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Effects of Two Heating techniques on Greenhouse Tomato (*Solanum lycopersicum*) Production

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***Abstract*— Greenhouse heating is compulsory for precocious crop production in Tunisia. However, energy consumption and its corresponding high costs for farmers has been the most important disadvantage. In this context, the use of latent heat stored during sunny periods and geothermal sources for greenhouse heating could be an interesting alternative. Thus, new agronomic/climatic approaches were developed to produce several crops such as tomato in a sustainable way. The objective of this study is to evaluate the performance of a heat pump coupled with a heat exchanger and a solar air collector with a latent storage system in heating greenhouses. In this context, the yields of tomato cultivated inside greenhouses equipped with a new solar air collector with latent storage (IGHLS) and a heat pump (IGHP) were studied The results show that IGHLS microclimatic conditions positively affected maturity and led to an early fructification and an increased yield. The solar collector revealed to be an efficient competitive system in comparison with the heat pump system. It allowed an early maturity and increased tomato yields and considerably reduced greenhouse heating costs as it uses a highly solicited natural renewable energy.**

***Keywords*— Solar air collector, heat pump, greenhouse, tomato, yield, quality**

I. INTRODUCTION

Tomato (*Solanum lycopersicum.* L) is one of the most popular and worldwide consumed vegetable crop [1]. Tomatoe is a very good source of nutrients and bioactive compounds [2]. While, the nature and concentration of synthesized compounds are subject to environmental factors, agricultural practices, variety and ripeness [3]. Besides to its economic importance, this species serves as a model for the study of plant growth and development [4]. Meanwhile, both genetic and environmental factors govern the biosynthesis of bioactive tomato compounds [5]. In this context, growing conditions can markedly influence its yield and fruit quality even under controlled greenhouse conditions.

The major climatic factors that affect tomato growth and precocity under greenhouse conditions are carbon dioxide, light, relative humidity and temperature. Temperature, in particular, affects photosynthesis and respiration as well as growth rate, flowering and maturity developmental stages.

In Tunisia, one of the major problems encountered under greenhouse culture conditions is microclimate control. Eventhough air temperature rarely decreases below 10°C during winter, the lack of heating has unfavorable effects on the precocity of greenhouse-cultivated tomato. The most common heating systems used under conventional greenhouses are based on fossil fuels. Unfortunately, the continuously rising price of such fuels increases crop production costs and affects farmer's income [6]. Therefore, it seems that the use of a suitable heating system, with low cost, is crucial to furnish optimum indoor conditions during cold months. Moreover, natural resources are considered as rare specially in Tunisia [7] while the energy requirement is increasing continuously. Consequently, it is necessary to replace the current conditioning units by new more efficient systems based on renewable energies such as solar and geothermal.

In this context, a new Solar Air Heater with Latent Storage Collector (SAHLS) using spherical capsules as a packed bed absorber and a geothermal system (GSHP) using a geothermal Heat Pump and a conic basket geothermal heat exchanger were designed in the Center of Research and Technology of Energy (CRTEn) in Tunisia and used for greenhouse heating purposes.

This work reports the energy status of both geothermal and solar air collector and evaluates the performances of GSHP and SAHLS in greenhouse air conditioning. Considering the lack of information regarding the effects of such heating systems on tomato fruit production and quality, we carried out an experiment under greenhouse conditions using each of the heating systems and monitored the development and production of tomato. The objective of the work is the optimal control of tomato developmental stages for an improved yield and fruit nutritive value.

II. MATERIALS AND METHODS

In this study, three identical greenhouses with an East-West orientation were installed. The first is an Insulated Greenhouse (IG) (Fig. 1-a). The second is an Insulated Greenhouse Heated with Latent System (IGHLS) is equipped

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with a collector air heater with latent storage system (CAHLS) (Fig.1b). The third Insulated Greenhouse with Heat Pump (IGHP) is equipped with a heat pump system (Fig. 1c).

