Heating canarian greenhouse with a passive solar water–sleeve system: Effect on microclimate and tomato crop yield

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ABSTRACT

Heating greenhouses is indispensable for plant development particularly in winter when air temperature is lower. In that sense, passive solar heating is a promising alternative compared to classic methods such as fossil fuels that are cost impacted and harmful to the environment.

The current work is devoted to the study of the effect of a solar heating system using black plastic sleeves filled with water on the microclimate, tomato yield and the dynamic population of the tomato key pest, Tuta absoluta (Lepidoptera: Gelechiidae) in canarian greenhouses.

The results show that the use of this heating system, improves the nighttime temperature inside the greenhouse by 3.1 °C and reduce by 10% the relative humidity compared to the control greenhouse. This microclimate improvement has a positive impact on the tomato production. It has increased by 35% compared to the control greenhouse. It was also noted that the presence of this heating system lead to a decrease in the development the population of T. absoluta in the heated greenhouse.

Based on these results, the solar passive water–sleeve heating system can be an eco-friendly tool to prevent intensive use of fuel fossil and negative effect on the environment.

1. Introduction

The main goal of the greenhouse is to provide a suitable microclimate in order to improve off-season production and to prevent the entrance of key pests such as whiteflies, thrips, Tomato leafminer and others (Hanafi, 2003). However, in winter season, the greenhouse structure is generally not sufficient to maintain indoor air temperature at an appropriate level, so heating systems are needed (Sethi et al., 2013).

However, due to rising fossil fuel prices and restrictions on CO2 emissions, an alternative is needed instead of the conventional heating systems to ensure plant production in winter.

Solar energy is considered one of the most promising alternative to fossil fuels, the annual solar radiation in Morocco varies between 5.28 kWh/m²/day and 6.33 kWh/m²/day. The maximum is received in the south of Morocco (Vighouchi et al., 2016). It has the advantage of being endlessly renewable and non-polluting energy source (Sethi et al., 2013) and can therefore be used in agriculture to respond to the increasing social and economic demands that, for reasons of energy saving and the protection of the environment, want to limit the use of fossil energy resources.

Recently, several solar systems used to heat greenhouses have been recommended by researchers in the world such as rock-bed storage (Kurklu et al., 2003; Gourdo et al., 2018; Jain, 2005), water storage (Du et al., 2012; Bargach et al., 1999; Ntinas et al., 2014), movable insulation, ground air collector (Jain and Tiwari, 2003), phase change material storage (Berroug et al., 2011; Kern and Aldrich, 1979; Lacroix, 1993) and north wall storage (Bourdeau, 1980).

The passive water heating systems is a promising alternative compared to classical methods, given their multiple benefits i.e. easy to install and low investment cost. Different systems have been reported under various cover materials e.g. PE, glass, filon and polycarbonate, and under various greenhouses types around the world (Sethi and Sharma, 2008; Santamouris et al., 1994). Nash and Williamson (1978) suggested a 1 m³ water tanks blacked out to heat a 30 m² greenhouse located in Nashville in USA. This system was able to maintain the inside
air temperature 2–3 °C higher than the outside air temperature. Kozai et al. (1986) tested a water tank heating system filled with 36 m³ of water, installed in a 856 m² floor area greenhouse located in Tokyo, Japan. It was able to maintain inside air temperature of the greenhouse 8–10 °C higher than outside air temperature. As for Govind et al. (1987), they used four 0.8 m³ blacked out water drums placed on the north side of a 15.4 m² greenhouse located in Delhi in India. The system was able to maintain the inside air temperature 5–6 °C higher than the outside air, during extreme winter nights in December and January. Dutt et al. (1987) studied water tanks, filled with 1 m³ of water, placed on the north side in a 20 m² PE covered greenhouse situated in Delhi (India). Inside air temperature was maintained 3–4 °C higher compared to outside air conditions on winter nights. Mavrogianopoulos and Kyritsis (1993), investigated a transparent polyethylene tubes placed on the soil in a 200 m² PE covered greenhouse in Athens (Greece). The average minimum temperature was 3–4 °C higher than the outside air and about 1 °C higher than the control greenhouse. Water inside the tubes was circulated at a very low pressure to improve the thermal storage capacity in the greenhouse (Santamouris et al., 1994). Interior air temperatures of 3–4 °C higher than the minimum outside air were observed. Black steel tanks were also used on the north side of a greenhouse for thermal energy storage (Santamouris et al., 1994). This system was able to maintain the inside air 2–10 °C higher than the minimum outside air temperature. 22 m³ of water was stored in black steel barrels placed in the north side of 167 m² filament covered greenhouse located in Flagstaff (USA) where vegetables were grown. The inside air temperature observed was 13–22 °C higher than the minimum outside air temperature (Santamouris et al., 1994). Another study carried out by Sethi et al. (2003) have tested a galvanized tank placed on the north side of 21 m² glasshouse located in Ludhuana (India). Nighttime greenhouse temperature increased by 4–5 °C compared to outside air temperature in December-January 2001. In Table 1, we regroup a summary of the performance of various passive solar greenhouses using water storage. Ntinas et al. (2014) studied a hybrid solar energy system; it consisted of a transparent water-filled polyethylene sleeves and two perforated air-filled polyethylene tubes on the top peripheral sides of it. Above the sleeves and between the two tubes, rockwool substrates were placed for hydroponic cultivation of tomato crop; the results of these system sowed that the additional energy provided by the hybrid solar system reached approximately 23% during the examined period.

