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Performance assessment of combining rock-bed thermal energy storage and water filled passive solar sleeves for heating Canarian greenhouse

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ABSTRACT

During the winter period, in Mediterranean region, the storage and reuse of solar energy in thermal form is an important issue for heating greenhouses. In the present work, the performance of a combination of two systems i.e. rock-bed thermal energy storage and water filled passive solar, for heating canarian greenhouse was analyzed and discussed. The surplus thermal energy available inside the greenhouse was stored in the rock-bed and in the water during daytime for use during cold periods. An experimental study was carried out in two Canarian-type greenhouses, the first is equipped with the combined heating system and the second without. Results show that the combined heating system can improve the nocturnal inside air temperature, during the winter period, by 3–5 °C during clear days and by 2–3 °C in cloudy/rainy days with less fluctuations. A reduction of 10–15% in the air relative humidity was observed in the heated greenhouse during the night. This heating system also improves the substrate temperature during the night by 4 °C on cloudless days and 3 °C on cloudy/rainy days. A very good growth of plants and an increase of 49% of tomato yield has been noted in the heated greenhouse. The thermal energy restored by this system covers a large part of the greenhouse heating requirements. It was also noted that the presence of this heating system lead to a decrease in the development the population of *Tuta absoluta* in the heated greenhouse. An economic analysis revealed that this system is very profitable and could generate profits for farmers.

1. Introduction

The Mediterranean region experienced an important evolution in the agricultural field, especially in Morocco. Different types of greenhouses are installed (Canarian, multispans, tunnels, etc.) to create a favorable microclimate for crops and to make possible producing during the off-season, which cannot be available in open fields. These greenhouse systems are aspects of the integration of new technologies in agricultural production (Emekli et al., 2010). In the greenhouse, the environment control parameters i.e. light, carbon dioxide, nutrients, relative humidity and temperature, should be delivered at optimal levels (Sethi and Sharma, 2008; Bennis et al., 2008; von Elsner et al., 2000; Max et al., 2009) for good plant growth.

Even this evolution and increasing of the protected crops area in the Mediterranean region, the producers have recently seen an important decrease in the quantity and quality of production during the cold period. The climatic conditions are unfavorable due to the low temperatures recorded during this period. Therefore, the improvement of the greenhouse climate by heating systems is crucial to extend the crop production season.

The Mediterranean region is characterized by a moderate climate and a great availability of solar radiation even in winter. Thus, inside the greenhouse, a large quantity of thermal heat is available. The storage of this energy can have a cooling effect and its recovering can be used for heating operation. To control the greenhouse microclimate, systems of heating and cooling are used within the greenhouse. Consequently, these will have a positive impacts on the agricultural yield, cultivation time, and quality of production (Sethi and Sharma, 2008; Tiwari, 2003). We distinguish the conventional systems such as boilers and heaters that use fossil fuels (Nelson, 2003), and the solar systems using renewable energies in greenhouse applications (Nayak and Tiwari, 2009; Kolokotsa et al., 2010; Chua et al., 2010; Kim et al.,

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2000; Rousse et al., 2000; Chou et al., 2004). The first systems have a negative impact on the environment, such as greenhouse gas emissions, and the second ones are proposed to minimize this impact.

Particularly, the solar systems based on the thermal energy storage have been successfully applied in the greenhouse sector. For this purpose, several studies are available in the literature, using water storage (Grafiadellis, 1987; Lazaar et al., 2004), ground air collector (Bartok and Aldrich, 1983; Kurata and Takakura, 1991; Bargach et al., 2000; Bakos et al., 1999; Adaro et al., 1999), rock-bed storage (Fotiades, 1987; Bouhdjar et al., 1996; Willits et al., 1985; Bazgaou, 2018; Bouhdgar and Boulbing, 1990), north wall storage (Berroug et al., 2011), and phase change materials storage (Abhat, 1983; Boulard et al., 1990; Öztürk, 2005; Kern and Aldrich, 1979). All of these studies were given in depth by many authors in order to improve the greenhouse climate.

Two types of solar heating systems are proposed, passive and active. The passive systems operate without any energy supply while the active system rely on an external device to enhance heat transfer. The literature on these heating systems is abundant. Sethi and Sharma (2008) have analyzed and discussed several studies of passive systems based on sensible and latent solar thermal storage to increase the temperature inside the greenhouse. Also, Bargach et al. (2000) used a solar flat-plate collector to improve the internal greenhouse microclimate. For their part, Barral et al. (1999) showed that the passive system constituted of transparent and light synthetic thermal blanket improves the winter horticultural production inside greenhouses. Santamouris et al. (1996) showed that the buried pipes reduce the energy consumption for heating greenhouses and increases the inside air temperature. Gourdo (2019) studied the capacity of a passive solar water–sleeve system to improve the canarian greenhouse microclimate and tomato production.

In contrast, the active systems need energy for its operation. Several studies have been conducted to examine the performance of these systems in terms of greenhouse heating. Yang and Rhee (2013) used an active system (heat pump system) to store the surplus air thermal energy during day and provide it at night for heating operation. Bargach et al. (1999) studied a solar collector system to improve climatic conditions inside greenhouse. Bouadila et al. (2014a) studied a new solar heating system to investigate its impact on relative humidity and inside air temperature of the greenhouse. Concerning the heating effect of passive and active systems on plant growth and agricultural production, the studies are scarce in literature.

In order to better take advantage of the two systems, our study will be devoted to the assessment of combining the two approaches, active and passive, with water and rocks as heat storage materials, respectively. The new heating system will combine a rock-bed active thermal energy storage and water filled passive solar sleeves systems.

The emphasis will be placed on the impact that will have the resulting heating system on the microclimate, plant growth, plant development and yield of tomato crop under canarian greenhouse.

2. Materials and methods

2.1. The greenhouses description

The experiments were carried out in two similarly canary greenhouses with North-South orientation. One of the two greenhouses was equipped with the combined solar heating system, and the second one without and considered as control for comparatives studies. The both greenhouses occupy an area of 165 m^2, 15 m long, 11 m wide and 5 m high at the center. They are located in Souss-Massa region (Altitude: 80 m, Longitude: 9°23, Latitude: 30°13), southern Morocco. The structure of the two greenhouses is entirely made of galvanized steel fixed to the ground with concrete and stones. The description of the two greenhouses and the combined heating system are displayed in Fig. 1.

The combined heating system is composed of an active rock-bed heating system and a water filled passive heating system as shown in Fig. 2. Rock-bed heating system consists of three rows of rock-bed and each row contains two inlets and two outlets. The inlet and outlet PVC tubes are installed at 2.5 m and 0.5 m, respectively, from the ground. All inlets and outlets are equipped with fans, its volume flow rate is 2.15 m^3/min with a consumption of 18 Watt. During day, all fans are operating continuously to store the thermal energy available inside the greenhouse and recovered it at night for heat the inside air. These fans allow to circulate air from the greenhouse to the rock-bed with less energy. The choice of low power fans (18 W) is to minimize the power consumption cost of the greenhouse.

The passive heating system consists of 8 plastic black sleeves filled with 0.769 m^3 of water volume, with 30 cm diameter and 10 m length for each sleeve. These sleeves are placed on the soil on both sides of all 4 rows of tomato plants in direct contact with the substrates. During the day, the mass of water inside the sleeves is heated by infrared radiation transmitted inside the greenhouse. At night, when the temperature of inside air drops below the optimum temperature of plants, the thermal energy stored will be released for heating the inside air and the substrate.

The storage mode for the combined heating system is sensible heat with the water and the rocks as thermal storage materials. In addition to presenting a low investment cost compared to conventional boilers, this system ensures a low environmental impact related to the use of fossil fuels.

2.2. Crop

The crop planted in the two greenhouses was tomato (Solanum lycopersicon cultivar: Zayda), planted on october 11, 2017 in soil-less container on a carbonaceous substrate. The properties of the used substrate are shown in Table 1.

The crop rows were oriented north-south, perpendicular to the direction of the prevailing wind, with a density of 2 plants/m^2 i.e. 30 plants per row, with 30 cm apart, arranged in 4 rows with 1.20 m apart. The heated greenhouse and the control greenhouse were fertigated using the same irrigation system with the same amount of water and fertilizers.

2.3. Functioning principle of the combined solar heating system

Fig. 3 illustrates the operating principle of the combined heating system. During daytime, the inlet fans draw warm air from the upper part of the greenhouse to circulate it through the rock bed, i.e. storage media. The solar thermal energy stored in the rocks during the day will be released by the outlet fans at the level of the plants during night. At the same time, the solar thermal energy, stored during the day in water contained in the black sleeves, will be released passively during the night at the substrate level.

2.4. Measurement of climatic parameters in greenhouse

Different climatic parameters are measured inside and outside of the greenhouse. A Kipp and Zonen CMP11 pyranometer was used to measure global solar radiation inside and outside the greenhouse. The relative humidity and the temperature for inside air were measured, in the center of the greenhouse at 1.5 m above the ground using HMP60 sensors. The substrate and water temperatures were measured PT107 temperature Probe. All these sensors were connected to data logger, model Campbell CR3000 (Shepshed, UK) where data were recorded every 5 s and averaged on a 10 min time scale before being processed.

Details on the accuracy and the range of the using sensors are presented in the Table 2 below.

2.5. Monitoring of the agronomic parameters

In order to estimate the effect of the combined heating system on

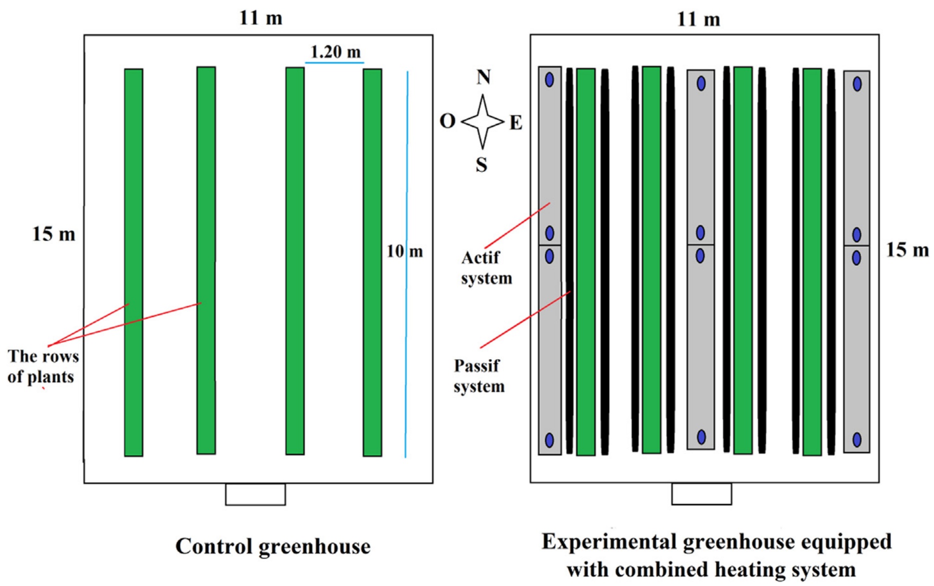

Fig. 1. Description of the two greenhouses and the combined solar heating system.

