Research Article

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The Effectiveness of Using Two Sustainable Night Heating Modes on Greenhouse Cultivation

Douja SELLAMI[1*], Hassen BOUGHANMI[2], Salwa BOUADILA[2], Mariem LAZAAR[2], and Asma BEN SALEM-FNAYOU[3]

[1] *Depatement of Biology, Faculty of Science Tunis, University El Manar, Tunisia.*

[2] *Department of Energy, Faculty of Science Tunis, University El Manar, Tunisia.*

[3] *Department of Biology, Biotechnology Center of Borj Cedria, Tunisia.*

***Correspondence:**
Douja SELLAMI, Depatement of Biology, Faculty of Science Tunis, University El Manar, Tunisia.

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ABSTRACT

The main purpose of this paper is to study the efficiency of the deployment in Tunisia of the Ground Source Heat Pump (GSHP) system and of a solar air heater with latent storage (SAHLS) for heating mode application. A pilot GSHP system using conic ground heat exchanger and a SAHLS were installed and experimented in the Research and Technology Center of Energy (CRTEn), Borj Cédria, northern Tunisia. The status of geothermal and the solar air collector energies and their utilization are pointed out, the evaluation of both systems is examined for air heating. Their effect in the growth rate and yield of tomato are also studied. The main results show that the SAHLS gives the appropriate microclimate for plants under greenhouse in comparison with GSHP: high night temperature and low relative humidity. This leads to earliness of 2 weeks and a good quality and quantity of fruits represented by high relative growth rate, high phenolic compounds and a high quantity of marketable fruits.

Keywords
Solar air collector, Heat pump, Yield, Greenhouse, Fruits.

Introduction

Worldwide, tomato (*Solanum lycopersicum.* L) represent one of the most popular and extensively consumed vegetable crops [1]. Besides to its economic importance, this species can serve as an experimental model for the study of fruit development [2]. Otherwise, growing *conditions* influence its productivity and quality even under greenhouse.

The major environmental factors that affect the growth and the precocity of of plants' production under greenhouse are carbon dioxide, light, humidity and temperature. Temperature affects photosynthesis, respiration. It intervenes in the growth rate, flowering and earliness of maturity.

In Tunisia, one of the major problems encountered in greenhouses is the control of the internal climate. The lack of heating has unfavorable effects on the precocity of production. Moreover, natural resources are considered as rare specially in Tunisia [3] while the energy requirement is increasing continuously. Various types of heating systems used in the conventional greenhouses utilize the fossil fuels. Indeed, the increasing of the price of the fossil fuels rises the production cost and reduces the income of farmers [4]. Consequently, it is necessary to replace the current conditioning units with new technologies better energy efficiency, based on renewable energies. Henceforth, we should aim towards the use of renewable energy such as solar and geothermal energy to compensate this need.

So, to provide an amount of heat nocturnal use, a new Solar Air Heater with Latent Storage Collector (SAHLS) using spherical capsules as a packed bed absorber and a geothermal system using a geothermal Heat Pump and a conic basket geothermal heat exchanger were designed and realized in the Research and Technology Center of Energy (CRTEn) in Tunisia and used for heating the greenhouse.

The status of geothermal and the solar air collector energies and their utilization are pointed out, the evaluation of the GSHP as well as the SAHLS systems is examined for air conditioning. There is little information about the effects of climatic conditions generated by these heating systems used in greenhouses on tomato fruit quality produced. This study underscores the range of suitability of each heating system for plants grown under greenhouses using them.

Therefore, to get a clear picture of suitable technology to improve performance and to minimize greenhouse in terms of energy requirements and costs, the state of the plant behavior under greenhouse heated with two different technologies will be discussed in this research. Thus, the work is aimed to control crop production, the improvement of the yield and of the visual quality and the nutritive value of the greenhouse-grown tomato fruits.

Materials and Methods

Three insulated greenhouses were used. They were designed and constructed to investigate a comparative study. The first is considered as a reference named (IG) (Figure 1a). The second is using a solar air heater with latent storage collector (SAHLS) and was named IGHLS (Insulated Greenhouse with Latent Heat System), shown in (Figure 1b). The third is using a heat pump system and named IGHP (Insulated Greenhouse with Heat Pump) (Figure 2).