The study presented in this paper falls in this sphere since it focuses the use of passive heating system based on the principle of storing solar energy in the water contained in a black plastic sleeves to heat a tomato canary greenhouse under Moroccan climate. The stored energy comes mainly from solar radiation during the day and used to heat the greenhouse at night.

Unfortunately, the studies on this matter are scare and concern more particularly the effect of these passive heating systems on the microclimate under the greenhouse without being interested in their effects on the crop yield and the pest dynamics.

Table 1
Summary of the performance of various Passive solar greenhouses using water storage.

<table>
<thead>
<tr>
<th>Passive system type</th>
<th>Performance</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ground tubes</td>
<td>2–4 °C higher</td>
<td>Kyritsis and Mavrogianopoulos (1987)</td>
</tr>
<tr>
<td>Water tanks</td>
<td>2–3 °C higher</td>
<td>Nash and Williamson (1978)</td>
</tr>
<tr>
<td>Water tanks</td>
<td>13–22 °C &gt; Tair</td>
<td>Santamouris et al. (1994)</td>
</tr>
<tr>
<td>Water barrels</td>
<td>5–6 °C higher</td>
<td>Govind et al. (1987)</td>
</tr>
<tr>
<td>Water tanks</td>
<td>3–4 °C higher</td>
<td>Dutt et al. (1987)</td>
</tr>
<tr>
<td>Water tanks</td>
<td>8–10 °C higher</td>
<td>Kozai et al. (1986)</td>
</tr>
<tr>
<td>Black steel tank</td>
<td>2–10 °C &gt; Tair</td>
<td>Santamouris et al. (1994)</td>
</tr>
<tr>
<td>Water tanks</td>
<td>4–5 °C higher</td>
<td>Sethi et al. (2003)</td>
</tr>
<tr>
<td>Water tubes</td>
<td>3–4 °C &gt; Tair</td>
<td>Santamouris et al. (1994)</td>
</tr>
</tbody>
</table>

To fill in this information gap, this paper discusses the effects of the microclimate induced by black plastic sleeves on the yield of tomato and the population of the tomato leafminer T. absoluta (Lepidoptera: Gelechiidae) population, considered as a key pest of the tomato crop in the Mediterranean basin.

This work cumulates several originalities: (i) The use of black sleeves that absorb solar radiation unlike other studies that have used transparent sleeves. (ii) Study of the effect of this heating system on the tomato yield, plant height and the population of T. absoluta, parameters that have not been studied in previous studies. This system developed in this paper can be generalized to the all types of greenhouses and in all climatic conditions.

