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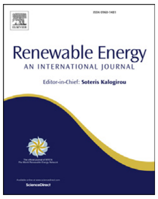

Effect of active solar heating system on microclimate, development, yield and fruit quality in greenhouse tomato production

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ABSTRACT

Heating greenhouses is essential to provide favorable climatic conditions for growing plants under cold periods. In this article, we have studied the performance of an Active Solar Heating System (ASHS) consisting of two solar water heaters equipped with flat solar collectors, two storage tanks and exchanger pipes. During the day, the water is heated in the thermosyphon solar collectors and stored in tanks before being placed into circulation in the exchanger pipes to distribute the heat to the aerial and root zones of plants.

To assess the performance of the Active Solar Heating System, climatic and agronomic parameters were monitored in two identical canarian greenhouses, one equipped with ASHS heater and the second without. Experimental results show that the ASHS system improve the nocturnal climatic conditions under greenhouse. The thermal comfort created by the ASHS system in root zone, increases the absorption of nutrients, which improve the external quality (color, size, weight and firmness) and the internal quality (sugar content, acidity and taste) of tomato fruits. This improvement is also reflected by increasing total tomato yield by 55% in winter period. The results of economic analysis indicate that the ASHS system is a cost effective in terms of investment and energy saving.

1. Introduction

The greenhouse is a controlled environment system that protect plants from extreme weather conditions and give the ability to adjust the internal climatic conditions in order to create a suitable environment for good crop growth, in terms of both quality and quantity [1,2].

Due to the recent energy price fluctuations, the greenhouse energy consumption became a major issue for crop production sector around the world and especially in south Mediterranean area, since energy constitutes a substantial fraction of the total production costs [3].

In the last few years, the southern Mediterranean countries had invested greatly in the scientific research into renewable energies such as solar energy. In fact, these countries could meet their energy needs by only making maximum use of this available natural resource. Using the solar thermal energy to heat greenhouses during the cold periods, was one of the explored tracks over the past decade by several researchers. There are many studies in this field, which raise questions about heating greenhouses by solar thermal energy storage such as rock-bed solar system [4], solar black plastic sleeves filled with water [5], hybrid solar heating system [6], solar collector heating system [7], hybrid solar energy saving system [8], and combined solar heating system [9]. These systems can ensure an optimal temperature for plants and save energy during winter periods [10] with positive effects on quality and quantity of crops under greenhouses [11].

In addition to their action on air temperature of greenhouses, these solar heating systems act also on the temperature of the crop root zone, which promotes the growth and development of plants [12–14].

The root zone temperature control is crucial for plant

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development, because it affects physiological processes of roots such as water and mineral nutrients absorption.

Compared to conventional heating systems, the use of the solar heating system produces a thermal equilibrium between soil and inside air temperatures, with significant effects on root activity (i.e. absorption of water and nutrients, respiration, …) [15].

Solar heating systems have attracted the most serious attention owing to their large advantages with respect to resource conservation, lower equipment investment and operating costs and long-term applicability. These systems are classified into two types, passive and active. The passive ones are operated without energy input, which transferred heat between greenhouse inside air and the storage media [16–18]. The thermal storage materials which are widely used in this application are: soil [19,20], water [21–23], air [24,25], rocks [26,27], and Phase change materials (PCM) [28–32]. Despite the usefulness of these systems, they cannot meet greenhouse heating needs when the outside temperatures are very low. Their capacity of heat storage is limited and their efficiencies of heat recovery and supply are low. Hence the need of forced air circulation to improve the storage and the recovery of heat.

The active solar systems operate with energy supply and constituted of several components such as: thermal collectors, heat storage material, circulation pumps, storage tanks, heat exchangers and control system. The ensemble operates to maintain optimal thermal comfort for plants at both root and aerial zones.

The thermal effectiveness of these systems has been demonstrated by several researchers; Sellami et al. [33] studied the effect of active solar air heater on agronomic and physiological performances of tomato crop under a chapel-shaped greenhouse. They showed that the night recovered heat, by this system, reaches 30% of total heating requirements. Consequently, microclimatic conditions of heated greenhouse positively affected plant growth and led to an early fructification and an increased yield compared to the unheated greenhouse. Bazgaou et al. [34] analyzed the performance of an active rock-bed heating system in a conventional Canarian type greenhouse in Morocco. Results showed that the temperature at night inside the heated greenhouse exceeds that of the unheated one by 2.6 °C, and the relative humidity was 10% lower at night. The tomato production was improved by about 29% under the heated greenhouse.

For their part, Kooli et al. [35] demonstrated that the active solar heating system with latent heat storage increase the nocturnal temperature inside greenhouse by 2 °C. Yang and Rhee [36] used the active heat pump system to heat the greenhouse under Korean climatic conditions during the cold season. They found that this system maintained the optimal thermal comfort for crop growth during the three months, from January to March.

Generally, the active solar heating systems with solar collector installed outside the greenhouse and directly exposed to sunlight, have benefits in agricultural applications [37–39]. These heating systems can improve the utilization of solar energy and effectively improve the thermal environment in greenhouses during the winter period.

Despite the abundance of research works on the application of theses active solar heating systems in several types of greenhouses over the word, no study was conducted on canarian greenhouses.

To fill this lack of information gaps, we carried out this study to evaluate the thermal performance of an Active Solar Heating System (ASHS) used to heat a canarian greenhouse and to assess its effect on crop quality and quantity.

2. Materials and methods

2.1. Greenhouse description

The measurements were carried out in two similar and independent Canarian greenhouses with a galvanized steel structure, located in the experimental station of the Regional Center for Agricultural Research, local office of the National Institute of Agricultural Research (INRA) south of Agadir (30 °13 Latitude, 9 °23 Longitude, 80 m Altitude), on the Atlantic coast of Morocco. This greenhouse type is a conventional agricultural production shelter, widely installed in the Mediterranean regions. These two greenhouses are presented an almost flat roof and covered with a 200 μm polyethylene plastic thermal film (its characteristics are shown in Table 1). The orientation of its spans is North-South, perpendicular to the prevailing wind direction.

The first greenhouse is equipped with an active solar heating system and called experimental greenhouse, and the second one is without heating and considered as a control greenhouse for comparative studies. Each greenhouse occupies an area of 165 m^2 (15 m long and 11 m wide) with a height of 5 m in the center and 4 m in gutters, as illustrated in Fig. 1.

Both sides opening of the two greenhouses are covered with an insect-proof above where there is a plastic film. These plastic side covers could be rolled up or down up to ventilate the greenhouse. The opening side opens at 9 a.m. to evacuate excess humidity that has accumulated at night, and closes at 4 p.m. to limit heat exchange between inside and outside of the greenhouse during the night. The same operations were done for both greenhouses at the same time.

2.2. Description of the active solar heating system ASHS

The active solar heating system (ASHS) adopted in the current study consists of two flat solar thermal collectors based on the thermosyphon circulation. They include two storage tanks of 300 L each with a closed-circuit circulation system, with an area of 2 m^2 each (Fig. 2).

The thermal panels are oriented towards south to make optimal use of sunlight. Their inclination is equal to latitude of the experimental site, approximately 30°.

Fig. 3 shows the different ASHS components and its connection to the heating distribution network inside the greenhouse:

- Two flat thermal panels (solar collector) with a storage volume of 300 L with a closed water heating and cooling circuit.
- A mixer that mixes hot water from the tanks and cold water before injecting the fluid into the greenhouse heating network, with an outlet temperature of 36 °C.
- The PPR (polypropylene random) tubes with an internal diameter of 12 mm and an external diameter of 16 mm. These tubes are insulated by a heat-insulating sponge foam rubber tube. This PPR network forms two circuits: hot-water supply circuit and cold-water return circuit.
- A network of black polyethylene (PE) exchanger tubes with a 16 mm diameter, installed in the root zone of the tomato crop and in the aerial zone of the crop rows moving vertically upwards simultaneously to his growth.
- A thermostat that control the water circulation according to the desired temperature on the aerial or root zone of crops.

