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Effect of Glazing Materials on Warming up Automated Commercial Greenhouses

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ABSTRACT

The influence of greenhouse glazing materials on automated greenhouses based on complete solar heating system was studied in two identical greenhouses for producing cucumber crop. Two different glazing materials; polycarbonate plates and double layer of polyethylene sheets were used. The indoor microclimatic conditions (air temperature, relative humidity, dew-point temperature, and intensity of solar radiation) can be monitored, controlled and recorded on a data-logger for analysing that unit with cucumber crop yield response. A mathematical model was developed to simulate the microclimate conditions at and around the leaves surface. The obtained results revealed that, during the growing season at night-time the greenhouse covered with the polycarbonate plates reduced the total heat energy consumption by 27.89% as compared with the greenhouse covered by polyethylene sheets. Using the solar heating system for both greenhouses provided 44.83% and 32.33% of the total heat energy consumption during the growing season, respectively. The obtained results also indicated that, the use of a mixed system (solar and electrical energy) was favourable in providing microclimatic conditions for both greenhouses since the indoor air temperature, relative humidity, and vapour pressure deficit were at and around the desired level. Due to the optimal level of microclimatic conditions for the two greenhouses, the production rates of cucumber fresh yield were 6.529 and 4.933 kg/m^2 of floor area. However, the annual costs of polycarbonate cover and the double layer of polyethylene cover are 2,831.25 and 2,432 EGP, respectively, with an increasing percentage of 16.42%.

Keywords: Solar energy, Greenhouse, Heating load, Heat energy consumption.

INTRODUCTION

Greenhouses are mainly used in order to provide more favourable environmental conditions for plant growth. The most important factor affecting plant growth is the solar radiation, and the most crucial process requiring solar radiation and governing plant growth is the photosynthesis process. Therefore, the characteristics of the greenhouse glazing materials, which can affect the level and quality of the transmitted solar radiation and hence the physiological behaviour of plants, become of primary concern for greenhouse cultivation. The solar radiation level inside a greenhouse is dependent mainly upon the transmittance of the covering material, the structural form, and the orientation of the greenhouse. Originally, glass cover was used, but now plastic films, fiberglass reinforced plastic, acrylic panels, and polycarbonate panels are used. The future holds promise of new covering materials which will reduce the heating load and cooling, and new frame designs which will be more economical (Fabrizio, 2012).

In Egypt, low indoor air temperature (T < 10°C) and vapour pressure deficit (VPD < 0.43 kPa) are currently observed in the greenhouses at nighttime during the winter season. Whilst, the indoor air temperature during the daylight-time exceeding 35ºC in winter and vapour pressure deficit is increased (VPD > 3.0 kPa). A large variation in indoor air temperatures of greenhouse between the daylight and night times (dT > 10ºC) during winter season resulting in decreasing the fresh yield and quality of protected cropping. Low indoor air temperatures of a greenhouse at nighttime during winter season demands an adequate amount of heat energy to rise up the indoor air temperature into a desirable level. Several proven energy conservation measures are being widely used and numerous others are being tested and developed. With the utilization of plastic film (polyethylene sheets) in the mid-sixties, double layer glazing polyethylene was observed to provide an insulating effect which reduced heat losses 30 to 40% (ASAE, 2013). Comparison between the polyethylene and glass covers has been investigated by Papadakis *et al.* (2000), they concluded that a greenhouse covered with polyethylene sheets had a higher total heat energy consumption than a glass cover. Particular interest is the durability of these materials and their capacity for affecting the indoor microclimate of the greenhouse. These characteristics of the greenhouse glazing materials are dependent strongly upon their mechanical and physical properties. Three different modes of heat energy losses (conduction, convection, and thermal radiation) are mainly occurring from the warm interior to the colder exterior (Nelson, 2006; Montero, 2009). Most heat energy is lost by conduction through the glazing materials of greenhouses. The second mode of heat loss is that of cold air infiltration (natural convection) through spaces between panes of glass or fiberglass or cracks in plastic sheets. The third mode of heat loss is that of thermal radiation, when the warm interior objects emit radiant heat energy through air to colder objects without warming the air significantly (Omid *et al*., 2011).

Most widely used heating system in Mediterranean countries is based on hot air supplied and distributed in the

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greenhouse through perforated plastic ducts. Recently, there has been presenting trend to install hot-water pipes system in new greenhouses. The heating system in continuous process, should supply the heat energy just enough to compensate which is lost (Ghosal and Tiwari, 2014). Several greenhouse heating systems have been studied and reported by numerous investigators over the last 40 years and are briefly reviewed below. Using the polycarbonate sheets to reduce the thermal transmittance of covering and the solar capture based on low cost plastic solar collectors were studied by Ozkan *et al.* (2011). Their results reveal that providing of the order of 30% can be achieved using more insulated transparent materials. The heat energy used for controlling the environment of greenhouse is still high because of the fact that the greenhouse technologies mainly tend to maximise the solar radiation transmittance and do not guarantee a thermal insulation as good as the civil buildings (Djevic and Dimitrijevic, 2009; Benli and Durmus, 2012). Renewable energy technologies produce marketable energy by converting natural phenomena into useful forms of heat energy. Installation and operation of renewable energy systems for different agricultural applications is provided several benefits such as; energy saving, generation of job opportunities, and minimise of environmental pollution. Nowadays, significant progress is made by improving the collection and conversion efficiencies, lowering the initial and maintenance costs, and increasing the reliability and applicability (Falconett and Nagasaka , 2010). Because of intermittent nature of solar energy, and energy storage unit is required to be attached with solar heating system for using when solar radiation is not available. Therefore, the storage system constitutes an important component of the solar energy utilisation system (Singh *et al*., 2010). Due to uncertain price rise and depletion of fossil fuels, the greenhouse industry has been seeking for the alternative fuel sources to provide heat energy required for heating greenhouse. The technical and design feasibility of using biomass heat energy to assist solar heating system at the eastern area of coastal delta was evaluated by Abdellatife *et al.* (2016). They concluded that over 180 days heating season the solar heating system provided 30.32% of the total heat energy required for heating the commercial greenhouse. Whilst, the biomass heating system provided 58.55% of the total heat energy required. Thus, the hybrid heating system has provided 88.87% of the heat energy required for heating the greenhouse.

To protect the optimal fresh yields of greenhouse cucumber crop in the eastern area of coastal delta during winter growing season when the indoor air temperatures are lowered by 10ºC, the greenhouse should be supplied by a significant amount of heating load. Therefore, the aim of this study is to examine the effect of greenhouse glazing materials (polycarbonate plates and double layer polyethylene sheets) on the heating load supplying into the automated commercial greenhouses.

MATERIALS AND METHODS

Greenhouse facilities:

The experimental work were conducted during winter growing season of 2018/2019 (from December to April) in two identical commercial gable-even-span greenhouses, orientated in east-west direction, and situated at the Agricultural Research Centre of Mansoura University (Latitude and longitude angles, respectively, are 31.045 ºN and 31.37 ºE, and altitude 6.0 m above the sea level). The geometrical characteristics of each greenhouse were; total width of 9.0 m, eaves height of 2.30 m, curtain height of 0.20 m, gable height of 2.293 m, rafter length of 5.05 m, total length of 32.0, total floor surface area of 288.0 m, and total volume of 1049.8 m^3 as shown in Fig. (1). Each rafter was tilted at 27^o to reduce the wicked side effects of wind load and at the same time it may maximise the intensity of solar radiation on the roof of the greenhouse during winter months. The structural frames of the two greenhouses are formed of 38.1 mm (1.5-inch) hot dipped galvanised pipes. The two greenhouses (G1 and G2) were covered by two different glazing materials, single layer of polycarbonate panels 6.0 mm thick, and double layer of polyethylene sheets each one 200 µm thick. The greenhouses facility used in this research work was covered with the ratio of cover surface area to the total greenhouse surface area of 1.849.

