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Development and Performance Evaluation of the Double Ventilated Solar Dryer for Drying some Agricultural Products

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ABSTRACT

The experimental work was carried out in the summer season of 2023 at Agricultural and Bio-systems Engineering Department, Faculty of Agriculture, Damietta University, Egypt (Latitude 31°25′35″ North, Longitude 31°39′03″ East) to manufacture and develop the double ventilated solar dryer for drying chill, lemon and tomato. The manufacture dryer consists of the solar collector which attached with the drying chamber through 3 isolated pipes. All ambient and solar dryer conditions were measured using a locally calibrated solar radiation, temperature and relative humidity data loggers with thermocouples, and also a Weather Total Station. The maximum solar radiation for the dryer chamber, collector and ambient were 1000, 1000 and 1100 W/m^2, respectively. The maximum temperatures for the entrance; upper, middle, lower trays; exit; and collector were 41, 64, 62.5, 61.79, 42.29, and 83.9°C, respectively. The minimum air relative humidity at entrance and exit slots were 11 and 13%, during the day hour of 2pm, while the maximum air relative humidity at entrance and exit slots were 71 and 65%, during the day hour of 9am. The decrease of moisture content ratio were decreased from 85.4, 86.6 and 88.2% fresh product to 10.46, 13.52 and 8.83% dry product in total drying time of 15, 21 and 19h for chilli, lemon and tomato, respectively in the upper tray and air suction speed of 0.6 m/s. The drying rate were decreased after the first hour of drying from 9.37, 8.46 and 8.32% to 5, 3.48 and 4.18% during total drying time of 15, 21 and 19h for chilli, lemon and tomato, respectively in the upper tray and air suction speed of 0.6 m/s. The higher values of solar collector efficiency (η_C) were 74.27, 75.74 and 73.09% at the day hour of (1pm) during three drying days of 29, 30 and 31/8/2023, respectively and 1.6 m/s air suction speed. The lower values of (S.R.U.E) were 46.35, 46.35 and 51.90% around the day hours between (2 and 3pm) at three drying days of 26, 27 and 28/8/2023, respectively and 0.6 m/s air suction speed. The dried amount of chilli halves, lemon slices and tomato slices for each upper tray were 32.40, 28.62 and 25.59 kg/month; 23.58, 23.58 and 20.61 kg/month and 21.33, 25.29 and 16.92 kg/month at different air suction speeds of 0.6, 1.1 and 1.6 m/s, respectively. The solar drying cost of chilli halves, lemon slices and tomato slices for each upper tray were 10.28, 11.65 and 13.03 L.E/kg.month; 14.14, 14.14 and 16.17 L.E/kg.month and 15.63, 13.18 and 19.70 L.E/kg.month at different air suction speeds of 0.6, 1.1 and 1.6 m/s, respectively. The net present worth of total cash income from drying of chilli, lemon and tomato under solar dryer was found to be 5250 L.E. The benefit cost of chilli, lemon and tomato in solar dryer was found to be 17025 L.E. So, the payback period for drying of chilli, lemon and tomato in solar dryer was found to be 98 days or (3 months and 8 days).

1. INTRODUCTION

The earth's surface has received approximately 1014 kW of solar energy from the sun. The energy equivalent of around 1 HP or 1 kW is supplied by one square meter of land exposed to direct sunlight. Large-scale conversion of solar energy involves a large investment of resources. In contrast to other sources of electricity, solar energy has some strong advantages. Solar radiation does not contaminate the atmosphere or jeopardies environmental equilibrium. It prevents serious problems such as mining, extraction and transportation. They protect agricultural produce from insect pests, dust and rain damage. Higher temperatures, lower relative humidity and lower product moisture content are produced by solar dryers. Solar dryers can be considered one of the solutions to the food and energy shortages of the planet. Solar dryers are mainly divided into three groups, which are: Direct solar drying, indirect solar drying and mixed mode solar drying. Drying refers to a process in which water is removed from a moist material by using heat as the energy input. The mechanism of drying is a complex phenomenon involving combined heat and mass transfers within a biological food material. Drying has been reported to account for anywhere from 12% to 20% of the energy consumption in the industrial sector, **Raghavan *et al.* (2005)**. The basic essence of drying is to reduce the moisture content of the product to a level that prevents deterioration within a certain period of time, normally regarded as the safe storage period, **Ekechukwu (1987)**. Drying involves the removal of moisture from the product by heating and the passage of air mass around it to carry away the moist vapor. Drying is an energy-intensive process because the latent heat has to be supplied to the material to evaporate the moisture from the product. Drying offers a means of preserving foods in a stable and safe condition as it reduces water activity and extends shelf-life much longer than that of fresh foods and agricultural products. A major challenge of drying fresh foods and agricultural products is to reduce the moisture content to a certain low level while maintaining the quality attributes such as color, texture, chemical components and shrinkage, **Orsat *et al.* (2007)**. In conventional heating, such as hot air and infrared drying, thermal energy is transferred from material surface to interior due to temperature gradients. These drying processes have low drying rates causing long drying times in the falling rate period of drying. The long drying times at relatively high temperatures often lead to undesirable thermal degradation of the finished products, **Zhang *et al.* (2006)**. Sun drying is a cheap method of preserving fruits and vegetables because it uses sunlight as its source of heat. However, it is generally accepted that open-air sun drying has limitations such as dust contamination, bird and rodent attacks, fungal attacks and the risk associated with sudden rainfall on the product being dried, **Ojike *et al.* (2010)**. **Sharma *et al.* (1994)** gave a preliminary economic analysis for an indirect type solar fruit and vegetable dryer. The analysis stressed that the most significant economic parameters in the lifecycle costing of the system were the payback period and internal rate of return. And the important and influential parameters, namely, initial investment, fuel price, interest on fuel price, etc. Artificial drying is high energy intensive and expensive process. It raised the cost of final product. A systematic approach for the classification of solar energy dryers were also evolved, identifying two generic groups, namely, passive or natural circulation solar energy dryers and active or forced convection. It is fertile to get infected from foreign particles, rain, and beast. Therefore, it is important to develop solar dryer in third world countries to avoid the shortcoming of natural drying, **Yaldiz *et al.* (2001)**. The drying methods used for vegetables and fruits depend on using heat in an appropriate manner until the moisture content in vegetables decreases to (4-6%) and in fruits to (18-22%) due to containing a higher percentage of bound sugar, which reduces the amount of free water available for microbial activity. There are factors that help the success of the food drying process such as adjusting the temperature, air speed, and relative humidity, while controlling the drying duration. The Arab countries, especially (Egypt and Libya) having a large number of sunshine hours in summer and winter. Therefore, this solar energy can be exploited to dry many agricultural products (vegetables and fruits). So, the objectives of this study are to:

1. Manufacture a double-ventilation solar dryer using local materials.
2. Develop of double-ventilation solar dryer to improve product quality and reduce production costs.
3. Study the most appropriate operational factors during drying process to obtain the best quality of the dried product
4. Evaluate the manufactured solar dryer from an economic perspective.

2. MATERIALS AND METHODS

The experimental work was carried out in the summer season of 2023 at Agricultural and Bio-systems Engineering Department, Faculty of Agriculture, Damietta University, Egypt (Latitude 31°25′35″ North, Longitude 31°39′03″ East) as shown in **Fig. (2.1)** to manufacture and develop the double ventilated solar dryer for drying some agricultural products under Egyptian conditions; investigate and estimate both the performance and the dryer efficiency in both solar collector and drying chamber during drying process. The main experiments were carried out during the summer season of 2023 at the late August from 20/8/2023 until 31/8/2023.

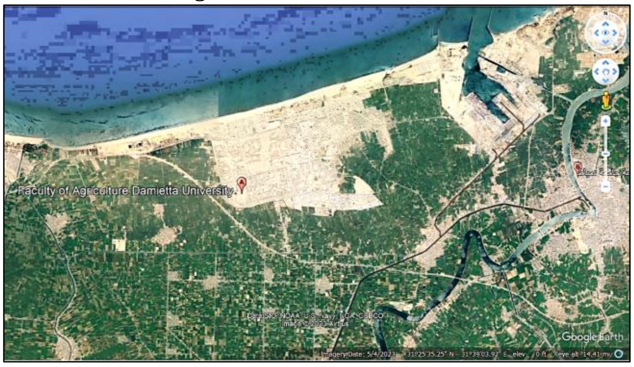


Fig.(2.1): Location of experimental work according to Google Earth 2023.

2.1. Materials:

2.1.1. Agricultural products:

Fresh red chilli (Chilli variety), Lemons (Balady variety) and Tomatoes (080 variety) used in this study were bought from a local market at New Damietta city, Damietta governorate, Egypt, as shown in **Fig. (2.2)**.

