Investigation of the behavior of tomato plants grown under greenhouse heated by a solar air collector

DOUJA SELLAMI[a], SALWA BOUADILA[a], ASMA BEN SALEM-FNAYOU[b]
[a]Thermal Processes Laboratory, Research and Technology Centre of Energy, Borj Cedria, TUNISIA
[b]Laboratory of Molecular Physiology of Plants, Biotechnology Centre of Borj Cedria,, TUNISIA
Sellami.douja@gmail.com

Abstract: - Yield has been often reported to be unstable, depending on the growing conditions. Therefore, a tomato (*Solanum lycopersicum L.*) crop was grown in three greenhouses during the winter in Tunisia. Sidewalls and northern roof of two greenhouses were covered with sandwich panels (Insulated greenhouses (IG)) from which one is equipped with a heating system with latent storage (IGHLS). The other greenhouse was transparent (TG). These greenhouses were mechanically ventilated when air temperature exceeded 28°C. The overall mean air temperature was significantly increased by 1.42 and 4.34 °C (day) and 2 and 3.2 °C (night) in IGHLS as compared to IG and TG, respectively. Temperature maxima in IGHLS averaged about 2 and 4.35°C higher than in IG and TG, respectively. The relative humidity was similar at day but higher at night in TG than in IG and IGHLS with 1% and 2%, respectively. The relative water content was significantly lower in TG (76.86) than in IG (94.02) and IGHLS (117.92). The relative growth rate was increased by optimal conditions, whereas the electrolyte leakage and lipid peroxidation of leaves was suppressed in the IGHLS. Total fruit yield was higher in IGHLS (4,98 kg plant^{-1}) than in IG (3,2 kg plant^{-1}) and TG (2.3kg plant^{-1}). The quantity of undersized (mostly parthenocarpic) and blossom-end rot (BER)-affected fruits was reduced in IGHLS. However, the proportion of marketable yield was significantly higher in IGHLS (4.86 kg plant^{-1}) than in IG (3.05 kg plant^{-1}) and TG (2.22), owing largely to an increased incidence of undersized fruits in TG and IG. Higher undersized fruit incidence coincided with lower fresh weight and Ca concentration in the fruits in TG and IG. It is concluded that in greenhouse with technical modification allowing an increase of night temperature and dehumidification will improve protected tomato production.

Key-words:-Tomato, greenhouse, yield, renewable energy, nutrient elements, growth

Nomenclature

IG: Insulated greenhouse	RWC: Relative water content
IGHLS: Insulated Greenhouse with Latent Heat System	PCM: Phase change material
RGR: Relative growth rate	T: Temperature
RH: Relative humidity	TG: Transparent greenhouse
	WAT: week after transplanting

1 Introduction

Tomato (*Lycopersicon esculentum* Mill) is an important vegetable crop grown all over the world under greenhouse, where night temperature and relative humidity are limiting factors in its growth. In Tunisia, almost throughout the bad season, both air temperature and relative humidity not reached the optimal for tomato. In fact, mean daily air temperature in the range of 21–27°C (Sato et al. 2000) and relative humidity around 60% (Peet et al. 2003) have been mentioned to be optimal for tomatoes. Moreover, according to Dane et al. (1991), high day and night temperatures drastically impede tomato flowering, pollination (Adams et al. 2001) and fruit set (Peet et al. 1997) resulting in high numbers of parthenocarpic fruits and hence lower marketable yields (Kleinhenz et al. 2006). Furthermore, it has been signaled that relative humidity beyond plant growth optimal inhibits transpiration (Dorais et al. 2004), pollination and fruit set (Peet et al. 2003) and is presumed to deteriorate the tomato fruit quality according to Banuelos et al. (1985).

In general, greenhouses facilitate the control of environmental conditions and provide protection against heavy rain and low temperature. Therefore, high-value vegetables become increasingly produced under protected cultivation. It has become a common practice to cover ventilation openings with insect-proof screens enabling to reduce the frequency of pesticide application which is beneficial for growers (Moller et al. 2004); however, this also allows decreasing wind speed and air exchange (Harmanto et al. 2006). Tomato yield is not an isolated characteristic and depends on the growth of the whole plant. Therefore, the interaction between plant morphology, physiology and growth conditions determined the yield. Low night temperature is known to adversely affect vegetative and generative growth of tomato plants. It induces stomata closing leading to reduced transpiration and photosynthesis (Liu et al. 2011), whereas respiration processes are enhanced (Morales et al. 2003). Therefore, biomass production and xylem transport rates decrease (Adams and Ho, 1993).

The proportion of marketable yield and fruit quality in tomatoes are impaired with two prevalent physiological disorders which are blossom-end rot and fruit cracking (FC). Likewise, blossom-end rot (BER) can cause yield losses by an amount up to 50% (Taylor and Locascio, 2004) and fruit cracking by 95% (Dorais et al. 2004). In fact, BER is mainly a result of insufficient transport of Ca particularly into the distal parts of the fruits (Ho and White, 2005) while FC occurs predominantly in later stages of fruit development in the proximal half of the fruits. The main reason for FC appears to be the high fruit extension-growth, particularly through water uptake (Peet and Willits, 1995). In addition to that, high levels of intensity, air temperature and relative humidity have been mentioned to increase the incidence of blossom-end rot (Ho and White, 2005) as well as fruit cracking (Peet, 1992) possibly entailing reduced yield and/or fruit quality.

When adverse conditions disrupt the equilibrium, photooxidation occurs because the ability to eliminate activated oxygen weakens. Therefore, the accumulation of reactive oxygen species is proven as one of the fast kinetic events that expose plants to various stresses. It results in an irreversible inactivation of the photosynthetic system. Furthermore, recovery takes more than a week, which deals to a severe decrease of plant productivity (Kudoh and Sonoike, 2002). Moreover, color is one of the most important quality parameters of tomato fruit that affects customer purchase decision. The main color quality of tomato is redness and it is affected by lycopene content.

Alleviation of the adverse effects of low night temperature and high relative humidity on tomato yield and fruit quality is, therefore, a prerequisite for sustainable tomato production in Tunisia hence a need of heating. Sethi and Sharma (2008) evaluated all heating technologies for worldwide agricultural greenhouses and discussed the representative applications of each technology.

Many heating systems for air-conditioning greenhouse used renewable energy sources (Nayak et al. 2009). In most cases the actions taken have led to use of latent storage for night heating (Bouadila et al. 2014) in the greenhouse. For an economic evaluation of the various techniques which may be used to enhance greenhouse production, it is essential to know how much the productivity of the crop is improved by the new heating system.