Table 1
Properties of the polyethylene thermal film used to cover greenhouses.

Conductivity	0.41 W/m K
Specific heat	1383 J/kg K
Diffusivity	2.991×10^{-7} m^2/s
Transmittance	75%
Thickness	200 μm

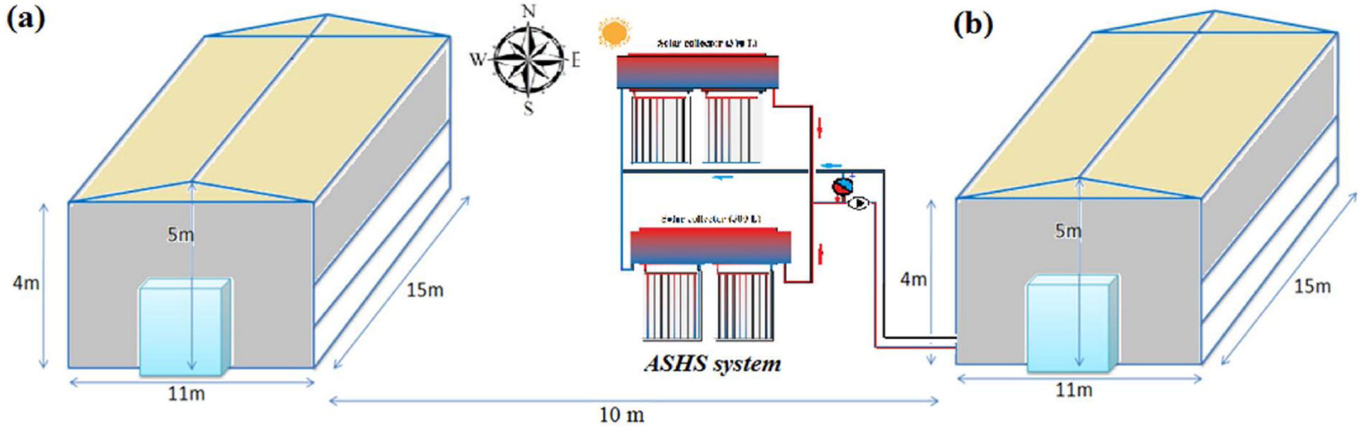

Fig. 1. Description of the control greenhouse (a) and the experimental greenhouse (b).

Fig. 2. Thermosiphon thermal solar collectors with water closed-circuit and 300 L of storage volume.

- Two water circulation pumps connected to the heating network tubes inside the greenhouse. These pumps have a low flow rate in order to increase the heat transfer between tubes surface and air.

2.3. Operating principle

The ASHS is equipped with an automatic control system that regulates the circulation of water between the solar collector and the greenhouse at night (Fig. 4). During the day, the water is heated by the solar collectors before being stored in the storage tanks using the thermosiphon circulation. At night, when the temperature of the aerial and the root zones are below the setpoint values, the control system (thermostat) activates the pumps to mix the hot water from the tanks with the cold water to reach an outlet temperature of 36 °C. This water flows through exchanger pipes to distribute the heat inside the greenhouse.

According to Castilla and Hernandez [40] the optimum air temperature for tomato crop should be maintained between 12 and 30 °C inside the greenhouse. The temperatures above 30 °C limit the flowering and reduce the plants growth rate, and those below 12 °C (the point of zero growth of tomato) delay the germination and slows the fruits precocity [41]. The optimal temperature of the root zone should be maintained between 20 and 30 °C according to the studies of Sugiyama [42] and Teasdale & Abdul-Baki [43].

Given the above, the thermostat of the ASHS was set to be activated when the temperature inside the greenhouse is below the point of zero growth of tomato ($T_{set} = 12\,^{\circ}C$).

2.4. Crop

The crop planted in the two greenhouses was two stems grafted

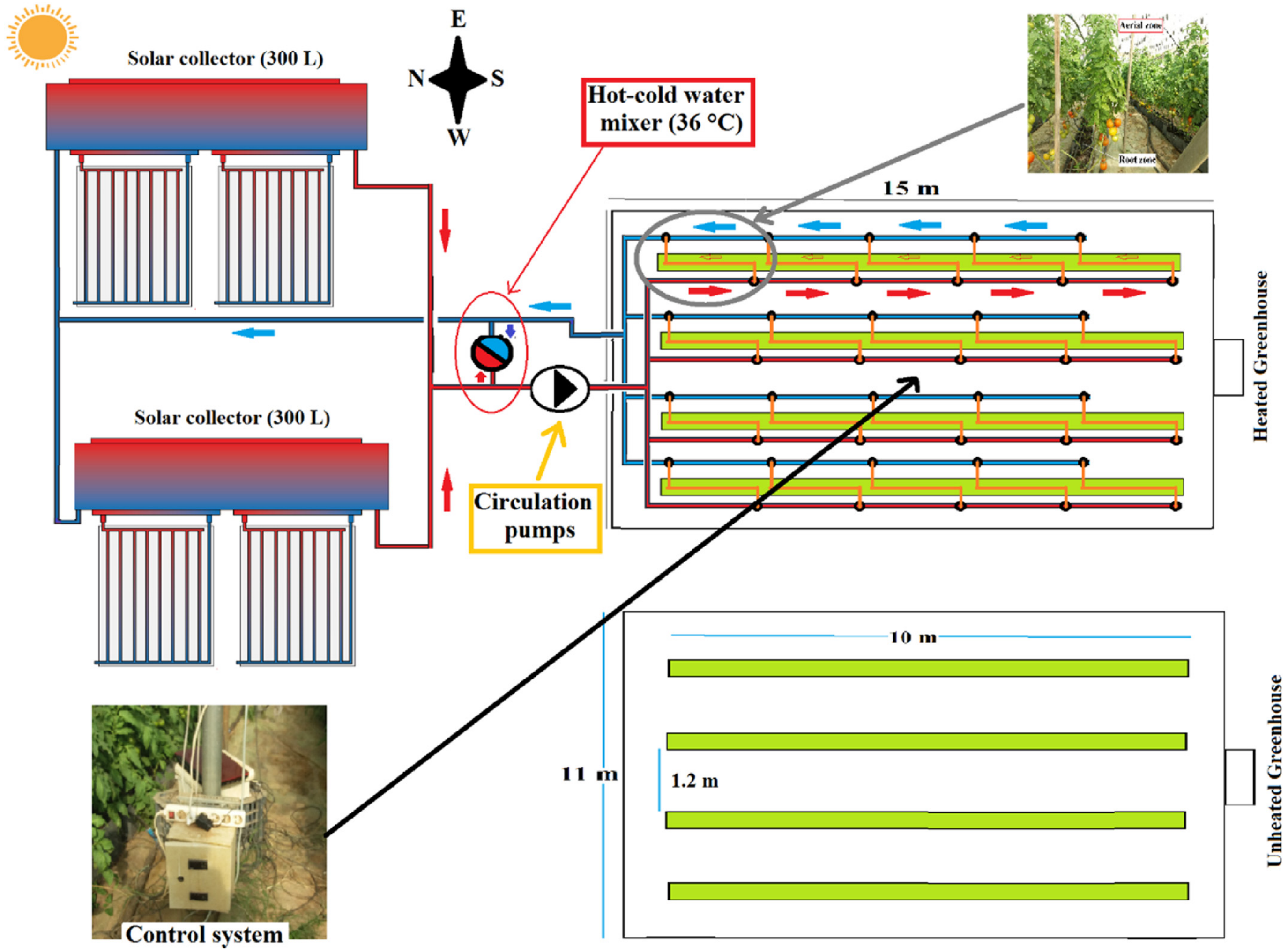

Fig. 3. Simplified diagram of the active solar heating system ASHS and its connection with the heating distribution network in the greenhouse.