A. Experimental Greenhouse Design and Site Description

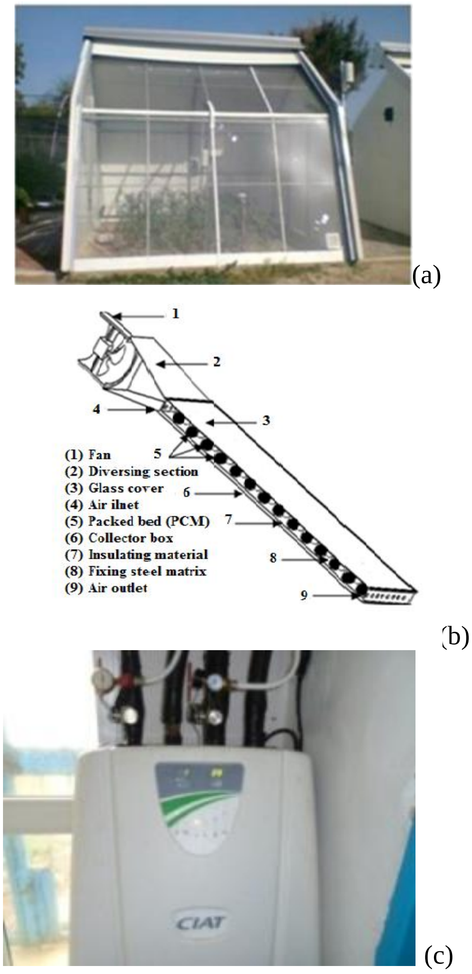

Fig.1: Insulated greenhouse (IG) (a), a collector air heater with latent storage system (CAHLS) (b) and a heat pump (c).

All three experimental greenhouses were chapel-shaped and 1.5m in width, 2.5m in length and 2m in height in the center; with a 14.8 m^2 area. The South-oriented roofs of the greenhouses as well as walls are covered with 3mm-thickened glass plates. The side walls and the north roofs are made of 0.4m and 0.6m thick sandwich panels, respectively. The south wall and the south roof have slopes that are worth 30 ° and 33 ° respectively. A centrifugal fan checked up via a thermostat is installed in the side wall to extract hot air if the temperature exceeds that desired (28 °C).
The solar air collector was applied for greenhouse heating at night.

The operating principle of the collector is based on loading and unloading processes. The loading process occurs during the sunny period. The black bed absorber of the SAHLS absorbs a part of the solar radiation which forms the thermal energy. This energy is stored in the collector as a sensible and latent heat.
As soon as the sun goes down and during the night, a radiant heat exchange in the IGHLS causes the air temperature drop inside the greenhouse. During this phase, a fan extracts the air through the PCM capsules and lets the stored heat escape, so that the unloading process takes over.

As for the greenhouse using a heat pump system, it is composed of 1-a geothermal heat pump unit which is a reversible water-to-water Ageo CIAT type. It is considered as an individual heating and cooling system and 2- vertical geothermal heat exchangers which are installed horizontally, underground, at 3 m depth.
In order to evaluate the performance of the geothermal system in greenhouse heating, a multilayer heat exchanger system (44 m in length) is installed inside the greenhouse, both on the roof and on the ground (Fig.2).

Fig.2. Roof and ground multilayer heat exchangers inside the greenhouse.

B. Measurements

1) *Plant Growth and Fruit Classification*: tomato plantlets were arranged in 4 rows with 40 cm between the rows and 35 cm between the plants at a density of 2 plants /m^2. Thus, in each greenhouse 28 plantlets were cultivated. A drip-irrigation system allowed a regular irrigation of tomato plantlets along the experiment. Axillary young shoots, up to the first flower cluster, were regularly removed to allow flowering.
During the experiment, plant height, stem diameter and shoot number were measured at 2 days intervals. Anthesis dates were recorded for 10 plants to identify fruit setting period. Fresh shoot and root biomasses were recorded and dry biomasses were measured after oven drying at 75 °C. Biomass measurements were done at the beginning and the end of the experiment.