Therefore, the main objectives of this study were:

- to investigate the effects a new solar air collector with the latent storage heating system on microclimate, relative water content and the influence of these factors on tomato yield and fruit quality in Tunisia.
- to determine if temperature given by this heating system can be manipulated to increase growth of plants and development for future commercial application.

2 Material and methods

2.1 Experimental setup

To investigate a comparative study, an experimental setup of three greenhouses (Fig. 1) is designed and constructed. One is transparent and two identical insulated greenhouses, one of them uses a heating system. Each greenhouse was a 3.7m-wide, 4m-long and 3m-height. The greenhouse wall and roof oriented to the south are covered with plates of glass with 3mm of thickness. Sidewalls and the northern roof of the two insulated greenhouses are built by sandwich panels with 0.4m and 0.6m of thickness, respectively. Each greenhouse was equipped with a centrifuge fan controlled by a differential thermostat.

The greenhouses are located with the following coordinates: Latitude 36°43' N and Longitude 10°25' in the Research and Technology Center of Energy in Borj Cédria, on the Mediterranean coast of North Africa, near the city of Tunis in Tunisia.

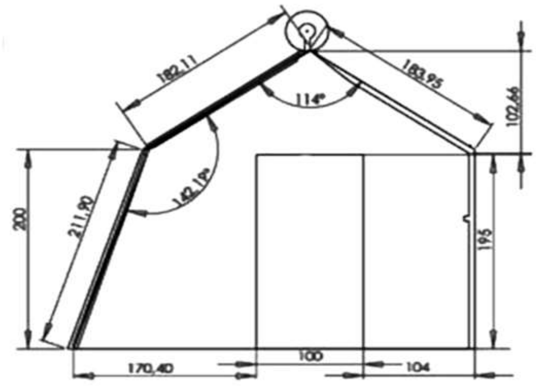

Fig.1: a schematic section and dimensions of greenhouse

2.1.1 The heating system

This research work has been preceded by an experimental evaluation of the thermal performance of this new solar air heater collector with a latent heat storage system (Bouadila et al. 2013). The heat system consisted of a new solar air heater collector using a packed bed of spherical capsules with a latent heat storage system (SAHLSC). The new SAHLSC was used as a mean to heat the interior environment of the greenhouse at nighttime (Fig.2a). It was with 2m of length, 1m of width and 0.28m^3 of total volume. A 0.004m thick transparent glass cover placed at 0.015m above a packed bed absorber which is the key component of the entire system. A 0.05m thick polyurethane insulation is placed in the bottom and the edge of the collector. It's with a heat conductivity of 0.028Wm^{-1}K^{-1} (Fig.2b).

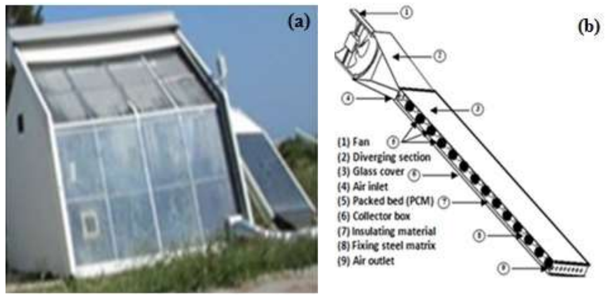

Fig.2: (a) External view of the insulated greenhouse equipped with the solar air heater, (b) schematic section of the SAHLSC

2.1.2 Methodology

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

According to Bouadila et al. (2014), for the performance of SAHLSC, the nighttime recovered heats attain 30% of the total heating requirements. The stored heat is equivalent to 56% of the daytime total excess heat inside the greenhouse. The SAHLSC create a passive dehumidification process at night and allow a relative humidity from 10 to 17% lower than the IG greenhouse.

2.2 Cultural practices

Seeds of the indeterminate hybrid tomato (*S. lycopersicum* L.) variety (Amal, Tunisia) was sown in peat moss in December.2013.

On January, 84 plants were transplanted into the greenhouses (4 rows with each 28 plants, planting density: 1.5 plants m^{-2}) using a local potting mix. All plants were cultivated with one stem using a high wire growing system. Data collection and sampling were done on randomly selected plants. For details on plant cultivation, pruning procedures, pest control, and fertilizing see Max and Horst (2009) and Liebisch et al. (2009). 84 plants were transplanted into the greenhouses (4 rows with each 7 plants, planting density: 1.5 plants m-^{2}) using a local potting mix. Data collection and sampling were distributed to the four rows.

2.3 Data acquisition

T and RH inside and outside the greenhouses were monitored with a HMP155 A sensor, installed in the center of every greenhouse half, 1.8m above the floor and outside.

Global solar radiation was measured with the pyranometers type CM11 (Kipp and Zonen, Delft, The Netherlands) positioned in the greenhouse, 1.5m above the floor. Data were sampled every 15s, transferred to a data-logger (BGT, Leibniz University Hannover) and recorded as mean values every 10mn. All sensors were calibrated prior to the start of the experiment.

2.4 Measurements

2.4.1 Plant growth analysis

10 randomly selected plants were selected to determine plant height, diameter stem and number of leaves every two days. The growth of vegetative tomato plants can be characterized by their relative growth rate (RGR). The number of fruit clusters, and fruit biomass were also recorded.

Fruits were picked twice a week starting from WAT 9 and divided into marketable yield and other non-marketable fruits (undersized <50 g, misshaped or disease-affected fruits). All yield fractions were counted and weighed separately. At the end of the trial, 9 randomly selected plants were destructively sampled for biomass analysis. To determine the dry weight, the samples were oven-dried at 80 °C until a constant mass was reached.

Solution samples were analyzed for Ca as well as Mg and Cu contents with a spectrophotometer (Model 6300) and a flame photometer (Model PFP 7, both Jenway, Dunmow, Essex, England), respectively. The extraction and the determination of the ferrous iron in the leaves is carried out according to the method of Katyl and Sharma (1980).

2.4.2 Measurements of photochemical activities

2.4.2.1 Electrolyte leakage

Twenty freshly cut leaf discs (0.5cm^2 each) were rinsed 3 times (2–3mn) with distilled water and subsequently floated on 20ml of distilled water in the dark at room temperature for 24 hours. After hydration, the free conductivity (C1) in the solution was measured using microprocessor-type conductivity Cellox 325 WTW. The conductivity is expressed in microseconds cm^{-1}.

After this measurement, the washers are placed in a water bath at 100°C for 1 h. After cooling 18 hours, allowing the complete diffusion of the ions, the total conductivity (C2) was then measured. The electrolyte leakage is measured according to this formula:

$[1- (C1/C2)]*100$.

Results were expressed as percentage of total conductivity.

