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# SOLAR ENERGY COLLECTION, STORAGE, AND UTILIZATION IN GREENHOUSES ROOT-MEDIA HEAT TREATMENT PROCESS

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## ABSTRACT

A complete solar energy system was designed and constructed in the workshop of Agricultural Engineering Department. It was installed on the roof of the department at altitude angle of 31.045 °N in order to collect, store, and utilize the solar energy available in heat treatment process of greenhouse root-media mixture. The solar energy system was mainly consisted of three components: solar water heater has a surface area of 2.0 $m^2$ (2 x 1 m), insulated storage tank (332 litres), and heat distributing system (heat exchanger) using parallel flow system. Water was continually pumped between the insulated storage tank and the solar water heater during daylight time. The container of heat treatment was equipped by a heat exchanger and filled up by 0.6 $m^3$ of greenhouse root-media. In order to catch and hold more heat energy and reduce the heat losses, the upper surface of root-media container was covered with polyethylene sheet. After sunset of each day (six and five successive days were recorded during the two experiments) the hot water (heated by solar heating system) was pumped between the insulated storage tank and the heat distributing system (heat exchanger) inside the container of root-media. Solarization technique in heat treatment of root-media was also functioned after fulfilled the heat treatment process was. Two mathematical models were developed and used to compute the water and soil-based root-media temperatures according to the heat energy balance on the storage tank and root-media heat treatment unit, respectively. The total microbial contamination of root-media samples were bacteriological analysed before and after the heat treatment process. The obtained data revealed that, the daily average overall thermal efficiency of the solar water heater during these experiments was 71.99%, consequently 28.01% of the total solar energy available was lost. The daily average solar energy stored in the storage tank during the experimental work was 12.807 kWh/day, which gave an average storage system efficiency of 82.99%. The predicted water temperatures in the storage tank were validated very well with that measured by 98.61 % which gave an excellent agreement. The predicted root-media mixture temperatures in the heat treatment unit were validated very well with that measured by 99.65% which gave an excellent agreement. The daily average effectiveness of heat distributing system during the experimental work was 76.09%. Due to use the solar heating system in root-media heat treatment process, there were no any weeds observed in all pots of the plants, the *E.coli* microbial content on average reduced from 5.311 x $10^3$ to 8.1154 x $10^{-3}$ CFU/g, and the *Salmonella* organisms on average reduced from 3.20 x $10^3$ to 100 CFU/g. The technique of solarization for heat manipulating of root-media led to destroy the remained of microbial organisms in the root-media.

# INTRODUCTION

Solar energy as a renewable energy is accepted as a key source for the future, not only for Egypt but also for the whole world. Egypt has a considerably high level of renewable energy sources that can be provided a portion of the total energy consumed in the country. The greatest advantage of solar energy as compared with other forms of energy is that it is clean and can be supplied without any environmental pollution. Due to the desirable environmental and safety aspects it is widely believed that solar energy should be utilized instead of other alternative energy sources, even when the total costs involved are slightly higher (Kalogirou, 2004). Solar energy is mainly utilized in numerous applications such as heating and cooling different buildings by both active and passive systems. It is used to heat water for domestic, agricultural, and industrial uses and many others (Duffie and Beckman, 1991).

Root-media in general must serve four functions: provide water, supply nutrients, permit gas exchange to and from the roots system, and provide support for the plant. The decreased availability of mineral soils, the increased use of herbicides in field crop production, the need for more rapid plant growth to shorten cropping time, and the need to lower production costs were just some of the seasons motivating researchers and growers to look for alternative root-media (Nelson, 1998). Protected cropping and commercial greenhouse crops were not grew in soils alone. They had grown in mixture of soil, peat moss, perlite, sand, vermiculite, sawdust, wood chips, and other products. Soil is only part of the total mass that called a growing media. A medium is the substance in which the growing of a crop is accomplished. The growing medium used in protected cropping is different from the soil in the fields where the farmer grows crops (Boodley, 1998). The physical components of root-media include air, water, and solid proportions. The typical percentage of these components in a 15 cm pot of soilles medium are 10 to 20% solid, 20 to 30% air, and 50 to 70% water. Container size determines the actual proportion of air and water, the amount of air and water held in a given root medium is a function of the height of the medium column. The shorter the column is the greater amount of water and the less amount of air (Aldrich and Bartok, 1990).

Greenhouse root-media should be treated by heat or chemicals or biological control, at least once per year, and more often as required, to rid them of harmful disease organisms, nematodes, insects, and weed seeds. Electrical heat, stem heat, soil solarization, and chemical biocides are the primary methods of soil disinfection in greenhouse production. The fifth method of disease suppression is biological control. Soil fumigants such as methyl bromide are, of course restricted in organic production (Change *et al.*, 1986; Baker, 1992; Grossman and Liebman, 1995).

Electrical heat treatment, which is done inside a steel chamber surrounded by heating coils, is limited to treating about a cubic yard of soil at a time. Its primary use is in the pasteurization of small batches of sand and soil for potting mixes. Accordingly, steam pasteurization and soil solarization are the two most viable options for sterilizing greenhouse soils or large volumes of soil-based mixes. Biological control is complementary to these two methods. Steam sterilization can be an economically viable alternative to methyl bromide fumigation in a number of crops. Furthermore, steaming has the extra advantage of following growers to replant up to three weeks sooner than methyl bromide treated fields (an important economic advantage in cool climates). More recently, small portable steam generators have been developed and used greenhouse benches in the USA and Netherlands (Grossman and Liebman, 1995; Anonymous, 1995; and Greer and Diver, 1999).

Greenhouse root-media heat treatment using numerous procedures has been studied and investigated by several researchers (Greer and Diver, 1999; McNamara *et al.*, 2002; Stevenson and Verburg, 2005; DiFonzo and Jewett, 2006; and many others). However, there are no available informations about the possibility of utilizing solar energy system for heat treatment of greenhouse root-media. Therefore, the main goal of this research work was to study and investigate the possibility of using solar heating system for heat manipulating of root medium mixture for protected cropping.