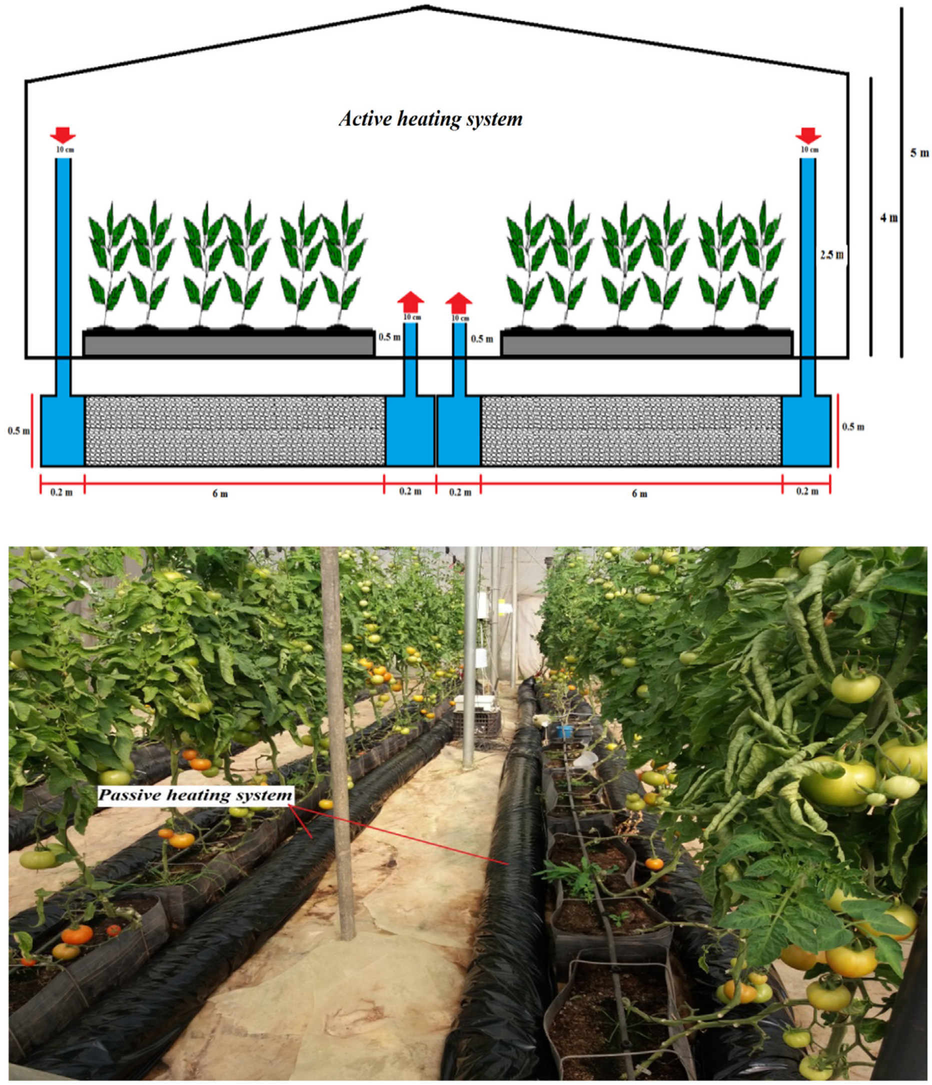

Fig. 2. Description of active heating system and passive heating system.

Table 1
The characteristics of the carbonaceous substrate.

Density	650–700 kg/m^3
Dry matter content	45–55%
Organic matter content	75–90%
Ash content	10–25%
Carbon content (dry mass)	40–50%
pH (H2O)	5.0–6.0
Macro-elements	N, P, K, Ca, Mg
Micro-elements	Fe, Mn, Cu, Zn, B, Mo

the agronomic performance, the plant height and number of fruits harvested were monitored during the crop cycle. Five replicates (plants) per row were selected randomly in each greenhouse to measure the crop evolution for plant height. The weight of tomato fruits harvested from each was determined using an electronic balance which has a resolution of 0.5 g and compared. For each harvest, the total yield was calculated by adding the weight of fruits.

2.6. Population dynamics of Tuta absoluta

The tomato leafminer *T. absoluta* (Lepidoptera: Gelechiidae) is a very destructive pest of tomato crops. The damage caused by this insect on the tomato can result in a severe damage at harvest under low control (França, 1993). There are several methods to control this pest. The common control method is to spray chemicals that are very harmful to humans and the environment. Farmers also use insect-proof to keep pests out of the greenhouse. The biological control methods using natural enemies and biopesticides remain the safest approaches despite their relatively high cost (Nilahyane et al., 2012; Redouan, 2019). The most effective approach is to combine all the above methods with other methods such as mass trapping, cultivar resistance, mulching and climate management inside the greenhouse. This strategy is defined as an integrated pest management system.

To monitor population dynamics of *T. absoluta* in both heated and control greenhouses, we have used a delta pheromone traps (Reference product: PH-937-1RR, Russel IPM, UK). During trial, an abnormal increase of *T. absoluta* was observed then, two water traps were installed in each of the two greenhouses to reduce the population of this pest. In order to evaluate the effect of the heating system on the population dynamics of *T. absoluta*, we calculated the reduction rate of this pest using the following Eq. (1):

$$\%reduction = \frac{P_{HG} - P_{CG}}{P_{CG}} \times 100 \tag{1}$$

where P_{CG} and P_{HG} are the *T. absoluta* population in control greenhouse and heated greenhouse, respectively.

2.7. The thermal load leveling

The thermal load leveling (TLL) is defined as a relative factor to indicate the fluctuation of inside air temperature of the greenhouse. So, a better environment for plants is ensured when the inside temperature has minimum fluctuations. In this condition, the TLL should have a minimum value (Adams et al., 2001).

The performance of combined system as a composition of the two heating systems, active and passive, for the greenhouse applications will be assessed in terms of TLL, using the Eq. (2):

$$TLL = \frac{T_{in,max} - T_{in,min}}{T_{in,max} + T_{in,min}} \tag{2}$$

2.8. Heating requirements of the greenhouse

At night, all the walls of the greenhouse are closed. So, the inside air behaves like a closed thermodynamic system and exchanges energy with the external environment. The energy requirements ($Q_{h,r}$) of greenhouse inside air, to have its nocturnal temperature equal to the optimum value of tomato growth (12 °C), is calculated by the following Eq. (3):

$$Q_{h,r} = \sum_{t(T_{in} < T_{op})}^{t(T_{in} \geq T_{op})} m_a c_a (T_{op}(t) - T_{in}(t)) \tag{3}$$

where m_a and c_a are the air mass inside the greenhouse, 742.5 kg, and specific heat of air at 25 °C, 1005 J/kg K. $T_{op}(t)$ and $T_{in}(t)$ are optimum temperature of tomato growth and the inside temperature, respectively.

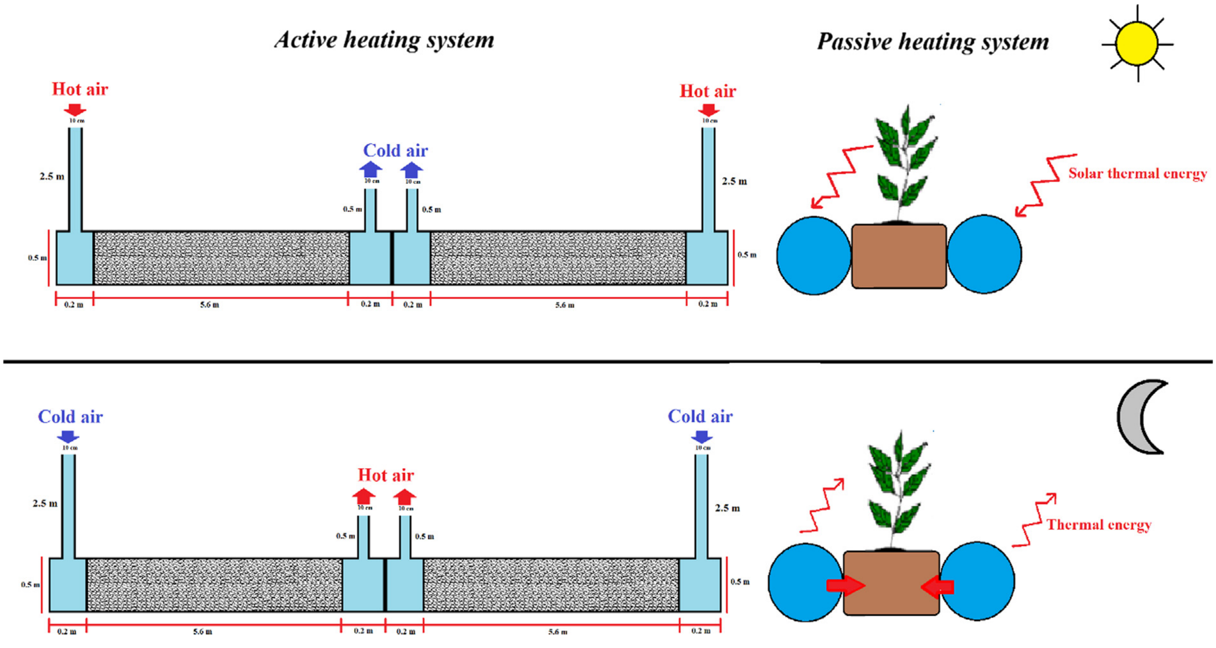

Fig. 3. The operating principle of the combined heating system.