2.4.2.2 Total antioxidant capacity (AOA)

The test of AOA is based on the reduction of molybdenum (VI) to molybdenum (V) by the plant extract. This reduction leads to acidic pH, formation of a green phosphate / Mo (V) complex (Prieto *et al.* 1999). An aliquot of 0.1ml of extract was combined with a tube with 1ml of sulfuric acid solution composed of (0.6N), sodium phosphate (28mm) and ammonium molybdate (4mM). The tubes are incubated at 95°C for 90mn. After a break of 6mn at room temperature, the absorbance is measured at 695nm against a blank containing methanol in place of the extract. AOA is expressed in mg of Gallic acid equivalents per gram of dry matter (EAG mg. g DM^{-1}).

2.4.2.3 Lipid peroxidation

Lipid peroxidation is estimated by the malondialdehyde assay (MDA), final derived from membrane lipid peroxidation, according to Yagi (1976). TBA reacts specifically with aldehydes mainly MDA, a product of the oxidative breakdown of lipids and polyunsaturated fatty acids.

Samples of 0.5g were ground in liquid nitrogen in a porcelain mortar. The powder obtained is homogenized in 5ml of trichloroacetic acid (TCA) 0.1%. This homogenization is followed by centrifugation for 5min at 10 000 rev/min at 4°C. To the supernatant, was added an equal volume of thiobarbituric acid (TBA) 0.5% prepared in 20% TCA. The mixture was incubated at 100°C for 30mn. In those circumstances, the essential aldehyde malondialdehyde compounds will react with TBA to form the TBA-MDA complex. The reaction is stopped with immediate cooling for 10mn with crushed ice. The absorbance of the supernatant obtained after a second centrifugation at 10 000 rev/min for 5min is read at 532nm. The optical density is then corrected by subtracting the non-specific absorbance of a blank containing a mixture of TBA-TCA read at 600nm.

Concentration expressed as MDA (µmol g MF^{-1}) is calculated using its extinction coefficient (e = 155 mM^{-1} cm^{-1}).

2.4.3 The relative water content (RWC)

RWC was measured at midday following the methodology proposed by Barr and Weatherley (1962), which briefly consisted of three steps. First, disc samples ($2cm^2$) from the youngest fully expanded leaf were cut, and immediately weighed to obtain fresh weight (FW). Second, the same discs were allowed to float for 2h in Petri dishes with distilled water and, after a gentle blotting to remove water excess, they were weighed to obtain the turgid weight (TW). Finally, the discs were weighed after drying them at 60°C for 48h until the constant dry weight was reached (DW). Having these three parameters, the RWC was calculated using the following equation:

$RWC (\%) = (FW - DW) /(TW - DW) * 100$

RWC measurements were performed in triplicate.

2.4.4 Color quality

Color measurements were performed on the surface of tomato three points in the bottom and the equatorial region with a portable colorimeter (CR-400, Konica Minolta, Tokyo, Japan) and recorded in color space coordinates (L^*, a^*, b^* and C^*). Before the color measurement, the colorimeter was calibrated. Optical assays were performed in triplicate. Chroma [$C^* = (a^{*2}+b^{*2})^{0.5}$] and hue angle [$h^\circ = \tan^{-1}(b^*/a^*)$ when $a^*>0$ and $b^*>0$ or $h^\circ = 180^\circ+\tan^{-1}(b^*/a^*)$ when $a^*<0$ and $b^*>0$] were calculated from a* and b* values (Lancaster et al., 1997). L* represents the lightness, ranging from 0 = black to 100 = white, chroma refers to color saturation which varies from dull (low value) to vivid color (high value) and hue angle is defined as a color wheel, with red-purple at an angle of 0°, yellow at 90°, bluish-green at 180°, and blue at 270° (McGuire, 1992).

Color differences vis-a-vis the fresh samples are obtained by calculating the color intensity:

$$E = (L^{*2} + C^{*2})^{1/2}.$$

2.5 Statistical analysis

The results of the present study were expressed as mean values of three separate experiments. Statistical analysis of the data was performed with STATISTICA software (STATISTICA release 7). For post hoc analysis, Student–Newman–Keuls' multiple comparison test was applied at 0.05 significance level.

3 Results

3.1 Greenhouse microclimate

The global solar radiation profile inside the greenhouses corresponded to this outside (Fig. 3A). The averaged intensity of incoming radiation, over the entire observation period outside greenhouse was 281.36 Wm^{-2}. The inside radiation of the three greenhouses was similar view that the southern front wall is made of the same glass plates whose emissivity is: e=0.9 and transmissivity for solar radiations =0.85 (Bouadila et al. 2014). Thus, the intensity was significantly reduced inside the greenhouses.

Concerning solar radiation regimen, during the day the transparent greenhouse receives more solar radiation than the other two greenhouses view that these four sides are transparent. Overnight, its heat transfer surface with the outside is much elevated compared to thermally insulate greenhouses whose north facades and the two sides East and West covered by sandwich panels reduce the heat transfer.

During the first 2 weeks, the solar radiation was 236,79 Wm^{-2}. However, from WAT 3 onwards the reduction of the radiation became increasingly high, resulting in a declining maximum temperature in the three greenhouses from 30.25 to 25.15°C in the IGHLS and 28.83 to 24.04 in IG. The corresponding values for TG were 25.90 to 23.62°C.

Weekly mean average and the maximum temperature were consistently lower in TG as compared to the IG and the air inside IGHLS (Fig.3B). During the first two weeks the highest maximum temperature was observed in IGHLS. After WAT 3, the differences between TG and others greenhouses air were stabilized (Fig.3D and E) until WAT 7. Especially in the last third of the trial, daily temperature maxima in IGHLS exceeded 30°C frequently and remained above 32°C for several hours, whereas in IG and IGHLS the daily maximum temperature scarcely reached values above 28°C.

Overall, the temperature differences between TG and IGHLS as well as air inside the IG were highly significant. Averaged over the entire trial duration, daytime temperature in the three greenhouses was around 23˚C. Night temperature was much more pronounced in IGHLS averaging 1,2˚C higher than IG and 2˚C higher than TG. The difference between day and night time mean temperature averaged highest in TG (10.75˚C) intermediate in IG (9.50˚C) and lowest in IGHLS (9˚C). Mean temperature, but not RH steadily increased form WAT 7 onwards. Average T and RH outside the greenhouses exceeded the lower and upper limit, respectively, of the growing optimum for tomatoes almost all throughout the experiment.