## MATERIALS AND METHODS

A complete solar energy system was designed and constructed in the workshop of Agricultural Department, and installed on the roof of the department. It consisted of three major components: solar water heater, insulated storage tank, and heat distributing system (heat exchanger). Solar water heater consisted of six components: a collector box, an absorber black plate, a copper pipes, an insulation material, a glass cover, and a movable frame as shown in Fig. (1). The solar collector box is rectangular in shape and made of 25 mm aluminium bar. The gross dimensions of the box are 2.1 m long, 1.1 m wide, and 0.1 m deep, with a net upper surface area of 2.31 m². The absorber plate is also rectangular in shape and formed of an aluminium sheet. It was painted with matt black paint in order to absorb the maximum amount of the solar radiation incident on its surface. The gross dimensions of the absorber plat are 2 m long, 1 m wide, and 2 mm thick, with a net upper surface area of 2 m². A 12.7 mm diameter copper pipes (10 pipes) were distributed at equidistant of 10 cm and attached to the upper surface of the absorber plate using slap ties each 10 cm long throughout the length of each pipe. They were also painted with matt black paint. In the bottom and sides of the collector envelop 50 mm thick of fibreglass wool insulation sheets was situated to reduce the solar collector total heat losses. To minimize the reflection of radiation and reduce the heat losses by convection, clear glass cover 5 mm thick was placed to cover the solar collector box. The air space between the absorber black plate and the glass cover was 5 cm as suggested by many researchers (Duffie and Beckman, 1991; and Kalogirou, 2004). The solar water heater was mounted on a movable turntable frames in order to track the sun's rays from sunrise to sunset. This frame is carried on five small wheels (10 cm diameter) and screwed pin (as an axial point) for changing the orientation of solar collector (where the small wheels are moved around the axial pin).

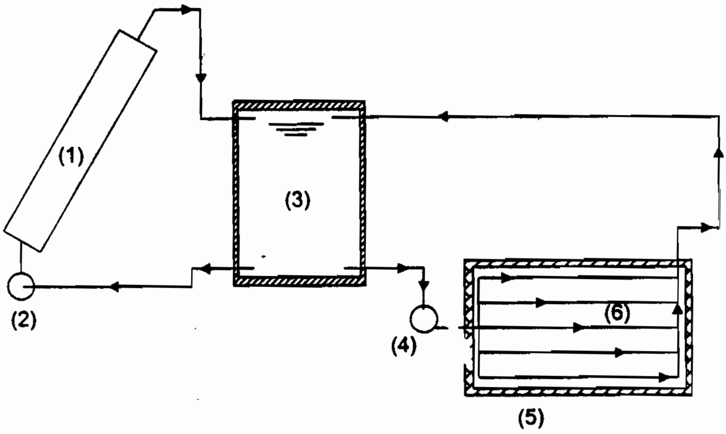

Fig. (1): Schematic diagram of solar heating system
(1) solar collector. (2), (4) water pumps.
(3) insulated storage tank. (5) wooden box.
(6) heat exchanger (heat distributing system).

The insulated storage tank is cylindrical in shape, and made of steel sheet (2 mm thick). To minimize the heat energy losses from the storage tank, 2.5 cm of fibreglass wool insulation sheet was rolled around the external curved surface. The storage tank was connected to the solar water heater by two junctions. One junction is between the bottom of the storage tank (cold water) and the bottom of the solar heater (water inlet). The other one is between the top of the storage tank and the top of the solar heater (water outlet). The water was pumped between the storage tank and the solar heater using 0.5 hp water pump. After the water passing through the solar heater it was stored in a 332 litres insulated storage tank.

To provide and maintain positively a temperature of 60 °C during the heating period such as is required for heating root-media, a wooden box having a gross dimensions of 2 m long, 1 m wide, and 0.3 m deep was equipped with the solar heating system. To utilize the stored solar energy in the storage tank for heating the root-media mixture inside the wooden box, a heat exchanger using parallel flow system was employed. It consisted of five parallel rows of water galvanized pipes (25.4 mm diameter). The five parallel water galvanized pipes were situated at a horizontal equidistant of 20 cm between two successive pipes, in order to provide and adequate area of heat transfer. The heated water in the insulated storage tank was pumped to circulate through the heat exchanger during the heating process of root-media mixture.

Twelve thermocouples (type K) coated and sealed using epoxy resin were functioned to measure temperature at different points in the solar energy system. The inlet and outlet water temperatures of the solar water heater were measured using two thermocouples. One thermocouple was used to measure the water temperature in the storage tank. The inlet and outlet water temperatures of the heat distributing system (heat exchanger) were measured using two thermocouples. Four thermocouples were evenly distributed on the central plane throughout the heat exchanger pipes to measure the peripheral heat exchanger temperatures. The temperatures of root-media mixture at three different depth (5, 15, and 25 cm deep) and locations were measured using three thermocouples. These sensors were connected to a data logger system (Digi-Sens-Scanning thermometer). A disk solarimeter was situated and fixed on the upper portion of the solar water heater in order to measure the solar radiation flux incident on the tilted surface. The meteorological data from a meteorological station (WatchDog model 550) which installed just above the roof of the department was utilized throughout this research work. The data were displayed on the video screen and updated by a scan of all the sensors every minute. The average of 60 scans was recorded on hard-disk every hour using data logging programme (SpaceWare 6.02).

The experimental work was carried out on the roof of the Agricultural Engineering Department, Faculty of Agriculture, Mansoura University during July 2005 and June 2006. The thermal performance test included: solar energy available (Q), absorbed solar energy ($Q_A$), absorption efficiency ($\eta_A$), useful heat gain to storage ($Q_C$), heat transfer efficiency ($\eta_H$), heat losses ($Q_L$), overall thermal efficiency ($\eta_O$), solar energy stored ($Q_S$), and storage efficiency ($\eta_S$), can be executed and computed using a series of equations as follows:-

$$Q = R\,A_c \qquad \text{, Watt} \qquad (1)$$

$$Q_A = \tau\,\alpha\,R\,A_c \qquad \text{, Watt} \qquad (2)$$

$$\eta_A = \frac{Q_A}{Q} \times 100 \qquad \text{, \%} \qquad (3)$$

$$Q_C = m\,C_p\left(T_{fo} - T_{fi}\right) \qquad \text{, Watt} \qquad (4)$$

$$\eta_h = \frac{Q_C}{Q_A} \times 100 \qquad \text{, \%} \qquad (5)$$

$$Q_L = A_c\,U_o\left(\bar{T}_p - T_a\right) \qquad \text{, Watt} \qquad (6)$$

$$\eta_o = \frac{Q_c}{Q} \times 100 \qquad \text{, \%} \qquad (7)$$

$$Q_s = M\,C_p\left(T_{ke} - T_{kb}\right) \qquad \text{, Watt} \qquad (8)$$

$$\eta_s = \frac{Q_s}{Q_c} \times 100 \qquad \text{, \%} \qquad (9)$$

A mathematical model was developed and employed in order to compute the hourly average thermal performance of the solar energy system. The effectiveness of heat distributing system (Eff) during this experiment can be calculated as follows:-