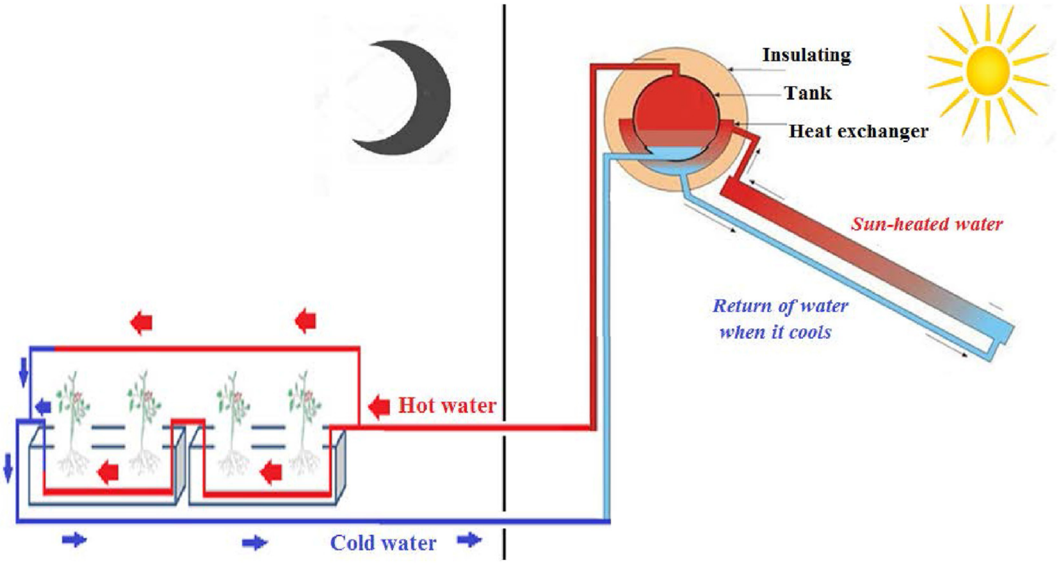

Fig. 4. General functioning scheme of the ASHS system.

tomato (*Solanum lycopersicum cultivar*: Zayda), planted in October 02, 2019 on soil-less substrate with a density of 2 plants (two stems)/m2. Crop rows were oriented North-South, perpendicular to the prevailing wind direction. The distance between rows was 120 cm and between plants was 33 cm. The heated greenhouse and the control greenhouse were irrigated using the same system and received the same amount of water and fertilizer which is 3.25 L/Plant/Day.

2.5. Climatic parameter measurements

To study the effect of the ASHS system on the greenhouse microclimate, different climatic parameters influencing the crop growth were measured by calibrated sensors.

2.5.1. Greenhouse microclimate

In the two greenhouses air temperature and relative humidity were measured in the center of the greenhouse at three different heights using temperature and humidity sensor (HMP60, Campbell Scientific Ltd., UK). The soil temperature was measured at 6–8 cm deep by means of a thermocouple type E (TCAV-L, Campbell Scientific Ltd., UK). The temperature in the root zone is measured using a thermistor (108, Campbell Scientific Ltd., UK) planted in the substrate in center of the greenhouse, as illustrated in Fig. 5.

The net solar radiation was measured inside the greenhouse at 4 m above the ground by a radiometer (CNR4-Net, Campbell Scientific). This parameter corresponds to the difference between the solar radiation transmitted by the cover and the solar radiation reflected by the different components of the greenhouse (inside air, crop, soil, cover). The heat flux exchanged across the soil was measured by the flat heat flux meter (HFP01, Campbell Scientific) placed at 8 cm under the ground.

2.5.2. External climatic conditions

The outside climatic data were obtained from a weather station, located above the greenhouse. It continuously measures the following climatic parameters: The temperature and relative humidity of the outside air above the greenhouse using Vaisala (HMP60); the average soil temperature using a thermistor PT107; global solar radiation by a CMP11 pyranometer. All these data were stored in a data logger (CR3000 Campbell Scientific).

2.6. Agronomic and quality parameters monitoring

The agronomic parameters monitoring is very important to analyze the ASHS system efficiency in order to assess its effect on the crop growth. In this study, all agronomic parameters were recorded from the beginning to the end of the crop cycle.

The weekly agronomic measurements were focused on growth parameters (stem height, leaf area, stem diameter), yield indicators (flowering, fruit set, fruit set rate, average fruit weight, size, soluble matter content (% Brix), acidity rate (% citric acid equivalent) and firmness. Fig. 6 shows a descriptive diagram of the location of the selected plants in the two greenhouses.

The total of the selected plants in each greenhouse is 24 plants, i.e. 6 plants per row. These plants are arranged in the middle and the sides of each row, so that the average value of each agronomic parameter, measured on the 24 plants, will be recorded and compared between the two greenhouses.

2.6.1. Fruit color

Each fruit or vegetable has a specific color indicates its maturity. The fruit color is measured with a “Minolta 200″ chromameter by light transmission. This device explains the color spectral distribution and the results can be obtained by two methods: “the spectrum wavelength values” or “the international lighting systems (Yxy, Lab)". This latter is based on the use of the three parameters L, a and b. Also, this device represents a measurement time of 1 s and a minimum measurement interval of 3 s. The measurement conditions for temperature and humidity are: 5–40 °C and 80% or less with no condensation, respectively.

The coloring is defined by its intensity “L" and its coordinates in a color plane of the two axes “a” and “b”. The formula of the color index (CI) is obtained by the combination of these tree parameters [44]. The CI for tomato fruits is giving by Eq. (1):

$$CI = \frac{2000 \times a}{L \times \sqrt{a^2 + b^2}} \tag{1}$$

where:

L is the light reflected by the fruit in the green zone of the spectrum, it indicates the percentage of its brightness; a is the difference between the light reflected from the fruit in the red and green zone of the spectrum. The negative values and the positive

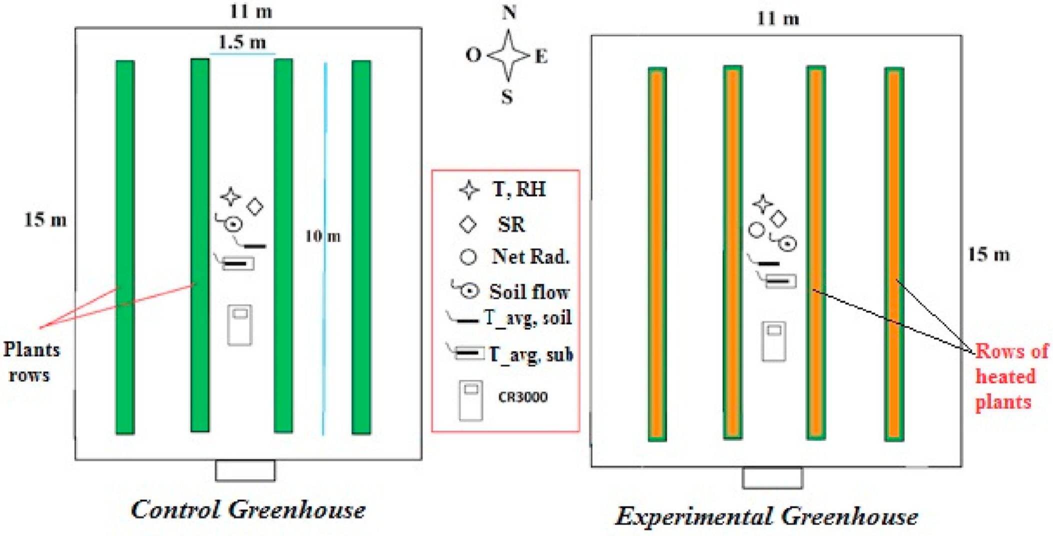

Fig. 5. Top view of the location for the different sensors installed in the two greenhouses.