The two greenhouses were supplied with two complete solar heating systems to provide hot water to be stored during daylight-time for using the stored heat energy at night-time as revealed in Fig. (2). Each one comprehends; 6 individual solar collectors each having gross dimensions of 2 m long and 1 m wide with net surface area of 2 m^2, insulated water storage tank (2.0 m^3) situated inside the greenhouse, heat exchanger (parallel heat distributing system) consisted of 7 parallel rows of hot dipped galvanized pipes (1.5-inch in diameter) which are located 2.35 m above the floor level, two water pumps (one linked between the solar collectors and the storage tank, and the other linked between the storage tank and the heat distributing system), and two electrical heaters used as an auxiliary heater (each one 9 kWh nominal power) witch operated when the solar energy stored was insufficient to provide an adequate amount of heat energy for heating the greenhouse. The 6 solar collectors are arranged in two parallel banks with three collectors in series array in each bank. The two greenhouses were equipped by a complete evaporative cooling system based on fan and cooling pad system. Two extracting fans (single speed, belt driven, 110 cm diameter, and 43,000 m^3/h discharge) was located on the leeward side of each greenhouse and the cooling pads (cross-fluted cellulose pads of 9.0 x 2.0 m, mounted in a vertical fashion) on the side toward the prevailing winds. The cooling process by ventilating was mostly used when the outdoor air temperature is lower than 20^oC. But when the air temperature outside the greenhouse is raised above 20^oC, the evaporative cooling system was used.

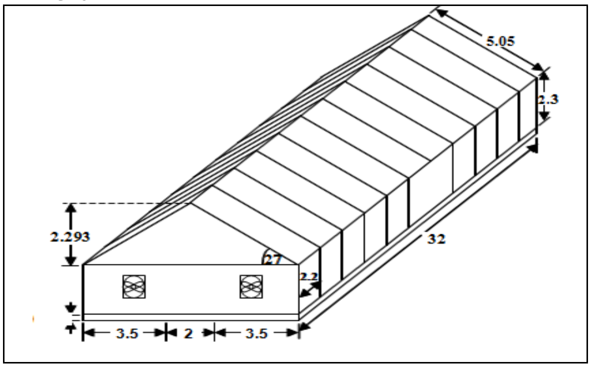

Fig. 1. Commercial gable-even-span greenhouse (dimensions in metre).

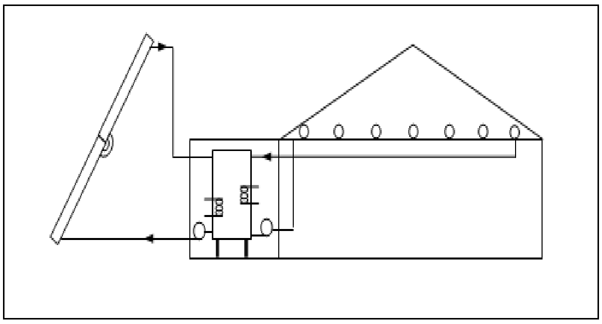

Fig. 2. Schematic diagram of the complete heating system.

The two greenhouses were also supplied with an environmental control board. The indoor air temperature during the daylight-times was monitored using an on-off controller in order to expel the excessive indoor heat at 26ºC (switching on the two fans) and interrupt the electrical current (switching off) when the indoor air temperature reached to 24ºC. The indoor air temperature at nighttime was also monitored using an on-off controller to initiate heating at 18ºC (switching on) and switched off at 20ºC. The indoor air temperature at 2.25 m above the floor surface at night-times was also monitored using an on-off to initiate heat energy supplying at 18ºC (switching on) and interrupt it at 20ºC (switching off). Adequate heat energy was continuously gained by the indoor air and the leaves of cucumber plants from the galvanized heating pipes (heat distributing system) through convection and radiation heat transfer modes.

The indoor floor surface area of the two greenhouses was divided into six wide piles (90 cm wide, 20 cm high, and 50 cm space between two consecutive piles). Two rows of each pile were directly planted on 5^{th} of December 2018 by seven hundred and forty four seeds of cucumber crop (Laurens F1, cv., Enza Zaden co., Netherlands). After four days of planting seeds the cucumber plants were raised in the beds with 97.6% germination ratio. The cucumber plants were watered twice a week by one cubic metre during each watering operation using drip irrigation system (long bath GR, 4-litre/hr discharge, 50 cm equidistance). To conserve and provide the irrigation water in agricultural operations, the irrigation water performance indicators which comprehend; water use efficiency (WUE) and annual water productivity (AWP) were estimated at the end of growing seasons (April 2019). The plants of cucumber inside the two greenhouses were watered by half cubic meter of water each irrigating operation based on the dripping irrigation system to provide good root-to-soil contact. One and half cubic meters of water per week were continuously supplied to each greenhouse. The water use efficiency (WUE) was estimated at the end of growing season using the following formula (Lorite *et al.*, 2004):

$$\mathbf{WUE} = \frac{CPV, kg}{W_{con.}, m^3}, \quad \mathbf{kg/m^3} \quad (1)$$

Where,

CPV, is the total value of crop productivity in kg, and $W_{con.}$ Is the total water consumption in m^3

Measurements and data acquisition unit

The macroclimate conditions comprehend; air temperature, air relative humidity, wind speed, rainfall amount, and solar radiation were measured and recorded using meteorological station (Vantage Pro 2, Davis, USA) installed 5 m above the ground level. A twelve channels data-logger system (Digi-sense scanning thermometer type) was used to measure and store reading from different sensors (thermocouple type K) situated at different locations inside the two greenhouses. It measured and recorded with a time interval 5 min. different temperatures such as; water in the storage tanks, inlet and outlet of solar heating system, air just leaving the cooling pads, air at the centre of greenhouse, and air just prior to leaving the extracting fans. The microclimate conditions of the two greenhouses include; intensity of solar radiation above the plant canopy, air temperature relative humidity dew-point temperature, heating pipe temperature, and soil temperature at 5 cm deep, were also measured and recorded at 2.25 m above the floor level using data-logger (Watch-dog, 1000 series, USA). The following measurements for each greenhouse were recorded:

1. Dry and wet-bulb temperatures, relative humidity, and dew-point temperature of the indoor air were recorded at the middle of greenhouse at 2.25 m above the floor surface
2. The soil temperature, heating pipes temperature, air temperature just leaving the cooling pads, and air temperature prior to leave the greenhouse were also measured and recorded.
3. The intensity of solar radiation incident on the crop canopy inside the greenhouse was measured and recorded.
4. The inlet and outlet water temperatures of the solar heating system, the water temperature in the storage tank, and the inlet and outlet water temperature of the heat exchanger (heat distributing system) were also measured and recorded.

All the previous mentioned measurements were centralised on two data-logger systems and data-logger of 12 channels on which the data were measured every 10 seconds and averaged on 5 minutes time scale before being processed.