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.

1) *Chlorophyll Content and Photosynthetic Parameters:*

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Chlorophyll contents of the youngest fully expanded leaves were measured at midday. Chlorophyll content index (CCI) were recorded 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 [8]. Gas exchange parameters (photosynthesis rate (A), transpiration rate (E) and intercellular CO_2 concentration (Ci)) were determined at 9:30–11:30 on a sunny day using a Li-cor handheld photosynthesis system (Li-Cor 6200, Li-Cor Nebraska, USA).

2) *Phenolic Compounds:* To investigate the contents of phytochemical compounds, three tomatoes were randomly harvested at maturity and lyophilized. The contents of secondary plant compounds, in the homogenate were determined in triplicate. Plant powder (1g) was slurred in 10ml methanol 80%. After 30 minutes of magnetic stirring and 24 hours incubation at 4 ° C in the dark, the mixture was filtered through ashless filter paper. The extract obtained was finally stored at 4 °C in the dark until analysis. The chemical analyses were also carried out in triplicate.
Phenolic compounds were extracted following the method outlined by [9]. The determination of total flavonoids was done according to the method of [10]. Lycopene content in tomato samples was extracted using the method outlined by [11].

III. Results

A. Climatic Conditions

Fig.3A shows that the night air temperature inside IGHLS can reach a value equal to 15.44 °C. The temperature degreased as the stored heat into the PCM decreased. Regarding to IGHP, the air temperature is lower than in IGHLS as well as at day and night. This decrease of temperature is due to the shade done by the multilayer heat exchanger.
On the other hand, Fig.3B shows that the relative humidity inside IGHLS is lower than under IGHP and IG. This is due to the increase of temperature by the solar air heater.

B. Gas Exchange Measurements and Chlorophyll Content

Records of gas exchange parameters of tomato plants cultivated under different greenhouse conditions allow to observe significantly increased net photosynthesis (A) and transpiration (E) under IGHLS, while a decreased stomatal conductance (gs) and intercellular CO_2 (Ci) were observed in comparison with IGHP (Table 1). Under IGHP conditions, net photosynthesis was 15.10 mol CO_2 m^2s^{-1} but stomatal conductance and Ci were the highest. Generally, the lowest gas exchange parameter values were measured under IG.
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 (Fig.4).

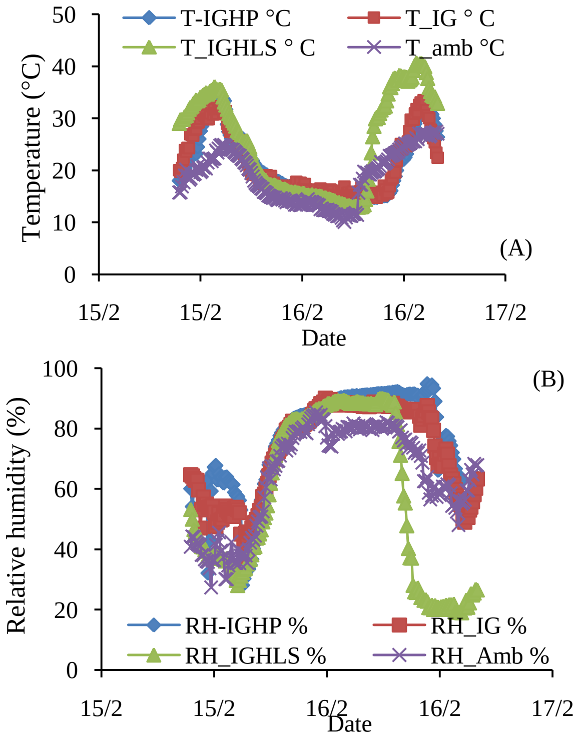

Fig.3 Air temperature (A) and relative humidity(B) outside and inside the experimental greenhouses during 15th-16th February, 2014).