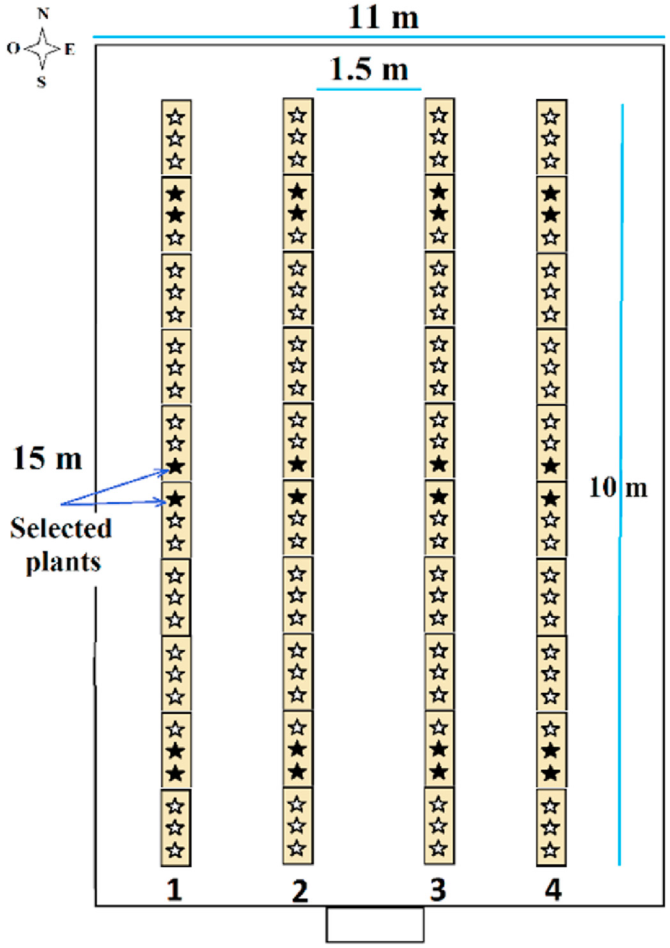

Fig. 6. Location of the selected plants in each of the two greenhouses.

Table 2
The adopted color index standards.

CI index	Color
$I.C. < -15$	Dark green color
$-15 < I.C. < -7$	Green to light green color
$-7 < I.C. < 0$	Light green to green-red color
$0 < I.C. < +7$	Light red color
$+7 < I.C. < +15$	Dark red color

values indicate the green and red coloring, respectively; b is the difference between the light reflected from the fruit in the blue and yellow zone of the spectrum. The negative values indicate a blue color, while the positive ones indicate a yellow color.

The color index standards adopted in our study are those of Jiménez-Cuesta et al. [44] (see Table 2).

The coloring measurement is done on two diametrically opposite zones on the fruit. Each fruit is measured individually, then an average is calculated on the number of sample fruits. Fruits ready to harvest have a light red color, and its positive color index is between 0 and 7.

2.6.2. *Firmness of tomato fruits*

Fruit firmness is one of the most important quality variables that quantify the resistance of fruits during storage and handling. It is in direct relation with the cohesion of cells and the membrane and the cell wall of the fruits. With the degradation of the membrane in particular, the flesh softens and becomes less resistant to pressure.

Fruit firmness is measured using an electronic penetrometer. The latter measures the force required to penetrate a tip to a certain depth in tomato fruit. The operating range of this device is 50–15,000 g for the fruit weight and 120 mm for its maximum diameter. Fruit firmness depends on the maturity and its stage of development.

2.6.3. *Sugar content*

The estimate of sugar content is based on the optical property of a sugar solution to reflect light. The percentage of dry matter thus measured is called the refractometric index, which corresponds to the percentage of sucrose in the juice, it is expressed in degrees Brix (°Brix).

To measure the refractive index, we need to put some drops of the fruit juice on the prism of the refractometer after cleaning with distilled water. The value displayed in °Brix must be corrected as a function of the juice temperature according to the following equation (Eq. (2)):

$$\text{Soluble Dry Extract } (SDE) = {}^{\circ}Brix \pm 0.08 \times \left(T\left({}^{\circ}C\right) - 20\right) \tag{2}$$

We use the sign "+" when the temperature is above 20 °C and the sign "−" if the temperature is below 20 °C.

The refractometer has a sugar content and temperature measuring range of 0–85 °Brix and 0–80 °C, respectively with an accuracy of ±0.2 °Brix and ±0.3 °C.

2.6.4. *Acidity rate*

The acidity measurement is carried out by neutralizing the total free acidity with a soda decinormal solution (sodium hydroxide NaOH).

The evolution of the neutralization is followed by a pH-meter or a color reagent (phenolphthalein). The dosing is stopped when the indicator turns pink/orange (phenolphthalein turning point) or when the pH reaches 8.1 to 8.2 (all acids are neutralized).

To prepare this acid-base dosage, just take 10 ml of filtered and homogenized juice and 10 ml of distilled water and place the pH-meter electrode in the juice or pour 3 to 4 drops of phenolphthalein, then pour the soda solution (placed in a graduated burette) drop by drop until reaching pH 8.1 to 8.2 or reaching the turning zone (pink/orange).

It is recommended to use a magnetic stirrer to facilitate the mixing of the solution soda with the juice.

The Citric Acidity is expressed by this formula (Eq. (3)):

$$\%\,Citric\ Acidity = \frac{Q_A}{10 \times d} \tag{3}$$

where Q_A is the amount of acid in the juice is giving by:

$$Q_A = 0.64 \times V_{(NaOH)} \tag{4}$$

and d is the density of the fruit juice and given by:

$$d = \frac{Mass\ juice}{Juice\ volume} \tag{5}$$

3. Results and discussions

3.1. Inside climate analysis during the whole measurement period

3.1.1. Solar radiation

The variation of the external global solar radiation and that transmitted inside the greenhouse as well as the net radiation measured above the crop, from 12 to January 17, 2020 are given in Fig. 7. The intensity of the external solar radiation increases from sunrise to reach its maximum value at noon when the sun is at its peak. The maximum daily value obtained outside is approximately 760 W/m2. 75% of this radiation is transmitted inside the greenhouse (about 560 W/m2).

The average value of the net solar radiation which corresponds to the ratio of the solar radiation reflected by all greenhouse components to that transmitted one is around 450 W/m2. This value represents 60% of the solar radiation received inside the greenhouse.

As illustrated by the Fig. 7, the net and transmitted radiation follows the same trend as the global solar radiation, and its fluctuations also correspond to the fluctuation of the solar radiation received inside the greenhouse.

3.1.2. Air temperature and humidity

Fig. 8 shows the evolution of the inside air temperature, as a function of time, in the two greenhouses. The temperature outside is always lower than air inside the two greenhouses due to the solar radiation trapping phenomenon. This temperature does not exceed a maximum value of 22 °C during the day, and fall to a minimum of 0.5 °C at night. The temperature difference between the inside and the outside is 18 °C during day, and only 1 °C at night.

At night, the temperature in the heated greenhouse is on average 6 °C higher than in the control one. During the day, air temperatures in the two greenhouses are almost identical due to the natural ventilation which occur in the two greenhouses.

According to the literature [45–48] the vegetation zero for tomato plants is located at 12 °C. Bellow this value the flower appearance, fertilization and fruit set are delayed. Giving the work of Heuvelink [49] the optimal growth temperature for tomato, is situated between 22 and 26 °C during the day and 13–18 °C at night.

Following this literature information and our experimental results, we can deduce that the ASHS used in this study recreates perfectly the optimal thermal conditions for an optimal growth for tomato plants during the cold periods.

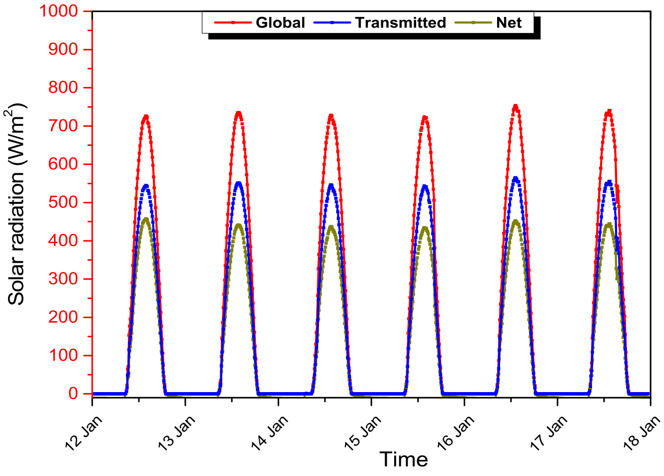

Fig. 7. Evolution of the global, transmitted and net solar radiations measured inside the greenhouse from 12th to January 17, 2020.

