the fresh fruits with the electrical energy consumed by fans, respectively, was 0.738, 0.503, and 0.907 kg/kWh.

Effect of Solar Dehydrating on Quality of Dried Tomato

The technology of solar-dehydrating tomato fruits has many benefits, including energy savings (asymptotically zero energy costs), shorter drying times, needs less surface area, improved quality of dried tomato for local marketing (domestic use) and international marketing. Moreover, this technology increases process efficiency, and environmental protection. The dried product (dried tomato) can be used for many industrial processes because solar dehydrators offer quick and consistent dehydration under hygienic circumstances. However, the dehydration process significantly affects the physical characteristics of the agricultural product being drying using any method (natural sun, solar dehydrator, or industrial drying). This preservation process is leading to changes in shape, volume, colour, texture, and nutrient components. The effect of drying process on the quality of final product had investigated and examined as one of the main goals of this study. Before and after the drying process for the three distinct dried procedures, four different physical and chemical components, including the percentage of nitrogen and ash, total lycopene in mg/100 g, and total ascorbic acid in mg/100 g, were tested and measured

Fig. (15) shows the effect of drying process using three different drying modes (lean-to and curved lean-to solar dehydrators, and natural sun dehydrating) on the percentage of nitrogen and ash, while Fig. (16) shows total lycopene, and total ascorbic acid in mg/100g. Tomato fruits are a rich source of nitrogen content, as the total nitrogen present in fresh tomatoes was 2.18%. This percentage of nitrogen content had decreased after the drying process into 0.99%, 0.70%, and 1.05%, respectively. Accordingly, the total nitrogen content of the dried tomatoes produced by natural sun drying was higher than that achieved by the lean-to and curved lean-to solar dryers. It also observed that, the drying process of tomato fruits led to an increase in the percentage of ash in dried tomatoes using the three patterns as compared with the fresh tomato fruits. The percentages of ash in the fresh tomato fruits, was 7.5% that increased into 38.03%, 30.21% and 30.92% for the lean-to, curved lean-to solar driers and natural sun drying, respectively. An increase in its essential lycopene content had observed between fresh and dried tomato fruits, as it had affected by the drying processes and drying time of the three different drying methods. It augmented from 0.201 mg/100 g in the fresh yield into 6.506, 19.912, and 7.739 mg/100 g in the dried product using the three different drying processes, respectively. A decrease in its essential content of ascorbic acid had observed between fresh and dried tomato fruits, as it also affected by the drying processes and drying time for the three different drying methods. It decreased from 76.190, mg/100 g in the fresh tomato crop into 13.514, 10.811, and 24.324 mg/100 g in the dried product for the lean-to, curved lean-to solar driers, and natural sun drying, respectively. Consequently, the drying process decreased the ascorbic acid by 82.26%, 85.81%, and 68.07%, for the three different methods of drying, respectively. These obtained results are agreement with that published by Elfar (2022).

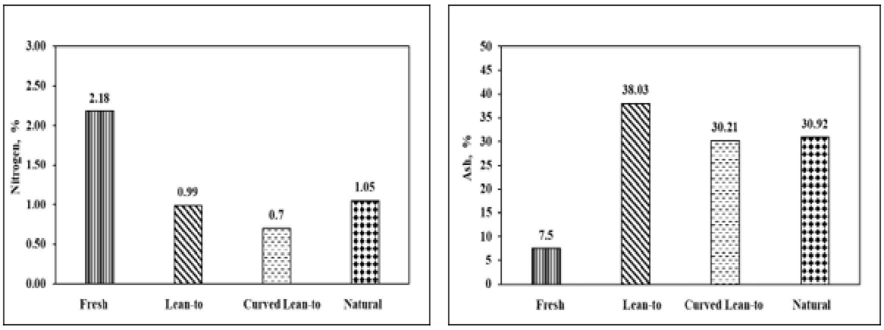


Fig. 15. Chemical components of fresh and dried tomato comprehended Nitrogen and Ash

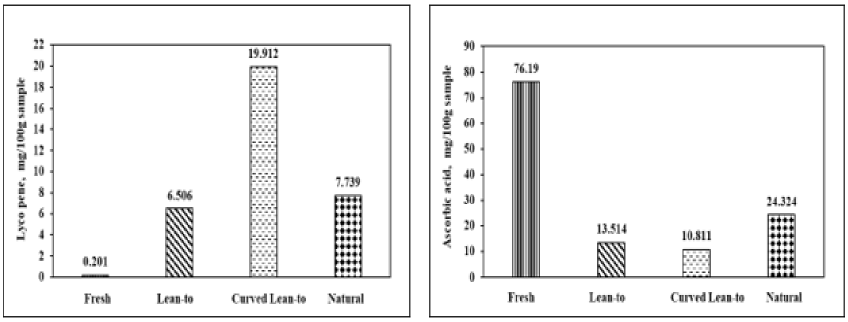


Fig. 16. Chemical components of fresh and dried tomato comprehended Lycopene and Ascorbic acid

Finally, solar drying process using solar dryers with different architectural forms (lean-to and curved Lean-to) for the fresh tomato fruits were converted into dried tomatoes with a higher level of quality as compared with the natural sun-drying. In addition, the quality of dried tomatoes, which dried using lean-to solar dryer, was higher than the dried product by curved Lean-to solar dryer.

CONCLUSION

For the duration of the experimental work, the achieved and obtained results can be summarized in the following points:

(1) The hourly average incident solar radiation outside and inside the lean-to solar dryer during the drying time, respectively, was 628.8 W/m2 and 523.4 W/m2, while, the intensity of solar radiation outside and inside the curved lean-to solar dryer, respectively, was 621.4 and 513.7 W/m2. As a result, the two different solar driers (lean-to and curved lean-to) raised the drying air temperature over the outside by 8.7 ºC and10.0 ºC, respectively. The hourly average bulk temperatures of tomato fruits inside the two solar driers during the dehydrating period, respectively, were 40.5 and 39.1 ºC.