2. Materials and methods

2.1. Site and greenhouse description

The experiments were carried out in two similar and independent canarian greenhouses with metal structures, located in the experimental station of the Regional Center for Agricultural Research, the local office of the National Institute for Agricultural Research (INRA) in south of Agadir (30°13 Latitude, 9°23 Longitude, 80 m Altitude), on the Atlantic coast of Morocco. The surface of each greenhouse was 172 m² i.e. 15.6 m width by 11 m length and a height of 4 m at gutter level and 5 m at span level (Fig. 1). These greenhouses are covered by a 200 µm polyethylene plastic thermal film (Table 2) and the orientation of its spans was North-South i.e. perpendicular to the prevailing wind direction.

The lateral side openings (two 11 m sides and two 15.6 m sides) were 4 m – high and were covered with an insect-proof net, used to prevent the intrusion of insects.

The plastic covers were superposed over the insect-proof net on all lateral sides. These lateral plastic covers could be rolled up or down to ventilate the greenhouse. The opening side open at 6 am, to evacuate excess humidity accumulated during the night, and close at 3 pm to limit exchanges between the air of the greenhouse and the outside during the night.

The experimental greenhouse was equipped with a solar water-sleeve heating system, while the control greenhouse was not heated.

2.2. Crop

The crop planted in the experimental and the control greenhouses was tomato (cv. Solanum lycopersicum L.), planted on January 9, 2017 in soil-less container on a carbonaceous substrate. The planting rows were oriented north-south, perpendicular to the direction of the prevailing wind. The experimental greenhouse and the control greenhouse were fertigated using the same system; and received the same amount of water and fertilizers.

The two greenhouses experimental greenhouse and the control greenhouse were fertigated using the same system and received the same amount of water and fertilizers which is 1.5 L/Plant/Day.

Table 3 summarizes all planting characteristics in the two greenhouses concerned.

2.3. Monitoring of the agronomic parameters

In order to estimate the effect of the heating system on the agronomic performance, the plant height and number of fruits harvested were monitored during the crop cycle. Seven replicates (plants) were selected randomly in each greenhouse to measure the crop evolution at 16, 18, 20, 22, 24, 26, 31, 34, 38, 46, 50, 58, 81, 92, 100, 107, 113, 129 days after plantation for plant height and during 5 harvests for the number of fruits. The quality of fruits at each harvest and the total yield at the end of the crop cycle in both greenhouses was compared. Data analyses were performed using the SPSS general linear model (GLM) by
SPSS software (IBM SPSS statistics 23) procedure for ANOVA at a level of P < 0.05). Then, when significance was confirmed, resulting means were compared using Newman-Keuls test.

2.4. Monitoring of the population of tomato leaf miner (Tuta absoluta)

The tomato leafminer *T. absoluta* (*Lepidoptera: Gelechiidae*) is a highly destructive pest of tomato crops. The damage caused by this pest on tomato can lead 100% crop loss (França, 1993) under weak control. There are several methods to control this pest. The common control method is spraying chemicals products which are very harmful to humans and environment. The farmers use also the insect-proof nets to keep out this pest from the greenhouse. The biological control methods using natural enemies and biopesticides remain the safest approaches despite their fairly high cost (Nilahyane et al., 2012). The most effective approach is to combine all the previous methods together with others like mass-trapping, cultivar resistant, mulching and management of climate inside greenhouse. This strategy is defined as integrated pest management IPM.

The pesticides were sprayed at recommended dosage using sprayer lance. The same equipment was used in both greenhouses (experimental and control).

To monitor *T. absoluta* adults, traps type Delta (containing sticky white card and *T. absoluta* pheromone lure trap, Russell IPM, PH-937-1RR, UK) were used. One trap was hanged in the middle of each greenhouse (experimental and control) at 1.5 m height. The lures have been replaced every 4 weeks in both greenhouses. The traps were checked weekly and the number of *T. absoluta* captured was recorded and the results were presented in Fig. 11.

2.5. Description of the passive heating system

The passive heating system is composed of 8 black plastic sleeves, each 32 cm in diameter by 10 m in length and 220 µm in thickness (Table 4). Each sleeve is filled with 0.71 m³ of water (Table 5). These sleeves were placed on the ground and extended on both sides of the 4 rows of crops close to their roots (Fig. 2).

The mass of water inside the ducts is heated by infrared radiation absorbed in the greenhouse during the day. The stored heat is recovered inside the greenhouse by natural convection and radiation during the night and used to heat the air inside the greenhouse.
The characteristics of this water sleeves heating system are summarized in Table 5.