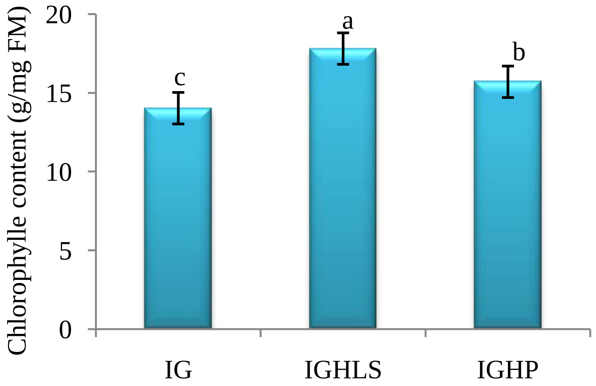

Fig.4 Chlorophyll content of tomato plants cultivated under different greenhouse conditions, (IG) Insulated greenhouse as a reference, (IGHLS): Insulated greenhouse equipped with a solar air collector and IGHP heated using a heat pump.

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TABLE I

Gas exchange parameters of plants cultivated under different greenhouse conditions IG, IGHLS and IGHP, (IG) Insulated greenhouse as a reference, (IGHLS): Insulated greenhouse equipped with a solar air collector and IGHP heated using a heat pump.

	Ci (µmol mol^{-1})	**E (mmol H_2O m^2s^{-1})**	**gs (ms^{-1})**	**A (mol $CO_2m^2s^{-1}$)**
IG	219,0±61,54 b	3,24±0,48 b	0,21±0,05 c	14,86±3,73c
IGHLS	226,8±27,35 b	3,94±0,20 a	0,30±0,03 b	18,88±2,30a
IGHP	389,7±0,95a	3,09±0,56 b	0,42±0,10 a	15,10±0,20b

C. Growth Rate and Flower Number: Temperature strongly affected relative growth rates of stem diameter (RGRd) and height (RGRh) (Fig.5). RGRh of plants cultivated under IG conditions were significantly lower than under greenhouses equipped with heating systems, recording around 0.034 mm day^{-1} under IG and 0.038 and 0.040 under IGHP and IGHLS, respectively. Furthermore, plants cultivated under IGHLS conditions had high RGRd (0.024mm day^{-1}) in comparison with IGHP or IG.

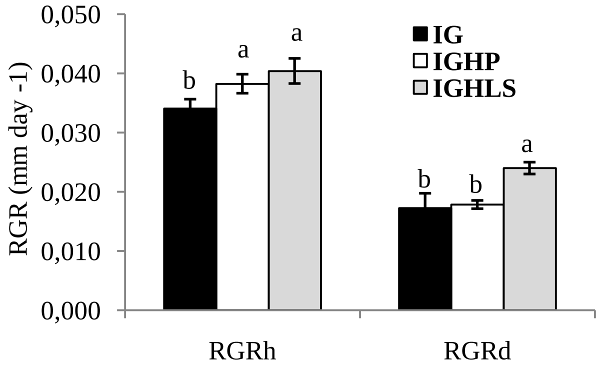

Fig.5 Stem height and diameter Relative Growth Rates (RGR) of ten tomato plants cultivated under different greenhouse conditions.

The results related to flowering show a significantly increased flower number in plants grown under IGHLS (Fig. 6). Eventhough, the number of flowers was similar under the different greenhouses from the 31st of January till the 20th of February, a marked increase was observed from the 20th of February till the 22nd of March under IGHLS conditions where an average number of 7 flowers/plant was counted.