Outside, relative humidity is significantly higher than inside greenhouses (Fig.3 D and F). As expected averaged highest in TG especially during the night (78 in IGHLS and 88 in IG and TG). The corresponding values at day were at mean 62% inside the three greenhouses. From WAT 4 until WAT 6, night relative humidity can exceed 90% under TG. The SAHLSC create a passive dehumidification process at night time due to the increase of the air temperature inside the IGLHS.

3.2 Vegetative growth

In the first week the vegetative development of the relative growth rate of height and diameter stem was similar in the greenhouses of the three types. However, until 7 WAT, the overall visual impression of the plants was slightly better in IGHLS, resulting in significantly greater plant heights and higher average cumulative numbers of trusses per plant. Thereafter, plant development was enhanced in IG than in TG (Fig.4a and b). A significant difference between the greenhouse types were observed in cumulative leaf number (Fig.4c) or vegetative

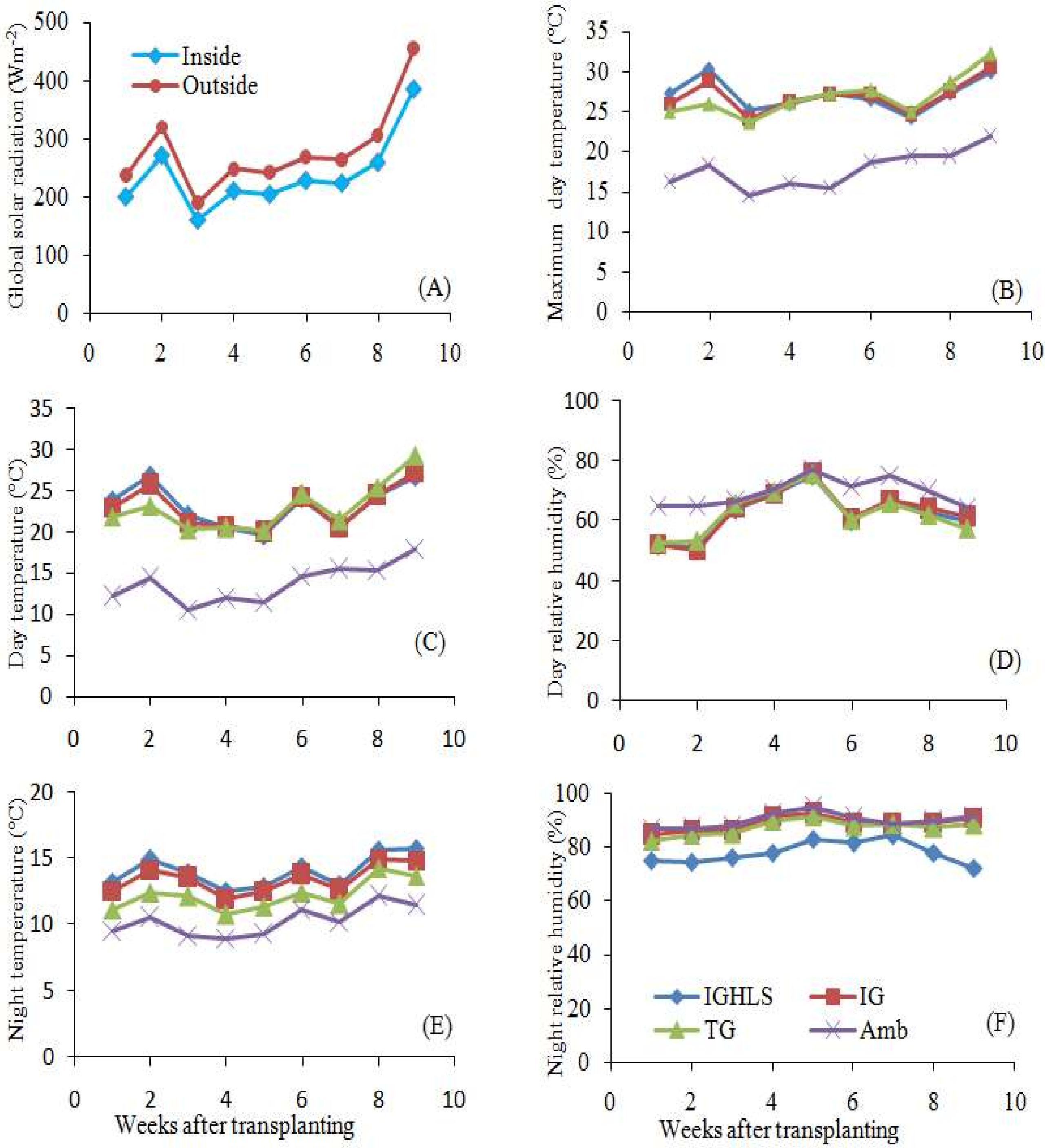

Fig.3. Weekly means of average daily global solar radiation (A), daily maximum temperatures (B), average day (C and E), and nighttime (D and F) temperatures (C and D) and average relative humidity (E and F) inside greenhouses cropped with tomato during winter. Greenhouses were either transparent (TG) or thermally insulated (IG) or insulated and equipped with a latent system (IGHLS). T and RH values are means of four sensors (each one inside every greenhouse) and one outside. Global solar radiation values are means of one sensor (inside the greenhouse).