Table 2
Accuracy and measurement range of the sensors used for the climate characterization.

Sensors	Measurement Range	Accuracy
Pyranometer CMP11	0–4000 W/m^2	Level accuracy 0.1°
HMP60 sensor	T: −40 °C to +60 °C RH: 0–100%	± 0.6 °C ± 3% RH (0–90%) ± 5% RH (90–100%)
PT107	−35 to 50 °C	≤ ± 0.01 °C (−35 to 50 °C)
Data Logger CR3000	± 5000 mV ± 1000 mV ± 200 mV ± 50 mV ± 20 mV	± (0.04% of reading + offset), 0–40 °C ± (0.07% of reading + offset), from −25 °C to 50 °C ± (0.09% of reading + offset), −55 °C to 85 °C

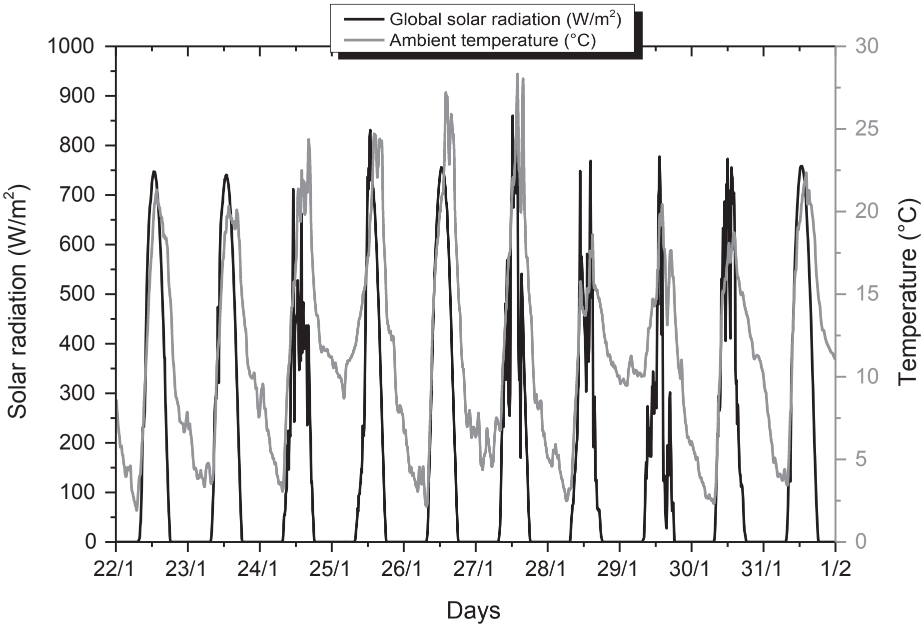

Fig. 4. Daily variations of solar radiation and ambient temperature from 22th to 31th January 2018.

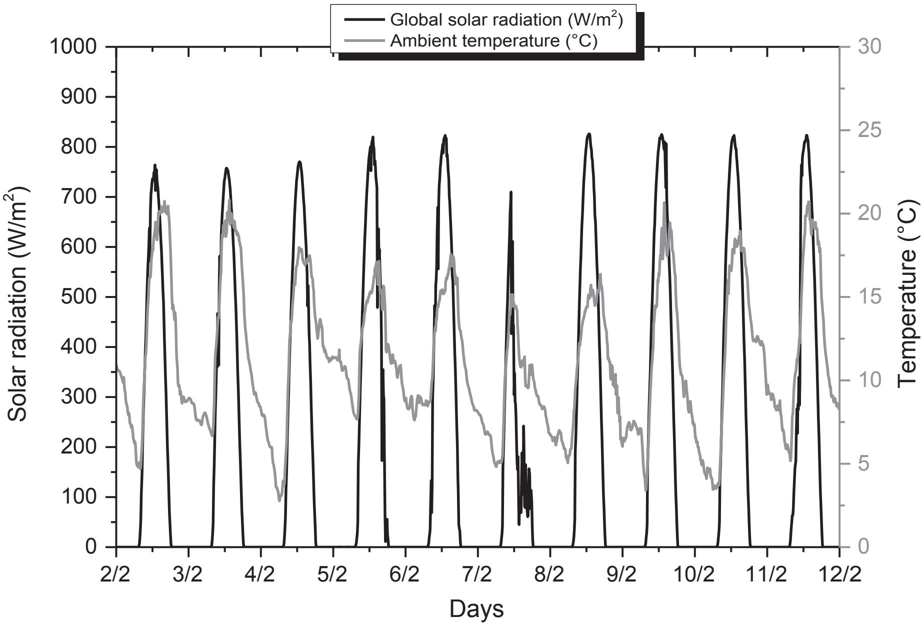

Fig. 5. Daily variations of solar radiation and ambient temperature from 2th to 11th February 2018.

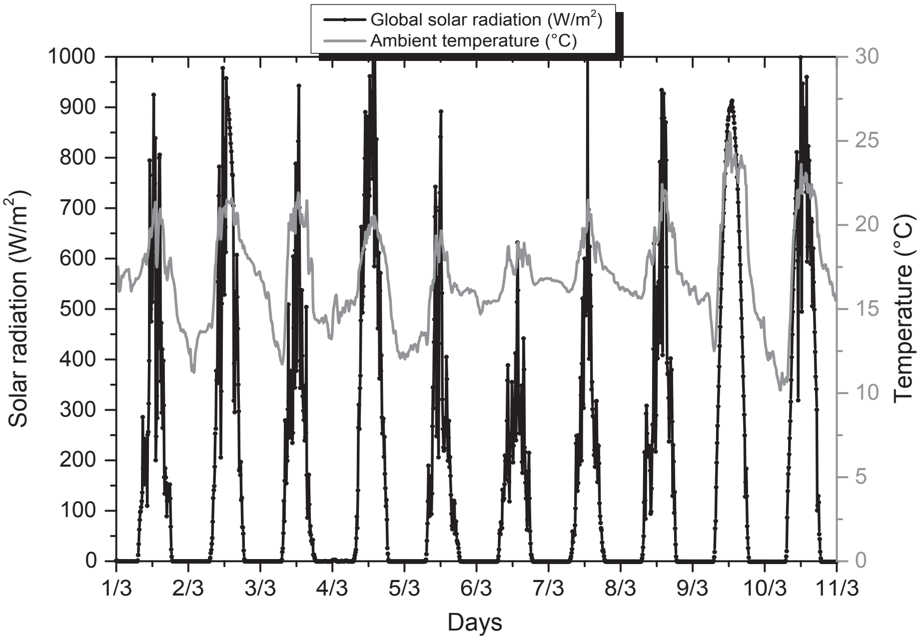

Fig. 6. Daily variations of solar radiation and ambient temperature from 1st to 10th March 2018.

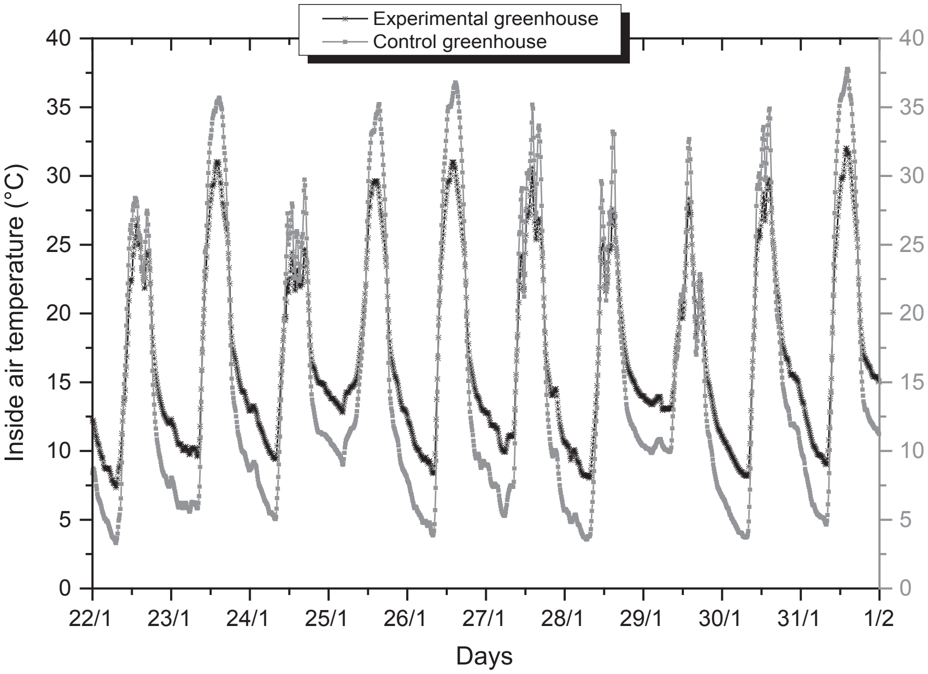

Fig. 7. Air temperature inside experimental greenhouse and air temperature inside control greenhouse as a function of time (22th–31th January 2018).

3. Results and discussions

3.1. Detail of the indoor climate in the two greenhouses

Figs. 4–6 show the ambient temperature and the global solar radiation in the two greenhouses for three periods of ten days in January, February and March 2018, respectively. The measurement periods were characterized by clear and sunny days in January and February and cloudy and rainy days in Mars. The maximum of global solar radiation falling on greenhouse varied between 750 and 850 W/m^2, 700–830 W/m^2 and 600–1000 W/m^2 in January, February and March, respectively. The daily maximum and minimum temperature are 28 and 2 °C, 22–3 °C, 25–10 °C for the measured periods in January, February and March, respectively. The climate during the two months of January and February is colder compared to Mars. The ambient temperature follows the same trend as solar radiation, and its fluctuations also corresponds to the fluctuation of solar irradiation received at the soil level.