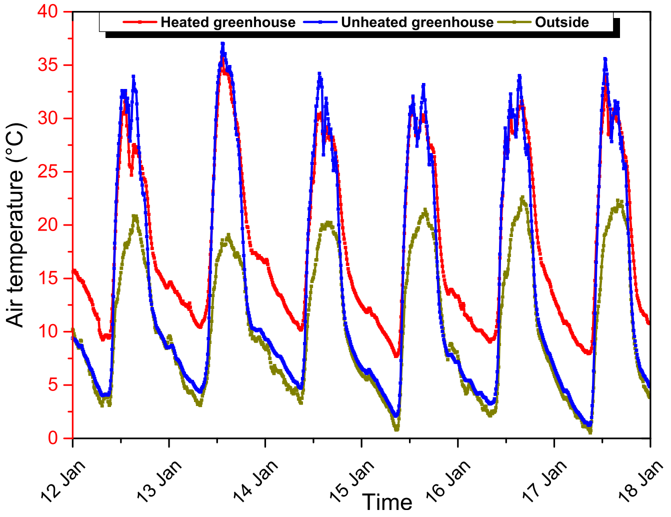

Fig. 8. Evolution of air temperature inside the heated greenhouse, unheated one and outside from 12th to 17th January 2020.

Other heating systems were tested under similar climatic conditions and gave less favorable thermal conditions. Among them we can mention the active heater system studied by Bouadila et al. [50,65] who have recorded only 5 °C improvement in the temperature inside the greenhouse in Tunisia despite the good insulation of the greenhouse. Bargach et al. [51] found that an active solar system with a heating network installed in the ground of a tunnel greenhouse increase the inside temperature at night by 1.2 °C. For their part, Gourdo et al. [4] and Bazgaou et al. [52] found an improvement of 1 °C and 2.6 °C respectively using rock bed active solar system.

With regard to air humidity, Fig. 9 illustrates the evolution of the relative humidity in the two greenhouses and the outside. This figure shows that air humidity in the heated greenhouse is on average 24% less than in the unheated one. This reduction in humidity is due mainly to the passive dehumidification affect generated by the ASHS during its operating periods.

This dehumidification process is beneficial for plants since it

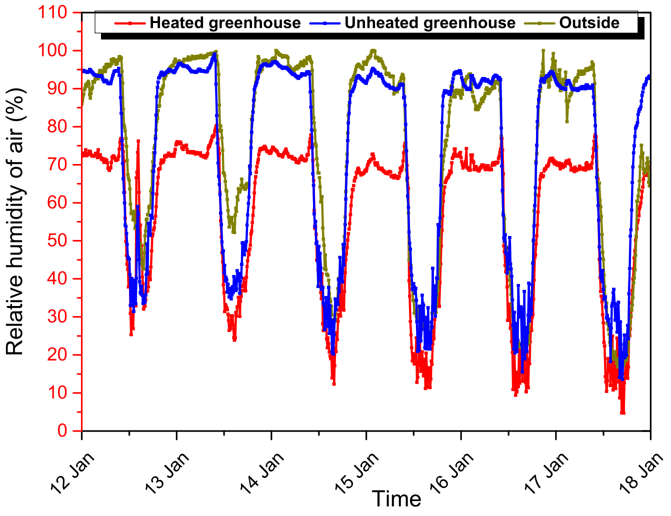

Fig. 9. Evolution of humidity relative in heated/unheated greenhouse and ambient humidity from 12th to 17th, 2020.

reduces the frequency of condensation on plants and thus avoids favorable conditions for the development of cryptogamic diseases [53].

3.1.3. Root zone temperature

Fig. 10 shows the temperature variation in the root zone in the heated greenhouse and in the control one. The evolution of the root zone temperature shows that the heating begins when the aerial temperature is below 12 °C at 8 p.m., and stopped at 10 a.m. when it is above this sit value (Fig. 11). The ASHS has a very positive effect on the evolution of the root temperature, which varies between 19 and 26 °C. The improvement of this latter is reached 10 °C at 8 a.m. and 14 °C at 10 a.m. compared to that of the unheated greenhouse. This thermal treatment is important for the absorption of nutrients.

The root temperature increases during the operation time of the ASHS system until inside temperature reaches 12 °C at 10:00 (Zone (1), Fig. 11). When the ASHS system is stopped the hot water in the exchanger tubes begins to cool down, consequently the temperature of the root zone in the heated greenhouse begins to decrease and varies inversely than that in the unheated greenhouse (Zone (2), Fig. 11). In addition, the evacuation of the heat accumulated in the root zone of the heated greenhouse, during heating, is done slowly and ends around 7.30 p.m. when the temperatures of the two root zones of the heated and unheated greenhouses equalize.

The improvement of the root zone temperature at night, is among the means of increasing the tomato crop yield under greenhouses. The experimental study by Teasdale and Abdul-Baki [43] established that the optimum temperature range for a good root growth of tomatoes under greenhouses is from 20 to 30 °C during the winter season. Early root growth and better yield are observed during the heating periods. For their side, Tindall et al. [54] showed that the optimal temperature for good root growth of Solanum lycopersicum tomatoes (cultivar: Zayda) (the same as the tomato crop used in our study), is located between 20 and 25 °C. This temperature range provides maximum absorption of nutrients by roots. Another similar study made by Díaz-Pérez and Dean Batal [54] confirms that the growth and the yield of the tomato plants were higher when this zone is heated to a temperature of 20–32 °C.

3.1.4. Soil flux and average temperature

Fig. 12 displays the variation of the soil temperature in the heated greenhouse and in unheated as well as the temperature of external soil during the measurement campaign.

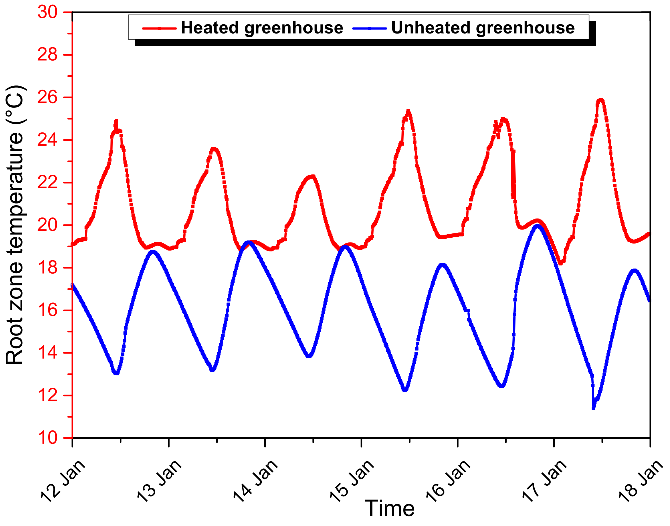

Fig. 10. Evolution of the root zone temperature in the heated greenhouse and the unheated one from 12th to 17th January 2020.

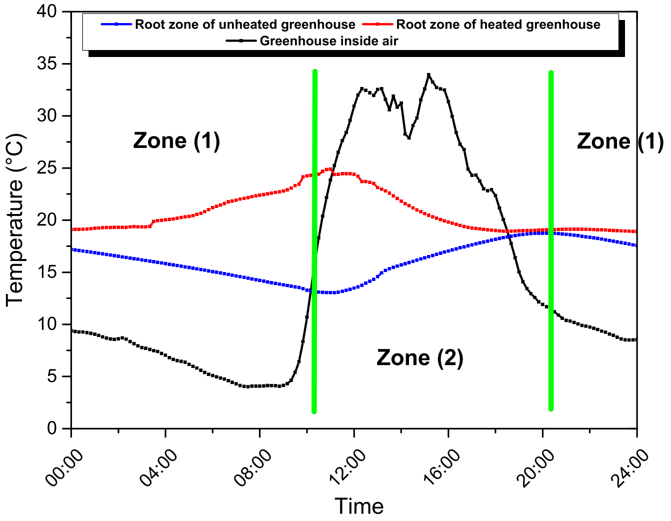

Fig. 11. Root zone temperature in both heated and unheated greenhouses (January 12, 2020).