Figure 1: Photo of the experimental greenhouses: (a): Insulated greenhouse (IG), (b): Insulated greenhouse with latent heat system (IGHLS).

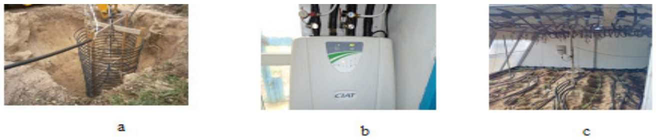

Figure 2: The components of the heating system of the third insulated greenhouse: (a): the Conic Basket Geothermal Heat Exchanger (CBGHE), (b): The geothermal heat pump (GHP), (c): a multilayer heat exchanger system.

Experimental Greenhouse Design and Site Description

The experimental setup has been installed at the Research and Technology Center of Energy in Borj Cedria, on the Mediterranean coast of North Africa, near the city of Tunis in Tunisia, with the following coordinates: Latitude 36°, 43' N and Longitude 10°, 25'.

The three experimental small chapel-shaped greenhouse occupies each one a floor area equal to 14.8m^2. The greenhouse wall and roof oriented to the south are covered by glass plates thickened of 3mm. Sidewalls are built by sandwich panels thickened of 0.4m and the northern roof thickened of 0.6m. The slopes of the southern wall are equal to 30° and of the southern roof is 33°C. The greenhouse was equipped with a centrifuge fan controlled by a differential thermostat. When the temperature inside the greenhouses exceeds the optimal growth temperature of the plant (28°C), the fan operates.

Experimental setup and methodology

The experimental greenhouse with latent heat system (IGHLS) is shown in Figure 1b. Experimental latent heat system has been preceded by an experimental evaluation of the thermal performance of a new solar air heater collector using a packed bed of spherical capsules with a latent heat storage system [5]. This new SAHLS was used as a mean to heat the interior environment of the greenhouses during the nighttime.

During the sunshine period, the charging process, a fraction of the total solar radiation received inside the greenhouse is absorbed by the black packed bed absorber of the SAHLS. The absorbed thermal energy is stored as sensible and latent heat forms into the collector. In the sunset and during the night, the greenhouse air temperature drop caused by a radiation heat exchange in the IGHLS. In this time a fan blows air across the PCM capsules and extracted the stored heat into the IGHLS, so the discharging process is done.

For the third greenhouse, the heating system essentially consists of two components which are geothermal Heat pump and two conic basket geothermal heat exchangers (Figure 2). The geothermal heat pump unit used is a reversible water-to-water Ageo CIAT type, which is considered as an individual heater (Figure 2b). The geothermal heat pump is equipped with two circulating pumps, one for hydraulic circuits and the other for external hydraulic circuits (Geothermal heat exchanger in the form of conical buried basket) and internal (the exchanger in the floor of the greenhouse and the suspended one). The two Conic Basket Geothermal Heat Exchanger (CBGHE) represented in (Figure 2a), are installed vertically at 3m depth in the ground. To evaluate the performance of the installed geothermal system for greenhouse heating, the greenhouse is equipped with a multilayer heat exchanger system (Figure 2c).

Measurements

Plant growth and fruit classification

During the culture, every two days, plant height and diameter of stem were measured. Ten plants were selected in order that the dates of flowering and the number of inflorescence and flowers will be recorded. The date of fruits' maturity is also recorded.

To obtain the cumulative yields and to evaluate fruit quality, the harvested tomatoes were also categorized into marketable fruits and other non-marketable fruits (undersized <50 g). All yield fractions were counted and weighed separately.

Photosynthetic parameters

Chlorophyll content

Chlorophyll content of the youngest fully expanded leaves was estimated at midday. Chlorophyll content index (CCI) were measured at random points (n=8-10) using an Opti-Sciences CCM-200.