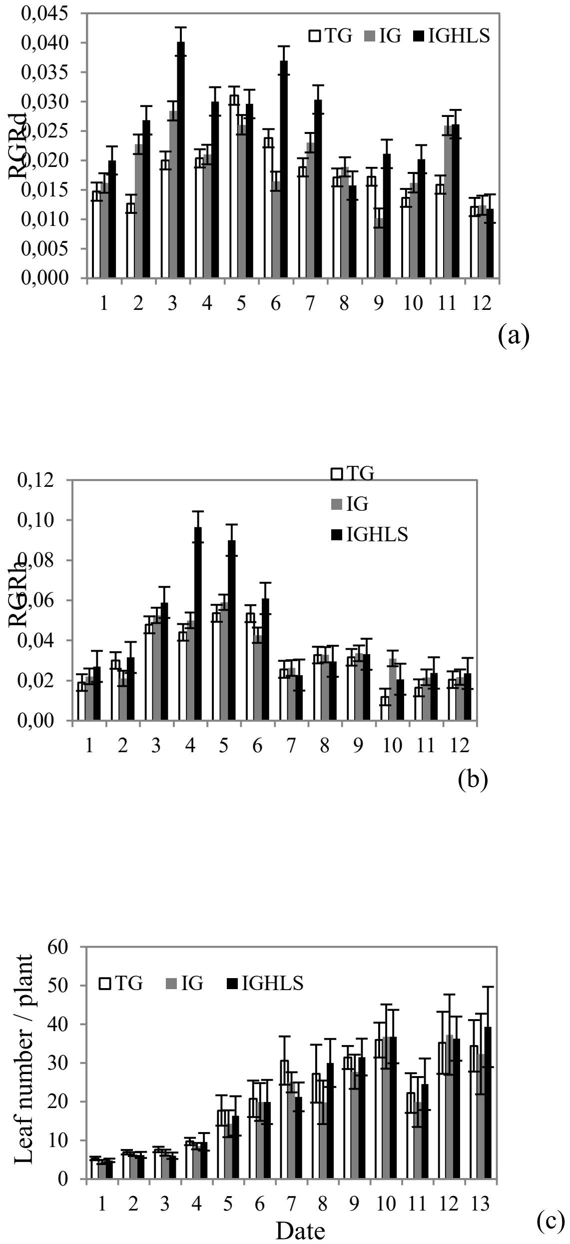

Fig. 4. The weekly relative growth rate of diameter stem (RGRd) (a) , height stem (RGRh) (b) and number of leaves (c) of tomato plants grown in greenhouses: either transparent (TG) or thermally insulated (IG) or insulated and equipped with a latent system (IGHLS).

and fruit biomass, either in the early stages of the harvesting period or at the end of the trial. Reflecting the visual impression of a better vegetative plant development in IGHLS, a trend to higher total biomass production was observed in this greenhouse at the end of the trial (Fig.5)

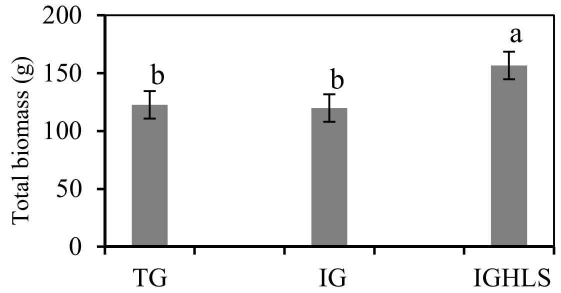

Fig.5: Total biomass of plants grown under three greenhouses either Transparent (TG) or thermally insulated (IG) or insulated and equipped with a latent system (IGHLS)., 10 WAT. The small letters show the significance of the difference between RWC (Newman-keuls test, a<0.05, n=9).

3.3 Water and nutrient balance

Although the variability of the measured values for relative water content (RWC) was high, the result that the RWC was higher in TG than in IG and TGHLS was significant for the overall average (IGHLS: 76%, IG:94% and TG: 117%). This is primarily ascribed to a higher transpiration in IGHLS through higher T. The absolute level of RWC during the 10 WAT was mainly dependent on microclimate.

Due to a high variability between individual plants there were mostly no significant differences between the greenhouses types in the concentrations of some elements calculated. However, there was a consistent trend of higher nutrient concentration in IGHLS than in IG and TG, respectively, during the period of treatment, certainly due to the enhanced mineral element uptake. The Ca concentration was significantly lower in IG and TG in both leaves and fruits with the high dependency of Ca uptake on transpiration. For the fruit, this difference between the greenhouse types disappeared and Mg and Cu concentrations leveled out. The mineral concentrations were significantly higher in leaves in comparison with the fruits. Except for Mg and Cu in the three greenhouses, the concentrations of the investigated mineral elements were moderated in leaves.

The concentrations of all detected elements were higher in IGHLS as compared to the other two greenhouses IG and TG, whereas – except for Ma and Cu – mineral element concentrations in the fruits did not differ significantly between the greenhouse types (Table 1).

Table 1

Average concentrations of mineral elements in different shoot fractions and fruits of tomato plants (Local variety) grown in greenhouses during winter in Tunisia. Greenhouses were either transparent (TG) or insulated (IG) or Insulated and equipped with a solar air heater (IGHLS). Samples were taken at 10 weeks after transplanting. Means with different letters are significantly different between greenhouse types ($p<0.05$).

Greenhouse type	Ca(mg g^{-1}Dry matter)	Mg (mg g^{-1} Dry matter)	Cu (mg g^{-1} Dry matter)	Fe^{2+}(µg Fe ml^{-1})
Leaves				
TG	43.2 b	4.5 b	4.20 a	17.4 b
IG	44.5 a	4.8 a	4.22 a	19.2 a
IGHLS	47.4 a	4.7 a	4.21 a	19.8 a
Fruit				
TG	1.6 b	1.4 a	0.20 a	1.29 c
IG	1.8 b	1.6 a	0.22 a	1.74 b
IGHLS	2.5 a	1.5 a	0.21 a	1.92 a

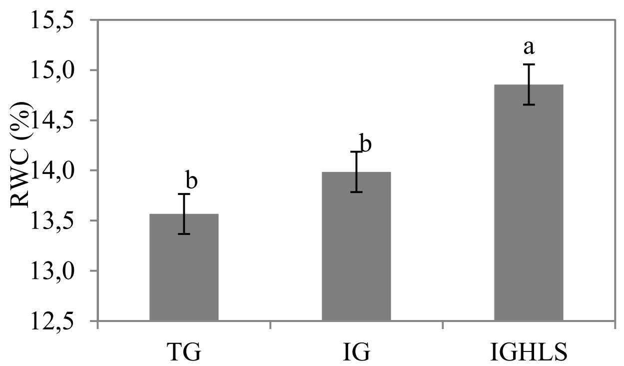

Fig. 6. Means of Relative Water Content (RWC%) of tomato plants, grown in the greenhouses: either Transparent (TG) or thermally insulated (IG) or insulated and equipped with a latent system (IGHLS). The small letters show the significance of the difference between RWC (Newman-keuls test, a<0.05, n=27).

3.4 Photochemical activities

3.4.1 Electrolyte leakage and lipid peroxidation

Electrolyte leakage, and lipid peroxidation showed completely, different patterns of response in the plants, exposed to different microclimatic conditions. Plants grown under IG and IGHLS did not show any change with electrolyte leakage (Fig. 7a) but exhibited significant improvement in the lipid peroxidation that was in IGHLS 22% lower than the control plants so-called grown under TG. The exposure of the plants to either of the climatic condition factors of TG significantly increased the values of lipid peroxidation (42%). Moreover, growing plants under IGHLS completely exhibited significant improvement in lipid peroxidation for fruits. The combined effects of these two factors (temperature and relative humidity) in IG generated values near to that of TG (0.26) (Fig.7b).