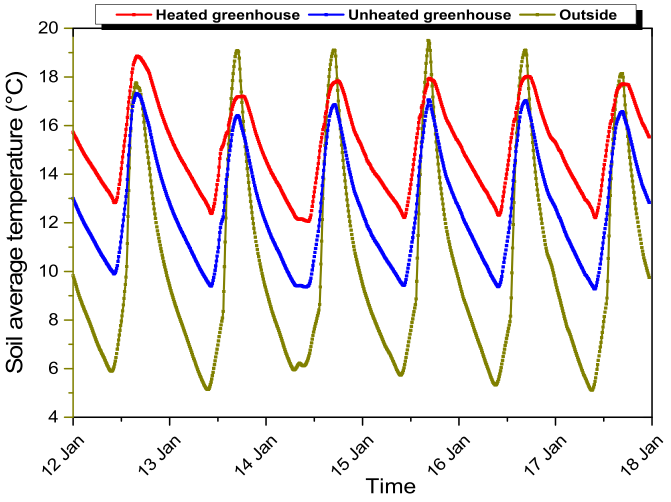

Fig. 12. Variation of the soil average temperature in heated greenhouse and in unheated one from 12th to 17th January 2020.

At night, the average temperature of the soil in the heated greenhouse is higher than that of the control one, this is due to the heat exchange carried out by conduction between the soil and the root zone. The temperature improvement reached a different of 2.5 °C between the soil of the two greenhouses. During the day, this temperature is slightly high in the heated greenhouse with a difference of 1 °C.

The heating treatment proposed in this study is capable of achieving thermal equilibrium in the different components of the greenhouse.

Fig. 13 represents the variation of the soil flux in the heated greenhouse and in the unheated one from 12th to 17th January 2020. The results show that the soil flux released at night in the heated greenhouse is less important compared to the control one. This may be explained by the temperature difference between the two greenhouses and the thermal equilibrium between the soil and the inside air in the heated greenhouse.

The soil absorbs thermal energy available inside greenhouse and also the energy generated by the heated system. This exchanged

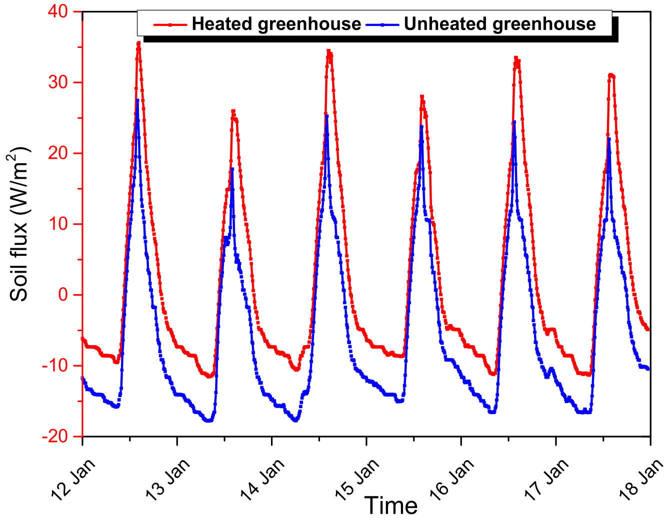

Fig. 13. Evolution of soil flux in the heated greenhouse and the unheated one from 12th to 17th January 2020.

energy between soil and air, varies between 25 and 36 W/m^2 during the day and 10 W/m^2 at night in the heated greenhouse. For the control greenhouse, these values are respectively, 17–27 W/m^2 during the day and 15–18 W/m^2 at night.

The greenhouse soil equipped by the ASHS absorbs a quantity of thermal energy, emitted by two sources; the greenhouse effect and the heating system. This amount absorbed varies between 25 and 36 W/m^2 during the day and that released is around 10 W/m^2 at night. For the control greenhouse, these values are respectively, 17–27 W/m^2 during the day and 15–18 W/m^2 at night.

3.2. Agronomic study

3.2.1. Plants foliage

According to studies conducted by Van Ploeg and Heuvelink [54] young plants grown at suboptimal temperatures produce thicker leaves, so they intercept less light and therefore have a lower productivity. This was also observed during our study in the unheated greenhouse, where the foliage is thicker than heated one, as shown in Fig. 14.

3.2.2. Tomato truss

Fig. 15 shows the evolution of the average number of tomato truss in the two greenhouses during three months after planting. The appearance of the first bouquet was observed on day 13 after planting in the two greenhouses. One week after the start of ASHS operation, the day that is the 76 days after planting, a difference in bouquet number was observed between the two greenhouses. This difference increases until it reaches 2 trusses on the 92 day after planting.

This increase in the average number of truss is reflected in the increase of the tomato production in the heated greenhouse.

4. Qualitative and quantitative analysis

The analysis qualitative of the harvested fruits, was studied by comparing the data related to the external aspect (the color, fruits size and its average weight and firmness) and the organoleptic quality (soluble matter content (°Brix) and acidity rate of citric acid equivalent) between the two greenhouses.

4.1. External quality

4.1.1. Fruit color

In heated greenhouse, the color index is higher than that of the control greenhouse with an improvement of 1.77 (Table 3). The ASHS system has a positive effect on the maturity of the tomato fruits. Therefore, the harvest seasons will be observed in the heated greenhouse compared to the control one.

4.1.2. Fruit size and average weight

The harvested fruits were grouped into seven sizes according to agronomic standards from the largest to the smallest: out of class (>85 mm), class 1 (75 mm < diameter <85 mm), class 2 (65 mm < diameter < 75 mm), class 3 (55 mm < diameter <65 mm), class 4 (45 mm < diameter <55 mm), class 5 (<45 mm) and fruit waste as illustrated in Table 4.

To measure the average weight of different sizes, we chose 5 samples per size and we averaged on its weights.

The results show that root zone heating, improves the average weight of the harvested fruits. For example, the sizes 2 and 3 have were increased by 15% and 19%, respectively. It is clear that the ASHS system has a very positive effect on the average weight of the harvested fruits which certainly due to the improvement of the absorption of nutrients at root level. Moss [55] shows that heating root zone to 20–25 °C increases the percentage of tomato fruit set, improves the size and fruit number per bouquet, and allows to increase the total weight of the harvested fruits by 15%.

Fig. 16 shows the percentages of tomato fruit sizes, which were harvested in the two greenhouses during the winter period. We observed that the size 2 is the most dominant in the heated greenhouse, whereas in the unheated one size 3 is the most dominant. So clearly the ASHS thermal treatment has a very positive effect on the size of tomato fruits.

4.1.3. Firmness of tomato fruits

The firmness results of tomato fruits harvested from the two greenhouses are displayed in Table 5 and expressed in g/cm^2.

The ASHS heating system improves the fruits firmness by 0.59 g/cm2 in the heated greenhouse compared to unheated one. Therefore, the heated fruits have a greater resistance of storage and handling than that of the unheated ones.

4.2. Internal quality

According to Beckles [55] the sugar content and citric acidity are the main parameters responsible on tomato flavor.

4.2.1. Sugar content

The Table 6 illustrates the average sugar content in Brix of fruits harvested in the two greenhouses, as well as the soluble dry extract (SDE). These data show that the ASHS thermal treatment improves the sugar content by 0.997 °Brix.

4.2.2. Acidity rate

Table 7 shows the average values of citric acidity in the heated fruits and unheated ones. The citric acidity of tomato fruits in the heated greenhouse is higher by 2.88% than in the control greenhouse. This improvement is largely attributable to the thermal comfort created by the ASHS system that an optimal absorption of essential nutrients at the root level.