The photosynthetic rate is typically measured by determining the net CO_2 fixation rate [6]. The photosynthetic rate was determined using a Li-cor handheld photosynthesis system (Li-Cor 6200, Li-Cor Nebraska, USA). The photosynthesis rate (Pn), transpiration rate (E) and intercellular CO_2 concentration (Ci) of the tomato's leaves from the corresponding sites were determined at 9:30 h–11:30h on a sunny day.

Extraction and determination of phenolic compounds

To investigate the contents of phytochemical compounds, three replicates containing three tomatoes (>150 g) were randomly harvested from different plants per greenhouse at a ripening stage at the same height in the canopy. After harvesting, each tomato per sample collection and per greenhouse was dried by lyophilization. The chemical analyses regarding the determination of the contents of secondary plant compounds, in the homogenate of each replication were performed in triplicate.

Plant powder (1g) was slurried in 10ml of 80% methanol. After 30 min of magnetic stirring and standing for 24h at 4°C in the dark, the mixture was filtered through ashless filter paper. The extract obtained is finally stored at 4°C in the dark for assay.

Determination of total phenolic compounds

The phenolic compounds were extracted following the method outlined by Dewanto *et al*. [7]. Subsequently, the extracts were analyzed spectrophotometrically using the Folin-Ciocâlteu reagent. In alkaline medium, polyphenols reduce this reagent in tungsten oxide and molybdenum blue. The absorbance was at a wavelength of 760 nm. The results are expressed as milligram Gallic acid per gram dry weight (mg GAE g^{-1} DW).

Determination of total flavonoids

The determination of total flavonoids is done according to the method of Zhishen *et al*. [8]. This assay involves the formation of a complex between the flavonoids and aluminum chloride. The identification of the flavonoids is done by a spectrophotometer at wavelength of 510 nm. Subsequently, the flavonoid contents are expressed as mg catechin equivalents per gram of dry weight (mg ECg^{-1}DW).

Determination of condensed tannins

The reference range is prepared with catechin at concentrations ranging from 50 to 600 mg.$^{-1}$. The tannin content in mg catechin equivalents per gram of dry weight (1mg EC.g^{-1}DW).

Determination of lycopene

Lycopene content in tomato samples was extracted using the method outlined by Benakmoum *et al*. [9]. Lycopene melting temperature is 175°C, since it is soluble then extraction is carried out either in cyclohexane (d = 0.78), dichloromethane (d = 1.32), and ethanol (d = 0.79).

The identification of the lycopene is affected by a spectrophotometer at wave-length of 472 nm. Subsequently, the contents of lycopene were expressed as microgram per g dry weight (µg 100 g^{-1}DW).

Results

Climatic conditions

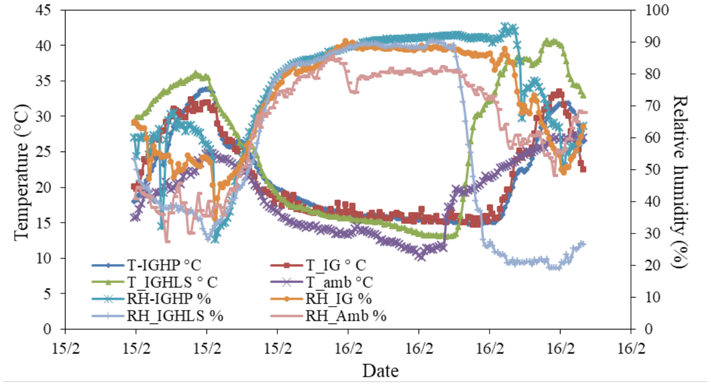

Figure 3: Ambient air temperature and relative humidity and inside the experimental greenhouses as a function of days (15th-16th February).

Figure 3 shows that, at the heating phase of the SAHLS, the inside air temperature of IGHLS is with an average value of 15.44°C. This temperature decreases gradually as the heating system operates. It reaches an average value equal to the ambient temperature when the stored thermal energy dropped. For the IGHP, diurnal and nocturnal temperature were lower than that under IGHLS and IG due to the effect of shading done by the multilayer heat exchanger system. The two heating systems, the SAHLS and the GSHP, allow a temperature elevation of 1.5°C and 0.67°C at average, respectively in comparison with the greenhouse without heating.