$$Eff = \frac{T_p - T_s}{T_k - T_s} \times 100 \qquad \text{, \%} \qquad (10)$$

Three hundred pots filled by 3.6 m³ root-media mixture which used for growing and producing hot pepper during winter season of 2004 – 2005 were loosened on the roof and divided into six equal amounts (0.6 m³) before the heating process. The container of heat treatment was filled up by 0.6 m³ of root-media mixture, and the upper surface of container was covered by polyethylene sheet (140 $\mu$ thick) in order to catch and hold heat energy in close contact with media so it can be of further value in rising the temperature. The experimental work was carried out from 24th until 29th July 2005 (6 successive days were recorded). After sunset of each day the hot water (heated by solar heating system) was pumped between the storage tank and the heat exchanger inside the container of root medium. The moisture content of the root-media was ranged between 27 to 35% wb. After the heat treatment process was accomplished, the root-media removed from the container and situated in a long narrow pile (6 m long, 1 m wide, and 0.75 m high). It was covered by polyethylene sheet and left under the sun's rays for three months in order to also utilize the technique of solarization in root-media heat treatment. The heated root-media was functioned for growing and producing cucumber crop during winter season of 2005 – 2006. Typical processing was carried out with the previous root-media after used in growing and producing cucumber crop. The total volume of root-media (3 m³) was also loosened on the roof and divided to five equal amounts. This experiment was executed from 10th until 14th June 2006 (5 following days were recorded).

For the nonstratified tank, an energy balance on the water tank attains the following equation (**Duffi and Beckman, 1991**):-

$$Q_S = Q_C - Q_{Loss} \qquad \text{, Watt} \quad (11)$$

The heat energy losses from the storage tank during daylight can be computed from the following equation:-

$$Q_{Loss} = U_{ot}\left(T_k - T_a\right) \qquad \text{, Watt} \quad (12)$$

The overall heat transfer coefficient ($U_{ot}$) of water storage tank can be calculated using the following equation (**Hollman, 1981**).

$$U_{ot} = \frac{1}{\dfrac{1}{h_i\,A_i} + \dfrac{\ln\left(r_o/r_i\right)}{2\,\pi\,k_s\,L} + \dfrac{\ln\left(r_s/r_o\right)}{2\,\pi\,k_i\,L} + \dfrac{1}{h_o\,A_o}} \qquad \text{, W/°K} \quad (13)$$

The heat energy balance on the water storage tank during daylight is represented by **Eq. (11)** which can be rewritten in a finite temperature difference form and solved for water tank temperature at the end of each hour ($T_{ke}$) in terms of the water temperature at the beginning of each hour as follows:-

$$T_{ke} = T_{kb} + \frac{3600}{MC_p}\left[\,Q_C - Q_{Loss}\,\right] \qquad \text{, °K} \quad (14)$$

A mathematical model was developed and functioned to compute the hourly average water tank temperature at the end of each hour with respect to the water tank at the beginning of each hour

The heat energy balance on the container of root-media mixture during the heat treatment process can be computed in terms of the heat energy supplied by the solar heating system ($Q_{sup}$), heat flow across a curvilinear section of the soil-pipe heat exchanger (Q), heat energy losses from the heat treatment container ($Q_{Loss}$), and heat energy stored in the root-media mixture ($Q_g$) as follows:-

$$Q_{sup} = Q + Q_{Loss} + Q_g \quad \text{, Watt} \quad (15)$$

$$Q_{sup} = m\, C_p \left(T_{hi} - T_{ho}\right) \quad \text{, Watt} \quad (16)$$

$$Q = S\, k\, \Delta T \quad \text{, Watt} \quad (17)$$

$$S = \frac{2\pi L}{\ln\left(2D/R\right)} \quad \text{, m} \quad (18)$$

$$Q_{Loss} = U_o\; A\; \left(T_S - T_a\right) \quad \text{, Watt} \quad (19)$$

$$Q_g = M_s\, C_{ps} \left(T_{se} - T_{sb}\right) \quad \text{, Watt} \quad (20)$$

The energy balance on the root-media mixture during the heat treatment process is represented by **Eq. (15)** which can be written in a finite temperature different form and solved for root-media temperature at the end of each hour ($T_{se}$) in terms of the root-media temperature at the beginning of each hour ($T_{sb}$) as follows:-

$$T_{se} = T_{sb} + \frac{3600}{M_s\, C_{ps}} \left[Q_{sup} - Q - Q_{Loss}\right] \quad \text{, °K} \quad (21)$$

A mathematical model was also developed and used to predict the hourly average root-media temperature at the end of each hour, and compare this temperature with that measured.

Nomenclature

| | |
|---|---|
| A | surface area of container, $m^2$ |
| A | solar heater aperture area, $m^2$ |
| $A_i$ | internal area of water tank, $m^2$ |
| $A_o$ | external area of water tank, $m^2$ |
| $C_P$ | specific heat of water, J/kg.°K |
| $C_{Ps}$ | specific heat of root-media, J/kg.°K |
| D | depth at which the pipe is buried, m |
| $h_i$ | internal heat transfer coefficient, $W/m^2$.°K |
| $h_o$ | external heat transfer coefficient, $W/m^2$.°K |
| $\bar{K}$ | thermal conductivity of root-media, W/m.°K |
| $k_i$ | thermal conductivity of insulation, W/m.°K |
| $k_s$ | thermal conductivity of steel sheet, W/m.°K |
| L | length of heat exchanger pipe, m |
| M | mass of water tank, kg |
| $M_s$ | mass of root-media, kg |
| M | mass flow rate of water, kg/s |
| $\dot{m}$ | mass flow rate of water through heater, kg/s |
| R | radius oh heat exchanger pipe, m |
| $r_i$ | internal radius of storage tank, m |
| $r_o$ | external radius of storage tank, m |
| $r_s$ | external radius of tank plus insulation, m |
| S | conduction shape factor, m |
| $T_a$ | ambient air temperature, °K |
| $T_{fi}$ | inlet water temperature, °K |
| $T_{fo}$ | outlet water temperature, °K |
| $T_{hi}$ | inlet water temperature of heat exchanger, °K |
| $T_{ho}$ | outlet water temperature of heat exchanger, °K |
| $T_t$ | mean water tank temperature, °K |
| $T_{tb}$ | water tank temperature at the beginning, °K |
| $T_{te}$ | water tank temperature at the end, °K |
| $T_p$ | mean temperature of pipe, °K |
| $T_p$ | mean temperature of absorber plate, °K |
| $\bar{T}_s$ | mean root-media temperature, °K |
| $T_{sb}$ | root-media temperature at the beginning, °K |
| $T_{se}$ | root-media temperature at the end, °K |
| $U_o$ | overall heat transfer coefficient, $W/m^2$.°K |
| A | absorptance of absorber plate, decimal |
| T | ransmittance of glass cover, decimal |
| $\eta_A$ | absorption efficiency, % |
| $\eta_H$ | heat transfer efficiency, % |
| $\eta_o$ | overall thermal efficiency, % |
| $\eta_s$ | storage system efficiency, % |
| ΔT | temperature difference between pipe wall and soil surface, °K |

The standard plate count technique marked out by the APHA (1989) was functioned in the determination of the total microbial contamination of root-media mixture samples. Bacteriological analysis of root-media samples before and after the heat treatment process included E.*coli* and *Salmonella* organisms was carried out during the experimental work. Weed seeds contain in the root-media before and after the heat treatment process was also tested during the experiments.