The acidity is important for a good development of the tomatoes taste and for an effective conservation of product [56]. The citric characteristics are classified, like the main acid of tomatoes, with other organic acids by Murdock [57]. The tomatoes citric acidity is started in ovarian shortly after the beginning of the flower buds

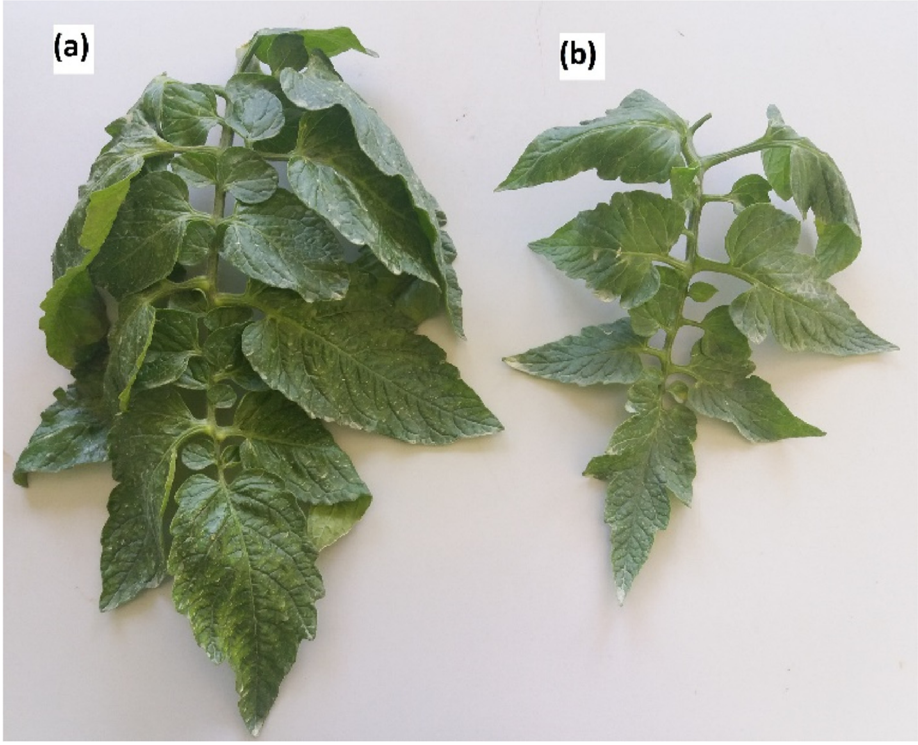

Fig. 14. Plant leaves in the unheated greenhouse (a) and in the heated greenhouse (b).

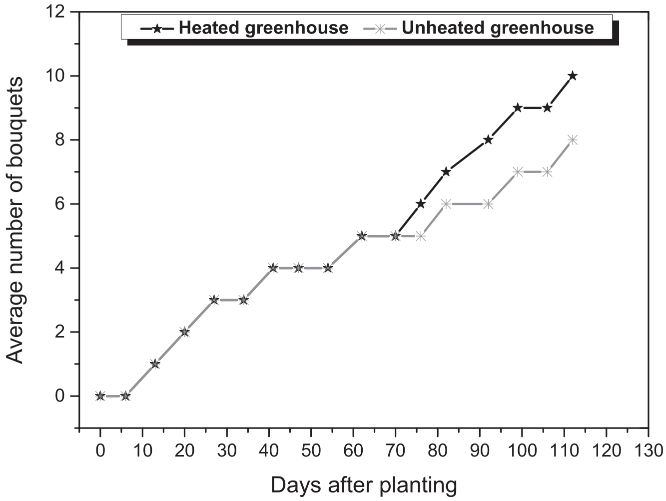

Fig. 15. Evolution of average number of truss in the two greenhouses as a function of time.

development, and gradually increases to a maximum when the first color change associated with normal ripening is visible in the fruit [58,59].

The taste is generally related to the relative proportions of sugars and acids in tomato fruits, mainly fructose and citric acid. The combination of high sugars and acids contents produces the tastiest tomatoes (Table 8).

Table 3
Average color index of fruits harvested in the two greenhouses.

	Heated greenhouse	Unheated greenhouse
Average color index	6.01	4.33
Corresponding color	Light red	Light red

We have noticed that the tomato plants under the unheated greenhouse, which represent the minimum temperatures in the root zone, have absorbed less of nutriments than those of the heated greenhouse where the root temperatures reach the optimum growth values.

4.2.3. *Tomato yield*

Fig. 17 illustrates tomato quantity for each harvest from the two greenhouses (Fig. 17 (a)) and the total production per square meter during the cold period of January, February and March (Fig. 17 (b)). This figure shows clearly that the production in the heated greenhouse is higher than that of the unheated one. In general, the active solar heating system improves the greenhouse production by 55%, during the cold season.

Other studies using solar thermal heating systems have found less production increases compared to ASHS heating system. Bargach et al. [60] found an improvement of 20 g/plant in crop melon yield using heating system based on solar thermal storage. Gourdo et al. [4] and Bazgaou et al. [27] showed that the rock bed solar heating system increase the tomato yield by 22% and 29% respectively. Bazgaou et al. [9] managed to increase the tomato yield by 49% by using a combined solar heating system (rock-bed and water filled passive solar sleeves).

Several studies are carried out in this research focus such as; the studies of Bargach et al. [60] found an improvement of 20 g/plant in the yield of crop melon using a heating system based on solar thermal storage. Another study by Gourdo et al. [4] showed that the rock bed solar heating system results increase the tomato yield by 22%, and 29% in studies of Bazgaou et al. [27]. In Bazgaou et al. [9] studies shows that the use of the combined solar system to heat the inside air and the plantation substrates has a positive effect on agricultural yield, and improves it by 49%.

Table 4
The average diameter and weight of each class in the heated and unheated greenhouses.

Sizes		Out of class	Class 1	Class 2	Class 3	Class 4	Class 5	Waste
Average diameter (mm)		>85	75–85	65–75	55–65	45–55	35–45	<30
Average weights (g)	Heated greenhouse	≥330	302	195	155	82	46	≤35
	Unheated greenhouse	≥300	280	170	130	70	40	≤30

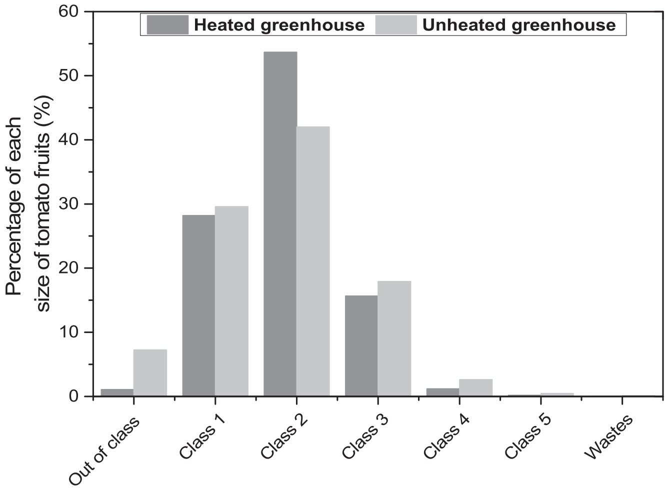

Fig. 16. The percentage of each fruits size in the two greenhouses during the winter period.

Table 5
The firmness of the fruits harvested in the two greenhouses.

	Heated greenhouse	Unheated greenhouse
Average firmness (g/cm^2)	3.35	2.76

Table 7
Average citric acidity in the tomato fruits harvested in the two greenhouses.

	Heated greenhouse	Unheated greenhouse
Average citric acidity (%)	26.33	23.45

Table 8
Association of citric acidity and sugar content in tomato fruits and its taste.

Citric acidity	Sugar content	Taste
High	High	Good
High	Weak	Sour
Weak	High	Bland
Weak	Weak	Without taste

5. Economic analysis

The economic assessment of the solar heating system is based on its investment cost, life cycle, heating efficiency and its profitability in terms of profit and benefit under agricultural production.