### Table 5
Characteristics of the water sleeves heating system.

<table>
<thead>
<tr>
<th>Description</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Volume of water in a row of sleeve</td>
<td>0.71 m³</td>
</tr>
<tr>
<td>Total volume of water in the sleeves</td>
<td>5.6 m³</td>
</tr>
<tr>
<td>Sleeve diameter</td>
<td>32 cm</td>
</tr>
<tr>
<td>Thickness</td>
<td>0.25 mm</td>
</tr>
</tbody>
</table>

The characteristics of this water sleeves heating system are summarized in Table 5.

#### 2.6. Measurements of different climate parameters

In order to study the influence of the heating system by black water filled plastic sleeves, we conducted simultaneous measurements in the experimental and control greenhouses.

In the experimental greenhouse we measured: the temperature and the relative humidity of air inside the greenhouse in its center, checking two heights with an HMP50 sensor (HMP50, Campbell Scientific Ltd., UK). We observed the average soil temperature using a Type E thermocouple wire (TCAV-L, Campbell Scientific Ltd., UK) which provides the soil temperature at 6–8 cm deep and the temperature of the water contained in the sleeves using a Thermistor (108, Campbell Scientific Ltd., UK).

At the same time, in the control greenhouse we measured the inside air temperature and relative air humidity in its center checking two heights. The soil temperature was recorded using a Type E thermocouple wire.

In addition to the climatic condition measurements inside the greenhouses, a weather station was installed outside the greenhouse to measure wind speed and direction by an ultrasonic anemometer (WINDSONIC1-L, Campbell Scientific Ltd., UK), the temperature and relative humidity by an HMP50 probe, the global solar radiation by a pyranometer (CMP11, Kipp & Zonen, USA), as well as the average temperature of the soil using a TCAV-L sensor.

All these sensors were connected to two data-loggers (Campbell CR3000, Campbell Scientific Ltd., UK) which instantly recorded data every 5 s and stored the average values in 10-min time steps on the computer and thereafter analyzed.

### Table 6
Characteristics of the sensors used in this experiment.

<table>
<thead>
<tr>
<th>Description</th>
<th>Sensors</th>
<th>Unit</th>
<th>Accuracy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air temperature</td>
<td>Vaisala HMP50</td>
<td>°C</td>
<td>± 0.6 °C</td>
</tr>
<tr>
<td>Relative humidity</td>
<td>Vaisala HMP50</td>
<td>%</td>
<td>± 3%</td>
</tr>
<tr>
<td>Water temperature</td>
<td>108</td>
<td>°C</td>
<td>± 0.2 °C</td>
</tr>
<tr>
<td>Soil temperature</td>
<td>108</td>
<td>°C</td>
<td>± 0.2 °C</td>
</tr>
<tr>
<td>Wind speed</td>
<td>WINDSONIC1-L</td>
<td>m/s</td>
<td>± 0.001 m/s</td>
</tr>
<tr>
<td>Wind direction</td>
<td>WINDSONIC1-L</td>
<td>Degree</td>
<td>± 1°</td>
</tr>
<tr>
<td>Net radiation</td>
<td>CNR4</td>
<td>W/m²</td>
<td>&lt; 1%</td>
</tr>
<tr>
<td>Global solar radiation</td>
<td>Pyranometer Kipp&amp;zonen</td>
<td>W/m²</td>
<td>± 0.2%</td>
</tr>
<tr>
<td></td>
<td>CMP11</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

In Table 6, the characteristics of sensors used in this measurement period are shown.

### 3. Results

#### 3.1. Climatic parameters

Solar radiation, temperature and relative humidity are the main climatic parameters that influence plantation development, during the measurement period; external solar radiation reaches 830 W/m² at 12.30 am. Both greenhouses, experimental and control are subjected to the same external climatic conditions. The solar radiation entering the greenhouse will increase the air temperature of the greenhouse and heat the water inside sleeves in the experimental greenhouse.