## RESULTS AND DESCUSSION

The thermal performance test for the solar energy system was executed on solar water heater mounted individually on movable frame. It was adjusted manually to change the orientation and tilt angle once each half an hour, so that at any time from sunrise to sunset the angle of incidence of the surface of the solar heater and sun's rays was set at zero. The mass flow rate of water (24 l/min) was adjusted and controlled every day using a control valve and measuring cylinder with stopwatch. The thermal performance data for the solar water heater during these experiments are summarized and listed in Table (1).

**Table (1): Daily average solar energy available (Q), absorbed solar radiation ($Q_A$), absorption efficiency ($\eta_A$), useful heat acquire to storage ($Q_C$), heat transfer efficiency ($\eta_H$), solar collector heat losses ($Q_L$), overall thermal efficiency ($\eta_O$), solar energy stored ($Q_S$), storage system efficiency ($\eta_S$), and ambient air temperature ($T_a$) during this experimental work.**

| Date | Q kWh/day | $Q_A$ kWh/day | $\eta_A$ % | $Q_C$ kWh/day | $\eta_H$ % | $Q_L$ kWh/day | $\eta_O$ % | $Q_S$ kWh/day | $\eta_S$ % | $T_a$ °C |
|---|---|---|---|---|---|---|---|---|---|---|
| 24/7/2005 | 21.734 | 18.583 | 85.5 | 16.070 | 86.48 | 2.513 | 73.94 | 13.613 | 84.71 | 31.2 |
| 25/7/2005 | 20.532 | 17.555 | 85.5 | 14.416 | 82.12 | 3.139 | 70.21 | 11.674 | 80.98 | 29.5 |
| 26/7/2005 | 20.095 | 17.181 | 85.5 | 13.920 | 81.02 | 3.261 | 69.27 | 11.142 | 80.04 | 29.3 |
| 27/7/2005 | 21.362 | 18.264 | 85.5 | 15.477 | 84.74 | 2.787 | 72.45 | 12.880 | 83.22 | 30.6 |
| 28/7/2005 | 19.806 | 16.934 | 85.5 | 13.603 | 80.33 | 3.331 | 68.68 | 10.808 | 79.45 | 29.2 |
| 29/7/2005 | 20.738 | 17.731 | 85.5 | 14.765 | 83.27 | 2.966 | 71.26 | 12.112 | 82.03 | 30.1 |
| 10/6/2006 | 22.408 | 19.159 | 85.5 | 16.434 | 85.78 | 2.725 | 73.34 | 13.823 | 84.11 | 25.1 |
| 11/6/2006 | 19.823 | 16.949 | 85.5 | 13.565 | 80.03 | 3.384 | 68.43 | 10.743 | 79.20 | 24.5 |
| 12/6/2006 | 22.666 | 19.379 | 85.5 | 16.963 | 87.53 | 2.416 | 74.84 | 14.522 | 85.61 | 26.1 |
| 13/6/2006 | 22.503 | 19.240 | 85.5 | 16.713 | 86.87 | 2.527 | 74.27 | 14.213 | 85.04 | 25.8 |
| 14/6/2006 | 23.735 | 20.293 | 85.5 | 17.853 | 87.98 | 2.514 | 75.22 | 15.352 | 85.99 | 27.9 |
| **Total** | 235.402 | 201.268 | — | 169.779 | — | 31.563 | — | 140.882 | — | — |
| **Mean** | 21.400 | 18.297 | 85.5 | 15.434 | 84.20 | 2.859 | 71.99 | 12.807 | 82.76 | 28.10 |

During the experimental work, solar energy available, absorbed solar radiation, absorption efficiency, useful heat acquire to storage, heat transfer efficiency, overall thermal efficiency, solar energy stored, and storage system efficiency were increased gradually with solar time from sunrise until they reached the maximum values at noon. They then slimed till arrived the minimum values just before sunset. However, there were many factors affecting thermal performance of solar heater such as, intensity of solar radiation flux incident, inlet water temperature, ambient air temperature surrounding the heater, and rate of heat energy consumed during root-media heat treatment process (heat energy to load). The daily average solar energy available for July 2005 and June 2006 was 20.711 and 22.227 kWh/day, respectively. There were evidently differences in solar energy available for the days recorded during these experiments, due to the effect of atmospheric conditions and solar altitude angle. The daily average absorbed solar radiation for the same period was 17.708 and 19.004 kWh/day, respectively. It was strongly dependent upon the transmittance of glass cover and the absorptance of the absorber plate which they had affected by the solar angle of incidence.

The daily average absorbed solar radiation converted into useful heat acquire to storage for July 2005 and June 2006 was 14.709 and 16.306 kWh/day, which gave an average heat transfer efficiency of 82.99% and 85.64%, respectively. It was found to be directly proportional to solar energy available and ambient air temperature, and inversely proportional to water inlet temperature. Mathematical analysis of the measured data revealed that, during early morning just after sunrise and prior to sunset (when the solar radiation flux incident at these times was less than 350 W/m$^2$) very little useful heat was acquired by the water passing through the solar heater. It was also observed that, the operating fluid (water) dissipated some of its heat energy to the absorber plate particularly before sunset. This phenomenon may be attributed to the large mass (10.828 kg) and large area (2 m$^2$) of the absorber plate and therefore, the amount of solar energy required to increase the absorber plate temperature above the water temperature was insufficient.

The daily average heat losses from the solar heater for the same period were 3.000 and 2.713 kWh/day, respectively. The heat losses of the solar collector were highly affected by the water inlet temperature and ambient air temperature. As the water inlet temperature increased, the absorber plate temperature increased over the ambient air temperature and heat losses are thus increased.