Chilli **Lemon** **Tomato**

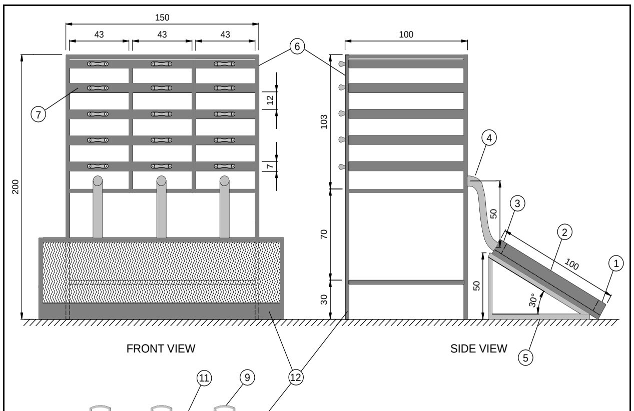
Fig.(2.2): Fresh (Red chilli, lemon and tomato) used in the study.

2.1.2. Solar dryer:

The solar dryer consists of two main components names: solar collector and drying chamber, as shown in **Fig. (2.3)**.

Fig.(2.3): Solar collector and drying chamber.

A. Solar collector: The solar collector is made of wood and covered with (2 mm) Polycarbonate transparent sheet at the top in order to concentrate the solar radiation into the inner area. The solar collector has dimensions of (200×100×25 cm) for length, width and thickness. The solar collector consisted of flat plate solar air heater having area of 2 m^2 and connected with drying chamber using three wire support flexible thermal pipes with diameter of 3 inches for each. The solar air heater has 2 mm thick serrated aluminum sheet painted with black color to absorb the incident solar radiation. The absorber plate was placed directly behind the transparent cover (Polycarbonate) with a layer thickness of air heating of 10 cm, **Fig.(2.4)**. The air to be heated passes from two side holes with square area of 30 cm^2 for each to the drying chamber through the flexible pipes. The longitudinal axis of the solar collector was located at the E-W direction facing the sun shine with an inclination angle of 30°. Two sensors for both solar radiation intensity and air temperature inside the solar collector were fixed into its middle area to determine their values.



No.	Part Name	No.off	Materials	Notes
1	Air inlet	1		(6*8cm)
2	Solar collector	1		
3	Air outlet	1		(3 Inch)
4	Thermal hose	3	Plastic	(3 Inch)
5	Collector stand	2	Wood	(95*82*48cm)
6	Drying chamber	1	Wood	
7	Tray	15	Wood+steel	(94*43cm)
8	Serrated sheet	1	Aluminum	(197*94cm)
9	Tray handle	15	Steel	
10	Suction fan	2		(15*15cm)
11	Spare fan	1		
12	Main frame	1	Wood	

Fig.(2.4): An engineering drawing for solar dryer.

B. Solar drying chamber: The solar drying chamber is made of wood and covered with 2 mm Polycarbonate transparent sheet from top, bottom and lateral sides in order to increase the drying air temperature coming from solar collector. The solar drying chamber has dimensions of (150×100×100 cm) for length, width and height, respectively. The solar drying chamber consists of 15 trays distributed through three vertical stacks; each tray has dimensions of (100×43×5 cm) for length, width and height, respectively. The tray frame was made of wood and the bottom side which carries the agricultural product was a galvanized metal mesh with rhombus in shape. The vertical distance between two trays was (10 cm) to allow the hot air passing through the products to be dried.

Nine sensors for solar radiation intensity, air temperature and air humidity were fixed inside the solar drying chamber to determine their values as following: Three sensors for air temperature and other three sensors for air humidity were fixed above the upper, middle and lower trays; one sensor for product temperature and one sensor for product moisture were fixed in the agricultural product.

The last sensor was fixed in the middle of the drying chamber at the upper side to determine the solar radiation intensity. The drying chamber supported with two air suction fans (50W) to force drying air to transfer from the solar collector to the drying chamber through the flexible pipes, each fan has suction diameter of (12 cm) rotating at different controlled speeds.

2.1.3. Air temperature data logger:

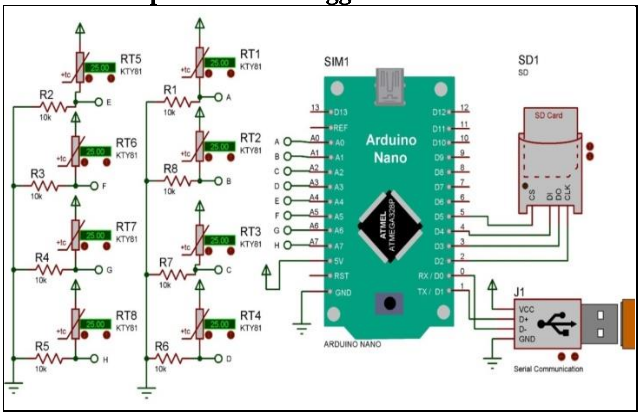


Fig.(2.5): Data logger for measuring temperature (8 ports), (Locally programed and assembled).

2.1.4. Solar radiation and air humidity data logger:

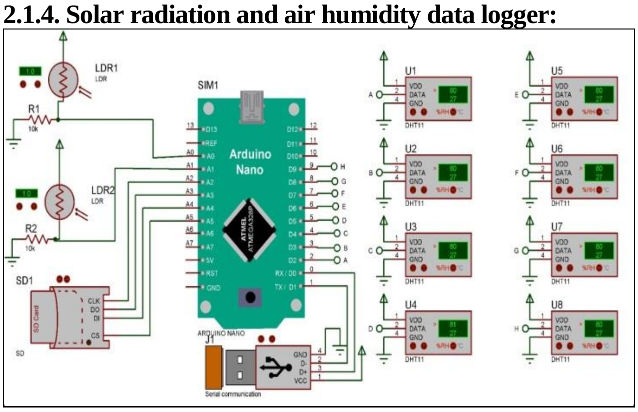


Fig.(2.6): Data logger for measuring relative humidity (6 ports) and solar radiation (2 ports), (Locally programed and assembled).

2.1.5. Weather total station:

The weather station components were purchased from an electrical store in Cairo city, and constructed by an electro-engineer to measure all weather conditions at all drying test runs. The locally weather station comprises the following components as shown in **Fig.(2.6)**.

- A 12-volt, 40-watt solar panel.
- Power regulation using the MAX1724EZK5a step-down regulator to charge the battery.
- A 7.4-volt battery composed of two 3.7-volt lithium-ion cells.
- A 5-volt regulator (LM7805).
- An Arduino Nano (ATMEGA328P).
- A Bluetooth module (HC-06).
- A 4GB SD card and SD card module.
- An ultrasonic module (HC-SR04) for rain gauge.
- An LDR module for light meter (lux).
- A wind fan module for measuring wind speed and direction.
- An anemometer module for wind speed measurement (meters per minute).
- A DUT22 sensor for measuring humidity and temperature.

This system continuously communicates data through a dedicated mobile application, and data is saved at 5 minute intervals on the SD card module for monitoring purposes.

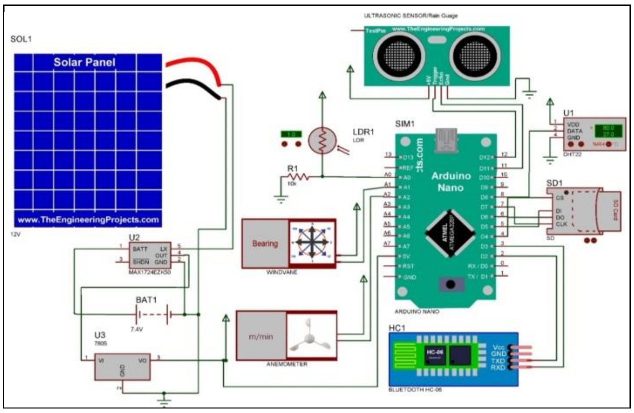


Fig.(2.7): Weather total station powered with solar panel, (Locally programed and assembled).

Fig.(2.8): Weather total station beside solar dryer.

2.1.6. Electrical suction fan: Two electrical Golden Sun 220V 0.23A suction fans (12×12 cm), made in China with 50 Watts and 5000 rpm was used to intake hot air from solar collector to the drying chamber at the adjustable speed.

2.1.7. Solar power meter: A digital solar power meter made in TENMARS ELECTRONICS CO., LTD, TAIPEI 114, TAIWAN, with a measuring range of solar radiation (1-1999 W/m^2) with resolution of 1W was used during the experimental treatments to determine the solar radiation outside of the drying device and also to calibrate both Data logger and Weather total station.

2.1.8. Anemometer: A digital anemometer made in China with a measuring range of air speed (0.8-40 m/s) with resolution of 0.01 ± (2.0%+30) was used during the experimental treatments to determine the air speed of the exhausted fans.

2.1.9. Digital balance: A digital balance made in China with a measuring range of 0-10kg ± 0.1g was used during the experimental treatments to determine the initial weight of the agricultural product and also the decrease in weight for each drying treatment.

2.1.10. Electrical oven: An electrical oven made in Italy, model A3-214-535V with an accuracy of ± (0.2-0.5%) was used to record the moisture content of agricultural product. Triple (100 g) of samples for each agricultural product were dried in the electrical oven at 105 °C for 24 h.

2.1.11. High performance liquid chromatography, (HPLC): The organic acids for fresh and dried agricultural products in this study separated and simultaneously determined by (HPLC).