For the relative humidity, it is higher inside IGHP than inside IG and IGHLS at night due to dehumidification done with the solar air collector by its outlet air temperature.

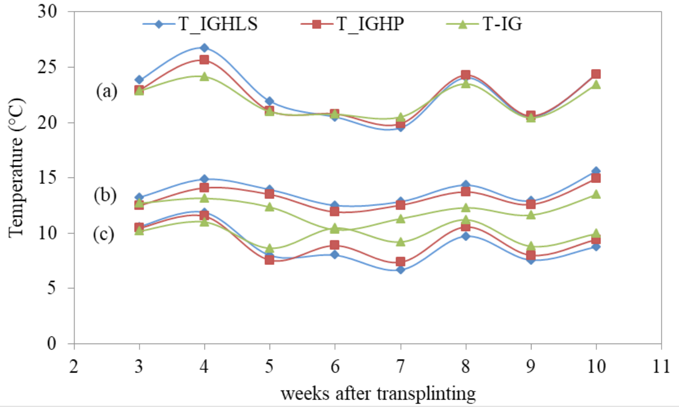

Figure 4. Weekly average diurnal temperatures (a), average nocturnal temperatures (b) and difference day/night (c) into experimental greenhouses during different weeks of tomato production.

Figure 4 shows the changes in the average temperatures during the experiment. Air temperature was slightly higher in the IGHLS than IGHP and IG. It reaches, at day, a maximal value of 26.73°C which exceeds IGHP and IG by 1.12°C and 2.59°C, respectively. At night, the maximum value reached is 15.60°C. This value is higher than those achieved in IGHP and IG, which are in the range of 14.92°C and 13.48°C, respectively. However, these values were within the range of optimal temperature required for tomato in general as recommended by Dumas *et al*. [10] who recommended ranges of 12°C–32°C.

At average, night temperature in the greenhouse heated with heat pump, is lower than that in IGHLS, while the day/night difference temperature was the highest one specially from the week 6 after transplanting, between 8.87°C and 9.42°C. The falls in day and night temperature observed with the greenhouse heated with heat pump seems to be due to shading done by the multilayer heat exchanger system.

Gas exchange measurements

Table 1 shows the photosynthetic capacities and transpiration of the tomato under the microclimatic conditions of experimental greenhouses. When grown under IGHLS, a significant stimulation in net photosynthesis (A) followed by a significant increased transpiration (E) were observed. A drop in stomatal conductance (gs) and in the intercellular CO_2 (Ci) was showed for the plants under this greenhouse in comparison with IGHP. Under IGHP, the net photosynthesis was 15.10 mol CO_2 m^2s^{-1} followed by a lower value under IG. The stomatal conductance and the Ci were the highest at this investigation. The lowest values were shown under IG.

Table 1: Gas exchange of plants in the greenhouses IG, IGHLS and IGHP, (IG) Insulated greenhouse as a reference, (IGHLS): Insulated greenhouse equipped with a solar air collector and IGHP which is insulated greenhouse heated via a heat pump. The comparisons of averages were calculated using one- and two-way analyses of variance (ANOVA) ($p < 0.05$), N = 21. Different small letters were determined using the Student–Newman–Keuls test indicating significant differences.

	Ci (µmol mol^{-1})	E (mmol H_2O m^2s^{-1})	gs (ms^{-1})	A (mol $CO_2m^2s^{-1}$)
IG	219,00 ± 61,54 b	3,24 ± 0,48 b	0,21 ± 0,05 c	14,86 ± 3,73 c
IGHLS	226,86 ± 27,35 b	3,94 ± 0,20 a	0,30 ± 0,03 b	18,88 ± 2,30 a
IGHP	389,71 ± 0,95 a	3,09 ± 0,56 b	0,42 ± 0,10 a	15,10 ± 0,20 b

Chlorophyll content

The chlorophyll content was higher under IGHLS as compared with IGHP and IG with 17.81, 15.70 and 14.02 g mg^{-1} FM, respectively (Figure 5). It is chlorophyll which allows the photosynthetic reaction. As chlorophyll is less abundant in IGHP, more light is needed to produce enough sugar to the life of the plant.