The overall thermal efficiency of the solar collector is a combination of absorption and heat transfer efficiencies. The daily average overall thermal efficiency for July 2005 and June 2006 was 70.97% and 73.22%, consequently 29.03% and 26.78% of the solar energy available was lost, respectively. The plot of overall thermal efficiency against temperature rise as shown in Fig. (2) was straight line with y-intercept ($F_R \tau \alpha$) and slope ($-F_R U_O$). It is showed that, ($U_O$) is a function of temperature difference between absorber plate and ambient air, and wind speed blowing over the solar collector. Also, the heat removal factor ($F_R$) is a weak function of the overall heat transfer coefficient ($U_O$). Thus, scattering in the plotted data occurred as revealed in Fig. (2). The daily average heat removal factor ($F_R$) was 0.979, and the daily average heat transfer coefficient was 5.558 W/m².°K. These obtained data are in agreement with the data published by Duffie and Beckman (1991) and Abdellatif *et al.* (2006).

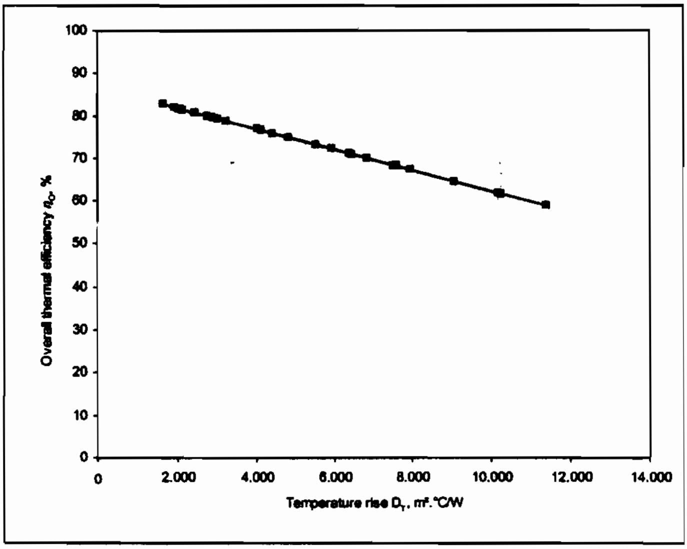

**Fig. (2): Overall thermal efficiency against Temperature rise.**

During this research work, the daily average solar energy stored in the storage tank for July 2005 and June 2006 was 12.038 and 13.731 kWh/day, which gave an average storage system efficiency of 81.74 and 83.99%, respectively. The solar energy stored in the storage tank and the storage system efficiency were directly related to the overall thermal efficiency of the solar collector, and the problems which affected the solar collector efficiency also affected the overall storage system efficiency as reported by Duffie and Beckman (1991) and Hepbasli and Ozgener (2004).

The mathematical model of heat energy balance on the storage tank that was destined previously, revealed that many factors affecting heat energy balance such as: heat energy storage capacity, useful heat gain to storage, and heat energy losses from the storage tank. The mathematical model of energy balance on the water storage tank which functioned to predict the water temperature at the end of each hour in terms of the water temperature at the beginning of each hour gave an excellent agreement. The measured water temperatures during daylight were plotted as a function of that predicted as revealed in Fig. (3). The predicted water temperatures were validated very well with that measured for July 2005 and June 2006 by 98.25% and 98.97%, respectively.

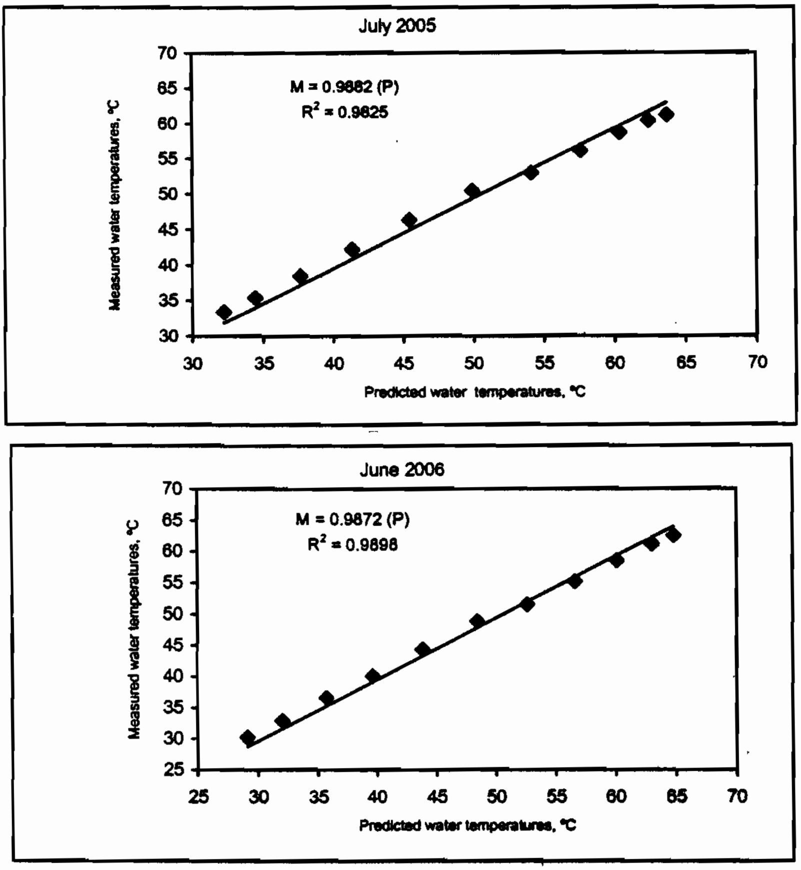

**Fig. (3): Measured water temperatures versus Predicted water temperatures in the storage tank for July and June.**

Root medium heat treatment process, in addition to eliminating organisms, is functioned to control nematodes, insects, and weed seeds. After sunset of each day during these experiments, the hot water (heated by solar energy system) was pumped between the storage tank and the heat exchanger inside the container of root-media. Heat energy was moved most rapidly within the root-media by convection and steady-state conduction multiple dimensions. The mathematical model of heat energy balance which was presented previously in Eq. (15), revealed that, there are many parameters affecting heat energy balance on root-media container during heat treatment process at night. These parameters and their affect on thermal energy balance are listed in Table (2). The monthly average daily heat energy supplied by the solar energy system into the heat treatment container of root-media for July 2005 and June 2006 was 71.876 and 68.306 kWh/month, respectively. It was varied from hour to hour, day to another, and throughout the experimental work depending upon the water temperature difference between the outlet and the inlet of heat exchanger.