2.2. Methods:

2.2.1. Drying product preparation:

Only good quality of fresh red chilli, lemon and tomato samples were brought from a local market in New Damietta city during the summer season of 2023 and checked up carefully to discard spoiled ones to prevent contamination of these products by bacteria or fungi. Each patch from these products was carefully washed and dried from water. Before solar drying experiments, the products were not treated with any chemicals and sliced as following, as shown in (**Fig.2.9)**.

Fig.(2.9): Sliced (Red chilies, lemons and tomatoes) before drying process.

- Chilli: were sliced into longitudinal halves.
- Lemon: were sliced into equal thicknesses of 5mm ± 1mm.
- Tomato: were sliced into equal thicknesses of 5mm ± 1mm.

Each patch with total weight of 1000 g from these products was dried until the required final moisture content was attained. The fresh product was located over the tray of drying chamber having about 90% perforation.

The initial moisture content was calculated by taking three different samples. During the experiment moisture content was calculated at every interval of one hour during the drying hours. The suction fan was operated for reducing of relative humidity inside the solar dryer. The different parameters were observed during the experiment hours at every interval inside and outside the solar dryer. Open sun drying method was also conducted to know the performance of the dryer. Solar dryer was tested for its performance in drying of these products by conducting three sets of experiments. The tests were conducted from 09.00 to 18.00 h and the hourly data were recorded from Data loggers and Total solar station.

2.2.2. Distribution of drying trays inside the dryer:

The full load test was conducted for evaluate the performance of the double ventilated and forced convection solar dryer in actual loading condition with a single thin layer of each product. The dryer contains 9 trays; 3 trays upper, 3 trays medium and 3 trays lower; 1000 g of red chilli, lemon and tomato were placed on the upper, medium and lower trays interchangeably, as show in **Fig.(2.10)**.

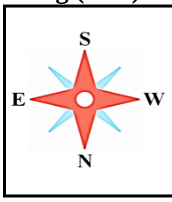
	**Tray (1) Lemon**	**Tray (2) Chilli**	**Tray (3) Tomato**	**Upper**
	Tray (4) Chilli	**Tray (5) Tomato**	**Tray (6) Lemon**	**Middle**
	Tray (7) Tomato	**Tray (8) Lemon**	**Tray (9) Chilli**	**Lower**

Fig.(2.10): Locations of drying trays inside the dryer chamber according to the original direction.

Loading and unloading the products into the solar dryer was done manually. 1000 g of fresh chilli, lemon and tomato were placed in the open air for natural drying for comparison purpose. The observations of the parameters were recorded at interval of one hour starting from 9.00 h to 18.00 h each day. By using oven drying method the initial moisture content of fresh red chilli, lemon and tomato were determined. The drying process was continued till the moisture content of these products tends to a constant value. The performance of drying unit was evaluated in terms of moisture content variation, drying rate, etc. For this purpose, the hourly reductions in weight of representative sample were recorded.

2.2.3. Study variables:

- Three different agricultural crops: Chilli, Lemon and Tomato.
- Three different drying air speeds: 0.6, 1.1 and 1.6 m/s.
- Three different tray locations: upper, middle and lower.

2.3. Measurements

2.3.1. Moisture content, wet basis, (%):

It is the ratio between the weight of moisture in the material and the total weight of the material (w.b), **Kenneth and Hellevang, (1995)**.

$$w.b = \frac{W_t - W_d}{W_t} = \frac{W_m}{W_m + W_d}, \% \ldots..(1)$$

Where: W_t = Total material weight (weight before drying), g
W_d = Dry weight of the material (weight after drying), g
W_m = Moisture weight in the material, g

2.3.2. Removed moisture by unit time: The moisture removed can be calculated by extracting the moisture content first before the drying process and then the moisture content after the drying process and the difference between them is equal to the amount of moisture to be expelled attributed to the completely dry weight of the material. Weight of moisture to be removed (evaporated) from one unit of fresh matte (M.R), **Arun and Adharsh (2014)**.

$$M.R = \frac{M_p (M_i - M_f)}{(100 - M_f)}, \% \ldots..(2)$$

Where: M_p = Sample weight, kg.
M_i = Initial moisture content, %.
M_f = Final moisture content, %.

2.3.3. Drying rate:

It is the weight of fresh material producing one unit of weight of the dried material (D.R). The drying rate is proportional to the difference in moisture content between material to be dried and the equilibrium moisture content. The concept of thin layer drying was assumed for the experiments as reported by **Fudholi, *et al*., (2013)**.

$$D.R = \frac{dM}{dt}, \ldots..(3)$$

Thus we can write from equation (4) as following:

$$D.R = \frac{M.R}{t}, \% \ldots..(4)$$

3.3.4. Solar collector thermal efficiency:

The solar collector's thermal efficiency is the ratio of useful heat gain by the collector to the energy incident in the plane of the collector. It was determined using the following equation **(Fudholi *et al.* 2014)**:

$$\eta_C = \frac{Q_u}{Q_i} = \frac{m_a . C_p .(M_{a.out} - M_{a.in})}{(I_T \times A_C)}, \ \% \ldots\ldots(5)$$

Where: η_C = Solar collector thermal efficiency, %.
Q_u = Heat gain, J.
Q_i = Energy incident in the plane of the collector, J.
M_a = Air mass flow rate, kg/s.
C_p = Specific heat of the agricultural product, 1.005 J/kg.°C.
$T_{a.out}$ = Outlet air temperature,°C.
$T_{a.in}$ = Inlet air temperature,°C.
I_T = Intensity solar radiation, W/m2.
A_C = Area of solar collector, m2.

3.3.5. Air mass flow rate:

The air mass flow rate (m_a) through the solar collector during the drying process was calculated as follows, **(Sadodin and Kashani, 2012)**:

$$m_a = A_h . v . \rho_a, \quad kg/s \ldots\ldots(6)$$

Where: A_h = Surface area of the suction fan, m^2.
v = Air speed of through the solar dryer, m/s.
ρ_a = Density of the drying air, 1.2 kg/m^3.

2.3.6. Solar radiation utilization efficiency:

The solar radiation utilization efficiency can be calculated as a percentage ratio with divided the temperature in the solar collector to the exhausted air temperature out from the suction fan.

$$E_D = \frac{T_E}{T_C}, \% \ldots..(7)$$

Where: T_C = Air temperature in the solar collector, °C.
T_E = Air temperature out from the suction fan, °C.

2.3.7. Solar dryer productivity:

The machine productivity was calculated during grinding operation by the following equation:

$$Pr = \frac{D_M}{t}, \% \ldots..(8)$$

Where: Pr = Solar dryer productivity, kg/month,
D_M = Dry mass of product, kg,
t = Time consumed in the drying operation, month.

2.3.6. Solar drying hourly cost: The cost per hour of drying process using the solar dryer is calculated from the following formula by **Awady, (1978)**.

$$C_H = \frac{P}{h}\left(\frac{1}{a} + \frac{i}{2} + t + r\right) + (W.e) + \frac{m}{300}, \ldots..(9)$$

Where:

Table (3.1): Cost analysis of drying operation using solar dryer.

Item	Value	Unit
C_H = Hourly cost	10	L.E/h
P = Price of solar dryer	15000	L.E
H =Yearly working hours	1500	h/year
a = Life expectancy of the dryer	7	Year
i = Interest rate/year	10	%
t = Taxes, overheads ratio	6	%
r = Repairs and maintenance ratio	7	%
W = Fan power	50	W
e = Hourly kW price	1.40	L.E/kW.h
m = Monthly average wage	1500	L.E/month
300 = Monthly working hours	300	h/month

3.3.7. Solar drying unit cost: The drying cost of the production unit using the solar dryer is from in the following equation:

$$C_U = \frac{C_H\,(\text{L.E/month})}{\text{Pr (kg/month)}}, (\text{L.E/kg})......(10)$$

Where: C_H = Monthly cost, L.E/month.

Pr = Solar dryer productivity, kg/month.

3.3.8. Payback period: The payback period is the length of time from the beginning of the project until the net value of the incremental production stream reaches the total amount of the capital investment. The payback period of the project is estimated by using the straight forward formula, **Kamble *et al*. (2013).**

$$P_A = \frac{I}{E}, \text{month}......(11)$$

Where, P_A= Payback period of the project.

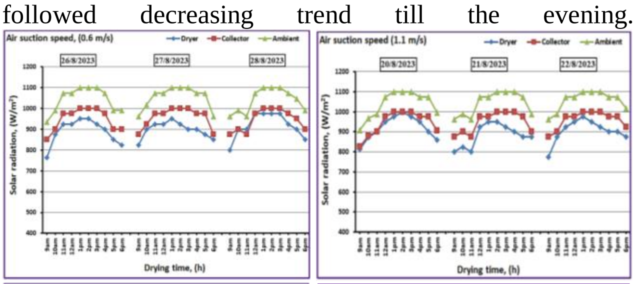
I = Investment of the project, L.E.

E = Monthly net cash revenue, L.E.

3. RESULTS AND DISCUSSIONS

3.1. Solar radiation at air suction speeds of (0.6, 1.1 and 1.6 m/s):

It was observed from **Fig.(3.1)** that the solar radiation during all the days of the experiment was of similar values. The maximum solar radiation for the dryer chamber, collector and ambient were 1000 W/m^2, 1000 W/m^2 and 1100 W/m^2, respectively. It was also observed that maximum solar radiations were around the day hour of (2pm) which was recorded the maximum solar radiation. These results agree with **Samreen *et al.* (2017),** who reported that the solar radiation was a minimum in morning increased to reach maximum at 1.00 pm, later it followed decreasing trend till the evening.