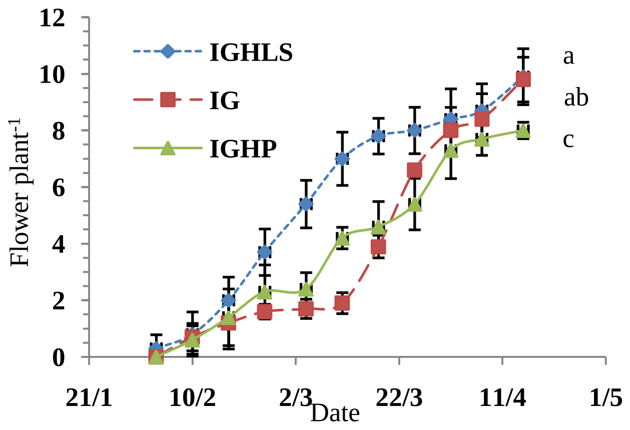

Fig.6 Average flower number $plant^{-1}$ in (IG) Insulated greenhouse as a reference, (IGHLS): Insulated greenhouse equipped with a solar air collector and (IGHP) heated using a heat pump.

D. *Yield:* The most important changes related to tomato fruits were their intrinsic qualities such as size and shape. Considering the IGHP tomato plants, berries were numerous since the first harvest (Fig.7b).

The results show that fruit yield and quality were affected by greenhouse microclimatic conditions. In fact, the yield of the marketable fruit has increased significantly under IGHLS greenhouse conditions, while undersized fruit production was low (Fig.7).

However, under IGHP, marketable fruit yield was low and most of the production was composed of undersized fruits (Fig.7).

E. Phytochemical Compounds: The fruit phenolics levels measured under IGHLS were significantly higher than those under IG and IGHP (14.65, 10.99 and 7.79 mg EAG g^{-1} DW, respectively) (Fig.8).

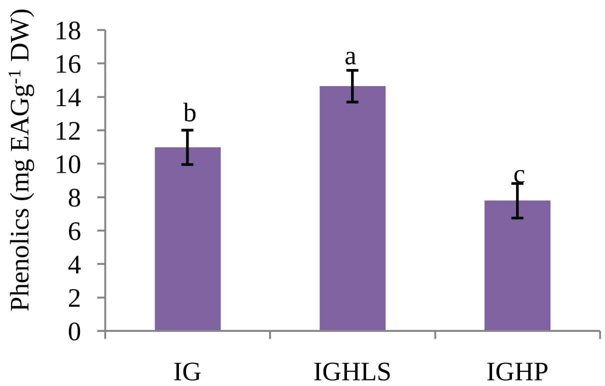

Fig.8 Phenolics levels in tomatoes under (IG): Insulated greenhouse, (IGHLS): Insulated greenhouse equipped with a solar air collector and (IGHP): heated via heat pump.

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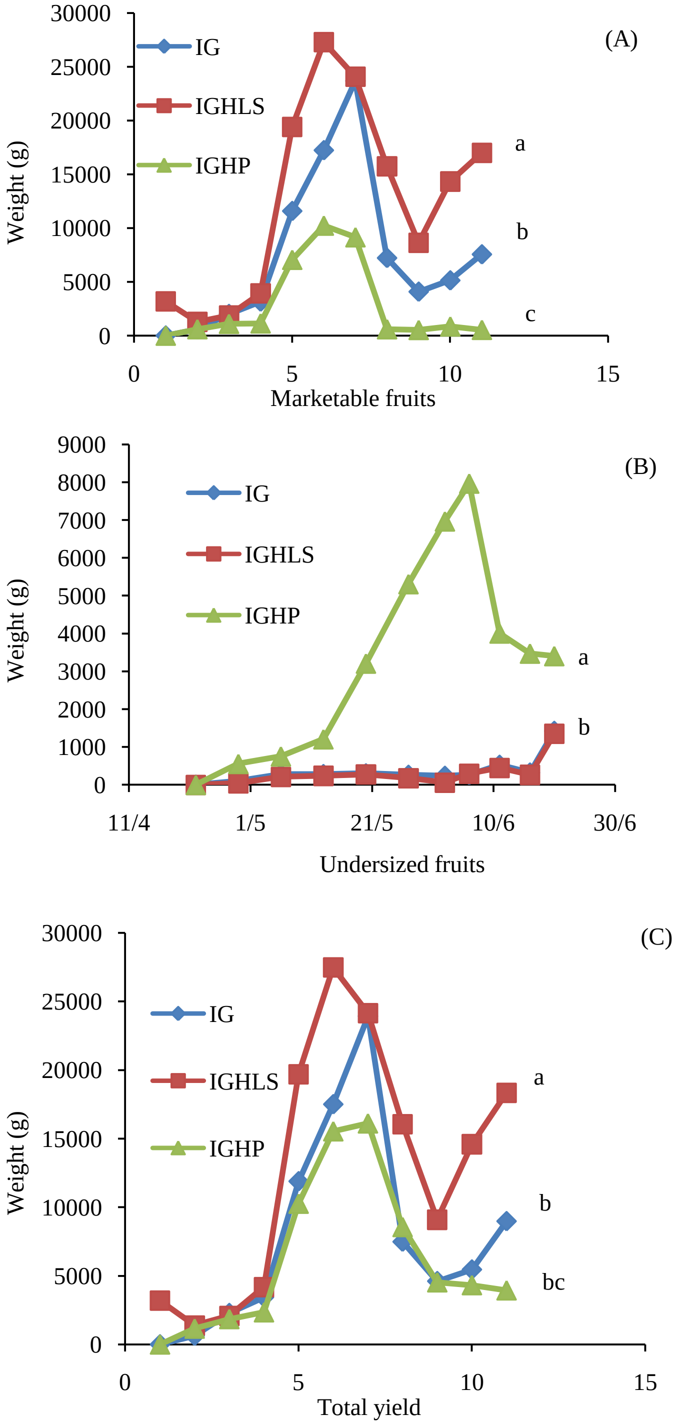