Figs. 7–9 illustrate the evolution of the inside air temperature in the heated greenhouse and in the control greenhouse for three ten-day periods in January, February and March 2018. The fluctuations of inside temperature in the two greenhouses follows the same trend as the outside weather conditions especially the outside air temperature and solar radiation. During day, in January and February, the maximum values of the inside air temperature recorded in the control greenhouse varied between 27 and 38 °C, while these values are between 25 and 36 °C in the heated greenhouse. This decrease of temperature in the

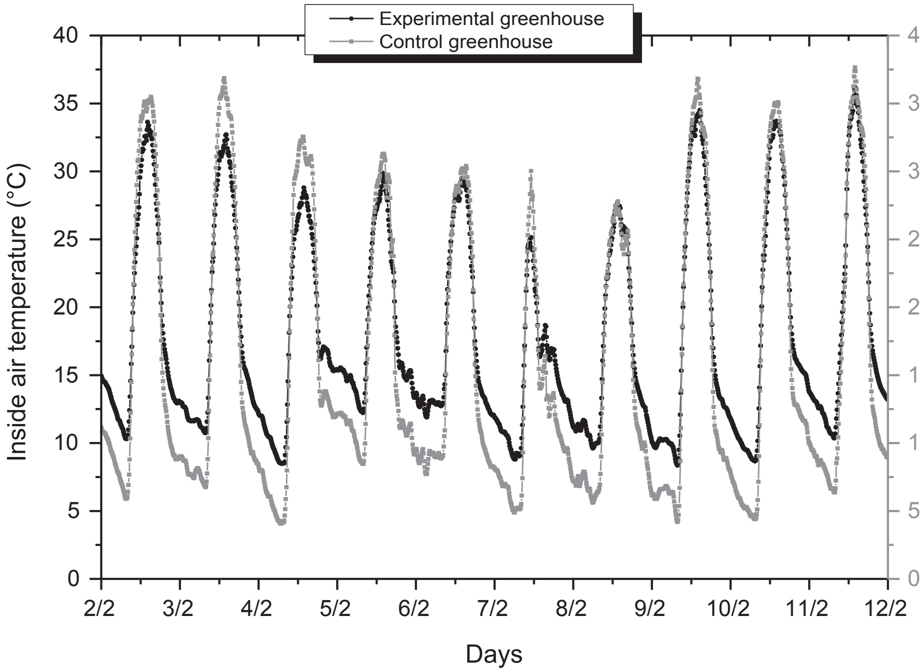

Fig. 8. Air temperature inside experimental greenhouse and air temperature inside control greenhouse as a function of time (02th–11th February 2018).

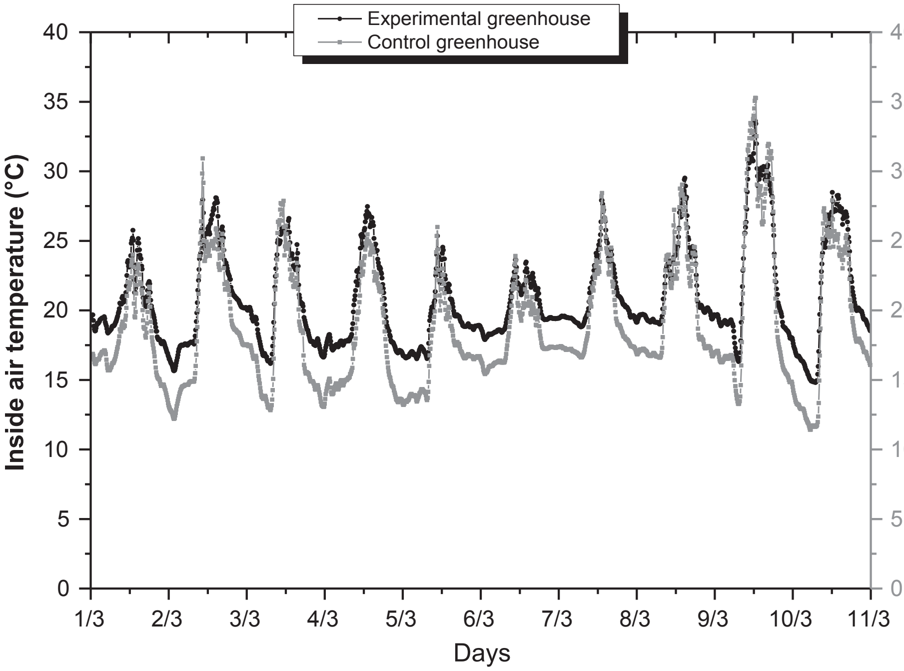

Fig. 9. Air temperature inside experimental greenhouse and air temperature inside control greenhouse as a function of time (1st–10th March 2018).

experimental greenhouse is due to the heat absorption of the thermal mass in the sleeve water and the rock-bed what provokes a cooling effect. In March, the maximum values of the internal temperature are varied between 25 and 35 °C for the two greenhouses.

At night, the minimum values of inside air temperature in the control greenhouse are 3, 3.5 and 12 °C on average for three ten-day periods in January, February and March 2018, respectively. These latter values are improved by the combined heating solar system in experimental greenhouse. The nocturnal temperature inside the heated greenhouse exceeds that of the control one by 3–5 °C during the clear days of the ten-day periods of January and February, and 2–3 °C during the cloudy and rainy days of the ten-days of March. These results lead to conclude that the combined heating solar system improves significantly the greenhouse microclimate in the winter period compared to the similar solar heating systems, active or passive. Bouadila et al. (2014a) studied a packed-bed solar system to improve the greenhouse microclimate at night and tested its performance during the month of February 2013. They found that the nocturnal temperature inside the isolated greenhouse equipped by this system exceeds the temperature in conventional greenhouse by 5 °C.

In the same area of Morocco, Bazgaou et al. (2018) studied the effect of a similar active system on the greenhouse microclimate. They have obtained an improvement of the nocturnal temperature by 2.6 °C. Bargach et al. (1999) used a solar system for heating the inside air of

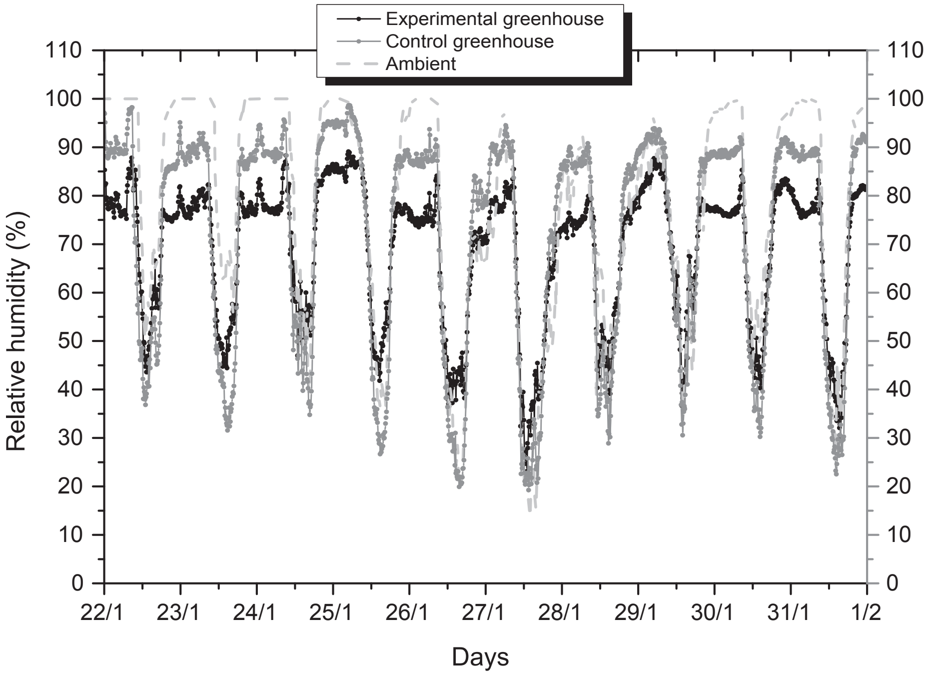

Fig. 10. Relative humidity inside experimental greenhouse and control greenhouse as a function of time (22th–31th January 2018).

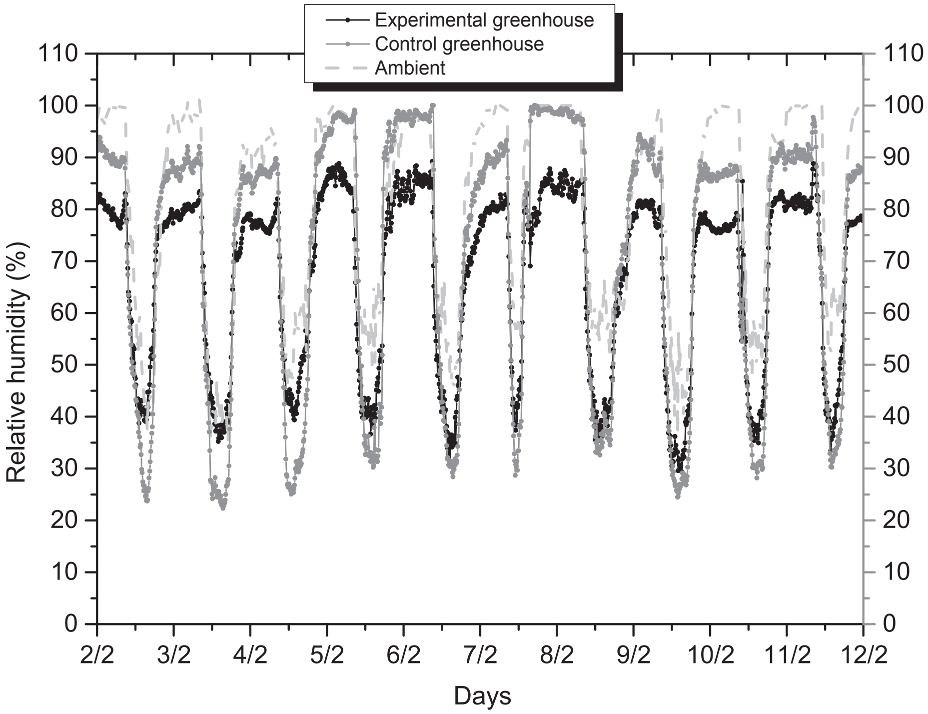

Fig. 11. Relative humidity inside experimental greenhouse and control greenhouse as a function of time (02th–11th February 2018).

greenhouse and they gained 1.2 °C increase of the nocturnal temperature. Gourdo et al. (2018) used a solar heating system with the sensible heat storage mode, this system improves nocturnal temperature of the greenhouse by about 3 °C.

Figs. 10–12 presented the effect of combined heating system on the relative humidity in the heated greenhouse and the control one. At night, the combined heating solar system is able to reduce the relative humidity value by 10–15% inside the experimental greenhouse compared to the control one. This solar system generates a passive dehumidification process, during the nights of cold period, due to the increase of the inside temperature in the heated greenhouse. During the day, the relative humidity varies inversely with the inside temperature. Knowing that the optimal value of the relative humidity for plant growth is around 75% (Wacquant et al., 1995) and beyond this value, crops begin to stress, this combined heating system makes it possible to restore the humidity conditions favorable to the good functioning of the plants under canarian greenhouses.