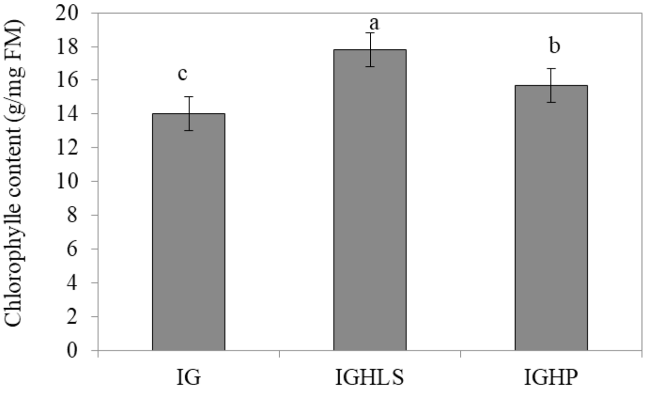

Figure 5: The chlorophyll content in different experimental greenhouses, (IG) Insulated greenhouse as a reference, (IGHLS): Insulated greenhouse equipped with a solar air collector and IGHP which is insulated greenhouse heated via a heat pump. The comparisons of averages were calculated using one- and two-way analyses of variance (ANOVA) ($p < 0.05$), N=30. Different small letters were determined using the Student–Newman–Keuls test.

Influence of microclimate in the growth rate and plants' development

Temperature strongly affected both relative growth rate of diameter and the height stem; RGRd and RGRh (Figure 6). According to the difference between the night temperature determined for both systems, it is suggested that RGRh of plants under IG was relatively stronger affected than RGRh of the plants grown under greenhouses with heating systems. It is around 0.034 mm day^{-1} against 0.038 and 0.040 for IGHP and IGHLS, respectively. Furthermore, it is shown that plants of IGHLS are favored by the high value of RGRd (0.024mm day^{-1}) in comparison with IGHP or IG.

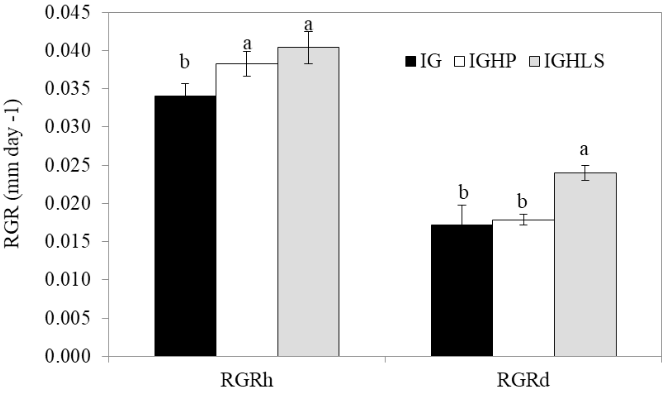

Figure 6: The Relative Growth Rate (RGR) of height and diameter stem of ten plants in experimental greenhouses. The comparisons of averages were calculated using one- and two-way analyses of variance (ANOVA) ($p<0.05$), N=180. Different small letters were determined using the Student–Newman–Keuls test.

It is shown in Figure 7 that the number of flowers per plant is the highest in plants grown under IGHLS. From 31 January until 20 February, the number of flowers was similar under the different greenhouses, peaked in the second period from 20 February until 22 March and become again similar at the third period (in April). The number reaches at average 7, 5.4 and 3.5 flower plant^{-1} under IGHLS, IGHP and IG, respectively in the second period.