#### 3.1.1. The effect of the heating system on the air temperature and humidity

Fig. 3 shows the variation of air temperature in both greenhouses i.e. control and experimental and outside. These data show that the temperatures inside the greenhouses are always higher than that on the outside; the temperature difference between the inside of the experimental greenhouse and the outside can reach 4.2 °C during the night. During the day, the temperature of the control greenhouse is higher than that of the experimental greenhouse and the difference can be more than 1 °C. Conversely, during the night, the air temperature of the experimental greenhouse is higher than that of the control greenhouse. The temperature difference between both greenhouses is 2.2 °C as an average and the maximum is 3.1 °C (Fig. 4).

The heating system with water-filled plastic sleeves operates by absorbing the incident solar radiation incoming inside the greenhouse, which results in an increase of the water temperature contained in the black plastic sleeves. At night, or when the greenhouse air temperature is lower than that of the water in the sleeves, the stored heat is released in the internal environment of the greenhouse by natural convection and radiation, so at night the water can increase the air temperature of
the greenhouse and in the same time the water will be cool. This cold water will refresh the greenhouse air during day time.

Fig. 5 shows the variation of the air relative humidity inside the experimental greenhouse, the control greenhouse and on the outside. It was found that during the night the air relative humidity of the outside is always higher than the relative humidity in the experimental and the control greenhouses.

During the night, the relative air humidity is higher in the control greenhouse compared to the experimental one. The difference in humidity between the two greenhouses exceeds 10%. This difference in humidity between the experimental greenhouse and the control greenhouse is due to the presence of the heating system. Relative Humidity varies according to temperature changes: it increases if the temperature drops and decreases if it rises. As the heating system has
increased, the air temperature of the experimental greenhouse by 3.1 °C compared to the control greenhouse, its relative humidity will decrease and it will be lower than that of the control greenhouse.

During the day, the relative humidity of the two greenhouses was similar, and reach minimums of 20% at 2 pm. This is due to the fact that the side openings were rolled up during the day to evacuate the excess humidity in the greenhouses, and avoid condensation.

3.1.2. Water temperature inside the plastic sleeves

Fig. 6 shows the evolution of the water temperature inside the sleeves over time. It is observed that the temperature of the water inside these sleeves reaches its maximum of 34.7 °C at 4.10 pm, while the peak of air temperature inside the greenhouse reaches a maximum of 38.4 °C at 2.30 pm (Fig. 4).

During the day, the water stored a quantity of energy equal to:

\[ Q = mc_p \Delta T \]  

where \( m \) is the water mass in the sleeves; equal to 5600 kg; \( c_p \) is the specific heat of water 4180 J/kg K and \( \Delta T \) is the water temperature difference between day and night.

This energy will be restored to heat the air in the greenhouse overnight.

The water temperature reaches a minimum value of 16.5 °C at 8.10 am, while the inside air temperature of the greenhouse reaches its minimum value of 9.5 °C at 6.30 am.

During the experiment period, from January 9 to May 2, 4914 kWh of energy was released by the solar water–sleeve system. This energy was used to heat the greenhouse in order to provide optimal temperature for crop growth. To produce this energy by conventional heating systems based on fossil energies, 386.9 kg of butane would be required. As 1 kg of butane releases 3.02 kg of CO2, this ecofriendly heating system was able to reduce 1168.5 kg of CO2 during the test period.

3.1.3. Effects of the heating system on the soil temperature

Fig. 7 shows the variation of the soil temperature of both greenhouses (experimental and control). By analyzing this graph, we observe that during the day the soil temperature in the control greenhouse is slightly higher than the soil temperature in the experimental greenhouse. This is due to the solar radiation absorption in the water-filled sleeves. At night, the soil temperature of the experimental greenhouse is higher than that of the control greenhouse, this is caused by the heat that was stored in the water during the day and released at night in the greenhouse. This freed heat in the greenhouse contributes to warm up the soil.

3.2. Effects of the heating system on the agronomic parameters

We have selected 24 plants in each greenhouse. These plants are spread over 4 rows (6 plants per row). We measured the height, the fruit quality and the yield of each of the 24 plants selected.

3.2.1. Plant height

Fig. 8 shows the evolution of the average height of the plants in both experimental and control greenhouses. While comparing the two curves, we noted that the mean crop height in the experimental greenhouse is higher than in the control greenhouse varied 50 cm at the fifth harvest. The increase of air temperature in the experimental greenhouse compared to the control greenhouse influenced the plant height, as well as the number of bouquets (two more bouquets in the experimental greenhouse).