The ASHS system presented in this work consists of two solar collectors, two storage tanks (300 L each), a network of plastic pipes for hot and cold-water circulation (PPR), and a network of PE black plastic exchangers (16 mm in diameter). The life cycle of this solar system is about 20 years [61,62] and that of PPR and PE is 50 years [63,64].

The total cost of active solar heating system comprises the investment cost and the electric energy consumption cost in American Dollars (USD). The investment cost includes the system components cost and the installation and maintenance cost [66,67]. The energy consumption is equal to the sum of the electrical energy consumed by the control system and the circulation pumps during the cold period (three months). The thermal performance of the solar system concerns the increase of the nocturnal temperature and the reduction in relative humidity of air inside the greenhouse.

To assess the economic profitability of this ASHS system, we have computed the total ASHS system cost per unit of heated area and the average profit of the tomato crop for 8 harvesting periods with a density of 2 plants/m^2. The total cost related to this ASHS system include the equipment cost, the cost of installation/maintenance and the energy consumption cost around 6.70 USD/m^2. We have to mention that the price of 1 KWh in Morocco is about 0.10 USD.

The gain in yield of the greenhouse equipped with the ASHS system is 9.81 kg/m^2, which corresponds to 55%, compared to the greenhouse without heating system. The unit cost of exportable tomatoes is around 1.43 USD/kg (i.e. 1.22 Euro, ICEX-Eurostat data).

The economic results presented in Table 9 show that the ASHS system is very profitable in terms of cost and thermal comfort. Despite its low investment cost per unit area (6.70 USD/m^2) and low-power consumption (0.57 USD/m^2). The total average profit is approximately 29.54 and 22.28 USD/m^2 for the heated and unheated greenhouse, respectively. So, the average benefit after installing the ASHS system and subtracting the total inputs cost is 7.26 USD/m^2.

In addition to this comparative study, we have also computed the output-input ratio of tomato production and energy use. This efficiency ratio indicates the relation between the amount produced of a good or a product and the quantity of inputs used in the production process. The productivity ratio is high (300%) which gives an idea about the system performance. The energy productivity is around 440%.

From an economic point of view, the proposed system has a very positive effect on yield precocity, particularly, for the first harvesting periods which ensures higher selling prices whether for the local or international markets. The cost/benefit and financial profitability analyses demonstrated that heating the canarian greenhouse with this ASHS system is very profitable and could generate significant benefits for farmers.

Table 6
The average sugar content and soluble dry extract in heated and unheated fruits.

	Heated greenhouse	Unheated greenhouse
Average sugar content (°Brix)	2.20	1.225
Average Soluble Dry Extract (°Brix) at $T = 18.6\ ^\circ C$	2.312	1.315

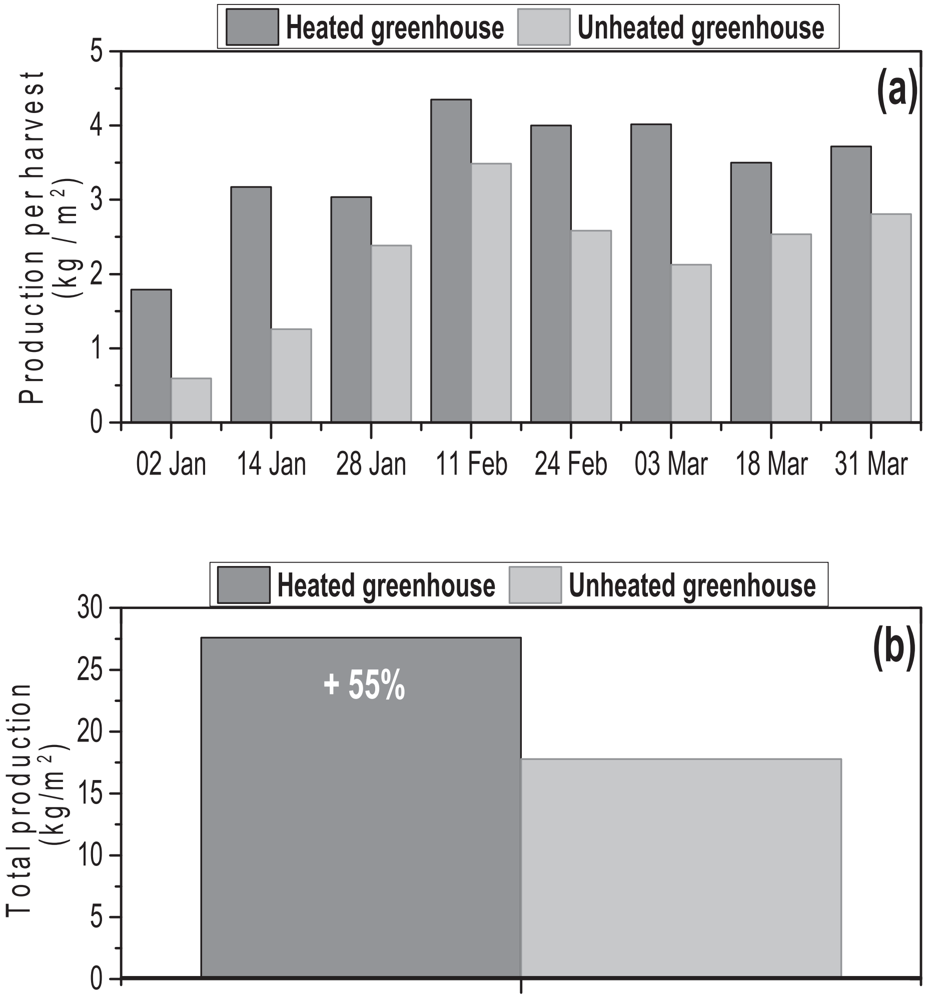

Fig. 17. Production at each harvest (a) and the total production (b) in the two greenhouses per unit area during the winter period.

Table 9
Economic assessment of active solar heating system in greenhouse application.

Thermal comfort	Improvement in nocturnal temperature	6 °C	
	Reduction in relative humidity	24%	
System cost (USD/m^2)		Solar panels	3.72
		Installation and maintenance costs	0.20
		Energy cost	0.57
		Plastic piping (PPR)	1.84
		Exchangers (PE)	0.37
Total costs of the ASHS system (USD/m^2)		**6.70**	
Exportable yield (Kg/m^2)	Unheated greenhouse	17.77	
	Heated greenhouse	27.58	
Difference of yields (Kg/m^2)		**9.81**	
Average gain of Yield in %		**55%**	
Investments and operational costs (USD/m^2)	Control greenhouse	3.13	
	Heated Greenhouse	9.83	
Average profit (USD/m^2)	Control greenhouse	22.28	
	Heated Greenhouse	29.54	
Average benefit of the ASHS system (USD/m^2)		**7.26**	
Economic productivity ratio in %		**300%**	
Energy productivity in %		**440%**	

6. Conclusion

The performance of the Active Solar Heating System used to heat a canarian greenhouse, was assessed in order to evaluate its effect on the microclimate and crop yield.

This assessment concluded that the ASHS system improve the nocturnal climatic conditions in the aerial part of plants as well as at the root level. The thermal comfort created in root zone, increases the absorption of essential nutrients, which improve the external quality (color, size, weight and firmness) and the internal quality (sugar content, acidity and taste) of tomato fruits. This improvement is also reflected by increasing total tomato yield by 55% in winter period.

Economic analysis indicates that the integration of ASHS system in greenhouse applications is very profitable and could generate profits for farmers.

CRediT authorship contribution statement

A. Bazgaou: Writing - original draft, Experimental studies and article writing. **H. Fatnassi:** Framing. **R. Bouharroud:** Agronomic studies. **K. Ezzaeri:** Experimental studies. **L. Gourdo:** Experimental studies. **A. Wifaya:** Agronomic studies. **H. Demrati:** Experimental studies. **F. Elame:** Economic study. **Á. Carreño-Ortega:** Handling protocol. **A. Bekkaoui:** Framing. **A. Aharoune:** Framing. **L. Bouirden:** Framing.

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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