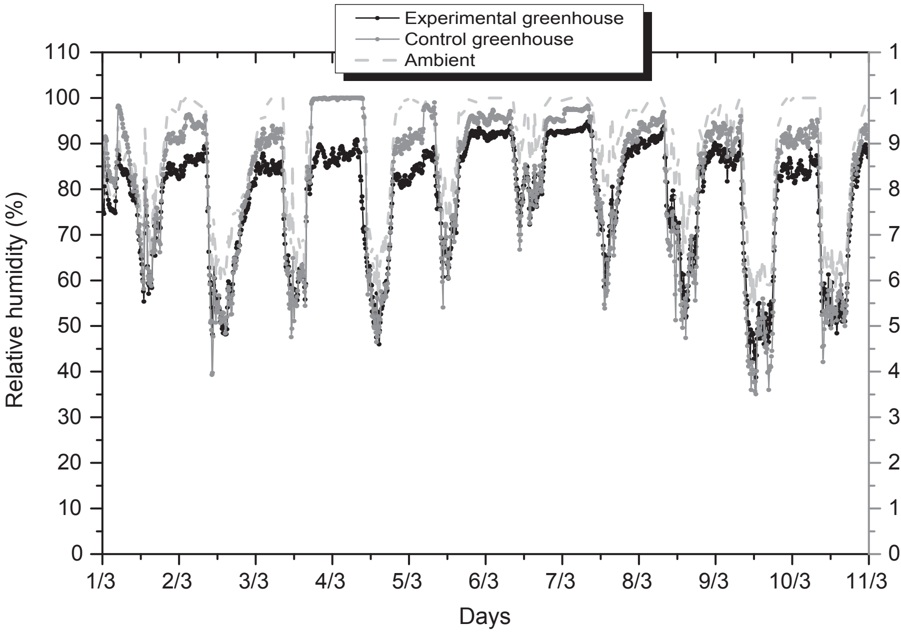

Fig. 12. Relative humidity inside experimental greenhouse and control greenhouse as a function of time (1st–10th March 2018).

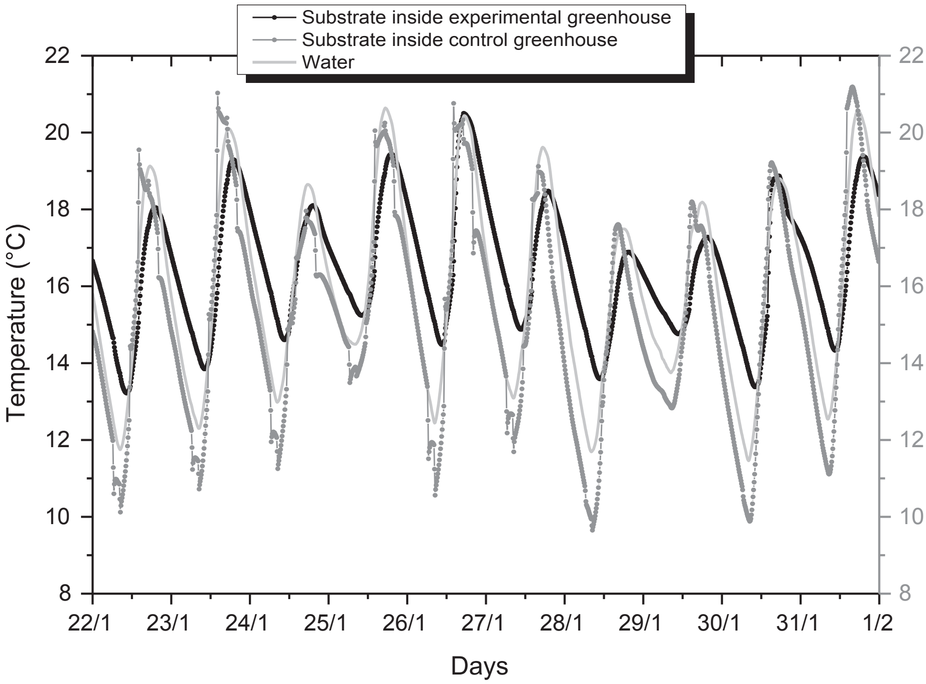

Fig. 13. Substrate temperature inside the experimental and control greenhouses and water temperature as a function of time from 22th to 31th January 2018.

3.2. The temperatures of substrate and water in the plastic sleeves

Figs. 13–15 illustrate the evolution of substrate temperature in the two greenhouses as a function of time. These figures represent also the water temperature in the plastic sleeves placed between plant rows in the heated greenhouse.

During the ten-days period in January, the water temperature in the sleeves is higher than the substrate in the experimental greenhouse, with a maximum value of 20.6 °C, due to the high solar radiation received by this greenhouse during day. The substrate temperature in control greenhouse is warmer than that in experimental one, with a maximum value of 21 °C and 20 °C, respectively. About the ten-days period in February, the substrate temperature and the water temperature, in heated greenhouse, are practically identical during daytime and the substrate temperature in control greenhouse is slightly higher than the two previous temperatures. The solar radiation received during the measurement period in February is higher than that in January. The maximum value of 21 °C for the substrate and water temperatures is recorded inside the greenhouse equipped with thermal storage solar system, and 23.5 °C for substrate temperature in the control one.

At night, the substrate temperature in heated greenhouse exceeds than that of the control one about 2–4 °C. The water temperature is lower than that of the substrate in the first greenhouse about 1–2 °C, meaning that an amount of the thermal energy lost by the water is recovered by the tomato substrate. The minimum value of the substrate

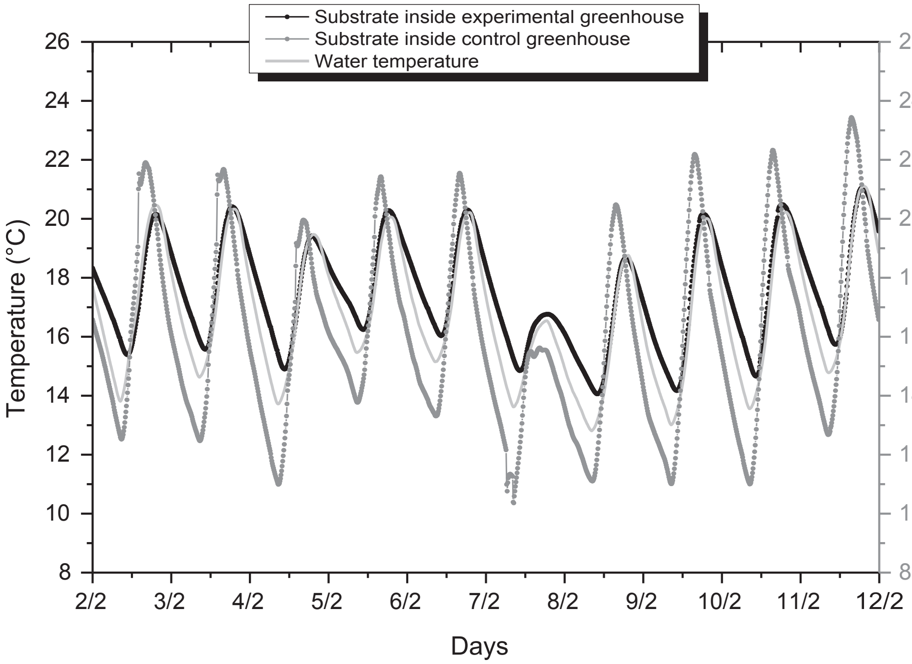

Fig. 14. Substrate temperature inside the experimental and control greenhouses and water temperature as a function of time from 02th to 11th February 2018.

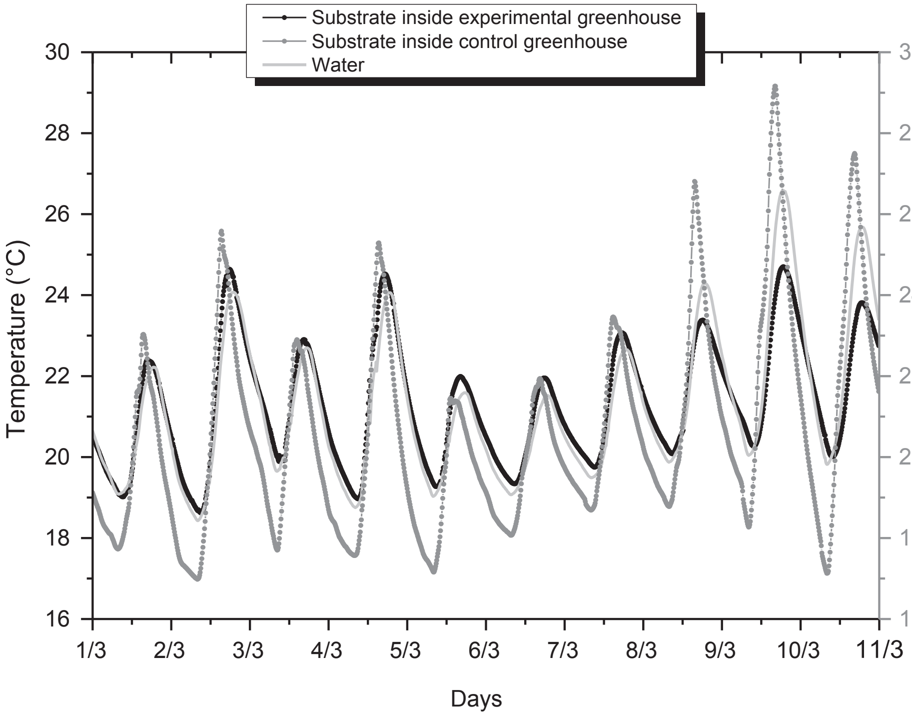

Fig. 15. Substrate temperature inside the experimental and control greenhouses and water temperature as a function of time from 1st to 10th March 2018.

temperature is about 13 °C in heated greenhouse and 9.5 °C in control one, during ten-days period in January. Concerning the ten-days period in February, a minimum value of 14 °C is recorded under heated greenhouse and 10 °C in control greenhouse.