Heating load:

Greenhouse heating is resided in the task of adding heat energy by the rate at which it is lost. Generally, the indoor air temperature of 18ºC is realised the demands of most protected cropping. Most undesirable heat losses form the greenhouses occur by conduction through the glazing materials, convection through the moving or mixing indoor moist air, long-wave radiation, and infiltration of outdoor cold air as revealed in Fig. (3). Heating load requirements for heating the greenhouses are determined by computing the sum of long-wave radiation, conduction and convection (q_{rc}), and infiltration (q_{inf}) based on the following formulas (Nelson, 2006; ASAE, 2013; Esen and Yulsel, 2013):

$$q_{rc} = \Sigma U_o A_c (T_{ai} - T_{ao}), \quad \text{Watt} \quad (2)$$

Where, **U_o, is the overall heat transfer coefficient in W/m² ºC, A_c, is the surface area of greenhouse cover in m², T_{ai} and T_{ao}, are the indoor and outdoor air temperatures, respectively, in ºC.**

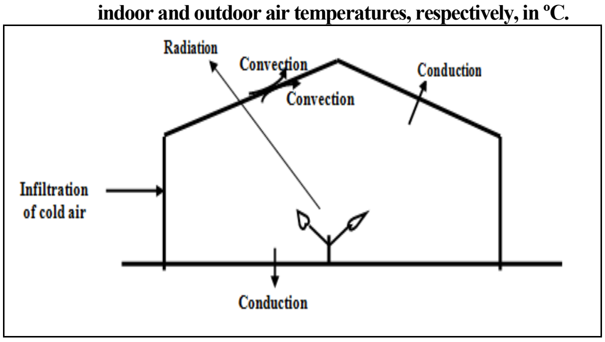

Fig. 3. Schematic diagram of heat losses from the greenhouse

The specific and thermal properties for the two different glazing materials are listed in Table (1). The greenhouse heat loss by infiltration of outdoor cold air can be determined based upon the total exchange between outdoor and indoor air witch is the sum of the sensible and latent heat energy exchanges:

$$q_{inf} = N\,V\,\rho\,[C_p\,(T_{ai} - T_{ao}) + h_{fg}\,(W_{ai} - W_{ao})], \text{ Watt} \quad (3)$$

In which, N, is the infiltration rate in s^{-1}, V, is the volume of greenhouse in m^3, ρ, is the density of indoor air in kg/m^3, C_p, is the specific heat of indoor air, J/kg ºC, h_{fg}, is the latent heat of vaporization of water at T_{ai} in J/kg and, Wai and W_{ao}, are the humidity ratio of indoor and outdoor air, respectively, in $kg_{water}/kg_{air.}$

Table 1. Physical and thermal properties for the polycarbonate and double layer of polyethylene (ASAE, 2013).

Glazing Material	Weight, kg/m^2	U_o, $W/m^2.ºC$	C_{pc}, J/kg ºC	k_c, W/mºC	N x 10^{-4}, s^{-1}
Polycarbonate, 6 mm thick	1.300	3.5	1200	0.205	3.6
Double layer of polyethylene, 0.4 mm	0.406	5.7	815	0.048	2.8

Solar energy collection, storage, and utilisation for heating the greenhouses:

The absorbed solar energy by the solar heating system (q_a) is determined by the following formula (Duffie and Beckman, 2013):

$$q_a = R\,A_{sc}\,(\tau\alpha), \text{ Watt} \quad (4)$$

Where,

R, is the measured solar radiation flux incident on the solar collector in W/m^2, A_{sc}, is the solar collector surface area in m^2, and (τα) is the optical efficiency in decimal.

The useful heat energy collected (q_u) is computed as:

$$q_u = m_f\,C_{pf}\,(T_{fo} - T_{fi}), \text{ Watt} \quad (5)$$

Where,

m_f, is the mass flow rate of fluid in kg/s, Cp_f, is the specific heat of fluid in J/kg ºC, T_{fo}, is the outlet fluid temperature, and T_{fi}, is the inlet fluid temperature in ºC.

The overall thermal efficiency of solar heating system is calculated as:

$$\eta_o = \frac{q_u}{q} \times 100 = \frac{m_f\,C_{pf}(T_{fo} - T_{fi})}{R\,A_{sc}} \times 100, \,\% \quad (6)$$

The solar energy stored in the storage tank (q_s) is computed as:

$$q_s = M_f\,C_{pf}\,(T_{ke} - t_{kb})/dt, \text{ Watt} \quad (7)$$

Where,

M_f, is the fluid mass in the storage tank in kg, T_{ke}, is the fluid temperature in the storage tank at the end of each day, T_{kb}, is the fluid temperature at the beginning of each day in ºC, and *dt*, is the the time interval during operating in s.

The storage system efficiency (η_s) is defined as a ratio of solar energy stored (qs) to solar energy collected (q_u) as follows:

$$\eta_s = \frac{q_s}{q_u} \times 100 = \frac{M_f\,C_{pf}(T_{ke} - T_{kb})/dt}{m_f\,C_{pf}(T_{fo} - T_{fi})} \times 100, \,\% \quad (8)$$

Heat energy consumption (q_{con}):

The quantity of heat energy consumption by the greenhouse is computed using the following equation:

$$q_{con.} = m_{hp}\,C_{pf}\,(T_{in} - T_{out}), \text{ Watt} \quad (9)$$

Where,

m_{hp}, is the mass flow rate of hot operated fluid within the heating pipesin kg/s, and T_{in} and T_{out}, is the operating fluid temperature difference during the heating cycle between the inlet and outlet in ºC.

Vapour pressure deficit (VPD):

The vapour pressure deficit is considered as a very good indicator to the environmental control performance for microclimatic conditions. Therefore, vapour pressure difference is mainly used to evaluate the disease threat, condensation potential, and water irrigation needs for the protected cropping. Accordingly, the vapour pressure deficit during daylight-times should keep lower than 2.0 kPa and at night-times must higher than 0.43 kPa (Pringer and Ling, 2004). The vapour pressure deficit was determined by computer Excel-sheet software using the following equation:

$$PDV = VP_{sat}\,(1 - RH), \text{ kPa} \quad (10)$$

Where, VPsat, is saturation vapour pressure in kPa, and RH, is the indoor air relative humidity in decimal. For the rest of this experimental work, the greenhouse covered with polycarbonate panels and the greenhouse covered with double layer polyethylene sheets are referred to as G1 and G2, respectively. Data were statistically analyzed using Excel program. Linear regression analysis was used to examine the relationship between the different microclimatic factors.

Experiments were carried out for 146 days since 5th of December 2018 until the end of growing season of cucumber crop (30th of April). Because of the experiments were spread over several months (almost five months), the hourly average macroclimate and microclimate data were taken in order to display the environmental conditions outside and inside the two greenhouses. Table (2) summarises and lists the mean values of macroclimate variables during these months.