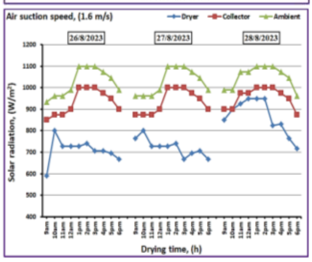
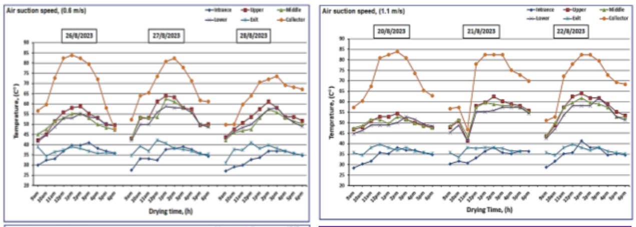


Fig.(3.1): Solar radiation in ambient, collector and drying chamber during drying time at different air suction speed of 0.6, 1.1 and 1.6 m/s.

3.2. Air temperature degrees at different air suction speeds of (0.6, 1.1 and 1.6 m/s):

It was observed from **Fig.(3.2)** that the maximum temperatures for the entrance; upper, middle, lower trays; exit; and collector were 41°C, 64°C, 62.5°C, 61.79°C, 42.29°C, and 83.9°C, respectively. While the difference between air temperature at the upper tray and the lower one was about 2.21°C at the day hour of (2pm).



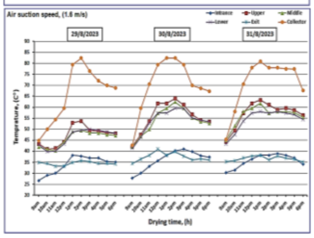
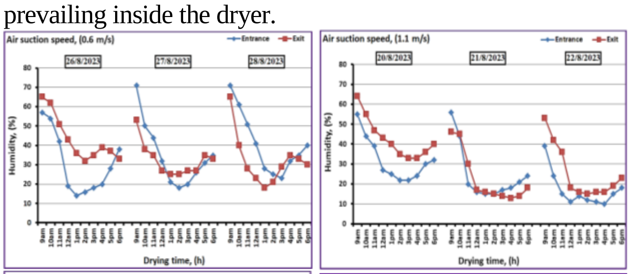


Fig.(3.2): Air temperature degrees at different locations during solar drying time at different air suction speeds of (0.6, 1.1 and 1.6 m/s)

However, the air temperature in the dryer was a little more 60°C to be suitable for drying agricultural products. A similar result was reported by **Kumi *et al.* (2020)** for an indirect type of dryers, the temperature rise in the dryer reached a maximum of above 50°C. This result also agree with **Basunia *et al.*, (2013)** mentioned that, raising temperatures above 60°C can be harmful for vegetables and can induce loss of volatile nutrients through the excessive loss of moisture.

3.3. Air relative humidity at different air suction speeds of (0.6, 1.1 and 1.6 m/s):

It was observed from **Fig.(3.3)** that the minimum air relative humidity at entrance and exit slots were 11% and 13%, during the day hour of 2pm, while the that the maximum air relative humidity at entrance and exit slots were 71% and 65%, during the day hour of 9am. The results show also that air relative humidity was increased after the day hour of 2pm to 38% and 43% at the same places at the day hour of (6pm). It was observed that there is always an inverse relationship between the relative humidity of the air and its temperature. These results agree with **Samreen *et al.* (2017)**, reported that the relative humidity of the dryer was found to be less than that of ambient relative humidity due to the high temperature prevailing inside the dryer.



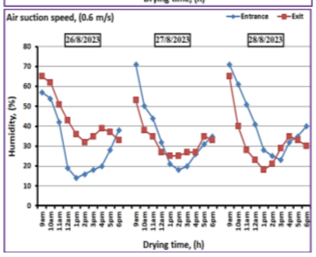


Fig.(3.3): Air relative humidity at entrance and exit slots during drying time at different air suction speeds of 0.6, 1.1 and 1.6 m/s.

3.4. Decrease of moisture content ratio during drying time:

Concerning to the effect of air suction speed on the decrease of moisture content ratio and the total required drying time, the results in **Fig.(3.4)** that show that the decrease of moisture content ratio were decreased from 85.4%, 86.6% and 88.2% fresh product to 10.46%, 13.52% and 8.83% dry product in total drying time of 15h, 21h and 19h for chilli, lemon and tomato, respectively in the upper tray and air suction speed of 0.6 m/s. Whereas the decrease of moisture content ratio was decreased to the same dry product ratio in more total drying time of 19h, 24h and 24h for chilli, lemon and tomato, respectively in the upper tray and air suction speed of 1.6 m/s. Relating to the effect of tray location on the decrease of moisture content ratio and the total required drying time, the results in **Fig.(3.4)** that show also that the decrease of moisture content ratio were decreased from 85.4%, 86.6% and 88.2% fresh product to 10.46%, 13.52% and 8.83% dry product in total drying time of 15h, 21h and 19h for chilli, lemon and tomato, respectively in the upper tray and air suction speed of 0.6 m/s. Whereas the decrease of moisture content ratio was decreased to the same dry product ratio in more total drying time of 27h, more than 29h and 20h for chilli, lemon and tomato, respectively in the lower tray and the same air suction speed of 0.6 m/s. It was observed that the drying process for chilli, lemon and tomato took less than 3 days to be completed. Similar results were reported by **Kumi, *et al.* (2020)**, where the solar dryer recorded total drying time of 35 h.

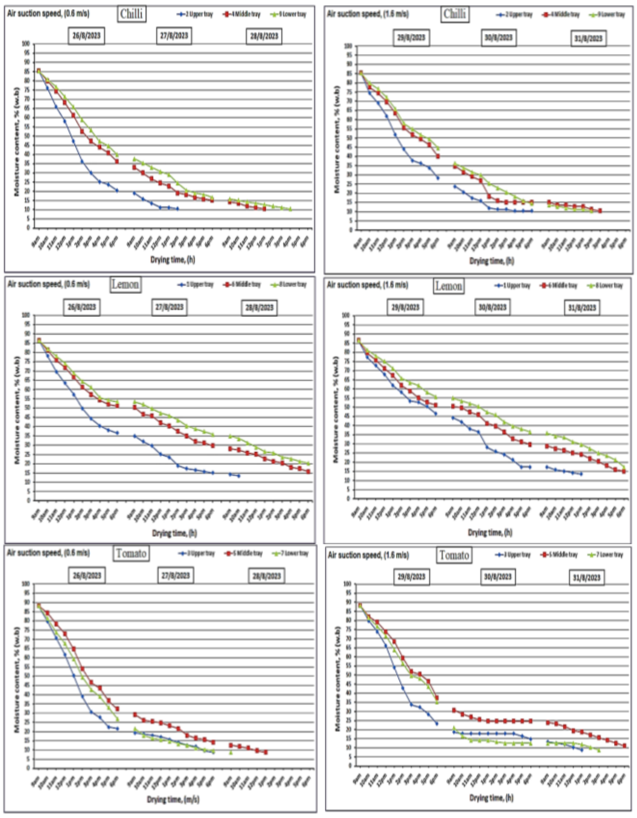


Fig.(3.4): Effect of air suction speed and tray location on the decrease of moisture content ratio for different agricultural products.

3.5. Drying rate per hour during drying time:

Concerning to the effect of air suction speed on the drying rate, the results in **Fig.(3.5)** that show that the drying rate were decreased after the first hour of drying from 9.37%, 8.46% and 8.32% to 5%, 3.48% and 4.18% during total drying time of 15h, 21h and 19h for chilli, lemon and tomato, respectively in the upper tray and air suction speed of 0.6 m/s. Whereas the drying rate was decreased from 10.93%, 9.23% and 8.32% to 3.94%, 3.04% and 3.31% in more total drying time of 19h, 24h and 24h for chilli, lemon and tomato, respectively in the upper tray and air suction speed of 1.6 m/s. These observations agree with **Kumar *et al.* (2020)** who reported that the drying rate was found to be higher during the initial stages of drying when the product surface has enough moisture to evaporate (constant rate period). It decreased towards the end of drying once its surface is depleted with moisture (falling rate period).