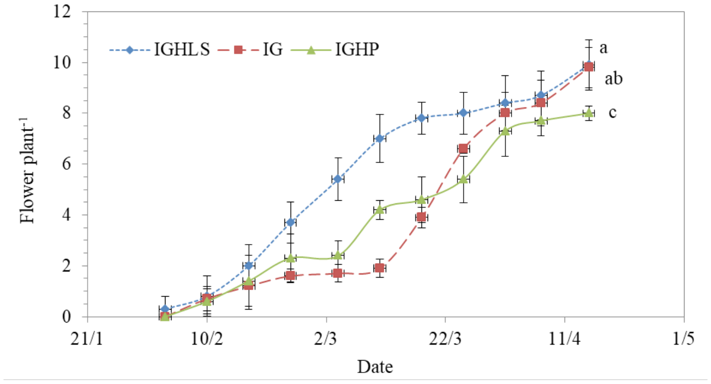

Figure 7: The average flower number plant^{-1} in (IG): Insulated greenhouse, (IGHLS): Insulated greenhouse equipped with a solar air collector and IGHP: insulated greenhouse heated via heat pump. The comparisons of averages were calculated using one and two-way analyses of variance (ANOVA) (p<0.05), N = 180. Different small letters were determined using the Student–Newman–Keuls test.

Yield

In the greenhouse heated via solar air collector, fruit maturity was held to 08 April. Compared with plants grown under IGHLS, the maturity of fruits of plants grown under IG was later by two weeks which took place by 22 April. For IGHP, the maturity of fruits was delayed by 10 days with a mediocre size of fruit.

The difference between the greenhouses concerning the cumulated fruit yield was conspicuous (Table 2). In IGHLS, the total crop harvested was equivalent at average to 9.43 t ha^{-1} (equivalent to 4.98 kg plant^{-1}). The total harvest is formed by a major quantity of marketable fruits and a low quantity of undersized fruit. As to IGHP, the harvest was more or less similar to that of IG with 0.81 t ha^{-1} and 0.74 t ha^{-1}, respectively. But, the majority harvest of IG consists of undersized fruit with 0.41 t ha^{-1}against 0.30 t ha^{-1} in IGHP.

Table 2: Total weight, marketable fruits and undersized fruits of tomato fruits (kg plant^{-1} and equivalent in t h^{-1}) grown for 20 weeks in greenhouses (IG, IGHP and IGHLS). Means with different letters are significantly different (NMK-test, p < 0.05).

Greenhouses	Marketable fruits		Undersized fruits		Total yield	
	kg plant^{-1}	t ha^{-1}	kg plant^{-1}	t ha^{-1}	kg plant^{-1}	t ha^{-1}
IG	0,17 c	0,33 b	0,22 a	0,41 a	0,39 b	0,74 b
IGHP	0,27 b	0,51 b	0,16 b	0,30 b	0,43 b	0,81 b
IGHLS	4,86 a	9,20 a	0,12 c	0,23 c	4,98 a	9,43 a

Phytochemical compounds

Biochemical analysis showed that the phenolics levels in the fruits of plants grown under IGHLS was significantly higher than those of IG and IGHP with values of 14.65, 10.99 and 7.79 mg EAG g $^{-1}$ DW, respectively (Figure 8).

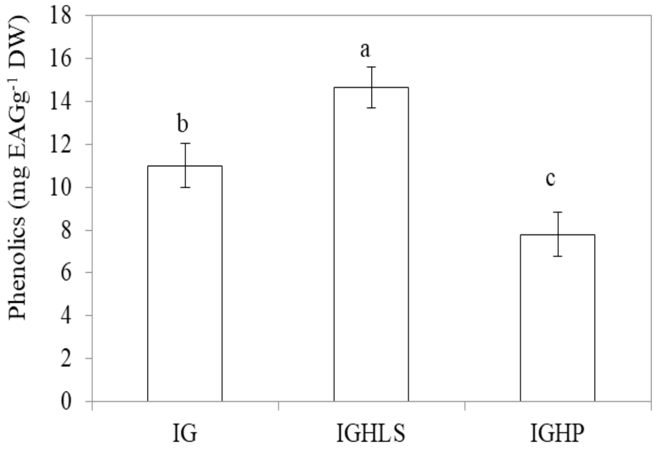

Figure 8: Effects of microclimatic conditions on phenolics in tomatoes of (IG): Insulated greenhouse, (IGHLS): Insulated greenhouse equipped with a solar air collector and IGHP: insulated greenhouse heated via heat pump. The values were tested using one- and two-way analyses of variance (ANOVA) (p<0.05), N=24. Different small letters indicate significant differences (p < 0.05).