Table 2. Hourly average macroclimate parameters during the experimental work

Month	Solar radiation, W/m^2	Air temperature, ºC	Relative humidity, %	Wind speed, m/s
December	264.6	12.1	77.3	2.5
SD	±62.8	±1.1	±9.7	±2.2
January	317.9	10.0	70.3	3.0
SD	±74.2	±1.3	±13.8	±1.8
February	348.4	11.2	75.0	3.6
SD	±71.3	±2.0	±12.8	±2.5
March	414.0	13.5	76.3	3.0
SD	±115.5	±1.6	±12.8	±1.8
April	522.7	15.7	69.8	1.6
SD	±107.4	±2.2	±14.2	±0.4
Mean	373.5	12.5	73.7	2.7
SD	±99.4	±2.2	±3.6	±0.7

RESULTS AND DISCUSSION

The macroclimate variables of the location basically are the most important factors that affect the growth and productivity rates of protected cropping economics of the greenhouse operation. A great amount of heating load must be supplied to the greenhouses at nighttime during winter season to provide and secure the desired level of microclimatic conditions. Uncertain price rise and rapid depletion of fossil fuels accelerated the development of renewable energy sources in the form of alternative power sources. Therefore, the concept of this research work is concentrated on the capability of solar energy in providing a significant amount of heat energy which supplying into the greenhouses.

Solar energy collection

Because of, the two solar heating systems having the same geometric characteristics and are situated at the same location under the same macroclimatic condition they received the same quantity of solar radiation. Accordingly, they have the same thermal performance analysis. The daily average thermal performance analysis over the heating period from 5th of December 2018 into 30th of April 2019 is summarised and listed in Table (3).

Table 3. Daily average thermal performance analysis of the solar heating system during the heating period

Month	q, kWh	q_a, kWh	q_c, kWh	η_h, %	q_L, kWh	η_o, %	q_s, kWh	η_s, %
Dec.	70.901 ±10.745	61.968 ±9.452	56.550 ±10.420	91.26 ±3.58	5.418 ±2.016	79.76 ±2.13	51.494 ±8.350	91.06 ±2.86
Jan.	73.180 ±14.387	63.959 ±12.542	58.745 ±12.828	91.85 ±4.25	5.214 ±2.32	80.27 2.19	53.152 ±10.972	90.48 ±3.22
Feb.	78.887 ±9.208	68.947 ±8.012	64.569 ±8.833	93.65 ±3.71	4.378 ±1.83	81.85 ±2.37	59.778 ±8.621	92.58 ±3.04
March	85.849 ±11.318	75.032 ±9.924	70.954 ±9.942	94.57 ±3.39	4.078 ±1.58	82.65 ±2.44	66.676 ±9.829	93.97 ±2.91
April	92.682 ±12.949	81.004 ±11.298	77.408 ±7.457	95.56 ±4.23	3.596 ±2.21	83.52 ±2.41	74.041 ±8.221	95.65 ±1.63
Total	401.499	350.910	328.582	-	22.684	-	305.141	-
Mean SD	80.300 ±9.016	70.182 ±7.880	65.716 ±8.562	93.38 ±1.81	4.537 ±0.767	81.61 ±1.58	61.028 ±9.436	92.75 ±2.12

During this period there was 1275-hr of bright sunshine of which 1106-hr (86.75%) were recorded and utilised in the thermal performance analysis. The daily average solar energy available (q) was 80.300 kWh of which 70.182 kWh was absorbed (q_a) by the solar heating system and achieved an average absorption efficiency of 87.40%. The daily average solar energy collected (q_c) was 65.716 kWh which realised heat transfer efficiency (η_h) and overall thermal efficiency (η_o) of 93.38% and 81.61%, respectively. The solar heating system was realised a daily average solar energy stored in the storage water tank (q_s) of 61.028 kWh with an average storage system efficiency (η_s) of 92.75%. In reality, the thermal performance analysis was changed from day to day and month to another according to the intensity of solar radiation flux incident on the tilted solar collectors during the heating period. This change in intensity of solar radiation occurred due to the changes in weather conditions (sky cover), solar altitude angle, and solar incident angle.

Heat energy consumption

The heat energy released from the heat distributing system inside the two greenhouses was independently monitored by measuring the mass flow rate of operating hot fluid, specific heat of operating fluid, and the temperature potential difference between the inlet and outlet of each system. Table (4) presents the hourly average heating pipe temperature (T_p), heat energy loss (q_{loss}), heat energy consumption (q_{con}), and heat energy supplied for each greenhouse at nighttime during the heating period. The quantity of heat energy transferred by natural convection into the indoor air and by radiation into the different subjects (crop leaves, floor, and structural frame) inside the two greenhouses was dependent upon the pipe temperature of heating distributing system. The pipe temperatures were changed from night to night and month to another according to the number of heating operating cycles and the temperature potential difference between the indoor and outdoor air. Therefore, the hourly average pipe temperatures for each greenhouse varied from 30.3ºC in April to 40 .6ºC in January month for greenhouse 1 (G1), whilst they changed from 33.1ºC to 47.1ºC in the same months for greenhouse 2 (G2) as listed in Table (4). Cyclic changes in pipe temperature were observed for both greenhouses at nighttime during one night in the coldest month (January 7) as long as the outdoor air temperatures were cold (Fig. 4).

At approximately 18:00 h the heating system of G1 was operated for the first cycle to supply heat energy into the greenhouse when the outdoor air temperature dropped to a level of 13.1ºC, while the heating system of G2 was operated for the first cycle at approximately 17:15 h when the outdoor air temperature was 14.2ºC. This lag in operating time (almost 45 minutes) between the two heating systems can be attributed to the heat energy accumulated from the solar radiation inside the greenhouse 1 and lower value of heat energy loss from the polycarbonate plates due to its lower value of the overall heat loss coefficient. More than 15 heating cycles were used to maintain the indoor air temperature at the desired set-point (18.0ºC). Therefore, the heating operating time for the two greenhouses during that day of January month, respectively, was 10:45 and 12:30 hours. At approximately 7:00 h the outdoor air temperature dropped into a lower level of 8.3ºC at which only continuous operation of the heating system could balance the heat energy loss from the two greenhouses. This condition (continuous operation) was clearly observed throughout the heating period.

Table 4. Hourly average pipe temperature (T_p), heat energy loss (q_{loss}), heat energy consumption (q_{con}), and heat energy supply (q_{sup}) for the two greenhouses during the heating period

Month	G1				G2			
	T_p, ºC	q_{loss}, kWh	q_{con}, kWh	q_{sup}, kWh	T_p, ºC	q_{loss}, kWh	q_{con}, kWH	q_{sup}, kWh
Dec.	36.3	13.373	13.852	16.520	40.0	17.504	16.839	20.470
SD	±5.6	±3.722	±2.376	±2.578	±4.0	±2.344	±1.671	±1.235
Jan.	40.6	16.405	16.348	19.498	47.1	20.217	19.830	22.930
SD	±7.5	±4.939	±3.153	±2.702	±4.8	±4.335	±3.096	±2.325
Feb.	40.3	15.769	16.280	19.410	46.2	19.954	19.439	22.479
SD	±4.8	±3.155	±2.014	±2.358	±4.4	±2.590	±1.846	±2.470
March	35.5	12.575	13.966	16.657	40.3	15.647	16.940	20.588
SD	±5.9	±3.908	±2.495	±2.600	±7.2	±6.521	±3.039	±2.920
April	30.3	8.583	11.594	13.828	33.1	12.345	14.063	17.261
SD	±7.6	±4.990	±3.186	2.945	±6.8	±3.848	±2.743	±2.125
Mean	37.1	13.341	14.408	17.183	41.4	17.330	17.422	20.746
SD	±4.7	±3.103	±1.981	±2.361	±5.7	±3.269	±2.330	±2.237