3.2.2. Total yield

By comparing the tomato production in the two greenhouses, we observed that the yield from the greenhouse equipped with the passive heating system is 35% higher than in the control greenhouse. This performance in yield was due to the improvement of the microclimate under the greenhouse given the better conditions for the development of tomato crop. We have selected 24 plants in each greenhouse, we measure the yield of each one, and then we calculate the average. This average is multiplied by the total number of plants in the greenhouse;
the total weight harvested in the two greenhouses during the experimentation period is represented in Fig. 9.

The researches related to the heating effect on tomato production are scarce in the literature. Among these research studies, we can found those of Canakci and Akinci (2006) who reported the beneficial effect of heating on tomato.

This positive effect of the solar heating system on production yield was also reported by Bargach et al. (2004), who found an improvement of 20 g/plant on the melon yield using a heating system with the same thermal energy storage mode. In a separate study in Agadir region, Bazgaou et al. (2018) show that the rock-bed heating system is able to improve the tomato yield by 29%. Gourdo et al. (2019) for their part

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**Fig. 6.** Variation of the water temperature inside the sleeves.

**Fig. 7.** Measured soil temperature in the experimental and control greenhouse.
find that the rock-bed heating system installed under the ground of the greenhouse improve the tomato yield by 22%.

### 3.2.3. Fruit quality

The harvested fruits were grouped into seven sizes according to agronomist standards from the largest to the smallest size: out of size (> 84.78 mm), size 1 (76.1 mm < diameter < 84.78 mm), size 2 (66.8 mm < diameter < 76.1 mm), size 3 (55.7 mm < diameter < 66.8 mm), size 4 (45 mm < diameter < 55.71 mm), size 5 (< 45 mm) and wasted fruits.

Fig. 10 shows the percentages of tomato fruit sizes, which were harvested in both experimental and control greenhouses. We observed that for the experimental greenhouse size 1 is the most dominant, whereas in the control greenhouse size 2 is the most dominant. So clearly the heating system with water-filled plastic sleeves has a very positive effect on the quality of tomato production.

### 3.3. Dynamics of T. Absoluta population

*T. absoluta* is considered as a key pest of tomato. It can cause losses of up to 80–100% on tomatoes. The larvae are the harmful stage of the tomato leaf miner life cycle.

Fig. 11 shows the dynamics of *T. absoluta* population in both the experimental and control greenhouses. Analyses of the data of the pheromone traps installed in the greenhouses revealed that the number of *T. absoluta* was relatively low in the greenhouse equipped with passive heating system compared to the control greenhouse.

It should be noted that the number of trapped *T. absoluta* individuals varied from 01 to 80 in the control greenhouse and between 0 and 25 in the experimental greenhouse. From March 27, 2017, the number of *T.
absoluta increased rapidly in both greenhouses due to the massive population of this pest outside of the greenhouses. The climate in the control greenhouse is more favorable to the development of this pest. In general, it appears that the presence of water sleeves has a negative effect on the development of T. absoluta. This reduction was very significant and a total of 100% reduction was recorded, especially at the beginning of the cycle until March 06, 2017. This reduction rate decreased after March 20, 2017 and did not exceed 69%. The population dynamics is described as the aspect of population ecology dealing with forces affecting changes in population densities of affecting the form of population growth. In fact Larsson (1989) and Wallner (1987) have described all factors affecting insect population dynamics which including among others the climatic parameters. Since this solar passive system (water sleeves) increase the temperature and decrease the relative humidity our study was also focused on the impact on the dynamic of T. absoluta population as a key pest of tomato crops under greenhouse. Krechemer and Foerster (2015) have reported that temperature affect inversely the longevity of both males and females of T. absoluta which means the shortness life of adults. Consequently, the lower population of T. absoluta adults and damage observed on tomato crop and fruits could be explained by the impact of temperature increase in the experimental greenhouse.

4. Discussion

This system of heating by black plastic sleeves filled with water installed in the greenhouse allows increasing the air temperature during the night; this is due to the heat stored in the water sleeves during the day and released into the greenhouse by radiation and convection.