During the ten-days period of March, the substrate temperature and the water temperature in heated greenhouse are confounded during the 24 h during the first seven rainy days, with a difference value varied between 1 and 3 °C at night compared to the substrate temperature in control greenhouse. Except, the last three days where the water temperature is higher than that of the tomato substrate, during the day, due to the large amount of solar radiation received by the greenhouses. During this measurement period, a large fluctuations of substrate temperature are observed inside the control greenhouse. It can be concluded those temperature fluctuations in root zone influence the comfortability of the tomato plant, hence their development and yield.

A very beneficial effect for the development of tomato plants will be accompanied by the increase of their substrate temperature. In the literature, the root heating for tomato crop increases agricultural yield by about 10% (Hurd and Graves, 1985).

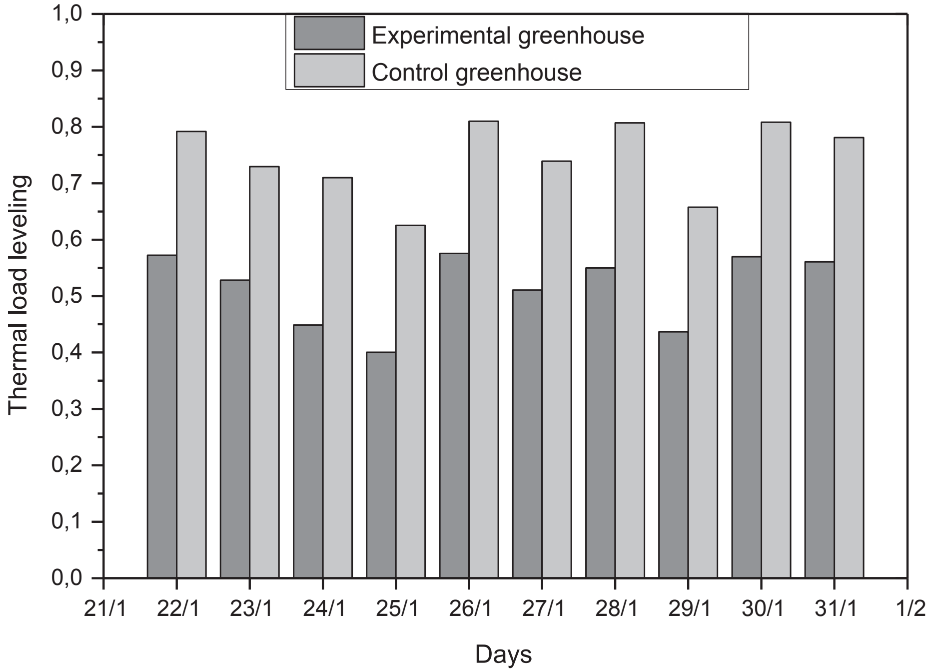

Fig. 16. Thermal load leveling, TLL, of experimental and control greenhouses as a function of time from 22th to 31th January 2018.

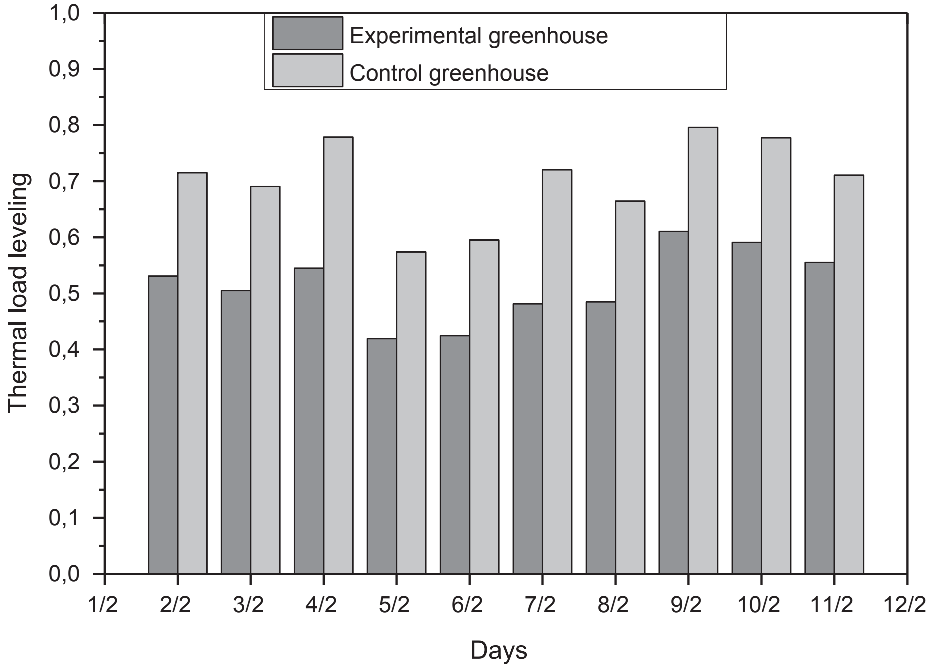

Fig. 17. Thermal load leveling, TLL, of experimental and control greenhouses as a function of time from 02th to 11th February 2018.

3.3. *Thermal load leveling (TLL)*

The performance of a combined heating system inside the canarian greenhouse has been evaluated in terms of thermal load leveling, TLL, using Eq. (2). The TLL give an idea about the fluctuation of air temperature inside the greenhouse. Less there are temperature fluctuations inside the greenhouse, better is the environment for plants.

Due to solar thermal storage in rock-bed and water, the maximum air temperature decreases and minimum temperature increases. Consequently, the TLL will have lower values caused by the increase of the term ($T_{in,max}$ + $T_{in,min}$) and the decrease in the term ($T_{in,max}$–$T_{in,min}$) compared to TLL calculated for the greenhouse without heating equipment (Sutar and Tiwari, 1995, 2000).

The results of the daily variation of TLL with and without heating system during ten-day periods in January, February and March 2018 are shown in Figs. 16–18. Higher values of TLL were observed in the unheated greenhouse compared to heated one. In the heated greenhouse, the fluctuations of indoor air temperature are reduced by 25% during measurement period in January, 24% in February and 13% in March. These results show that, if the inside air temperature exceeds the optimal growth value at night about 12 °C, its fluctuations become low.

These results are in agreement with those of other studies that evaluated passive and active greenhouse heating systems. Bouadila

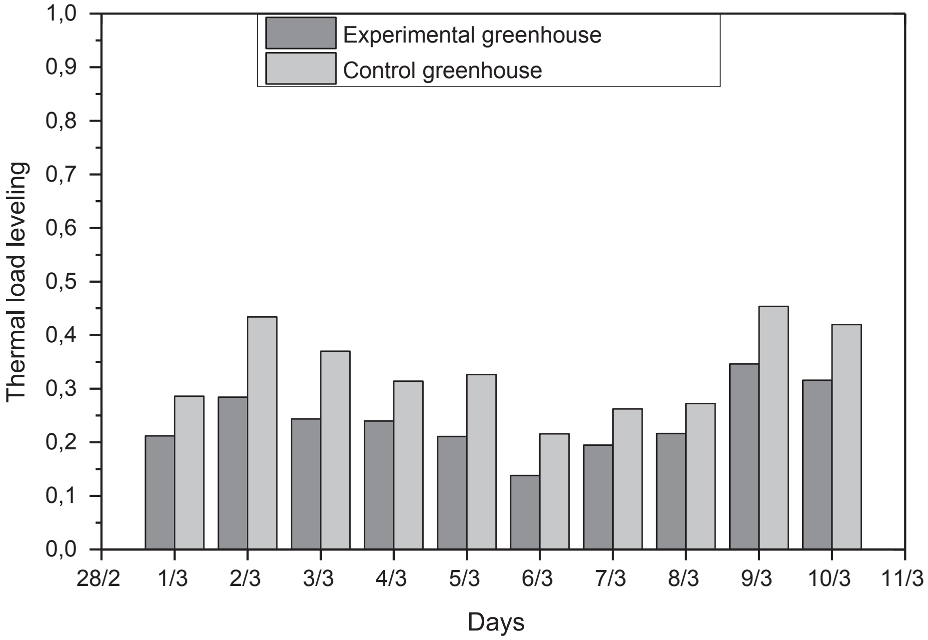

Fig. 18. Thermal load leveling, TLL, of experimental and control greenhouses as a function of time from 01st to 10th March 2018.

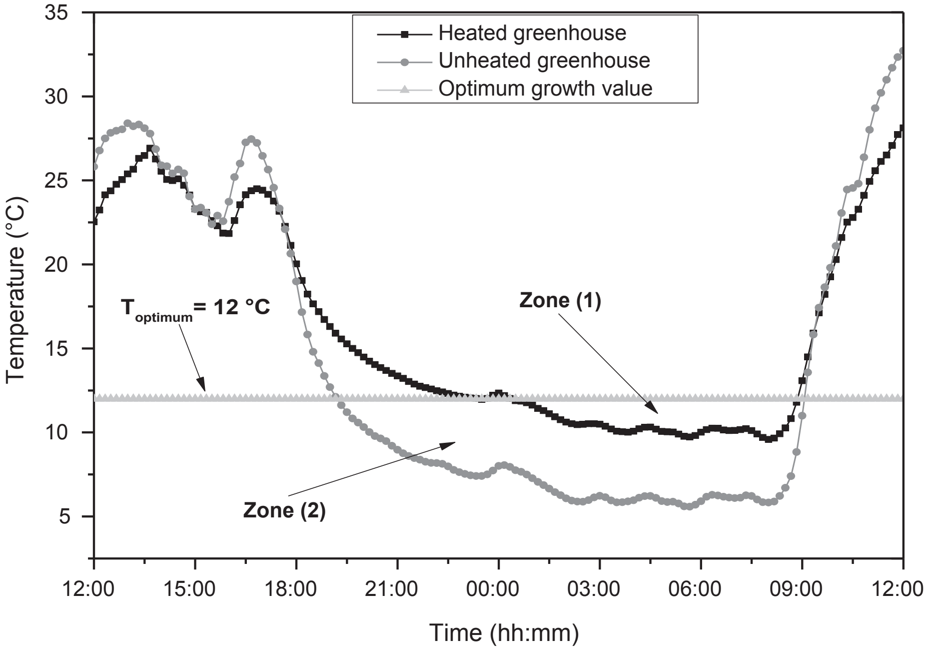

Fig. 19. Heating requirements covered and not covered by the combined heating system during the night of January 22, 2018. Zone (1): Heating requirements not covered, Zone (2): Heating requirements covered.

et al., 2014a) showed that the value of TLL is maximum for conventional greenhouse and its value is reduced by 25% when this greenhouse is isolated. Kumari et al. (2006) showed that the less fluctuations of inside air temperature are observed in greenhouse equipped by a passive thermal heating system. Tiwari et al. (2006) indicated that the thermal load leveling is lower in case of greenhouse with earth–air heat exchanger than without it. Din et al. (2003) showed that the solar thermal storage for thermal heating of a greenhouse reduces the TLL values, consequently the fluctuations of air temperature are less.