Fig.7 Marketable fruits, undersized fruits and total weight of tomato fruits in different harvest times (kg plant^{-1} and equivalent in t h^{-1}) grown under different greenhouses (IG, IGHP and IGHLS). Means with different letters are significantly different (NMK-test, p<0.05).

Regarding flavonoids and tannins, fruits harvested under IGHLS conditions had the highest level (2.21 and 1.11 mg EC g^{-1}DW, respectively) as compared to IG and IGHP (Fig.9).

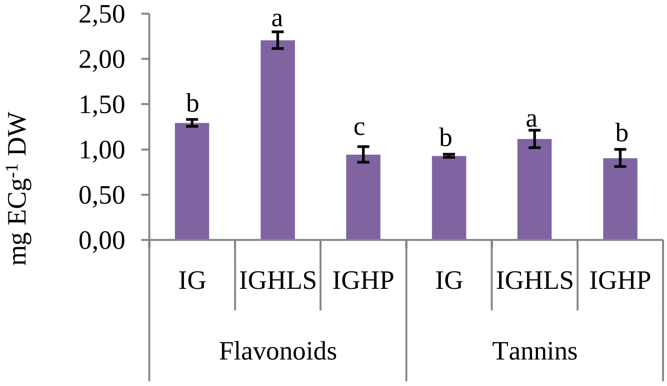

Fig.9 Effects of microclimatic conditions on flavonoids and tannins in tomatoes of IG, IGHLS and IGHP. (IG) Insulated greenhouse, (IGHLS): Insulated greenhouse equipped with a solar air collector and (IGHP) heated via a heat pump.

Lycopene rates obtained under IGHLS culture conditions were the highest as compared to those measured under IGHP and IG conditions with 0.020, 0.013 and 0.007 µg g-1 DW, respectively (Fig.10).

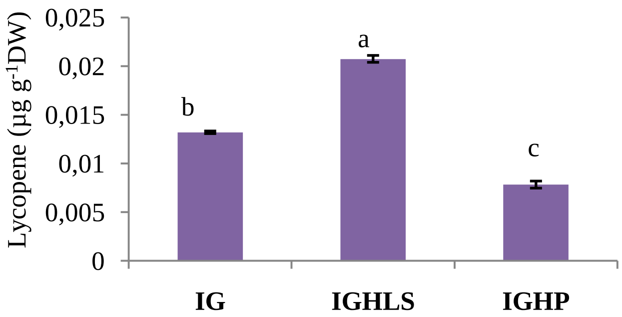

Fig.10 Effects of microclimatic conditions on lycopene in tomatoes of IG, IGHLS and IGHP. (IG) Insulated greenhouse, (IGHLS): Insulated greenhouse equipped with a solar air collector and (IGHP) heated via a heat pump.