For the flavonoids and the tannins, the fruits of IGHLS still have the high level reaching a value of 2.21 and 1.11 mg EC g^{-1}DW (Figure 9).

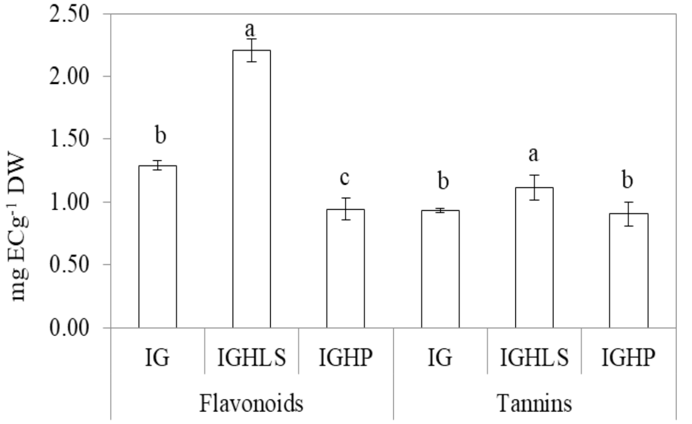

Figure 9: Effects of microclimatic conditions on flavonoids and tannins in tomatoes of IG, IGHLS and IGHP. (IG) Insulated greenhouse as a reference, (IGHLS): Insulated greenhouse equipped with a solar air collector and IGHP which is insulated greenhouse heated via a heat pump. The values were tested using one- and two-way analyses of variance (ANOVA) (p<0.05), N=24. Different small letters indicate significant differences (p < 0.05).

The lycopene values show that fruits of IGHLS enjoy the highest one against those of IGHP and IG. It reaches 0.020, 0.013 and 0.007 µg g-1 DW, respectively (Figure 10).

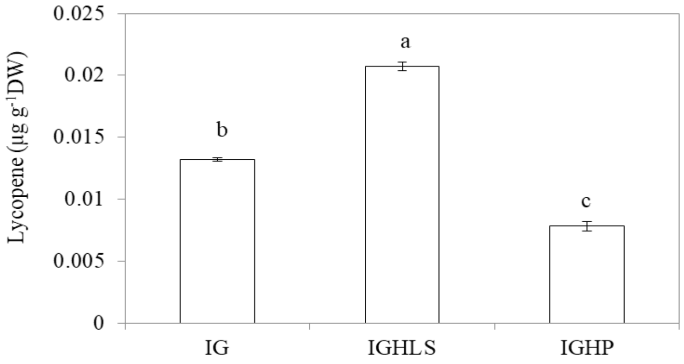

Figure 10: Effects of microclimatic conditions on lycopene in tomatoes of IG, IGHLS and IGHP. (IG) Insulated greenhouse as a reference, (IGHLS): Insulated greenhouse equipped with a solar air collector and IGHP which is insulated greenhouse heated via a heat pump. The values were tested using one- and two-way analyses of variance (ANOVA) ($p<0.05$), N=24.

Discussion

In this study, a decline in photosynthetic capacity accompanied by a reduction in gs, C1 and E in the IG (Table 1) was found, indicating that this response is one of the reasons for the low night temperature. The same results were observed in mango [11] and Tomato (Liu *et al*., 2012) treated with low night temperature. They demonstrated that photosynthesis is reduced in days following cold nights. Indeed, low night temperature treatment caused a substantial reduction in photosynthetic capacity in tomato [12].

Temperature is a key factor that regulates the photosynthetic processes of plants [13]. This parameter was enhanced by the night heating under IGHLS (Table 2) which is in agreement with the experimental warming in both species *P. asperata* and *A. faxoniana*, which indicated that night warming could accelerate photosynthesis by increasing chlorophyll concentration and apparent quantum efficiency [14]. In a consistent way with our findings (Figure 4, Table 1), Beck *et al*. [15] indicated that low temperature forms a stress decreasing chlorophyll biosynthesis, photosynthetic rate and carbohydrate metabolism which result in a reduction of crop yield (Table 2) and quality. At the physiological level in tomato, some negative impacts were also observed: low night temperatures of 6 or 9°C led to an irreversible reduction in the photosynthetic rate and stomatal limitation of CO_2 supply [12].