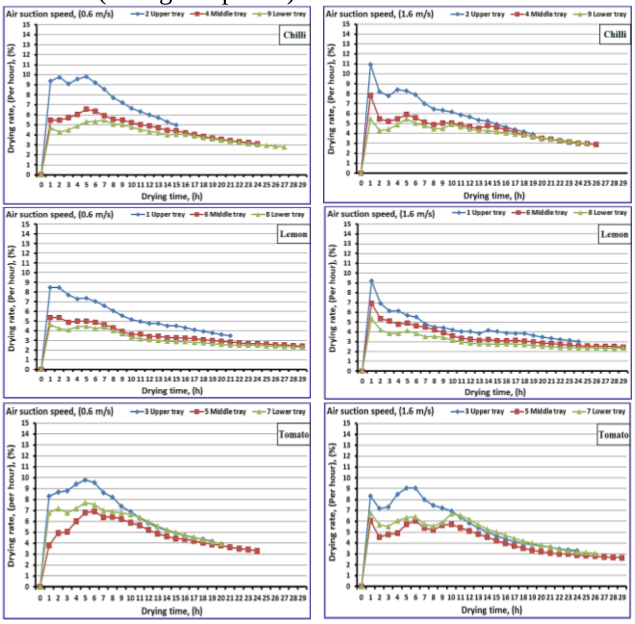
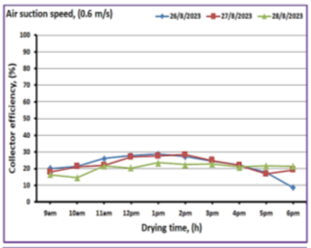


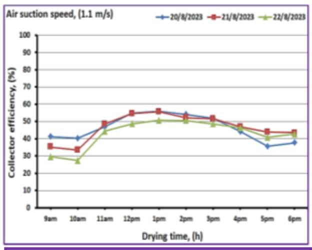
Fig.(3.5): Effect of air suction speed and tray location on the drying rate for different agricultural products.

Regarding to the effect of tray location on the drying rate, the results in **Fig.(3.5)** that show that the drying rate were decreased after the first hour of drying from 9.37%, 8.46% and 8.32% to 5%, 3.48% and 4.18% during total drying time of 15h, 21h and 19h for chilli, lemon and tomato, respectively in the upper tray and air suction speed of 0.6 m/s. Whereas the drying rate was decreased from 4.68%, 4.62% and 6.8% to 2.77%, 2.28% and 3.97% in more total drying time of 27h, 29h and 20h for chilli, lemon and tomato, respectively in the lower tray and the same air suction speed of 0.6 m/s. These results agree with **Samreen *et al.* (2017)** found that the drying rate of top, middle and bottom trays first increases and the trend decreases as the drying time increases. And also, agree with **Hossain *et al.* (2015)** reported that, the drying rate of the upper tray was higher than that of the lower tray because the upper tray temperature was higher than the lower tray.

3.6. Solar collector efficiency, (η_C) (%):

Fig.(3.6) shows the collector efficiency against drying time. The maximum values were 74.27, 75.74 and 73.09 % at constant air suction speed of 1.6 m/s at three drying days of 29, 30 and 31/8/2023, respectively. While the minimum values were 28.69, 27.66 and 23.64 % at constant air suction speed of 0.6 m/s at three drying days of 26, 27 and 28/8/2023, respectively. For all the three days, it was observed that, the highest percentage of collector efficiency occurred at (1pm) which usually the hottest time of the day. These results agree with **Fadhel *et al.* (2012)** reported that the maximum value of solar collector were 50% at the clear day and 14.2% at cloudy day around 11am to 1pm.





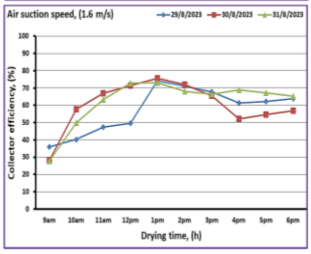
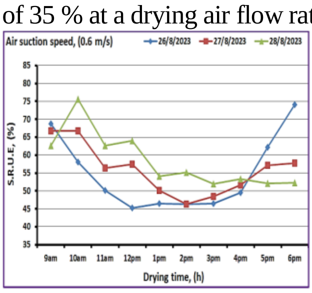


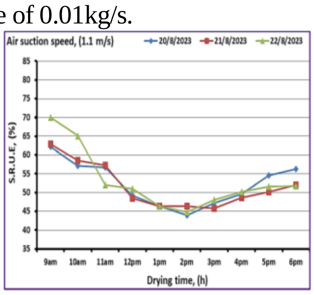
Fig.(3.6): Solar collector efficiency during drying time at different air suction speeds of 0.6, 1.1 and 1.6 m/s.

3.7. Solar radiation utilization efficiency, (S.R.U.E) (%):

The solar radiation utilization efficiency (S.R.U.E) which solar energy can be converted into more useful forms is one of the most important parameter concerning its utilization as available source of energy. The (S.R.U.E) was found to be at lower levels when the difference between air temperature at exit slot and collector is small. So, that the (S.R.U.E) was in high levels at earlier and late drying hours. **Fig.(3.7)** show that the lower values of (S.R.U.E) were 46.35%, 46.35% and 51.90% around the day hours between (2pm and 3pm) at three drying days of 26, 27 and 28/8/2023, respectively and 0.6 m/s air suction speed. On the other hand, the higher values of (S.R.U.E) were 68.67%, 66.74% and 62.66% at 9am, and were 74.15%, 57.77% and 52.26% at 6pm in the same drying days, respectively. Meanwhile, the lower values of (S.R.U.E) were 43.98%, 45.80% and 44.78% around the day hours between (2pm and 3pm) at three drying days of 20, 21 and 22/8/2023, respectively and constant air suction speed of 1.1 m/s. On the other hand, the higher values of (S.R.U.E) were 62.13%, 62.91% and 70% at 9am, and were 56.28%, 52% and 51.68% at 6pm in the same drying days, respectively.

Whereas the lower values of (S.R.U.E) were 43.32%, 47.53% and 46.27% around the day hours between (2pm and 3pm) at three drying days of 29, 30 and 31/8/2023, respectively. On the other hand, the higher values of (S.R.U.E) were 77.92%, 80.80% and 77.56% at 9am, and were 49.68%, 53.55% and 51.92% at 6pm in the same drying days, respectively. These results agree with **Chevli *et al.* (2016),** reported that the collector efficiency ranges from 20% to 43% and temperature rise was between 25 and 30 °C. And also agree with **Prakash and Satyanarayana (2014)** found the efficiency of the collector ranged from 42.18 to 71.4% with an average value of 35 % at a drying air flow rate of 0.01kg/s.





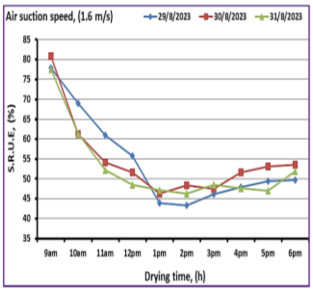


Fig.(3.7): Solar radiation utilization efficiency for dryer during solar drying time at different air suction speeds of (0.6, 1.1 and 1.6 m/s)

3.8. Solar dryer productivity, (kg/month):

Relating to the effect of agricultural product type on solar dryer productivity, **Fig.(3.8)** show that the dried amount of chilli halves, lemon slices and tomato slices for each upper tray were 32.40, 28.62 and 25.59 kg/month; 23.58, 23.58 and 20.61 kg/month and 21.33, 25.29 and 16.92 kg/month at different air suction speeds of 0.6, 1.1 and 1.6 m/s, respectively. The difference between trays productivity for the upper trays were due to the type of agricultural products which have different structure and dry matters.

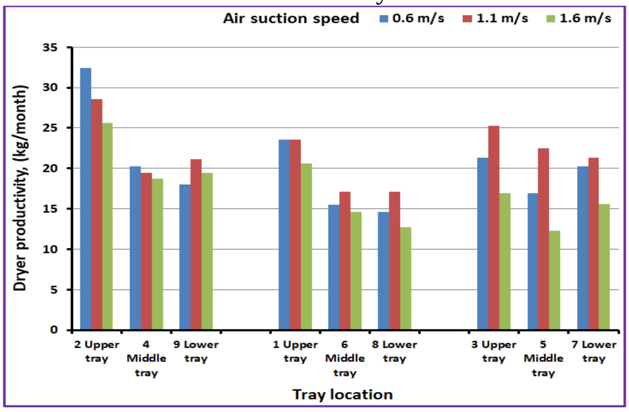


Fig.(3.8): Solar dryer productivity for three different agricultural crops at different tray locations in drying chamber and different air suction speeds.

Concerning to the effect of air suction speed on solar dryer productivity, **Fig.(3.8)** also indicated that the increase in air suction speed from 0.6 m/s to 1.6 m/s measured at the upper tray for chilli halves, lemon slices and tomato slices leads to decrease the tray productivity from 32.40 to 25.59 kg/month, from 23.58 to 20.61 kg/month and from 21.33 to 16.92 kg/month, respectively. Decreasing tray productivity with increasing air suction speed may be attributed to more amount of hot air delivered from the upper slots causing a decrease in air temperature inside the drying chamber.

As to the effect of tray location on solar dryer productivity, **Fig.(3.8)** illustrated that the upper tray recorded higher productivity than the lower one for all dried products. For chilli halves, the productivity of the upper tray was 32.40, 28.62 and 25.59 kg/month decreasing to 18.00, 21.15 and 19.44 kg/month at different air suction speeds of 0.6m 1.1 and 1.6 m/s, respectively. While for lemon slices, the productivity of the upper tray was 23.58, 23.58 and 20.61 kg/month decreasing to 14.58, 17.10 and 12.69 kg/month at different air suction speeds of 0.6m 1.1 and 1.6 m/s, respectively. And for tomato slices, the productivity of the upper tray was 21.33, 25.29 and 16.92 kg/month decreasing to 20.25, 21.33 and 15.24 kg/month at different air suction speeds of 0.6m 1.1 and 1.6 m/s, respectively. Increasing the upper tray productivity comparing with the lower one at the same other conditions may be due to the upper tray exposed to more solar radiation through the transparent upper side of drying chamber. So the total heat gains for the upper tray always more than the lower tray.