The lower values of TLL mean that the fluctuations of temperature decrease and thereby, improve the desired environment for crops inside the greenhouse.

3.4. *Performance of combined heating solar system inside canary greenhouse*

In this part, we have pointed out the heating requirements of the greenhouse to reach optimum air temperature for good plant growth and development. This energy requirement was calculated using Eq. (3).

Fig. 19 illustrates the evolution of the inside air temperature in the two greenhouses concerned, as well as the optimum temperature of tomato growth (12 °C) during the night of January 22th, 2018. This figure shows also the heating demand and the share of this demand covered by the combined heating system.

Figs. 20 and 21 presented the heating requirements and the thermal

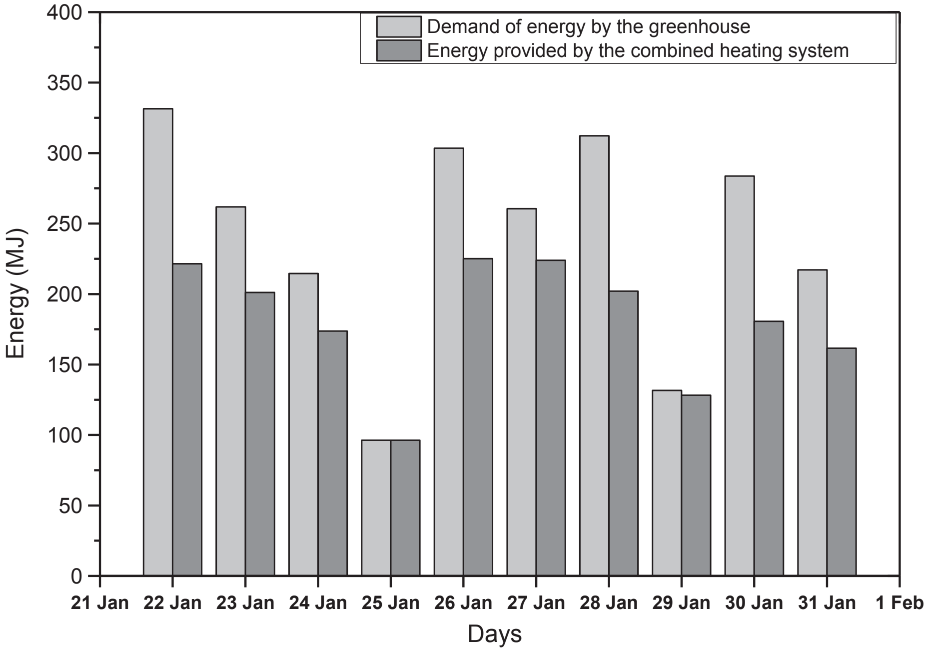

Fig. 20. The heating requirements and the thermal energy recovered by the combined heating system as a function of time from 22th to 31th January 2018.

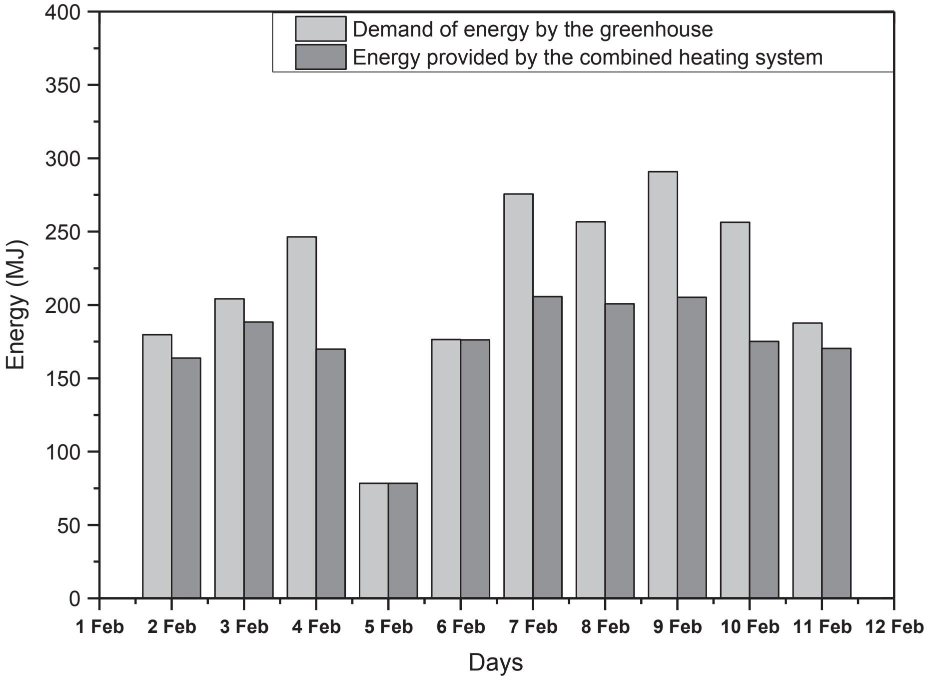

Fig. 21. The heating requirements and the thermal energy recovered by the combined heating system as a function of time from 02th to 11th February 2018.

energy recovered by the combined heating system, during the two periods in January and February, respectively. Concerning the period of Mars, the minimum values of inside air temperature recorded are higher than the optimal value of tomato growth, the heating system reduces the fluctuations of inside air temperature and the heated greenhouse becomes more comfortable for tomato plants compared to unheated one (see Fig. 18).

According to these two figures, the heating demands are higher in January compared to February. The amount of energy required to reach optimal growth levels inside the greenhouse is varied between 96 MJ/day as a minimum value and 331 MJ/day as a maximum value in January, and 78–290 MJ/day in February. The combined heating system was able to cover a large part of the heating requirements during the measurement periods. This coverage reached 100 percent in 25th January, 05th and 06th February 2018.

This heating need coverage was very optimistic compared to other studies. Bouadila et al. (2014b) found that the energy stored by a solar heating system based on latent storage energy cover only 30% of the nocturnal heating requirements of the greenhouse under similar climatic conditions. In another study, Bouadila et al. (2013) found also that the energy efficiency as a function of days of this system varied from 32% to 45%.

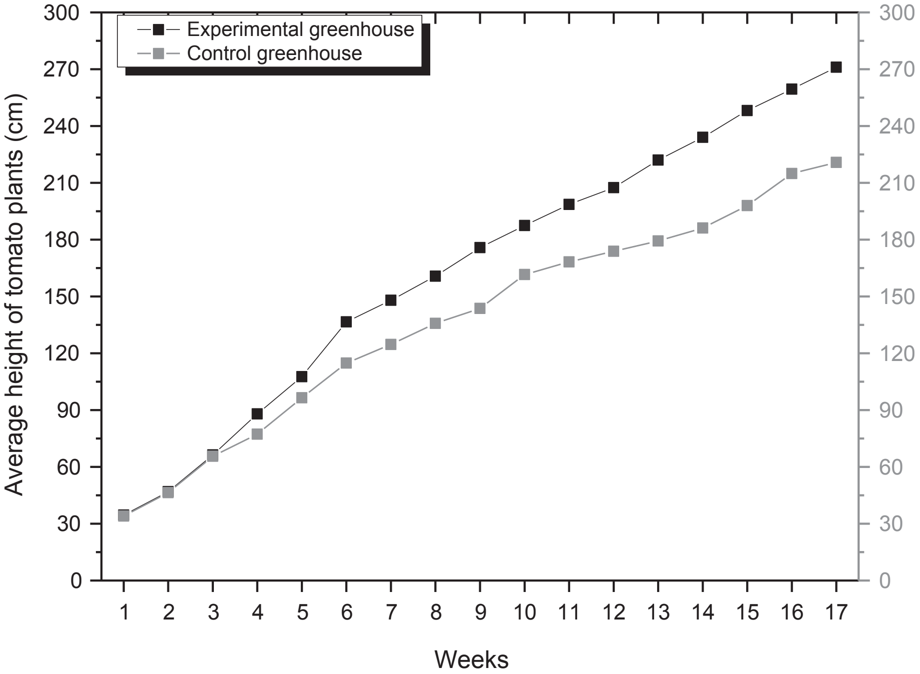

Fig. 22. The average height of the tomato plants as a function of weeks in experimental greenhouse and control greenhouse.

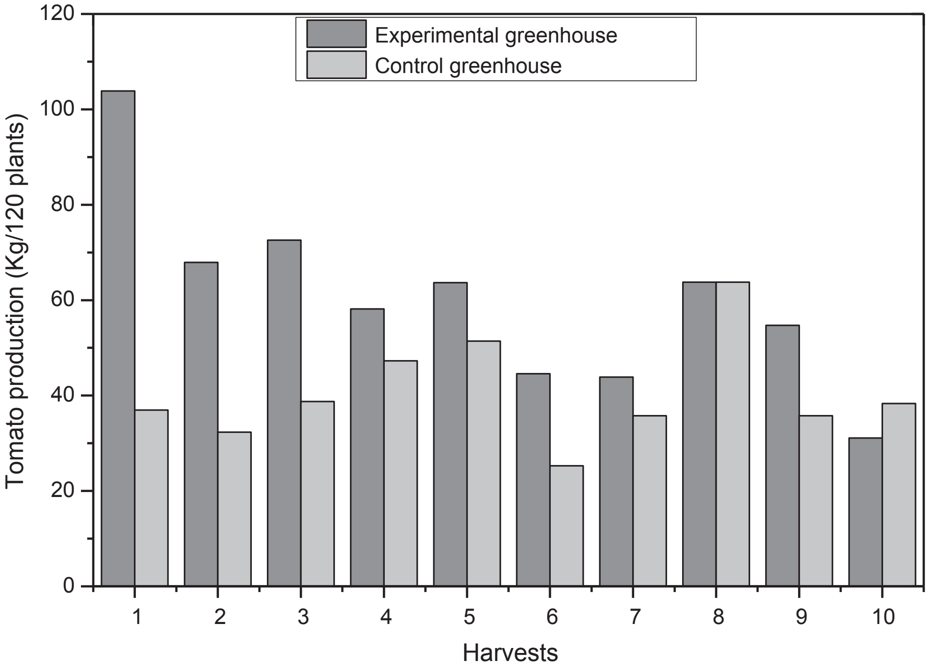

Fig. 23. Tomato production at each harvest in experimental and control greenhouses.