(2) The hourly average dehydrating-air-relative-humidity within the two solar dehydrators during the dehydration process of tomato fruits, respectively, was 38.9% and 36.2%, while the relative humidity of the outside air was 64.6% (±1.1). Consequently, the percentage reduction in air-relative humidity of drying air for the two solar dehydrators, respectively, was 39.78% and 43.96%.

(3) The hourly average useful heat energy gain for the lean-to solar dehydrator was 743.2 Watt of which 168.2 Watt used to evaporate water from the fresh yield during the drying process (68 h). As a result, the overall efficiency in evaporating water from the fresh tomato for the lean-to solar dryer was 22.63%.

(4) The hourly average useful heat energy gain for the curved lean-to solar dehydrator was 675.8 Watt of which 138.3 Watt was used to evaporate water from the fresh yield during the drying process (95 h). Consequently, the overall efficiency in evaporating water from the fresh yield for the curved lean-to solar dryer was 20.46%.

(5) The initial moisture content of tomato fruit before and after pre-treatment was 92.50% and 91.52% w.b., respectively.

(6) The total drying rates for the two different solar driers (lean-to and curved lean-to), respectively, were 284.44 g/h and 205.52 g/h. While, the total drying rate for the natural sun drying was 101.93 g/h. Consequently, the two solar driers were increased the drying rate by 179.05% and 101.63% as compared with the natural sun drying.

(7) Total amount of energy needed for drying fresh tomato fruits comprehended solar energy and electrical energy consumed by extracting fans, respectively, was 27.453, 40.457, and 22.065 kWh.

(8) The specific free water extraction rate by the three different drying systems was 0.738, 0.503, and 0.907 kg/kWh, respectively.

(9) The percentage of nitrogen content in the fresh fruits was 2.18% which decreased after the drying process for the three different drying methods (lean-to, curved lean-to solar driers, and natural sun drying) into 0.99%, 0.70%, and 1.05% for, respectively. The percentages of ash in the fresh tomato fruits was 7.5% that increased into 38.03%, 30.21% and 30.92%, respectively.

(10) The percentages of lycopene in the fresh tomato fruits, was 0.201 that increased into 6.506, 19.91 and 7.739 (mg/100 g) for the three different drying methods, respectively. The percentages of ascorbic acid were

76.19 in fresh tomato fruits, while it decreased to 13.514, 10.811, 24.324 (mg/100 g), respectively.

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تجفيف محصول الطماطم باستخدام شكلين هندسيين مختلفين للمجففات الشمسية

صلاح مصطفى عبد اللطيف ، ياسر مختار الحديدي ، حميدة خالد محمد فاروق و غادة على مسعد

قسم الهندسة الزراعية – كلية الزراعة – جامعة المنصورة

الملخص

الهدف الرئيسي من هذا البحث هو تجفيف ثمار الطماطم وتحويلها إلى بودر (مسحوق الطماطم) باستخدام نوعين مختلفين في الشكل الهندسي من المجففات الشمسية Lean-to and curved lean-to التي تعمل تحت نظام الحمل الجبري ومقارنتها بالطريقة التقليدية (التجفيف الشمسي الطبيعي). تم تقطيع ثمار الطماطم إلى أنصاف ومعالجتها بكلوريد الصوديوم (5%) وتوزيعها على صواني التجفيف الخاصة بكل مجفف شمسي وعلى صينية التجفيف التقليدية التي تتعرض لأشعة الشمس المباشرة. تعتبر شدة الإشعاع الشمسي ودرجة حرارة الهواء الجاف والرطوبة النسبية لهواء التجفيف من العوامل السائدة التي تؤثر علي عملية التجفيف، لذا فقد تم رصد وقياس هذه العوامل بدقة أثناء العمل التجريبي الذي تم إجراؤه في أغسطس 2022. أجريت التجارب العملية بمحطة التجارب والبحوث الزراعية بكلية الزراعة جامعة المنصورة عند زاوية خط عرض مقدارها 31.043 ºN وزاوية خط طول مقدارها 31.352 ºE وارتفاع مقداره 6.72 m عن مستوى سطح البحر. كان المحتوى الرطوبي الأولي لثمار الطماطم قبل وبعد المعالجة المسبقة 92.50% and 91.52% w.b. على التوالي وانخفض الي 7% w.b. w.b. (±0.74 w.b.) بعد التجفيف خلال 95 and 68 ساعة للمجففين بينما وصل إلي 15.64%w.b. خلال 178 ساعة للتجفيف الشمسي الطبيعي. كما أصبحت معدلات التجفيف للمجففين (lean-to and curved lean-to) على التوالي 284.44 g/h and 205.52 g/h بينما معدل التجفيف الشمسي الطبيعي 101.93 g/h أظهر التحليل التجريبي أن إجمالي الطاقة المستهلكة اللازمة لتجفيف ثمار الطماطم الطازجة من الطاقة الشمسية والطاقة الكهربائية المستهلكة بواسطة مراوح سحب الهواء من المجففات الشمسية كانت 27.453, 40.457, and 22. 065 kWh على التوالي. نتيجة لذلك كان معدل استخلاص الماء الحر بواسطة أنظمة التجفيف الثلاثة المختلفة 0.738, 0.503, and 0.907 kg/kWh على التوالي.

الكلمات الدالة: الإشعاع الشمسي – التجفيف – المجفف الشمسي