3.9. Solar drying cost, (L.E/kg.month):

The solar drying cost is highly affected by the solar dryer productivity, which affected with the parameter mentioned in (Solar dryer productivity title), and also affected with solar dryer materials, price of solar dryer, yearly working hours, life expectancy of the dryer, interest rate/year, wage for labor, taxes, overheads ratio, repairs and maintenance ratio, monthly working hours, fan power, hourly kW price and monthly average wage. The fixed and variable costs were represented in from **(Awady, 1978)** equation.

Regarding to the effect of agricultural product on solar drying cost, **Fig.(3.9)** show that the solar drying cost of chilli halves, lemon slices and tomato slices for each upper tray were 10.28, 11.65 and 13.03 L.E/kg.month; 14.14, 14.14 and 16.17 L.E/kg.month and 15.63, 13.18 and 19.70 L.E/kg.month at different air suction speeds of 0.6, 1.1 and 1.6 m/s, respectively. The difference between trays solar drying cost for the upper trays were due to the type of agricultural products which have different dry matters productivities. Relating to the effect of air suction speed on solar dryer productivity, **Fig.(3.9)** indicated also that the increase in air suction speed from 0.6 m/s to 1.6 m/s measured at the upper tray for chilli halves, lemon slices and tomato slices leads to increase the solar drying cost from 10.28 to 13.03 L.E/kg.month, from 14.14 to 16.17 L.E/kg.month and from 15.63 to 19.70 L.E/kg.month, respectively. Increasing solar drying cost with increasing air suction speed may be attributed to the decrease in solar productivity since the hourly operating cost was fixed at about 10 L.E/h.

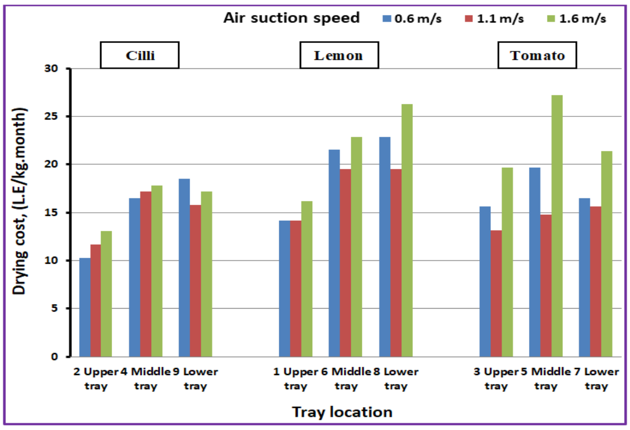


Fig.(3.9): Drying cost for three different agricultural crops at different tray locations in drying chamber and different air suction speeds.

Concerning to the effect of tray location on solar drying cost, **Fig.(3.9)** illustrated that the upper tray recorded lower drying cost than the lower one for all dried products. For chilli halves, the drying cost of the upper tray was 10.28, 11.65 and 13.03 L.E/kg.month increasing to 18.52, 15.76 and 17.15 L.E/kg.month at different air suction speeds of 0.6m 1.1 and 1.6 m/s, respectively. While for lemon slices, the drying cost of the upper tray was 14.14, 14.14 and 16.17 L.E/kg.month increasing to 22.86, 19.49 and 26.27 L.E/kg.month at different air suction speeds of 0.6m 1.1 and 1.6 m/s, respectively. And for tomato slices, the drying cost of the upper tray was 15.63, 13.18 and 19.70 L.E/kg.month increasing to 16.46, 15.63 and 21.41 L.E/kg.month at different air suction speeds of 0.6m 1.1 and 1.6 m/s, respectively. Decreasing drying cost for the upper tray comparing with the lower one at the same other conditions may be due to that the upper tray recorded high drying productivity than the lower ones.

3.10. Payback period, (month):

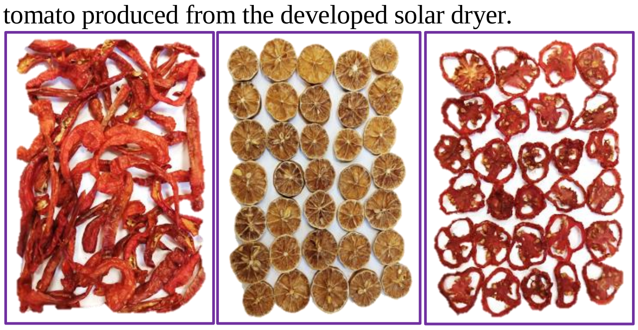
The production worth for chilli, lemon and tomato are presented in **Table (3.2)**. The net present worth of total cash income from drying of chilli, lemon and tomato under solar dryer was found to be 5250 L.E. The benefit cost of chilli, lemon and tomato in solar dryer was found to be 17025 L.E. The payback period for drying of chilli, lemon and tomato in solar dryer was found to be 98 days or (3 months and 8 days). Therefore, it was concluded that drying of chilli, lemon and tomato in solar dryer found to be economical as it showed more profit rate of 1.63, 2.62 and 4.46 %, for chilli, lemon and tomato, respectively. Drying agricultural production in solar dryer seems to be economical because the solar energy is freely available throughout the year thus no additional expenditure was incurred for air heating.

Agric. Product	Production value, (L.E/month)						
	Fresh product			Dry product			Profit Rate, %
	Unit cost, L.E/kg	Amount, kg/month	L.E/ month	Amount, kg/month	Unit cost, L.E/kg	L.E/ month	
Chilli	20	45	900	22.62	65	1470	1.63
Lemon	15	45	675	17.70	100	1770	2.62
Tomato	10	45	450	19.15	105	2010	4.46
			2025			5250	

These results agree with **Kamble *et al.* (2013)** reported that, the benefit cost ratio in solar cabinet dryer was found to be 1.11. The payback period for drying of chilli in solar cabinet dryer was found to be 7 month and 11 day. The drying in solar cabinet dryer seems to be economical because solar energy is freely available throughout the year thus no additional expenditure was incurred for air heating.

4.10. Quality of dried products:

Fig. (4.36) show some photos of the dried chilli, lemon and tomato produced from the developed solar dryer.



Chilli Lemon Tomato

Fig.(3.10): Photos of dried chilli, lemon and tomato using the developed solar dryer.

To determine the quality of the dried agricultural product, the main organic acids were analyzed and calculated using the (HPLC) system in the Center for Excellence in Research of Advanced Agricultural Sciences (CERAAS), Damietta

University, according to the procedures of **(Tusseau *et al.* 1986)**. The results in **Figs.(3.11)** occurred from (HPLC) show that the concentrations of some important organic acids in both fresh and dried chilli, lemon and tomato. It was observed that the Oxalic, Malic, Ascorbic, Lactic, Acetic and Citric acids concentrations (mg/g) in dried chilli were always higher than the same organic acids concentrations (mg/g) in fresh chilli especially Malic, Lactic and Citric acids which were increased by 76.67, 99.65 and 88.90 %, respectively.

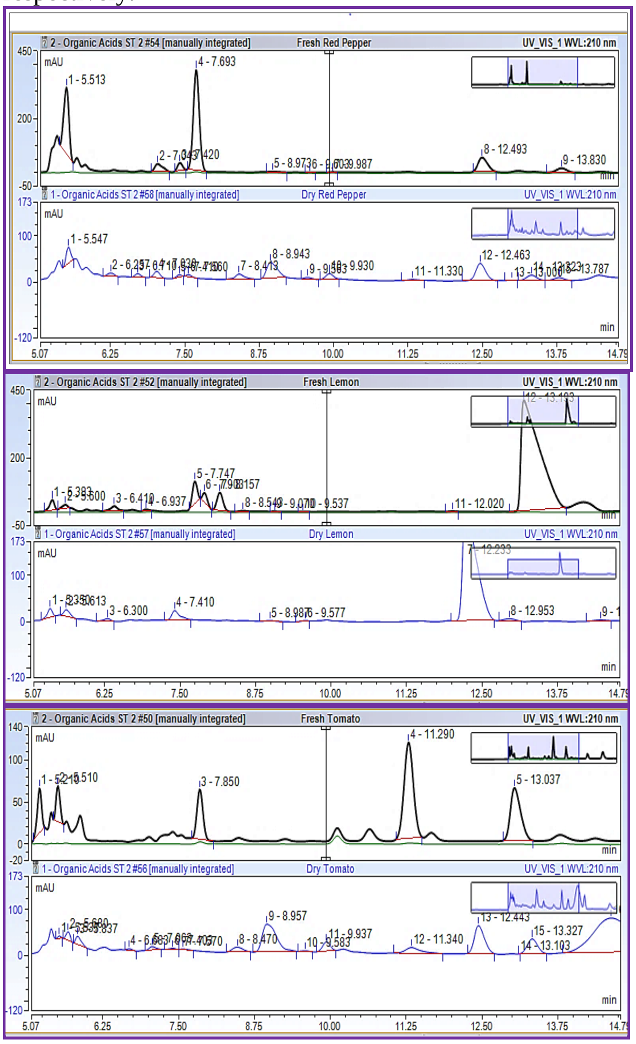


Fig.(3.11): (HPLC) analysis of some important organic acids for fresh and dried chilli, lemon and tomato using the developed solar dryer.