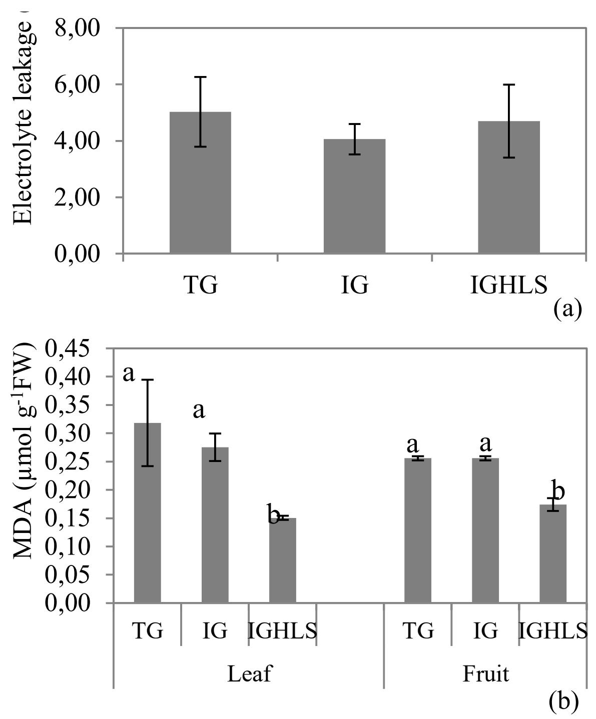

Fig. 7. Conductivity values (%) in leaf samples (a) and changes induced by microclimatic conditions in the amount of malondialdehyde (MDA) in leaves and fruits (b) of tomato grown under transparent

greenhouse (TG), insulated greenhouse (IG) and insulated and equipped with a latent system (IGHLS). Small letters mean significant differences, the Newman-keuls test was made fort separately for leaves and fruits.

3.4.2 The variations of antioxidant activities (AOA)

Fig. 8 shows that the total AOA for the leaves were lower in the TG compared to those in the IG, and reached their maximum in the IGHLS. The activities showed similar trends under IG and TG for fruits. In the control-level activity (TG) was 4.43±0.24 mg EAG, the activity levels under the other two climatic conditions were determined, respectively, as 4.70±0.28, 5.21±0.32 mg EAG g^{-1}DM.

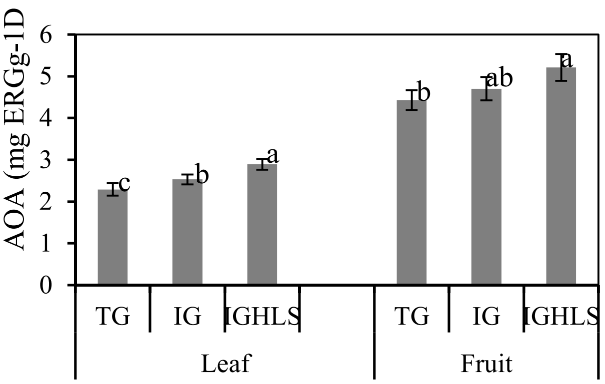

Fig.8: The total antioxidant activities (AOA) values (mg EAG g^{-1}DM) in leaf samples and in fruits of tomato grown under transparent greenhouse (TG), insulated greenhouse (IG) and insulated and equipped with a latent system (IGHLS). Small letters mean significant differences, the Newman-keuls test was made fort separately for leaves and fruits.

3.5.2 Fruit yield

Harvesting begun 22/04 where only a very few ripe fruits was picked. Under TG, there is no mature fruit yet. Towards 13/05 weekly fruit yield increased steeply and remained at a level of about 6-16kg in TG, 11-23 in IG and 19-27 kg in IGHLS until 02/06 (Fig. 9a). The marketable fruit rate was higher under the heated greenhouse specially from 13/05 until the 6/06 than IG and TG coinciding with increasing day and night temperatures during this period (WAT 6) (Fig. 3B, C and E). This high rate had practically increased the total weight of the crop (Fig. 9b). Subsequently, the fruit yields declined from week to week until the end of the trial. The percentage of undersized fruits was consistently higher in TG throughout the harvesting period. There was a sharp increase in the proportion of this yield fraction after 2/06 which was particularly pronounced in IG (Fig. 9c). In the later harvest date, undersized fruits occurred more frequently in the three greenhouses.

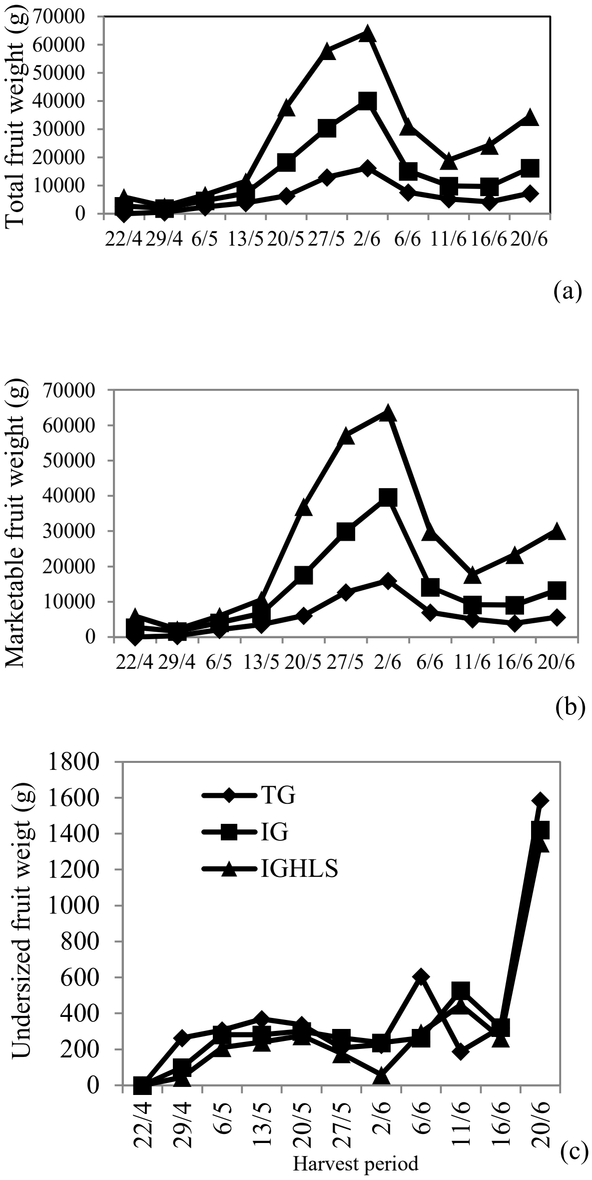

Fig. 9. Temporal development of weekly total yield (a) Marketable fruits (b), and undersized fruits (c) of tomato plants grown in greenhouses. Greenhouses were operated either transparent (TG) or thermally insulated (IG) and insulated and heated with a latent system (IGHLS).