III. Discussion

This study compares the performance of two heating systems on the development and yield of tomato. The results showed a decline in the photosynthetic capacity with a decrease in gas exchange under IG (Table I) due to the low night temperature. Similar results were observed in mango [12] and Tomato [13] cultivated under low night temperature conditions, which caused a substantial decrease in photosynthetic capacity in tomato [13].

Temperature is a key factor that regulates the photosynthetic processes of plants [14]. In our study, this parameter was enhanced by the night heating under IGHLS (Table I). This is in agreement with [15], reporting that night warming could accelerate photosynthesis by increasing

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chlorophyll concentration and apparent quantum efficiency in *P. asperata* and *A. faxoniana* [15]. In a similar context, [16] indicated that low temperature induces a decrease in chlorophyll biosynthesis, photosynthetic rate and carbohydrate metabolism which results in a reduction of crop yield (Fig.7) and quality. According to [13], low night temperatures of 6 or 9 °C led to an irreversible reduction in the photosynthetic rate and a stomatal limitation of CO_2 supply.

On the other hand, an improved development of tomato plants was observed under IGHLS. This is also attributed to the increased night temperature. Yet, decreasing night temperatures to 11 °C has been reported to decrease stem elongation of tomato (Fig. 5). Many researchers reported that a direct effect on plant growth, development and morphology was attributed to temperature [17]. [18] indicated that the difference between day and night temperatures is involved in the control of stem elongation and thus height [19].

According to [20], light and temperature inside the greenhouse are important factors that create a particular microclimate with significant effects on growth, development and crop productivity. According to [15], night-warming increased average diameter but had no significant effects on average plant height and stem base diameter of *P. asperata* and *A. faxoniana* [15]. Regarding flowering, a decreased number of flowers was observed under IGHP and IG (Fig.6) as reported by [21].

As far as phytonutrients are concerned, the low light intensity as well as the low night temperature registered under IGHP (greenhouse heated via heat pump) induced a lower content of phytonutrients in the fruit (Fig.8, 9, 10) compared to IGHLS. Similar results were reported by [22] who indicated that phytonutrients accumulation is strongly affected by the intensity, duration and quality of light. In a similar context, [23] reported that greenhouse temperature, production period and lighting conditions affect lycopene biosynthesis or accumulation process. They proved that higher temperatures observed in the glasshouses allowed a greater biosynthesis of lycopene [24].

Our results show that the solar air system is most efficient for greenhouse heating than the heat pump due to its shading effect. Previous works reported the negative effects of shading on the greenhouse air temperature [23] and the quality of fruits [25].

Under Tunisian climatic conditions, PCM assisted solar air heaters can maintain the internal air temperature of 15 °C under greenhouses, which is ideal for tomato cultivation [26]. [27] reported that PCM utilization under IGHLS allows to increase the inside night temperature to 15 °C while it doesn't exceed 8 °C outside the greenhouse.

IV. Conclusions

In this study, the beneficial effects of heating a greenhouse using a solar air collector on tomato development and yield were confirmed. These effects concern tomato early production, increased yield and improved fruit quality. Eventhough several heating systems are used for greenhouse crop cultivation, most of them generate high installation and operational costs. In this respect, the solar air collector represents an interesting alternative for greenhouse dehumidification and heating as it's based on the thermal stored energy. It favors also an appropriate microclimate for plant cultivation under greenhouse in comparison with GSHP and allows a better growth and development, maturation precocity, an improved yield and quality of marketable fruits.

As regards the heat pump, it is desirable to investigate solutions to avoid the shading effects of heat exchangers.

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