While, it was observed that the Oxalic, Malic, Ascorbic, Lactic, Acetic and Citric acids concentrations (mg/g) in dried lemon were always higher than the same organic acids concentrations (mg/g) in fresh lemon especially both Malic and Citric acids which were increased by 98.65 and 93.13 %, respectively. Moreover, it was observed that the Oxalic, Malic, Ascorbic, Lactic, Acetic and Citric acids concentrations (mg/g) in dried tomato were always higher than the same organic acids concentrations (mg/g) in fresh tomato especially Lactic, Acetic and Citric acids which were increased by 99.76, 93.95 and 91.11 %, respectively.

4. SUMMARY AND CONCLUSSION

The experimental work was carried out in Agricultural and Bio-systems Engineering Department, Faculty of Agriculture, Damietta University, Egypt (Latitude 31°25′35″ North, Longitude 31°39′03″ East) to manufacture and develop the double ventilated solar dryer for drying some agricultural products under Egyptian conditions. From the obtained results during the summer season 2023 for solar drying chilli, lemon and tomato, it could be concluded that:

1. The maximum solar radiation for the dryer chamber, collector and ambient were 750 W/m^2, 750 W/m^2 and 825 W/m^2, respectively.
2. The maximum temperatures for the entrance; upper, middle, lower trays; exit; and collector were 41°C, 64°C, 62.5°C, 61.79°C, 42.29°C, and 83.9°C, respectively.
3. The minimum air relative humidity at entrance and exit slots were 11% and 13%, during the day hour of 2pm, while the that the maximum air relative humidity at entrance and exit slots were 71% and 65%, during the day hour of 9am.
4. The decrease of moisture content ratio were decreased from 85.4%, 86.6% and 88.2% fresh product to 10.46%, 13.52% and 8.83% dry product in total drying time of 15h, 21h and 19h for chilli, lemon and tomato, respectively in the upper tray and air suction speed of 0.6 m/s. Whereas the decrease of moisture content ratio was decreased to the same dry product ratio in more total drying time of 19h, 24h and 24h for chilli, lemon and tomato, respectively in the upper tray and air suction speed of 1.6 m/s.
5. The drying rate were decreased after the first hour of drying from 9.37%, 8.46% and 8.32% to 5%, 3.48% and 4.18% during total drying time of 15h, 21h and 19h for chilli, lemon and tomato, respectively in the upper tray and air suction speed of 0.6 m/s. Whereas the drying rate was decreased from 10.93%, 9.23% and 8.32% to 3.94%, 3.04% and 3.31% in more total drying time of 19h, 24h and 24h for chilli, lemon and tomato, respectively in the upper tray and air suction speed of 1.6 m/s.
6. The higher values of solar collector efficiency (η_C) were 74.27, 75.74 and 73.09% at the day hour of (1pm) during three drying days of 29, 30 and 31/8/2023, respectively and 1.6 m/s air suction speed.
7. The lower values of (S.R.U.E) were 46.35%, 46.35% and 51.90% around the day hours between (2pm and 3pm) at three drying days of 26, 27 and 28/8/2023, respectively and 0.6 m/s air suction speed. On the other hand, the higher values of (S.R.U.E) were 68.67%, 66.74% and 62.66% at 9am, and were 74.15%, 57.77% and 52.26% at 6pm in the same drying days, respectively.
8. The dried amount of chilli halves, lemon slices and tomato slices for each upper tray were 32.40, 28.62 and 25.59 kg/month; 23.58, 23.58 and 20.61 kg/month and 21.33, 25.29 and 16.92 kg/month at different air suction speeds of 0.6, 1.1 and 1.6 m/s, respectively.
9. The solar drying cost of chilli halves, lemon slices and tomato slices for each upper tray were 10.28, 11.65 and 13.03 L.E/kg.month; 14.14, 14.14 and 16.17 L.E/kg.month and 15.63, 13.18 and 19.70 L.E/kg.month at different air suction speeds of 0.6, 1.1 and 1.6 m/s, respectively.
10. The net present worth of total cash income from drying of chilli, lemon and tomato under solar dryer was found to be 5250 L.E. The benefit cost of chilli, lemon and tomato in solar dryer was found to be 17025 L.E. The

payback period for drying of chilli, lemon and tomato in solar dryer was found to be 98 days or (3 months and 8 days).

11. The concentrations of organic acids (mg/g) in dried chilli, lemon and tomato were always higher than the in the fresh. For chilli, Malic, Lactic and Citric acids concentrations were increased by 76.67, 99.65 and 88.90 %, respectively. For lemon, both Malic and Citric acids concentrations were increased by 98.65 and 93.13 %, respectively. For tomato, Lactic, Acetic and Citric acids concentrations were increased by 99.76, 93.95 and 91.11 %, respectively.

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CONFLICT OF INTEREST:

The authors declare that they have no conflict of interest.

AUTHORS CONTRIBUTION:

All authors developed the concept of the manuscript. Aburyaq wrote the manuscript and achieved the experimental work and measurements. All authors checked and confirmed the final revised manuscript.

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تطوير وتقييم أداء المجفف الشمسي ذو التهوية المزدوجة لتجفيف بعض المنتجات الزراعية

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أجريت هذه الدراسة لتطوير وتصنيع وتقييم المجفف الشمسي ذو التهوية المزدوجة وذلك لتجفيف بعض المنتجات الزراعية خلال الموسم الصيفي من عام ٢٠٢٣ في قسم هندسة النظم الزراعية والحيوية بكلية الزراعة - جامعة دمياط. وقد نبعت فكرة هذه الدراسة من توافر طاقة الإشعاع الشمسي طوال العام وبالأخص في فصل الصيف ومدى إمكانية الاستفادة منها كطاقة مستدامة ونظيفة، وكذلك التغلب على المشاكل التي تواجه عملية التجفيف الشمسي التقليدي كالتلوث وعدم جودة المنتج المجفف وتكلفته العالية، وقد روعي في هذه الدراسة المحافظة على المنتج المجفف من التلوث ورفع جودته بالمحافظة على اللون ومكوناته من العناصر الغذائية المختلفة بالإضافة إلى تقليل تكلفة عملية التجفيف.

● **نظام التجفيف الشمسي المطور:** يتكون هذا النظام من جزئين أساسيين هما:

١. المجمع الشمسي: يقوم برفع درجة حرارة الهواء المستخدم في عملية التجفيف، وهو عبارة عن صندوق مصنوع من الخشب ومغطى بطبقة شفافة من البولي كربونات بسمك ٢ مم في الأعلى من أجل تركيز الإشعاع الشمسي في المنطقة الداخلية. تبلغ أبعاد المجمع الشمسي (٢٠٠×١٠٠×٢٥ سم) للطول والعرض والارتفاع. يحتوي المجمع الشمسي على صفائح ألمنيوم مسننة بسمك (٢ مم) مطلية باللون الأسود لامتصاص الإشعاع الشمسي. تم وضع صفائح الامتصاص مباشرة خلف الغطاء الشفاف (البولي) بسمك طبقة تسخين الهواء ١٠ سم، حيث يمر الهواء المراد تسخينه من فتحتين جانبيتين بمساحة ٣٠ سم ٢ لكل منهما إلى غرفة التجفيف عبر الأنابيب المرنة. يقع المحور الطولي للمجمع الشمسي في اتجاه E-W المواجه لأشعة الشمس بزاوية ميل ٣٠° (تم تثبيت مستشعرين لكل من كثافة الإشعاع الشمسي ودرجة حرارة الهواء داخل المجمع الشمسي في منطقته الوسطى لتحديد قيمهما).

٢. حجرة التجفيف: وهي مصنوعة من الخشب ومغطاة بألواح شفافة من البولي كربونات بسمك (٢ مم) من الجوانب العلوية والسفلية والجانبية من أجل زيادة درجة حرارة هواء التجفيف القادمة من المجمع الشمسي. تبلغ أبعاد غرفة التجفيف الشمسي (١٥٠×١٠٠×١٠٠ سم) للطول والعرض والارتفاع على التوالي. تتكون غرفة التجفيف بالطاقة الشمسية من ١٥ صينية أبعاد كل منها (١٠٠×٤٣×٥ سم) للطول والعرض والارتفاع، على التوالي. إطار صينية التجفيف مصنوع من الخشب وجانبها السفلي الذي يحمل المنتج الزراعي عبارة عن شبكة معدنية مجلفنة خلاياها ذات شكل معين. المسافة الرأسية بين كل صينيتين (١٠سم) للسماح بتخلل الهواء الساخن عبر المنتجات المراد تجفيفها. غرفة التجفيف مدعومة بمروحتي سحب هواء في أعلى الغرفة وبقدرة (٥٠ وات) وبقطر (١٢ سم) لسحب وتدفق هواء التجفيف من المجمع الشمسي إلى غرفة التجفيف عبر الأنابيب المرنة، مع إمكانية تغيير سرعتها.