At night the water transfers heat by convection to the greenhouse air which will reduce the water temperature inside the sleeves. This cold water will refresh the greenhouse air during day time.

This passive heating system allows also increasing the air relative humidity of the greenhouse during the day and lowering it at night.

Water-sleeve system creates favorable conditions for the good plant development (top temperature and humidity range) which positively influence the yield, plant growth and the size of the fruits. On the contrary, very low temperatures slow down plant development and reduce the absorption of water and mineral salts by the roots (Calvert, 1957; Hussey, 1965; Heuvelink, 1989). This is in agreement with the results found by Gourdo et al. (2019), Bazgaou et al. (2018), Verkerk (1955), Hurd and Graves (1985) and Adams et al. (2001) who found that the improvement of night temperature has a very positive effect on the growth, fruit size and development of tomato fruits.

The effect of heating system used in the current work on the development of T. absoluta can be explained by the low relative air humidity generated by such system inside the greenhouse. This finding has also been reported in some previous studies and confirms that lower relative air humidity reduces the number of eggs produced by females, shortens the life span and reduces the number of T. absoluta adults (Uchoa-Fernandes et al., 1995; Miranda et al., 1998; Guimapi et al., 2016; Cuthbertson et al., 2013).

The negative effect of the heating system on T. absoluta could also be explained firstly by the compensation of plant growth speed (higher in the experimental greenhouse) compared with the damage caused by this pest i.e. more the plant growth is higher more the injury is invisible. In the other hand, the tomato leaf volatiles have an effect on the flight behaviour, attraction and oviposition of T. absoluta (Proffitt et al., 2011). These volatiles are classified as secondary metabolites which depend especially on the climatic parameters and environment (Karppinen et al., 2016; Sampaio et al., 2016). More studies should be planned to investigate the chemical components involved in this phenomenon under passive heated greenhouses.

Emphasis has been placed on the climatic and agronomic performances to evaluate our heating system. By comparing the climatic and agronomic results of our passive heating system to those studied by other researchers, this system was observed to be more efficient compared to those using transparent tubes placed between the crop rows (Mavrogianopoulos and Kyritsis, 1993; Sethi and Sharma, 2008). Conversely, our system is less efficient than that using barrels filled with water set up in the north side of the greenhouse (Sethi and Sharma, 2008). However, the disadvantages of the latter system are that it can be set up in small greenhouses and the heat released by this system is not distributed evenly in the greenhouse.

The passive heating system developed in our study did not achieve the performance of the conventional boiler heating systems (Bargach
et al., 1999; Bouzidila et al., 2014) that can cover 100% of the heating needs of the greenhouse. Despite this lack of performance, the passive system has the advantage of being environmentally friendly and cheaper compared to the conventional systems operating with fossil fuels. In fact, the conventional boilers, are expensive and their consumption of energy can reach up to 1 L of fuel/m²/year (Attar et al., 2013).

To improve the efficiency of the passive solar heating system it is necessary to increase the volume of water used to store energy inside the greenhouse during the day. However, the diameter of the sleeves used must not exceed 32 cm, in order to not hinder the circulation of machines and workers between crop rows. To overcome this dilemma, more research must be carried out on other heat exchange fluids in order to increase the energy released in the greenhouse during the night.

5. Conclusion

The heating system studied in this paper has improved the inside microclimate of a canarian greenhouse. It allowed an increase in air temperature by 3.1 °C, and a reduction of air relative humidity by 10%. This improvement of the greenhouse microclimate favored the plant growth and improved the quality of tomato production as well as its yield.

This passive heating system will probably have a positive effect in terms of reducing the risk of the disease development on plants, due to the lowering of air relative humidity inside the greenhouse.

This heating system, using black plastic water-sleeve, is a eco-friendly system based on renewable resources and has the advantage to distribute the heat evenly to the plants. This system is more efficient compared to the heating systems using transparent ducts studied by other researchers. However, despite these advantages, their power is not as efficient as the conventional heating systems using fossil fuels. In fact, sometimes, the stored solar energy alone cannot meet the total heating requirements in the greenhouse. For this reason, other heat exchange fluids, that are capable of meeting these needs, must be investigated.

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