The accumulated fruit yield differs significantly between the greenhouse types. In IGHLS, on average, 139.45kg were harvested (equivalent to 4.98kg $plant^{-1}$

or 9.42 t ha^{-1}). In IG total yield was 89.67kg (3.20kg $plant^{-1}$ or 6.05 t ha^{-1}) against 66.67kg in TG (2.38kg $plant^{-1}$ or 4.45t ha^{-1}). The marketable fruits was significantly higher in IGHLS (136.10kg or 9.2t ha^{-1}) than in IG (85.67kg or 5.79t ha^{-1}) and (62.26kg or 4.21t h^{-1}) in TG. This was due to the fact, that the amount of undersized fruits had almost 1.05kg greater in TG as compared to IGHLS (Table 2), a highly significant result. In contrast, the quantity and proportion of undersized fruits were moderately

higher in IG.

The average weight of individual fruits was greater in IGHLS than in IG and TG, respectively (not shown) in all yield fractions.

Table 2: Total weight, Marketable fruits and undersized fruits of tomato fruits in (kg $plant^{-1}$ and equivalent in t h^{-1}) grown for 20 weeks in greenhouses during the wet season:(TG, IG and IGHLS). Means with different letters are significantly different between greenhouse types (NMK-test, $p<0.05$).

	Marketable fruits		**Undersized fruits**		**Total weight**	
	Kg $plant^{-1}$	t h^{-1}	kg $plant^{-1}$	t h^{-1}	Kg $plant^{-1}$	t h^{-1}
TG	2,22 **c**	4,21 **c**	0,157 **a**	0,30 **a**	2,38**c**	4,50 **c**
IG	3,05 **b**	5,79 **b**	0,142 **a**	0,27 **a**	3,2 **b**	6,06 **b**
IGHLS	4,86 **a**	9,20 **a**	0,119 **b**	0,23 **b**	4,98**a**	9,42 **a**

3.6 Fruit color

Analysis of variance for color attributes of tomatoes showed that internal microclimate had a significant effect on hue angle and chroma, while in TG, and IG low night temperature and high relative humidity affected lightness (Table 3). Tomatoes grown in IG and TG showed a very slight decrease in lightness values than the lightness value of tomatoes cultivated in IGHLS.

The different climatic conditions had even a significant effect on tomato color intensity (Table 3). Appropriate quantification of trichromatic colorimetry data is based on trigonometric functions (Hunter, 1942). Following the hue coordinates from Table 3 identifies the fruits from IGHLS and IG are said to be significantly redder than fruits of TG. Those of TG are indeed greener and possibly less ripe than the fruit of the other two treatments, as was surmised by the phenologic measurements.

Table 3:
The changes of color attributes of tomatoes grown under three greenhouses.

Greenhouses	**Light-ness, L^***	**Hue angle, h°**	**Chroma, C^***	**Intensity, E**
IGHLS	59,55 ± 0.72a	50,00± 2.57b	17,12± 1.24a	61.97± 1.02a
IG	33,55 ± 2.16b	45,05± 1.77b	17,78± 1.38a	38,13± 2.22b
TG	35,49 ± 3.22b	62,88± 4.01a	15,17± 0.91a	38,60± 3.26b

4 Discussion

In the Mediterranean climate of Tunisia, the average daily global radiation during the entire course of the trial (severe weather at winter) was as expected so much which is needed to store and use for heating when heat is defective. The present work is based on thermal performance of greenhouse heated with a solar air collector with latent storage (SAHLSC) under Tunisia environment. Despite the fact that this kind of research is new in Tunisia. The SAHLSC maintain the air temperature inside the IGLHS constant, around 20 °C, along the night and the relative humidity to 10-7% lower than the IG relative humidity. It creates a passive dehumidification process at nighttime due to the increase of the air temperature inside the IGHLS. The amount of the nighttime recovered heat of this system attained 30% of the total heating requirements. The stored heat is equivalent to 56% of the daytime total excess heat inside the greenhouse (Bouadila et al. 2014). Potential causes of the comparatively low greenhouse night temperature were transparent walls. In fact, the design of the IG is done to maximize solar radiation input while reducing heat losses due to the insulated northern wall covered by sandwich panels. At night T in TG – where Temperature at night was very close to those outside– was lower than in IG and IGHLS (Fig. 3E). Due to the solar air heater in IGHLS, air temperature was much higher than in the IG which was covered with sandwich panels and TG which was entirely transparent. This also accounts for the higher nighttime RH in TG (Fig.3F).

The average nighttime recovered heat of this investigated system is higher than reported for many heating systems such as an eutectic mixture of sodium hydroxide (NaOH) solution and chromium nitrite in a 445 m^2 experimental glasshouse, which produced a heat storage minimum air temperature of 8°C inside the greenhouse under extreme winter conditions and saved about 5000 l of oil (Paris, 1981); a storage system using 13.5 tons of $CaCl_2$ $6H_2O$ phase change materials in a glass-covered multi-span greenhouse with 500 m^2 ground area (Jaffrin and Cadier, 1982); a storage system with two different stacking configurations and air baffling integrated with greenhouse solar system which demonstrated significantly higher compact storage capacity than the rock or water storage (Huang et al. 1986); a seasonal thermal energy storage using 6000 kg of paraffin wax as a PCM with the latent heat storage technique which attempted to heat the greenhouse of 180 m^2 floor area (Ozturk, 2005) and it was found that the average net energy and exergy efficiencies were 40.4% and 4.2%, respectively and a latent heat storage system used by Benli and Durmus (2009) to heat up a greenhouse located in Turkey which provide only 18-23% of the total daily thermal energy.

In this study, we investigated the effects of different temperature and relative humidity levels on plant growth of tomatoes under greenhouse conditions. The strongly reduced night temperature and high relative humidity in TG (Fig. 3E and F) lowered the growth rate of the plants inside the greenhouse and thus the number of leaves (Fig.4). This is in agreement with (Cha-um et al. 2010) who documented that variations in relative humidity exert influences on plant growth, leaf CO_2 assimilation rate, stomatal aperture, transpiration and nutrient uptake. However, other reports showed that humidity had no alleviation effect on the growth of plants (Torres-García et al. 2009).

Consideration of RWC (%) in the leaves is probably the most appropriate measure of plant water status for the physiological consequences of cellular water deficit. Thus, assessment of plant water status can be achieved via measuring the energy status (e.g., water potential) or by monitoring the amount of water (i.e., relative water content) (Jones, 2007). In many plant species, RWC in the leaves ranged from between 88% and 95% in fully turgid transpiring leaves and to about 30–40% in severely desiccated and dying leaves, depending on the species (Schlemmer et al. 2005). In most crop species, typical leaf RWC at around the initial wilting is at about 60–70%. In our study, tomato showed significant amounts of reduction in their RWC from IGHLS to IG and TG (Fig.6). High relative humidity strongly reduced the RWC_4 h (relative water content after 4 h of leaflet desiccation) from 54 to 8% in a sensitive genotype for stomatal responsiveness to desiccation (Carvalho et al. 2016).