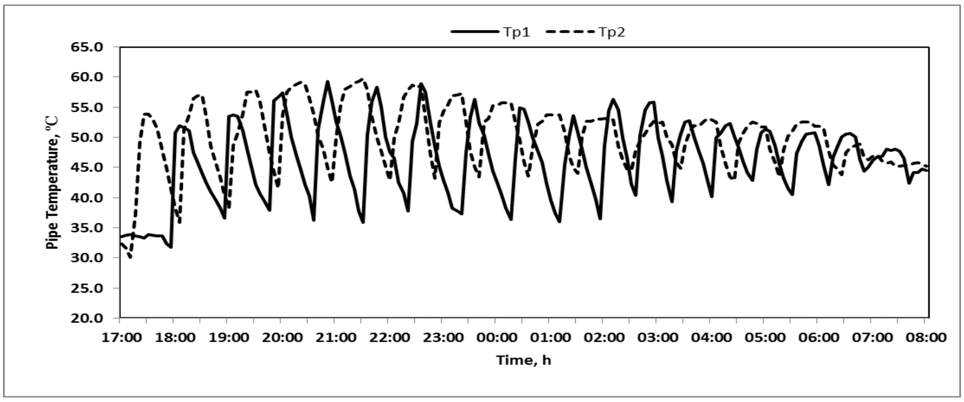

Fig. 4. Cyclic changes in pipe temperature: (—) G1 and (…) G2.

The heat energy loss from the two greenhouses was strongly dependent on the temperature potential difference between the indoor and outdoor air and the type of greenhouse glazing material. Due to the previous basic scientific knowledge, the hourly average heat energy loss varied from 8.583 to 16.405 kWh (G1) while, it changed from 12.345 to 20.217 kWh (G2) in April and January months, respectively. These variations in heat energy loss from the two greenhouses may be attributed to the values of overall heat loss coefficient for polycarbonate plates (3.50 W/m^2 ºC) and double layer of polyethylene sheets (5.70 W/m^2 ºC). Accordingly, the heat energy loss from G2 was higher than that from G1 by 29.90%. The heat energy consumption for the two greenhouses was also varied from 11.594 to 16.348 kWh (G1) whilst, it changed from 12.345 to 20.830 kWh (G2) in April and January months, respectively. Thus, the heat energy consumption by G2 (covered by double layer of polyethylene sheets) was higher than that consumed by G1 (covered by polycarbonate plates) by 20.92%. The greatest values of heat energy consumption occurred during January month when the nightly average outdoor air temperature dropped to 10.0ºC. Hourly average heat energy consumption for the two greenhouses (G1 and G2) per unit floor surface area was 50.0 and 60.5 W/m^2, respectively. These values are in agreement with the data published by (Bartzanas *et al*., 2005). Cyclic changes in heat energy consumption were also observed for both greenhouses (G1 and G2) at nighttime during the same day of January 7 as revealed in Fig. (5). The highest and lowest values of heat energy consumption for G1 (22.601 and 12.839 kWh, respectively) occurred at approximately 18.35 and 07:00 h, respectively. Whilst, the highest and the lowest values of heat energy consumption for G2 (25.118 and 15.470 kWh, respectively) were observed at approximately 21:00 and 07:00 h, respectively. Cyclic changes in heat energy consumption for both greenhouses were also observed at each nighttime during the heating period.

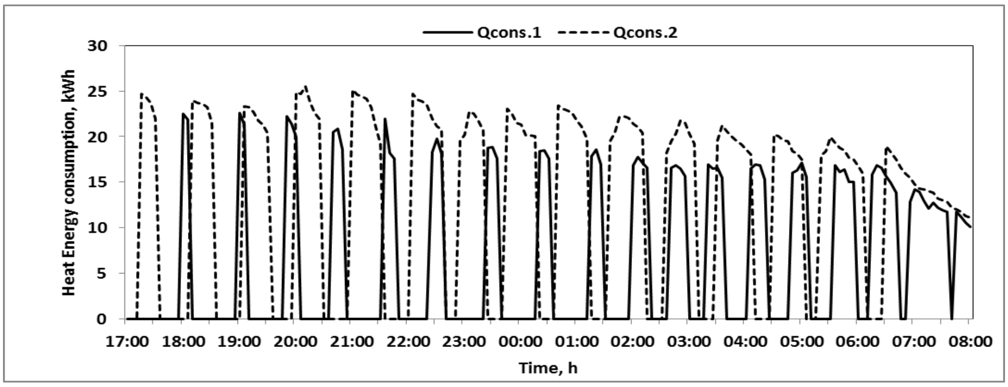

Fig. 5. Cyclic changes in heat energy consumption: (—) G1 and (…) G2.

Heat energy supplied

The quantity of heat energy transferred into the two greenhouses during the heating period varied from hour to hour, night to night, and month to another according to the pipes temperature of the heat distributing system, and to heat energy demined to maintain the desired level of set-point. Thus, the hourly average heat energy supplied to each greenhouse varied from 13.828 in April to 19.498 kWh in January month for G1, whilst they changed from 17.261 to 22.930 in the same months for greenhouse G2 as listed in Table (4). The nightly average heat energy supplied into the two greenhouses during the heating period, respectively, was 17.183 and 20.746 kWh. Therefore, by using the polycarbonate cover resulting in reducing the heat energy supplied by 17.17% as compared with double layer of polyethylene sheet. The greatest values of heat energy supplied also occurred during January month when the nightly average air temperature difference between set-point (18ºC) and outdoor (10.0ºC) was 8.0ºC. Cyclic changes in heat energy supplied were also observed for both greenhouses (G1 and G2) at nighttime during the same day of January 7 as shown in Fig. (6).

The highest and lowest values of heat energy supplied into G1 (24.949 and 17.839 kWh, respectively) were achieved at approximately 20:50 and 07:00 h, respectively. Whilst, the highest and the lowest values of heat energy supplied to G2 (25.160 and 19.017 kWh, respectively) were observed at approximately 21:30 and 08:00 h, respectively.

Because of, the pipes of heat distributing system for each greenhouse were full by hot water even after the heating cycles were interrupt, significant amount of heat energy was supplied by convection into the indoor air and radiation into the leaves of crops until operating of the following cycle started as revealed in Fig. (6). Cyclic changes in heat energy consumption for both greenhouses were also observed at each nighttime during the heating period.

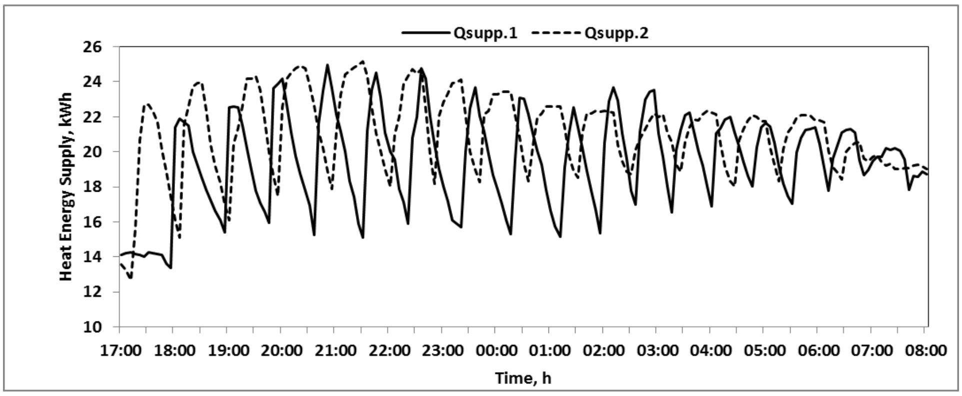

Fig. 6. Cyclic changes in heat energy supply: (—) G1 and (…) G2.