**Table (2): Monthly average daily heat energy supplied ($Q_{sup}$), heat flow across a curvilinear section (Q), heat energy losses from the heat treatment unit ($Q_{Loss}$), heat energy stored (gained) in the root-media ($Q_g$), and predicted heat energy supplied during the experimental work.**

| Month | $Q_{sup}$, kWh/month | Q, kWh/month | $Q_{Loss}$, kWh/month | $Q_g$, kWh/month | $Q_{sup}$, kWh/month predicted |
|---|---|---|---|---|---|
| July 2005 | 71.876 | 30.364 | 14.360 | 25.934 | 70.658 |
| June 2006 | 68.306 | 26.734 | 19.283 | 21.780 | 67.797 |
| **Total** | 140.182 | 57.098 | 33.643 | 47.714 | 138.455 |
| **Mean** | 70.092 | 28.549 | 16.822 | 23.857 | 69.228 |

For the duration of the experimental work, the monthly average daily heat flow across a curvilinear section of the heat exchanger pipes for July 2005 and June 2006 was 30.364 and 26.734 kWh/month, respectively. It was varied from time to time, day to another, and throughout the heat treatment process depending upon the temperature difference between average pipe-wall surface and root-media surface. It was almost presented 40.73% of the heat energy supplied by the heating system. The monthly average daily heat energy losses from the heat treatment container into the surrounding for the same period was 14.360 and 19.283 kWh/month, respectively. It was also varied from hour to hour, day to another and throughout the experiments according to the temperature difference between mean root-media and ambient air surrounding the container. It was almost presented 19.98% and 28.23% due to the mean ambient air temperatures during July 2005 and June 2006 were 25.02 °C and 20.93 °C, respectively. During these experiments, the monthly average daily heat energy acquired by the root-media mixture for July 2005 and June 2006 was 25.934 and 21.780 kWh/month, respectively. It was also varied from time to time, night to another, and throughout the heating process according to the temperature difference between the mean root-media at the end and beginning of each hour during the process. The heat energy gained by the root-media for the same period almost presented 36.08% and 31.89%, respectively.

The measured heat energy supplied by the solar energy system to the container of heat treatment was used as a function of that predicted during the experimental work as shown in Fig. (4). Regression analysis revealed a highly significant linear relationship ($R^2$ = 0.997; $P \leq 0.001$) between the measured and predicted heat energy supplied. The linear regression equation for the best fit was:-

$$Q_{sup}\,(\text{measured}) = 1.011\,(Q_{sup},\ \text{predicted})$$

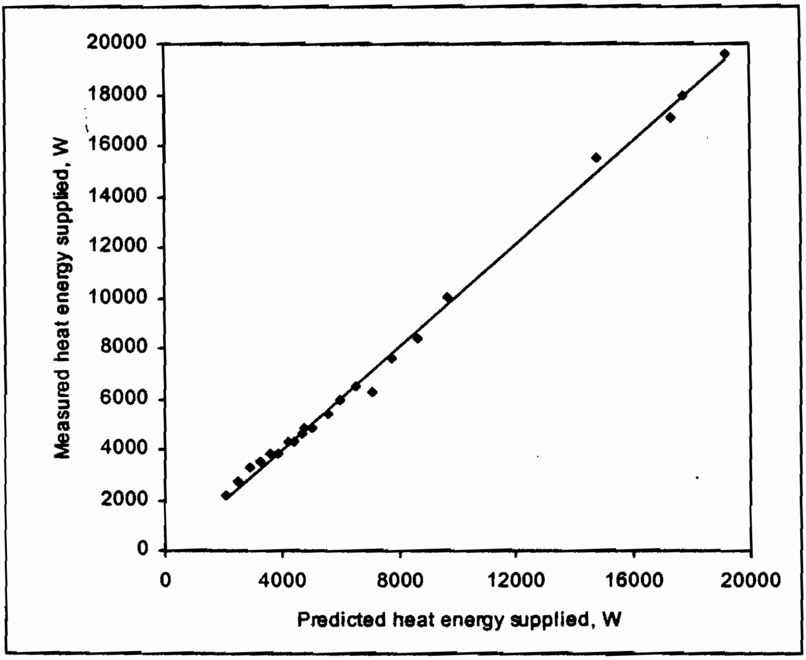

**Fig. (4): Measured heat energy supplied against predicted heat energy supplied.**

As evidently showed in Table (2) and Fig. (4), the difference between measured and predicted heat energy supplied was very small. Consequently, the predicted data were validated very well with that measured. Equation (21) evidently introduced and showed the parameters that affecting the prediction of root-media temperatures during the heating process at night. According to this model, the measured temperatures of root-media ($T_{sm}$) were examined with the predicted temperatures ($T_{sp}$) as revealed in Fig. (5). Regression analysis showed a highly significant linear relationship ($R^2$ = 0.993; P $\leq 0.001$) between the measured and predicted root-media temperatures. The regression equations for the best fit were:-

$$T_{sm}\left(\text{July 2005}\right) = 0.9823\ \left(T_{sp}\right)$$

$$T_{sm}\left(\text{June 2006}\right) = 0.9939\ \left(T_{sp}\right)$$

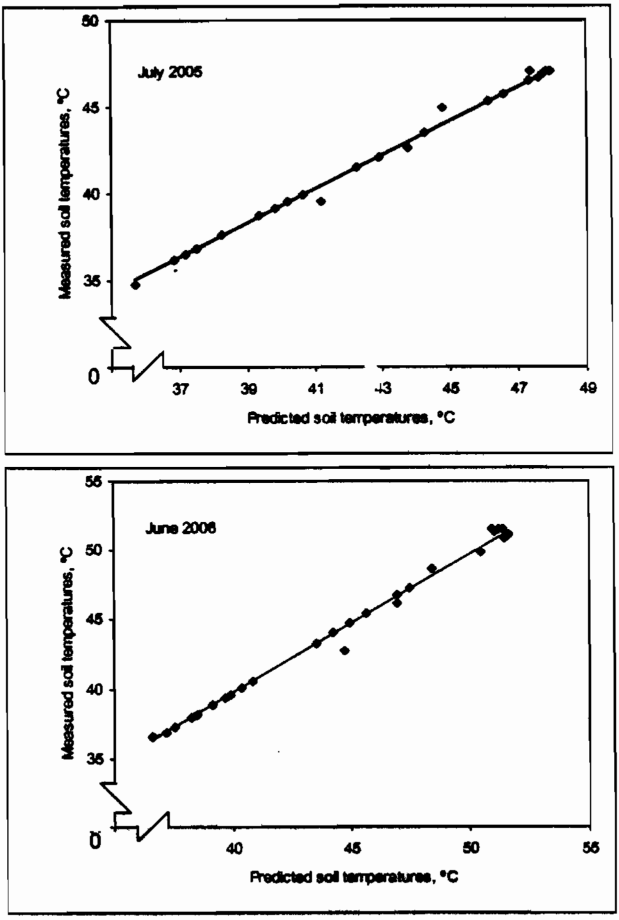

**Fig. (5): Measured soil temperatures versus Predicted soil temperatures for July-2005 and June-2006.**

The predicted root-media temperatures were validated with that measured (for July 2005 and June 2006) by 99.68% and 99.61%, respectively, which gave an excellent agreement.