In general, higher concentration of nutrient elements analyzed in the indicator sample reflected the more favorable growing conditions at the time of sampling. Hence, the Ca concentrations are significantly higher in the fruits in IGHLS than in IG and TG (Table 1), coinciding with increased fruit's fresh weights in IGHLS (Table 2), likewise proved by Leonardi et al. (2000), and thus decreased incidence of undersized fruits (Fig. 9C). Thus, it reflects that the climatic conditions under IGHLS is better than the other greenhouses and optimal for growth of tomatoes. For the reason that, the concentration of Ca in the fruit is linearly related to that of water (Adams and Ho, 1993), higher Ca concentration as well as higher fruit fresh weights in IGHLS can be ascribed to an improved water content in the fruits. In disagreement with our results, Ho (1989) found the transport of ^{45}Ca increased to the fruits of tomatoes, but decreased as to the leaves at high RH. In fact, Bradfield and Guttridge (1984) explained that nighttime rather than daytime RH is decisive for increasing the Ca translocation to the fruits. According to Bertin et al. (2000), more than 85% of water is supplied to the fruits through the phloem. This translocation is done with very low Ca concentrations (Clarkson, 1984) and only a little water with high Ca concentrations is imported into the fruits via the xylem (Johnson et al. 1992).

Temperature and relative humidity are from the most widespread environmental problems we are facing today in terms of not only food quality and crop productivity, but also in terms of its extensive effects on plants. Our results indicated that the elevated levels of the investigated AOA and the high extent of membrane lipid peroxidation were symptomatic for oxidative stress under both conventional and insulated greenhouses' conditions (Fig.7 and 8). It revealed that tomato had varying ability to deal with climatic conditions that might govern their differential sensitivity to different arrangements of temperature and relative humidity.

The accumulation of reactive oxygen species can cause peroxidation of membrane lipids, denaturation of protein and damage to nucleic acid ultimately upsetting homeostasis (Mittler, 2002).

In our study, the MDA levels in the tomato leaves increased by about a 2-fold under IG and GT during the growing period in comparison with IGHLS, suggesting that the prolonged climatic conditions (low night temperature and high relative humidity) caused membrane damage. All stress conditions induce an increase in MDA contents (Candan and Tarhan, 2012). However, it seems clear that under TG and IG, the plants suffer from a stress.

MDA is one of the products of lipid peroxidation and the result of cell membrane injury. A distinctive pattern was observed in the studies of Sánchez-Rodríguez et al. (2016) in reactive oxygen species accumulation and antioxidant responses which accumulation could be related to lower yield observed in cv Josefina engrafted and self-graft (Sánchez-Rodríguez et al. 2012).

In our experiment, the night relative humidity in TG remained at approximately 90%, but was 4.2 and 9.2% lower in IG and in IGHLS, respectively (Fig.3). So, these microclimatic conditions have been reported to increase yield (Fig.9). This tendency is in disagreement with other reports who found an increase of DW of fruits under high humidity only (Dannehl et al. 2012). Suzuki et al. (2015) demonstrated that high humidity alone in a greenhouse lie in increasing dry matter production because it seemed to be high enough to promote photosynthesis.

The yield is the most critical factor for growers in order to achieve profit. It is well-established that yield regards to fruit parameters, but is correlated with the tomato plant growth (Van Der Ploeg and Heuvelink, 2005). Besides, temperature affects fruit characteristics and nutritional components (Dorais et al. 2001). Total available heat and the extent of low and high temperature are the most important factors in determining growth rate and chemical composition of horticultural crops (Lee and Kader, 2000). We found that yield increases with the increase of night temperature and the decrease of relative humidity (Fig.9) but, according to a recent study each degree centigrade increase in average growing season temperature may reduce crop yield up to 17% (Lobell and Asnwer, 2003). Unfavorable environmental conditions during seed growth and development in the field and seed storage in storehouse can reduce germination, vigor and processing quality of seed of field crops (Gelin et al. 2006). Peet et al. (1997) proved that fruit set and seed production of tomato decreased when mean daily temperatures were as little as 2–4°C above optimal (25°C). Under unfavorable environmental conditions, parthenocarpic processing lines may be especially valuable (George et al. 1984). Eggplant (Solanum melongena) cultivars which produce parthenocarpic fruit under unfavorable environmental conditions are already available (Rotino et al. 1997). That is consistent with our results as shown in table.1, the unfavorable climatic conditions are in favor of the formation of undersized fruits.

In addition, color is a very important attribute of food, because it influences the consumer acceptability. Abnormal colors, suggesting the deterioration in the quality or character of the edible, are reasons for rejection by the consumer. Many reactions can affect the color during the heat processing of fruit and there of derivatives (Falade et al. 2007). In our study, the intensity, the result shows that when temperature increases, the color intensity increases, too (table 3).

Furthermore, color is often associated with the quality of the product and can be taken as an indicator of the level of deterioration of natural fresh foods. Other studies such as Camelo and Gomez (2004) stated that b* values changed insignificantly during ripening and the value were higher at the pink-light red stage. This may be related to the fact that 9-carotenes (pale-yellow color) reach their highest concentration before full ripening, when lycopene (red color) and β-carotene (orange color) achieve their peaks (Choi et al. (1995).

5 Conclusion

Under climatic conditions favoring optimal conditions of night temperature and relative humidity, there is an enhancement of relative growth rate. Thus, due to the growth potential, an enhanced fruit growth through water uptake, caused by the reduced electrolyte leakage and lipid peroxidation is reported. The same processes leading to decreased incidence of undersized fruits enhanced the incidence marketable ones enjoying high content of nutrient elements. Overall, it is concluded that in regions with high atmospheric relative humidity, the latent heat system allowing an increase of night temperature and a dehumidification without harming the plant will improve protected tomato production.

Furthermore, these experiments showed that the new solar air captor is able to warm up the greenhouse at night and this is beneficial for the tomato plant. In fact, the performance is best revealed in the greenhouse heated by this new system. Thus, a better production with a minor expense. Fruit production load by greenhouse heated by traditional means is greater than the use of renewable energy.

Author Contributions:

Salwa Bouadila: participated in the realization of the experimental protocol and the taking of certain measures.
Asma Ben Salem-Fnayou: Contributed to the writing and editing of the article.

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