Hastened development of tomato plants found in IGHLS has been reported to the increasing night temperature. Yet, decreasing night temperatures to 11°C at average has been reported to decrease stem elongation of tomato (Figure 5). Many researchers reported that a direct effect on plant growth, development and morphology was awarded to temperature [16]. Others indicated that the difference between day and night temperature involved in the control of stem elongation and thus height [17]. This is in consistent with earlier literature on poinsettia when lower night temperatures have decreased size and number of bracts Tsujita and Craig (1980). Otherwise, according to Dorais *et al.* [18], light and temperature inside the greenhouse represent factors which create a particular microclimate with significant effects on growth, development and crop productivity. Therefore, although night-warming increased average diameter and had no significant effect on average plant height and stem base diameter of both species *P. asperata* and *A. faxoniana* [14].

The reduced number of flowers was shown under IGHP and IG (Figure 7) as found by [19], when the number of flower trusses of 'Money-maker' was reduced by the low night temperature regime.

The lower light intensity received as well as the low night temperature reached by plants in the greenhouse heated via heat pump was the cause of the lower content of phytonutrients in the fruit (Figures 8, 9, 10) which was supported by Dorais *et al*. [20] who described that the phytonutrients accumulation is strongly affected by the intensity, duration and quality of light. Jarquín-Enríquez *et al*. [21] suggest that temperature in the greenhouse, season production and lighting conditions inside the greenhouse, affect lycopene biosynthesis or accumulation process. They prove that higher temperatures observed in the glasshouses allowed a greater biosynthesis of lycopene.

In our study, we found that the solar air system is most efficient for heating the interior of the greenhouse without secondary effect than the heating system via heat pump which hinder plants by shading done from the exchangers. It's consistent with previous works which reveal that shading reduce the intensity of solar radiation and the greenhouse air temperature [22] and consequently reduces the quality of the fruit [23].

It is proven for Tunisian climatic conditions that PCM assisted solar air heaters can maintain the internal air temperature of 15°C for greenhouses, which is ideal for tomato planting [24]. Kooli *et al*. (2015) found that PCM utilization in the insulated greenhouse with latent system is capable to keep the internal temperature at the level of 15 °C at night while the temperature outside reaches 8°C.

However, the combined system has several characteristic benefits. It is suitable from both economic and technical points of view and can be used instead of conventional systems [25].

Conclusion

Since greenhouse climate control is aimed to increase production, this control could also improve the visual quality and nutritive value of the greenhouse-grown tomato fruits.

In this context, the use of different heating systems involves installation and operational costs which the user has to bear. However, each system has some advantages and limitations, which the user has to think of before going for the installation. Thus, from our study we can define the special solar air collector as a greenhouse facility which can be used for dehumidification processes and to produce plants with the thermal stored energy. It gives the appropriate microclimate for plants under greenhouse in comparison with GSHP: The produced energy excess can also be used to cover the basic load for night heating inside greenhouses. Under the greenhouse heated with this solar system, we found a high RGRh and RGRd, an earliness of production with 2 weeks and a good quality and quantity of fruits represented by high phenolic compounds and a high quantity of marketable fruits.

As regards the other heating system via the heat pump, it is desirable to find a solution for heat exchangers in order not to interfere brightness which acts negatively on the growth of plants. Overall performance of a greenhouse coupled with any heating system is influenced by several interrelated parameters.

These findings should not be interpreted as meaning that solar air heating system should replace heat pump heating system in Tunisia. The performance for both systems is strong and the heat provided can satisfy the demand. The results do suggest that more attention might be directed toward improving greenhouse heating system via heat +pump installation. So, we can prove that the solar air heater with latent storage system is an effective method to achieve a suitable environment for crop growth and to enhance crop productivity and quality out of season.

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