Heat energy provided

For the duration of growing season (147 days) and heating period the solar heating system provided 9.660 MW (34.780 MJ) of useful heat energy acquired to storage of which 8.971 MW (32.296 MJ) was stored in each storage tank of the two greenhouses and employed for heating the indoor air temperatures and providing a portion of total heat energy supplied. The nightly averages total heat energy consumption (q_{con}), solar energy utilised (q_u), electrical energy consumption by electric heaters (q_e), and providing of total heat energy (E_p) during the growing season for the two greenhouses are listed in Table (5). The total heat energy consumption by G1 during the heating period was 20.011 MW (72.040 MJ) of which 8.971 was provided by the solar heating system and the remainder 11.040 MW (39.744 MJ) was supplied by the electric heaters. Consequently, the solar heating system during the growing season provided 44.83% of the total heat energy consumption. Whilst, the total heat energy consumption by G2 during the heating period was 27.750 MW (99.900 MJ) of which 8.971 was provided by the solar heating system and the remainder 18.779 MW (67.604 MJ) was supplied by the electric heaters. Accordingly, the solar heating system during the growing season only provided 32.33% of the total heat energy consumption. Therefore, the greenhouse covered with the polycarbonate plates as a glazing material resulting in reducing the total heat energy consumption by 27.89%.

Table 5. Nightly average total heat energy consumption (q_{con}), solar energy utilised (q_u), electoral energy consumption by electric heaters (q_e), and providing of total energy (E_p).

Month	G1				G2		
	q_{con}, kWh	q_u, kWh	q_e, kWh	E_p, %	q_{con}, kWh	q_e, kWh	E_p, %
Dec.	128.854	51.494	77.360	39.96	188.723	137.229	27.29
SD	±15.625	±8.350	±7.376	±3.75	±14.055	±6.761	±2.20
Jan.	176.558	53.152	123.406	30.10	253.071	199.919	21.00
SD	±17.580	±10.972	±10.183	±4.70	±14.861	±8.960	±2.35
Feb.	165.242	59.778	105.464	36.18	234.746	174.968	25.46
SD	±14.807	±8.621	±10.018	±3.53	±14.400	±6.648	±2.17
March	127.091	66.676	60.415	52.46	165.034	98.358	40.40
SD	±11.915	±9.829	±8.945	±2.68	±9.225	±6.035	±2. 29
April	82.897	74.041	8.856	89.32	102.306	28.265	72.37
SD	±7.604	±8.221	±3. 861	±2.55	±6.558	±3.347	±2.12
Total	680.642	305.141	375.501	-	943.880	638.739	-
Mean	136.128	61.028	75.100	44.83	188.776	127.748	32.33
SD	±36.913	±9.430	±44.341	±23.66	±59.766	±67.618	±20.89

Microclimatic conditions for the two greenhouses (G1 and G2)

The main prevalent microclimatic variables substantially affecting growth, flowering, and fruit set rates for the most protected cropping throughout the growing season are the indoor air temperature and relative humidity. The hourly average microclimatic circumstances at nighttime throughout the growing season comprehended; indoor air temperature, relative humidity, dew-point temperature, and vapour pressure deficit are summarised and listed in Table (6). At nighttime during the growing season, the indoor air temperatures for the two greenhouses (G1 and G2) varied between 18.2 and 19.2ºC, and between 17.1 and 18.2ºC, respectively, whilst, the outdoor air temperatures ranged from 10.0 to 15.7ºC. Accordingly, the temperatures difference between the set-point (18.0ºC) and the outdoor air temperatures ranged between 2.3 and 8.0ºC. The pipes of heat distributing system inside the greenhouse (G1) could be maintained the desired set-point temperature particularly during the critical month (January) when the hourly average indoor air temperature at nighttime was 18.2ºC. In spite of, the heat energy supplied into the greenhouse 2 was more than that the greenhouse 1 by 17.60% during January month, the heat distributing system inside the greenhouse 2 could not maintain the desired set-point when the hourly average indoor temperature was 17.1ºC, revealing that additional heat energy must be supplied to that greenhouse. This occurrence can be attributed to the higher value of heat energy loss through the polyethylene sheet at nighttime. The air temperatures inside the two greenhouses (G1 and G2) on January 7 are compared with the outdoor air temperatures as an important indicator to the effectiveness of heating system and environmental control system as revealed in Fig. (7). Cyclic changes in indoor air temperatures were observed for both greenhouses as long as the outdoor air temperatures were lowered at nighttime. After interrupt the heating system in each heating cycle inside the two greenhouses the indoor air temperatures were still raised above the set-point temperature due to the thermal buoyance forces from the hot surfaces of heating pipes which contain a hot water.

Table 6. Hourly average outdoor air temperature (T_{ao}) and relative humidity (RH_o), indoor air temperature (T_{ai}), air relative humidity (RH), dew-point temperature (T_{dew}), and vapour pressure deficit (VPD) for the two greenhouses during the heating period

Month	G1						G2			
	T_{ao}, ºC	RH_o,%	T_{ai}, ºC	RH_i, %	T_{dew}, ºC	VPD, kPa	T_{ai}, ºC	RH_i ,%	T_{dew}, ºC	VPD, kPa
Dec.	12.1	77.3	18.3	61.4	8.5	0.874	18.1	66.7	9.8	0.628
SD	± 1.1	±9.7	±1.7	±2.5	±2.3	±0.320	±2.3	±2.3	±1.6	±0.235
Jan.	10.0	70.3	18.2	64.2	9.4	0.774	17.1	70.3	10.4	0.515
SD	± 1.3	±13.8	±1.5	±5.5	±1.1	±0.266	±2.9	±6.4	±1.2	±0.225
Feb.	11.2	75.0	18.8	62.9	9.5	0.819	17.8	69.0	10.1	0.555
SD	± 2.0	±12.8	±1.8	±3.5	±1.0	±0.358	±2.4	±5.6	±1.4	±0.270
March	13.5	76.3	18.8	61.2	9.0	0.880	18.1	66.5	9.8	0.634
SD	± 1.6	±12.8	±2.6	±3.4	±1.5	±0.365	±2.2	±6.5	±1.3	±0.220
April	15.7	69.8	19.2	59.2	8.9	0.950	18.2	64.5	9.4	0.697
SD	± 2.2	±14.2	±3.5	±4.5	±1.9	0.245	±2.8	±3.8	±1.7	±0.225
Mean	12.5	73.7	18.7	61.8	9.1	0.859	17.9	67.4	9.9	0.606
SD	± 2.2	±3.6	±0.4	±1.9	±0.4	±0.057	±0.5	±2.3	±0.4	±0.071

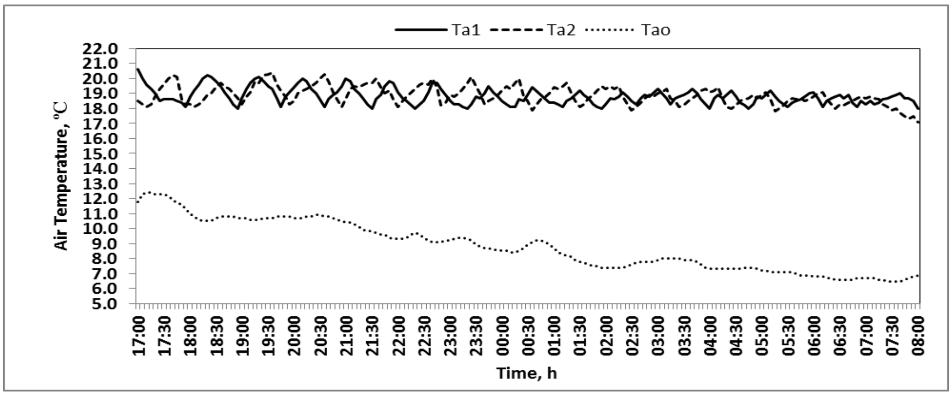

Fig. 7. Cyclic changes in indoor and outdoor air temperatures at nighttime.