3.5. Agronomic analysis

The tomato yield is subjected to the amount of light received by the plants (Newton and Economakis, 1999). The temperature is also among the key factors of growth and development aspects of tomato plants (Van Ploeg and Heuvelink, 2005). The period from anthesis to maturity of a tomato fruits decreases when air temperature in greenhouse increases from 14 to 26 °C (Hurd and Graves, 1985; Heuvelink and Marcelis, 1989; de Koning, 1994; de Koning, 1998). It has been confirmed that the optimal daily average temperature to improve the quality and the yield of tomato under greenhouse is between 12 and 30 °C. These values are around 22–28 °C during the day and 15–20 °C at night (Castilla and Hernandez, 2007). Cooper (1973) and Fujishige and Sugiyama (1968) have shown that the favorable temperature for the good development of tomato roots is around 20 and 30 °C. The relative humidity also has a significant effect on tomato production. Its high levels can lead to yield loss (Jolliet et al., 1991).

The combined solar heating system evaluated in the present study, has a positive effect on agronomic factors especially on the precocity of tomato fruits, growth and yield. The tomato crop in the heated greenhouse showed an earlier growth development compared to the unheated greenhouse. Fig. 22 displays the evolution of average height of tomato plants inside the control greenhouse and the heated one between 24th October 2017 and 13 February 2018. Each value was

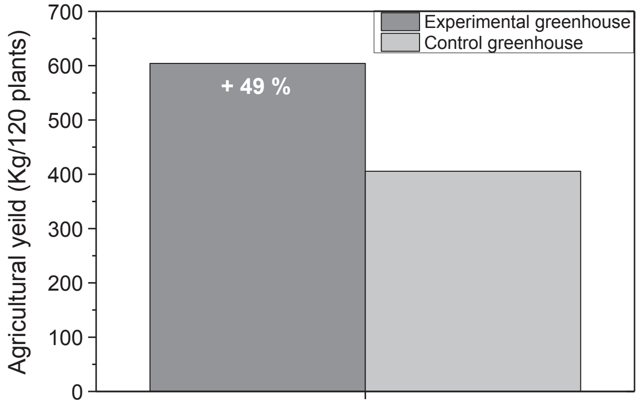

Fig. 24. Total yield in experimental and control greenhouses.

Table 3
Economic assessment for heated and unheated greenhouses.

Heating system costs (USD/m^2)	Rock-bed	0.83
	sleeves	0.25
	Labor	0.44
Costs of investments and operational (USD/m^2)	Control Greenhouse	3.13
	Heated greenhouse	4.64
Total costs of the heating system (USD/m^2)		**1.51**
Exportable yield (Kg/m^2)	Control Greenhouse	7.24
	Heated greenhouse	10.80
Difference of yields (kg/m^2)		3.56
Average gain of Yield		**49%**
Average profit (USD/m^2)	Heated greenhouse	3.05
	Control Greenhouse	2.03
Average benefit of the combined heating system (USD/m^2)		**1.02**

determined from the average of 20 plants. We noticed a very suitable impact of the heating on the plant development. This effect is very clear after the 4th week of measurement with a difference of 10 cm and 51 cm after the 17th week.

A significant effect of heating on agricultural yield is observed in heated greenhouse compared to the unheated one (Fig. 23). This production difference can reach 67 kg as a maximum value in the first harvest. Concerning the agronomic performance, the combined heating system was able to create a gain in tomato production of 49% compared to the standard yield in unheated greenhouses, as shown in Fig. 24.

The combination of the two heating systems (passive and active) allowed to increase tomato yield compared to the use of these systems separately. Indeed, the use of the solar rock-bed heating system alone resulted in a 22% increase of tomato yield according to Gourdo et al. (2018) and 29% in the (Bazgaou et al., 2018) studies. While the use of a solar water–sleeve system alone, improves the greenhouse production to 35% (Gourdo et al., 2019).

3.6. Population dynamics of *T. absoluta*

Fig. 25 shows the population dynamics of *T. absoluta* in the greenhouse equipped with a combined heating system and the control greenhouse. The analysis of this figure shows that the *T. absoluta* pressure was relatively low in the heated greenhouse compared to the control one.

The monitoring showed that the number of captured individuals of *T. absoluta* was ranged from 0 to 125 in the control greenhouse and from 0 to 45 in the heated greenhouse. The control greenhouse provides a more favorable climate for the development of this pest compared to the heated greenhouse. It was noted that the number of *T. absoluta* increased rapidly in both greenhouses, from 13 May, due to the outbreak of the population of this pest outside greenhouses. In general, it appears that the presence of the combined heating system has a negative effect on the development of the *T. absoluta* population and reduces it about 64%.

Gourdo et al. (2019) have reported that the presence of a passive heating system resulted in a decrease in the development of the *T. absoluta* population in the heated greenhouse.

3.7. Economic assessment of the combined heating system

The energy costs related to the heating requirement of the greenhouse crop production represent, generally, a significant part of production costs. In some cases, energy consumption in greenhouses accounts for 50% of the cost of greenhouse production.

Basically, greenhouse tomato farmers in the Mediterranean region did not use heating systems for their controlled greenhouses as the area was characterized by a mild climate with moderately low thermal

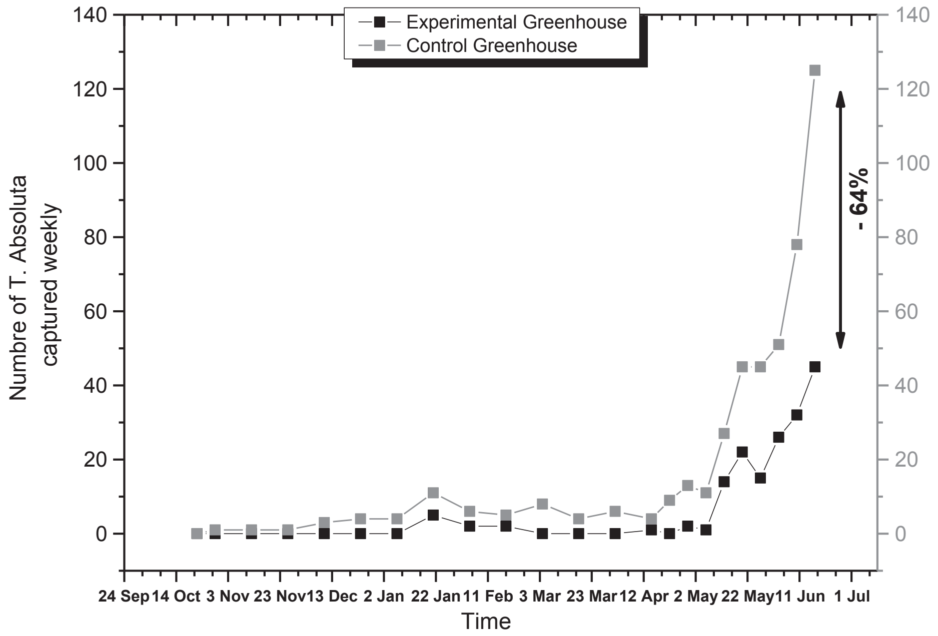

Fig. 25. The evolution of the number of *T. absoluta* adults captured as a function of time in experimental and control greenhouses.

ranges. With actual climate warning, winters in the Mediterranean region become long and cold hence the need to use heating systems to produce crops throughout the year.

The combined heating system proposed in this study has shown a significant gain in biomass and yield, particularly, in low temperature periods.

To assess the economic profitability of this combined heating system, we have computed the profit of the tomato crop for 10 harvesting periods with a density of 2 plants/m^2. The costs related to this combined heating system include the installation cost of rock-bed and passive solar sleeves. For an area of 165 m^2, the installation of the rock-bed required 9 m^3 of rocks that costed around 0.83 USD/m^2 including transport (1 USD = 9.69 MAD). It was also required to equip 4 rows with 80 linear meter of black sleeves costing 0.25 USD/m^2. The total cost of the combined heating system equipment as well as labor is around 1.51 USD/m^2. This work has shown significantly the impact that the heating system can have on tomato crop production compared to an unheated greenhouse. In fact, we recorded a 49% increase in yield using the combined heating system. In comparison with an unheated greenhouse, we have recorded an average profit of the combined heating system of 1.02 USD/m^2.

Indeed, for this study, the combined heating system energy cost per month is around 0.13 USD/m^2, whereas the average energy cost of other conventional systems mentioned in other works (Bouadila et al., 2014a; Vanthoor et al., 2012) can reach 1.14 USD/m^2. These results show the efficiency of the combined system used in this study in comparison to other systems.

In the standard production of tomatoes under unheated greenhouses, with a density of 2 plants/m^2, the yield is about 7.24 kg/m^2. The combined heating system improved this value to 10.80 kg/m^2, giving a difference in yield of 3.56 kg/m^2 and an average gain of 49%. The average profit of this system is 1.02 USD/m^2 i.e. 10 200 USD/ha as shown in Table 3.

4. Conclusion

The combination of two systems i.e. rock-bed thermal energy storage and water filled passive solar, for heating greenhouse was evaluated. The use of this system has significantly improved the nocturnal temperature in the greenhouse during the winter season with less fluctuations. A clear reduction in humidity inside the heated greenhouse was also observed which could explain the negative effect on *T. absoluta* development. The other beneficial effect of heating greenhouse with this combined system is the increase of the substrate temperature during the cold season, which positively influences the crop development and increase the tomato production.

From the economic point of view, the cost/benefit and financial profitability analyses demonstrated that heating the canarian greenhouse with this combined heating system is very profitable and could generate profits for farmers.

However, during the extreme cold season, the supply of energy stored during the day will not cover the total heating needs of the greenhouse, hence more research on the heat transfer fluid and energy storage materials will be needed to increase the efficiency of this system.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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