The daily average effectiveness of the heat distributing system (heat exchanger) during the experimental work for July 2005 and June 2006 was 72.82% and 79.35%, respectively. It was varied from time to time, night to another, and during the experiments according to the water temperature in the storage tank and the temperature difference between the pipe-wall surface and the root-media mixture. As the water temperature in the storage tank is increased over the mean temperature of root-media, more energy is supplied to the container of heat treatment making the heat distributing system more efficient. Therefore, the greatest effectiveness of heat distributing system (93.30%) was achieved at the beginning of heating period.

Meanwhile, the lowest effectiveness (49.20%) occurred at the end of heating process, due to reduction in water temperature inside the storage tank and increasing the root-media temperature.

Due to the temperatures of root-media mixture inside the container of heat treatment were increased from 29.2 to 47.1 °C (July 2005) and from 30.1 to 51.5 °C (June 2006) and remained at the high level of temperatures for about four hours, there were no any weed seeds contained in the root medium thereafter. The manipulated root-media by solar energy system on July 2005 was employed to grow and produce cucumber crop during winter season of 2005 — 2006, there were no any weeds observed in all pots of the plants. Also, the treated root medium on June 2006 was functioned for growing and producing tomato crop during winter season of 2006 — 2007 without any weeds. This is in agreement with data published by several researchers (Churchill *et al* ., 1995; Michel *et al*., 1996; and Nelson 1998), when they reported that, the most weed seeds are destroyed at temperature of 45 °C (113 °F).

During the root medium heat manipulation on July 2005, the high level of temperature (47.1 °C) and long time of heating process (four hours) led to destroy most harmful organisms while only a minimum of beneficial organisms were killed. Bacteriological analysis of root medium before and after the heat treatment process during July 2005 is listed in Table (3). It evidently shows that, a trace amounts of microbial contents were observed in all samples except three ones (2, 3, and 4) exhibited relatively high count of *coliforms* of fecal origin. The *E.coli* count on average was 10.46 x $10^3$ CFU/g which reduced to 3.08 x $10^{-5}$ CFU/g after the heat treatment process. This reduction can be attributed to the high temperature level of 47.1 °C and long heating time (four hours). It also reveals that, only two samples were found to be free from *Salmonella* organisms (1 and 5), the reminder specimens were exhibited relatively high count of *Salmonella* (7.2 x $10^3$ CFU/g). All the *Salmonella* organisms were destroyed during the heat treatment process of root-media. Therefore, this root-media was safely employed for growing and producing cucumber crop during winter season of 2005— 2006.

**Table (3): Effect of heat manipulation temperature on microbial content of root medium for six samples during July 2005.**

| **Specimen** | **Before heat treatment** | | **After heat treatment** | |
|---|---|---|---|---|
| | ***E. coli*, CFU/g** | ***Salmonella*, CFU/g** | ***E. coli*, CFU/g** | ***Salmonella*, CFU/g** |
| $S_1$ | 200 | 0 | 0 | 0 |
| $S_2$ | 15.7 x $10^3$ | 1250 | 4.81 x $10^{-5}$ | 0 |
| $S_3$ | 30 x $10^3$ | 2650 | 9.2 x $10^{-5}$ | 0 |
| $S_4$ | 15.4 x $10^3$ | 2300 | 4.1 x $10^{-5}$ | 0 |
| $S_5$ | 780 | 0 | 0 | 0 |
| $S_6$ | 1300 | 1000 | 3.9 x $10^{-5}$ | 0 |
| **Average** | 10.46 x $10^3$ | 1200 | 3.08 x $10^{-5}$ | 0 |

The temperature of root-media mixture was rose up from 30.1 °C to 50 °C within five hours and slowly increased till it reached to 51.5 °C after another three hours. It was remained at that high level for about three hours. Due to high level of temperature and long heating time, most harmful organisms were completely destroyed while only a minimum of beneficial organisms were killed. Bacteriological analysis of root-media samples before and after the heat treatment process during June 2006 is listed in Table (4). It evidently reveals that, only three sampled were found to be free from E.coli and Salmonella organisms, while the first and second specimens were exhibited high count of coliforms of fecal origin. A relatively high count of Salmonella organisms (25 x $10^3$ CFU/g) was observed in the first specimen as compared with all samples in July 2005. The E.coli count on average was 162 CFU/g, which reduced to 16.2 x $10^{-3}$ CFU/g after the heat treatment process. It also shows that, the percentage reduction in Salmonella on average was 96.15% meaning that ,the majority of Salmonella organisms were destroyed during the heat treatment process. Thus, this root-media was safely used for growing and producing tomato crop during winter season of 2006 — 2007. This technique of root-media heat treatment still uses until now, due to its high effectiveness and succeeding in eradicating of harmful organisms.

**Table (4): Effect of heat treatment temperature on microbial content of root-media for five samples during June 2006**

| **Specimen** | **Before heat treatment** | | **After heat treatment** | |
|---|---|---|---|---|
| | **E. *coli*, CFU/g** | ***Salmonella*, CFU/g** | **E. *coli*, CFU/g** | ***Salmonella*, CFU/g** |
| $S_1$ | 610 | 25 x $10^3$ | 81 x $10^{-3}$ | 1 x $10^3$ |
| $S_2$ | 200 | 1 x $10^3$ | 0 | 0 |
| $S_3$ | 0 | 0 | 0 | 0 |
| $S_4$ | 0 | 0 | 0 | 0 |
| $S_5$ | 0 | 0 | 0 | 0 |
| **Average** | 162 | 5.2 x $10^3$ | 16.2 x $10^{-3}$ | 200 |

Due to high level of root-media temperature and long heating time there were no any Nematodes observed in the samples thereafter. This is in agreement with the data published by Nelson (1998) when reported that, all the Nematodes destroy at temperature of 45.6 °C (114 °F) for about 30 minutes.

After the root-media heat treatment process were fulfilled, the root medium situated in a long narrow pile covered with polyethylene sheet and left under direct solar radiation for about three months in order to utilize the technique of solarization in root-media heat manipulation. There were no nay harmful organisms observed in the root-media mixture thereafter.