٣. **المستشعرات:** تم تثبيت المستشعرات الخاصة بشدة الإشعاع الشمسي ودرجة حرارة الهواء ورطوبة الهواء داخل المجمع الشمسي وغرفة التجفيف لتحديد قيمها وذلك من خلال مستشعرات نوع (DUT22) لكل من درجات الحرارة والرطوبة، و مستشعرات نوع (LDR) لشدة الإشعاع الشمسي، مع إمكانية تسجيل وحفظ البيانات كل (٥ دقائق) وتخزينها في كارت ذاكرة طوال فترة إجراء التجربة.

٤. محطة أرصاد جوية متكاملة: لقياس ومعرفة المتغيرات الجوية خارج المجمع الشمسي وغرفة التجفيف باستمرار، حيث تحتوي هذه المحطة على مستشعرات لكل من (شدة الإشعاع الشمسي، درجة الحرارة، الرطوبة النسبية، سرعة واتجاه الرياح وكمية مياه الأمطار الساقطة)، مع إمكانية تسجيل وحفظ البيانات كل (واحد دقيقة) طوال فترة إجراء التجربة وتخزينها في كارت ذاكرة أو ربطها بجهاز جوال عبر خاصية (Bluetooth) لمسافة تبلغ (٢٥م).

● **وقد أظهرت النتائج المتحصل عليها ما يلي:**

١. شدة الإشعاع الشمسي: كان الحد الأقصى للإشعاع الشمسي في كل من المجمع الشمسي، غرفة التجفيف والمحيط الخارجي هي: ١٠٠٠ ، ١٠٠٠ و ١١٠٠ وات/م٢، على التوالي.

٢. درجات الحرارة: درجات الحرارة القصوى لمدخل الهواء؛ الصواني العلوية والوسطية والسفلية ؛ مخرج الهواء والمجمع الشمسي هي: ٤١ ، ٦٤ ، ٦٢,٥ ، ٦١,٧٩ ، ٤٢,٢٩ و ٨٣,٩ م°، على التوالي.

٣. الرطوبة النسبية: بلغت الرطوبة النسبية الصغرى للهواء عند فتحات الدخول والخروج ١١ و١٣٪ عند الساعة ٢ ظهراً، بينما كانت الرطوبة النسبية الكبرى للهواء عند فتحات الدخول والخروج ٧١ و٦٥٪ عند الساعة ٩ صباحاً.

٤. انخفاض المحتوى الرطوبي: انخفضت نسبة انخفاض المحتوى الرطوبي من ٨٥,٤ ، ٨٦,٦ و ٨٨,٢٪ للمنتج الطازج إلى ١٠,٤٦ ، ١٣,٥٢ و ٨,٨٣٪ للمنتج الجاف في إجمالي وقت التجفيف ١٥ ، ٢١ و ١٩ ساعة لكل من الفلفل الحار والليمون والطماطم، على التوالي في الصواني العلوية وعند سرعة سحب الهواء ٠,٦ م/ث.

٥. معدل التجفيف: انخفض معدل التجفيف بعد الساعة الأولى من التجفيف من ٩,٣٧ ، ٨,٤٦ و ٨,٣٢٪ إلى ٥ ، ٣,٤٨ و ٤,١٨٪ خلال إجمالي وقت التجفيف ١٥ ، ٢١ و١٩ ساعة لكل من الفلفل الحار والليمون والطماطم، على التوالي في الصواني العلوية وعند سرعة سحب الهواء ٠,٦ م/ث.

٦. **كفاءة المجمع الشمسي** (η_C)**:** كانت القيم الأعلى لكفاءة المجمع الشمسي هي: ٧٤,٢٧ ، ٧٥,٧٤ و٧٣,٠٩٪ في ساعة النهار (١ ظهراً) خلال ثلاثة أيام التجفيف ٢٩ ،٣٠ و ٢٠٢٣/٨/٣١ على التوالي، وسرعة سحب الهواء ١,٦ م/ث. بينما كانت القيم الصغرى لكفاءة المجمع الشمسي هي: ٢٨,٦٩، ٢٧,٦٦ و٢٣,٦٤٪ في ساعة النهار (١ ظهراً) خلال ثلاثة أيام التجفيف ٢٦ ،٢٧ و ٢٠٢٣/٨/٢٨، على التوالي عند سرعة سحب الهواء ٠,٦ م/ث.

٧. كفاءة الاستفادة من الإشعاع الشمسي (SRUE): كانت القيم الصغرى لكفاءة الاستفادة من الإشعاع الشمسي هي: ٤٦,٣٥ ، ٤٦,٣٥ و ٥١,٩٠٪ حول ساعات النهار ما بين (٢ و ٣ مساءً) في ثلاثة أيام التجفيف ٢٦ ، ٢٧ و ٢٠٢٣/٨/٢٨،على التوالي وعند سرعة سحب الهواء ٠,٦ م/ث.

٨. إنتاجية المجفف: كانت الكمية المجففة من شرائح الفلفل الحار، الليمون والطماطم لكل صينية علوية هي: ٣٢,٤٠ ، ٢٨,٦٢ و ٢٥,٥٩ كجم/شهر؛ ٢٣,٥٨ ، ٢٣,٥٨ و ٢٠,٦١ كجم/شهر و ٢١,٣٣ ، ٢٥,٢٩ و ١٦,٩٢ كجم/شهر عند سرعات سحب هواء مختلفة تبلغ ٠,٦ ، ١,١ و ١,٦ م/ث،على التوالي.

٩. تكاليف التجفيف الشمسي: كانت تكلفة التجفيف الشمسي لشرائح الفلفل الحار، الليمون والطماطم لكل صينية علوية هي: ١٠,٢٨ ، ١١,٦٥ و ١٣,٠٣ جنيه/كجم شهرياً؛ ١٤,١٤ ، ١٤,١٤ و ١٦,١٧ جنيه/كجم شهرياً و ١٥,٦٣ ، ١٣,١٨ و ١٩,٧٠ جنيه/كجم شهرياً، عند سرعات سحب هواء مختلفة تبلغ٠,٦ ، ١,١ و١,٦ م/ث، على التوالي.

١٠. إعادة استرداد التكاليف: يمكن حساب فترة استرداد التكاليف اللازمة للتجفيف بالطاقة الشمسية وذلك من خلال قائمة المصروفات المدفوعة لتجفيف الفلفل الحار والليمون والطماطم في مجفف الطاقة الشمسية والتي بلغت ١٧٠٢٥ جنيهاً مصرياً. أما صافي العائد من المنتجات المجففة من الفلفل الحار والليمون والطماطم باستخدام المجفف الشمسي فقد بلغت ٥٢٥٠ جنيهاً مصرياً في الشهر. وبالتالي فإن فترة استرداد التكاليف المدفوعة لتجفيف الفلفل الحار والليمون والطماطم في مجفف الطاقة الشمسية تكون حوالي ٩٨ يوماً فقط أو (٣ أشهر و ٨ أيام).

١١. **جودة المنتج المجفف:** كانت تركيزات الأحماض العضوية (ملغم/جم) في الفلفل المجفف والليمون والطماطم دائما أعلى من تركيزاتها في الطازجة. بالنسبة للفلفل الحار، تم زيادة تركيزات أحماض الماليك واللاكتيك والستريك بنسبة ٧٦,٦٧ و ٩٩,٦٥ و ٨٨,٩٠٪ على التوالي؛ وبالنسبة لليمون، فقد زادت تركيزات أحماض الماليك والستريك بنسبة ٩٨,٦٥ و ٩٣,١٣٪، على التوالي؛ أما بالنسبة للطماطم، فقد زادت تركيزات أحماض اللاكتيك والخليك والستريك بنسبة ٩٩,٧٦ و ٩٣,٩٥ و ٩١,١١٪، على التوالي.

ولهذا توصي الدراسة باستخدام المجفف الشمسي المطور ذو التهوية المزدوجة لتجفيف شرائح الفلفل الحار والليمون والطماطم بأقل تكاليف ممكنة تحت الظروف الآتية:

١- استخدام تسع صواني موزعة بالتبادل داخل غرفة التجفيف لتحميل المنتجات الزراعية المراد تجفيفها في طبقة واحدة وبوزن ١,٥ كجم/الصينية.

٢- استخدام مروحتي سحب للهواء عند السرعة البطيئة (٠,٦م/ث)، والتي أعطت أفضل معدل لتدفق الهواء وعدم فقد الحرارة من حجرة التجفيف.

٣- حققت الأرفف العلوية أفضل إنتاجية للمنتج المجفف، غير أن الفرق بين إنتاجيتها وإنتاجية كلاً من الأرفف السفلية والوسطية لم يكن كبيراً، وبالتالي يمكن استخدام جميع الأرفف داخل غرفة التجفيف.

الكلمات المفتاحية: المجمع الشمسي، المجفف الشمسي، نسبة الانخفاض في الرطوبة، نسبة التجفيف، تكاليف التجفيف، محطة الأرصاد الجوية.