The indoor warm air which was produced from many heating cycles throughout the nighttime, resulting in an increase the dry-bulb temperature and reduce the air relative humidity, consequently, the vapour pressure deficit could maintain at the desired level. Accordingly, the nightly average vapour pressure deficit inside the two greenhouses, respectively, were 0.859 and 0.606 kPa which were higher than that the critical level of 0.430 kPa at nighttime (Pringer and Ling, 2004). Cyclic changes in vapour pressure deficit were also observed at nighttime on January 7 as shown in Fig. (8). According to Fig. (8), the minimum values of vapour pressure deficit for G1 and G2, respectively, were 0.618 and 0.473 kPa which occurred at 08:00 when the indoor air temperatures were 18.0 and 17.1ºC and the indoor relative humidity was 66.4% and 70.6%, respectively. Although, these minimum values of vapour pressure deficit were steadily higher than the critical level (0.430 kPa) particularly for G2. Therefore, the vapour pressure deficit considered optimal for growing and producing greenhouse cucumber crop and basically used as a threshold for dehumidification process. It has also been revealed that for vapour pressure deficit less than the critical level, the rate of fungi decay development increase rapidly (Pringer and Ling, 2004).

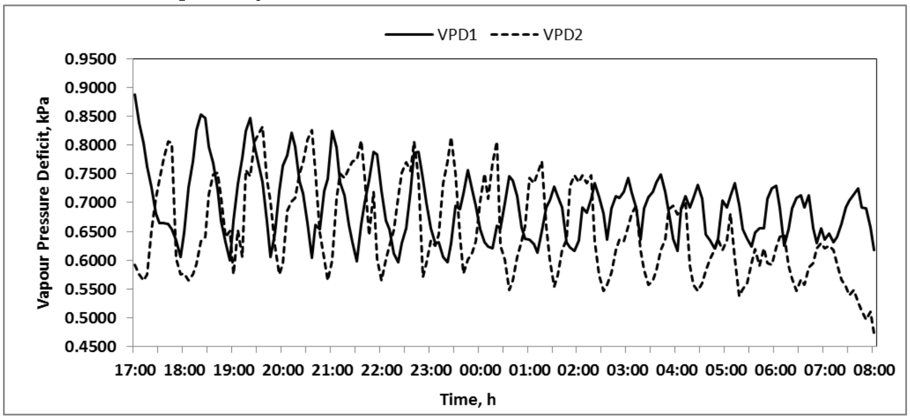

Fig. 8. Cyclic changes in vapour pressure deficit for the two greenhouses at nighttime.

According to the microclimatic conditions for the two greenhouses G1 and G2 were at and around desired level particularly the greenhouse covered with polycarbonate plates, an optimal level of growth, flowering, and fruit-set rates of cucumber plants were achieved. The harvesting operation of cucumber crop was started on January 17 after 43 days from the planting of seeds. The highest amounts of cucumber fresh yield for the two greenhouses were 829.045 and 584.100 kg, respectively, which achieved on February month as shown in Fig.(9). The total fresh yield of cucumber crop for the two greenhouses during the growing season, respectively, was 1880.375 and 1420.605 kg. Therefore, the rate of production per square meter for the two greenhouses was 6.529 and 4.933 kg/m^2, respectively. Consequently, using the polycarbonate cover resulting in increased the fresh yield by 32.35% as compared with the polyethylene cover. This variation may be attributed to the various metabolic processes reaction rates, such as; the nutrient elements absorption rate, and release of water by root system, which substantially affected by the indoor air temperature and relative humidity.

The irrigation water use efficiencies for the two automated commercial greenhouses during the growing season of cucumber crop (21 weeks), respectively, were 29.8 and 22.5 kg/m^3. These results clearly showed that, the irrigation water use efficiency for the two automated commercial greenhouses was higher than the optimal value (14.0 kg/m^3) which recommended by Lorite et al. (2004).

The purchase price of polycarbonate plates covering material is 22,650 EGP with salvage time of 8 years and the price of double layer of polyethylene sheets is 7,296 EGP with salvage time of 3 years. Therefore, the annual costs of polycarbonate plates and the double layer of polyethylene sheets, respectively, are 2,831.25 and 2,432 EGP. Consequently, the annual costs of polycarbonate cover are higher than the polyethylene cover by 16.42%. However, the polycarbonate cover is considered as the better type of glazing material for greenhouses due to its contributions in energy conservation, providing better microclimatic conditions, and produced high quantity of fresh yield.

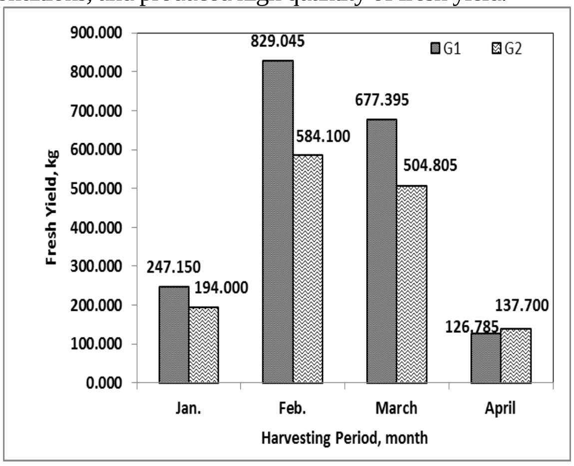

Fig. 9. Fresh yiled of cucumber crop during the harvesting period.

CONCLUSION

This research work was examined the influence of two different glazing materials (polycarbonate plates and polyethylene sheets) in a two commercial greenhouses with a cucumber crop at nighttime. The influence of these glazing materials on heat energy loss, heat energy consumption, heat energy supplying, providing rate of solar energy, and microclimatic conditions at nighttime was investigated during the growing season of 2108/2019.