# CONCLUSION

The solar energy system and root-media heat treatment system were operated satisfactorily for two seasons without any malfunction. The main results of this research work can be concluded and summarized as follows:-

1. The thermal performance of the solar water heater was computed by its overall thermal efficiency in converting solar energy available into useful heat gain to storage. Overall thermal efficiency of the solar water heater is a combination of optical efficiency and heat transfer efficiency. The daily average overall thermal efficiency during these experiments was 71.99%, consequently 28.01% of the total solar energy available was lost.
2. The daily average solar energy stored in the storage tank was 12.807 kWh/day, which gave an average storage system efficiency of 82.76%. Consequently, 17.24% of the total useful heat gain to storage was lost.
3. According to the heat energy balance on the storage tank of solar energy system, the predicted water temperatures in the storage tank were validated well with that measured by 98.61%, which gave an excellent agreement.
4. Greenhouse root-media should be treated at least once per year, and more often as required, to rid them of harmful disease organisms, nematodes, insects, and weed seeds. Root-media can be heat treated by rising it to a temperature of 40 – 60 °C.
5. The mathematical model which described and used to predict the temperature of root-media mixture at the end of each hour in terms of that at the beginning of each hour was validated very well with that measured by 99.65% which gave an excellent agreement.
6. The daily average effectiveness of heat distributing system (heat exchanger) during the experimental work was 76.09%.
7. Due to the temperatures of root-media inside the heat treatment container were rose from 29.2 °C to 47.1 °C during July 2005 and from 30.1 to 51.5 °C during June 2006, and remained at that high level of temperatures for about four hours, there were no any weeds observed in all pots of the plants.
8. Due to the same reason the E.*coli* microbial content was reduced from 10.46 x $10^3$ CFU/g to 3.08 x $10^{-5}$ CFU/g after the heat treatment process during July 2005. also, the Salmonella organisms (7.2 x $10^3$ CFU/g) was completely destroyed during the heat treatment process.
9. Bacteriological analysis of root-media samples before and after the heat treatment process during June 2006, revealed that, the E.*coli* microbial content was reduced from 162 CFU/g to 16.2 x $10^3$ CFU/g after the heat treatment process. *Salmonella* organisms were on average reduced from 5.2 x $10^3$ CFU/g to 200 CFU/g.
10. After the heat treatment process of root-media was fulfilled, the technique of solarization was used for heat manipulation of root-media mixture. There were no any harmful organisms observed in the root-media after this process for all samples.

Ultimately, the solar energy system can satisfactorily be used for heat treatment of greenhouse root-media mixture particularly for pots plant system with a very good reliability.

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# تجميع وتخزين واستغلال الطاقة الشمسية في عملية المعالجة الحرارية لبيئة جذور البيوت المحمية

**صلاح مصطفي عبد اللطيف و أحمد البهنساوي إسماعيل البهنساوي**
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تم تصميم وتنفيذ نظام كامل للطاقة الشمسية بورشة قسم الهندسة الزراعية, وضع هذا النظام فوق سطح القسم عند خط عرض ٣١,٠٤٥° شمالاً بغرض تجميع وتخزين و استغلال الطاقة الشمسية المتاحة في عملية المعالجة الحرارية لخليط بيئة جذور البيوت المحمية. يتكون نظام الطاقة الشمسية من ثلاثة عناصر أساسية هي: سخان ماء شمسي مساحته ٢ م$^{٢}$ (١X٢)، خزان تخزين معزول سعته ٣٣٢ لتر و أخيراً نظام توزيع الطاقة الحرارية (مبادل حراري) يستخدم نظام السريان المتوازي. أثناء ساعات النهار يتم دفع الماء بين خزان التخزين و سخان الماء الشمسي باستخدام طلمبة مياه قدرتها نصف حصان، تم تزويد وعاء المعالجة الحرارية بمبادل حراري كما تم ملئه بـ ٠,٦ م$^{٣}$ من بيئة جذور البيوت المحمية وتغطية وعاء المعالجة بطبقة من البولي إيثيلين للمحافظة علي الطاقة الحرارية المضافة لنظام المعالجة. تم دفع الماء الساخن (أثناء النهار) بعد غروب الشمس داخل المبادل الحراري الموجود بوعاء معالجة بيئة الجذور بعد مرور ١١ ساعة من المعالجة الحرارية تم إزالة التربة من وعاء المعالجة ووضعها في شكل كومة غطت بطبقة من البولي إيثيلين و تركت لمدة حوالي ٣ شهور بغرض استغلال تقنية التشميس في معالجة التربة. تم تطوير و استخدام نموذجين رياضيين لحساب درجات حرارة الماء داخل خزان التخزين و درجات حرارة التربة أثناء عملية المعالجة الحرارية تبعا لاتزان الطاقة الحرارية علي خزان التخزين و وحدة معالجة التربة. تم تحليل عينات من التربة قبل عملية المعالجة وبعدها وبعد عملية التشميس لتحديد أعداد الكائنات المرضية الملوثة لتربة بيئة جذور البيوت المحمية.

أوضحت النتائج المتحصل عليها ما يلي:-

١- بلغت الكفاءة الحرارية الكلية لنظام التسخين الشمسي في المتوسط ٧١,٩٩%، و بالتالي فان الفاقد من كمية الطاقة الشمسية المتاحة هو ٢٨,٠١%.

٢- كمية الطاقة الشمسية المخزنة يوميا في الخزان خلال التجارب بلغت ١٢,٨٠٧ كيلو وات ساعة/يوم، و التي تعطي كفاءة لنظام التخزين بمتوسط ٨٢,٨٩%.

٣- تمت مقارنة درجات الحرارة المتوقع وصول الماء في خزان التخزين لها مع درجات الحرارة المقاسة و أعطت نسبة قبول ممتازة هي ٩٨,٦١%.

٤- درجات الحرارة المتوقع أن يصل لها مخلوط بيئة الجذور في وحدة المعالجة الحرارية قورنت جيدا مع تلك المقاسة بنسبة ٩٩,٦٥% مما أعطي موافقة ممتازة.

٥- بلغت فعالية المبادل الحراري خلال التجارب ٧٦,٠٩%.

٦- قياسا إلي استخدام نظام التسخين الشمسي في عملية المعالجة الحرارية لبيئة جذور البيوت المحمية لم يلاحظ وجود لأي من بذور الحشائش في جميع أصص النباتات، و قد انخفض المحتوي الميكروبي لميكروبات الإيكولي في المتوسط من ٥,٣١١ X ١٠$^{٣}$ إلى ٨,١١٥٤ X ١٠$^{-٣}$ وحدة تكوين مستعمرة/جرام، و كانت ميكروبات السلمونيلا قد انخفضت بمتوسط من ٣,٢٠ X ١٠$^{٣}$ إلي ١٠٠ وحدة تكوين مستعمرة/جرام

٧- استخدام تقنية التشميس في المعالجة الحرارية لبيئة جذور البيوت المحمية أدى إلي القضاء علي المتبقي من الكائنات الحية الضارة الموجودة في بيئة الجذور