Each commercial greenhouse was equipped with a complete solar heating system with an electric heater as an auxiliary heating system. From this study the following conclusions can be drawn as:

1. The nightly average heat energy loss from G1 (covered with polycarbonate plates) at nighttime during the growing season was 213.456 kWh, whilst, the heat energy loss from G2 (covered by double layer of polyethylene sheets) was 277.280 kWh. Accordingly, using the polycarbonate plates reduced the heat energy loss by 23.02% as compared with the polyethylene sheets.
2. The nightly average heat energy consumption by G1 at nighttime during the growing season was 230.528 kWh, while, the heat energy consumption by G2 was 278.752 kWh. Consequently, the heat energy consumption by the G2 was higher than that by G1 by 20.92%.
3. The nightly average heat energy supplied into the two greenhouses, respectively, was 274.183 and 331.936 kWh. Accordingly, the polycarbonate cover reduced the total heat energy supplied by 17.23% as compared with the polyethylene cover.
4. During the growing season (147 days) and heating period the solar heating system provided 9.660 MW (34.780 MJ) of useful heat energy acquired to storage of which 8.971 MW (32.296 MJ) was stored in each storage tank of the two greenhouses and functioned for heating the indoor air temperatures and providing a portion of total heat energy supplied.
5. During the growing season the solar heating systems for the two greenhouses provided 44.83% and 32.33% of the total heat energy consumption, respectively.
6. Due to use an active heating system for the two greenhouses, the microclimatic conditions (air temperature, relative humidity, and vapour pressure deficit) were at and around the desired level for growing and producing cucumber crop. With the desired level of microclimatic conditions, the vapour pressure deficit was higher than the critical level, and therefore, the rate of fungi decay was at minimum level.
7. The total fresh yield of cucumber crop per square meter in the two greenhouses, respectively, was 6.529 and 4.933 kg/m^2 consequently; G1 was more productivity than G2 by 32.35%. High irrigation water use efficiency for the two automated greenhouses was achieved (29.8 and 22.5 kg/m^3, respectively) during the growing season of cucumber crop.

Finally, in spite of the annual costs of polycarbonate cover is higher than that the polyethylene cover by 16.42%, the obtained results clearly revealed that, the use of polycarbonate plates as a glazing material of greenhouse in addition to significantly improves the microclimatic conditions since it provides the indoor air temperature at the desired level and prevents the occurrence of condensation on the leaves surface; it also significantly reduces the total heat energy consumption.

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تأثير مواد التغطية على حمل التدفئة للبيوت المحمية التجارية المكيفة

ناصر مصطفى العشماوى

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أجريت التجارب العملية لهذا البحث بمحطة التجارب والبحوث الزراعية بكلية الزراعة جامعة المنصورة خلال الفترة من ديسمبر ٢٠١٨ وحتى إبريل ٢٠١٩ من خلال المشروع البحثى الممول من مكون دعم المشروعات البحثية التطبيقية والحملات الإرشادية التابع لمجلس البحوث الزراعية والتنمية – وزارة الزراعة وإستصلاح الأراضى. تم إستغلال بيتين محميين تجاريين أبعاد كل بيت محمى 9 x 32 m بمساحة إجمالية $288\ m^2$ كل بيت محمى مزود بنظام كامل للتهوية والتبريد بالتبخير للعمل أثناء النهار وأيضاً نظام كامل للتدفئة أثناء الليل يعتمد على الطاقة الشمسية كمصدر حرارى يتم تخزينها فى خزان مياه سعته $2\ m^3$ مع الإستعانة بسخانات كهربية عندما تكون الطاقة الشمسية المخزنة غير كافية للمحافظة على درجة حرارة الهواء الداخلى عند المستوي الأمثل لمحصول الخيار أثناء الليل (18ºC) تم تغطية البيت المحمى الأول (G1) بطبقة واحدة من إلواح البولى كربونيت بسمك 6 mm والبيت الثانى (G2) بطبقتين من البولى إيثلين بسمك 200 µm لكل طبقة واحدة بغرض دراسة تأثير نوع غطاء البيوت المحمية على الطاقة الحرارية المستهلكة فى عمليات التدفئة أثناء الليل خلال أشهر الشتاء الباردة وأيضاً تأثير نوع الغطاء على توفير الظروف المناخية الداخلية (درجة حرارة الهواء – الرطوبة النسبية للهواء – مقدار النقص فى الضغط البخارى) وآخيراً تأثير كل هذه العوامل على معدل إنتاج محصول الخيار بالنسبة للمتر المربع الواحد. يمكن تلخيص أهم النتائج العملية التى تم الحصول عليها خلال فترة التسخين (١٤٧ يوماً) فى النقاط التالية:أثناء فترة الليل وخلال مرحلة النمو كان متوسط الطاقة الحرارية المفقودة من البيت المحمى الاول (G1 = 213.456 kWh) والثانى (G2 = 277.280 kWh) وبالتالى فإن غطاء البولى كاربونيت للبيت المحمى الأول (G1) أدى إلى خفض الطاقة الحرارية المفقودة بنسبة 23.02% مقارنة بغطاء البولى إثيلين المزدوج فى البيت المحمى الثانى (G2). متوسط الطاقة المستهلكة أثناء فترة الليل للبيت المحمى الأول (G1 = 230.528 kWh) والثانى (G2 = 278.752 kWh) وتبعاً لذلك فإن الطاقة الحرارية المستهلكة للبيت المحمى الثانى (G2) تزيد عن البيت الأول (G1) بنسبة 20.92% .متوسط الطاقة الحرارية المزودة ليلاً لكلا البيتين كانت (G1 = 274.183 kWh) و (G2 = 331.936 kWh)على الترتيب ولذا فإن إستخدام غطاء البولى كاربونيت أدى إلى خفض إجمالى الطاقة الحرارية المزودة بنسبة 17.23% مقارنة بغطاء البولى إثيلين المزدوج. خلال فترة النمو والتسخين وفر نظام التسخين الشمسى (34.780 MJ) 9.660 MW من الطاقة الحرارية المستفادة والمطلوبة للتخزين والتى منها تم تخزين (32.296 MJ) 8.971 MW فى خزان التخزين لكلا البيتين المحميين حيث تستخدم هذه الطاقة فى تسخين هواء البيت الداخلى وتوفير جزء من الطاقة الحرارية المزودة خلال فترة الليل. إستطاع نظام التسخين الشمسي خلال فترة التسخين أن يوفر 44.83% للبيت الأول G1 وللبيت الثانى 32.33% من إجمالى الطاقة الحرارية المستهلكة لكلا البيتين المحميين على الترتيب. نتيجة لإستخدام نظام التسخين الديناميكى فان الظروف المناخية الداخلية (والتى تشمل درجة حرارة الهواء والرطوبة النسبية والنقص فى الضغط البخارى) لكلا البيتين كانت عند وحول المستوى المرغوب لنمو وإنتاج محصول الخيار. ونتيجة لهذه الظروف المثلى فإن مستوى النقص فى الضغط البخارى كان أعلى من الحد الحرج مما جعل معدل نمو الفطريات على نباتات محصول الخيار عند أدنى مستوى. بلغ الإنتاج الكلى للمتر المربع الواحد من محصول الخيار خلال موسم الزراعة على الترتيب ($G1 = 6.529\ kg/m^2$) و ($G2 = 4.933\ kg/m^2$) وبالتالى فإن البيت المحمى المغطى بالبولى كرونيت حقق إنتاجية أعلى من البيت المحمى المغطى بطبقتين من البولى إثيلين بنسبة 32.35%وأخيراً فإن هذه النتائج تظهر بوضوح أن إستخدام ألواح البولى كاربونيت كغطاء للبيوت المحمية يؤدى إلى خفض إجمالى الطاقة الحرارية المستهلكة وبالتالى تقليل التكاليف كما يؤدى إلى تحسين الظروف المناخية الداخلية والتى بدورها تصل للمستوى المرغوب فتمنع حدوث ظاهرة التكثيف على الأوراق.