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Root zone temperature control with thermal energy storage in phase change materials for soilless greenhouse applications

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A B S T R A C T

A new root zone temperature control system based on thermal energy storage in phase change materials (PCM) has been developed for soilless agriculture greenhouses. The aim was to obtain optimum growing temperatures around the roots of plants. The candidate PCMs were 40% oleic acid–60% decanoic acid mixture and oleic acid alone. Field experiments with these PCMs were carried out in November 2009 with *Cucurbite Pepo* and March 2010 with *Capsicum annum* plants. No additional heating system was used in the greenhouse during these periods. In the November 2009 tests with zucchini, 40% oleic acid + 60% capric acid mixture was the PCM and a temperature increase in the PCM container (versus the control container) was measured as 1.9 °C. In our March 2010 tests with peppers, both PCMs were tried and the PCM mixture was found to be more effective than using oleic acidalone. A maximum temperature difference achieved by the PCM mixture around the roots of peppers was 2.4 °C higher than that near the control plants.

1. Introduction

Man has been using finite energy resources as if they were infinite. Local production and less dependence on remote resources are the key elements of sustainability. Greenhouses provide environments to grow crops sustainably. Local production along with increased yields/area, longer harvest periods, and better controlled growing environment makes greenhouses attractive. There is an increasing interest in greenhouse production around the world. In Turkey, agriculture greenhouse area has reached 56,000 hectares in 2012 [1]. Growers who provide us with food and plants (i.e. potted plants, flowers, trees) hope to maximize their crops and at the same time to minimize their expenses. Heating is a major cost involved in greenhouses, and is usually provided by burning fossil fuels. Adverse environmental effects of fossil fuels like climate change and concerns over energy security are mandating the useof renewable energy sources more urgent than ever.

Thermal energy storage (TES) provides flexible solutions for renewable, continuous, and adaptable supplies of heating, cooling and dehumidification in greenhouses. The mismatch that exists between intermittent resources – like most of the renewables – can be narrowed by employing TES systems. The target duration of storage may be short (e.g. day/night) or long (e.g. summer/winter). For seasonal purposes, Underground Thermal Energy Storage (UTES) systems are mainly used. For short term applications thermal energy storage in Phase Change Materials (PCMs) are usually preferable. TES systems can be designed to exploit local and renewable energy sources through active or passive systems. PCMs can also help to control temperatures in passive systems. The transport of fresh and/or perishable products like food, medicines, serums, etc. [2], control of indoor temperature of built-in environments [3], heat management of electronic devices [4] are some applications that can use thermal energy storage in PCMs. For biomaterials, it was shown that temperatures can be kept within desired levels for six hours using PCMs [2]. In these systems, temperature is controlled by PCM passively via absorption of heat during melting and releasing heat during freezing. An appropriate PCM for this application needs to be selected with respect to their melting/freezing temperatures and latent heat. Normally, in active greenhouse systems, heat is transferred by a fluid (water or air) from central heating plants via ducts or pipes to the plants in the soil. Seasonal TES systems may be used for many applications for such active systems [5], thereby decreasing fossil fuel consumption while increasingyields. Soilless growing techniques are used widely by growers of ornamental flowers and organic plants. Here substrates replace soil as the growing medium in various sized pots and containers. A substrate heating system controls the

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Nomenclature

CA	capric acid
$Cp_{,l}$	heat capacity in liquid phase (kJ/kg K)
$Cp_{,s}$	heat capacity in solid phase (kJ/kg K)
$Cp_{,Sb}$	heat capacity of substrate (kJ/kg K)
M	the mass of PCM (kg)
m_s	the mass of substrate (kg)
OA	oleic acid
PCM	phase change material
Q_L	latent heat (kJ)
Q_{PE}	the difference in energy of the substrate in the container with and without PCM (kJ)
Q_s	sensible heat (kJ)
Q_T	total energy stored by PCM units (kJ)
T_{cs}	substrate temperature of the control container (°C)
TES	thermal energy storage
T_f	final temperature of the PCM (K)
T_i	initial temperature of the PCM (K)
T_{in}	inside greenhouse temperature (°C)
T_m	melting temperature of the PCM (K)
T_{out}	the outside greenhouse temperatures (°C)
T_{s1}	substrate temperature of the container with oleic–capric acid mixture (°C)
T_{s2}	substrate temperature of the container with oleic acid (°C)
$T_{sf,c}$	final substrate temperature of control container (K)
$T_{sf,PCM}$	final substrate temperature of container with PCM (K)
$T_{si,c}$	initial substrate temperature of control container (K)
$T_{si,PCM}$	initial substrate temperature of container with PCM (K)
UTES	underground thermal energy storage
η	thermal energy storage effectiveness
ΔH_L	latent heat (kJ/kg)
ΔT	temperature difference (°C)
ΔT_{max}	maximum temperature difference (°C)

substrate temperature – thereby improve root activities (water and nutrient uptake, respiration) significantly [6]. The interaction between the roots and the above-soil parts of a plant are also improved through heating. In the study by Fernandez and Rodriguez, a substrate heating system is prepared by embedding piping at a certain depth in the substrate. Such a system is more costly and requires a significant amount of installation [7]. PCMs with their isothermal behavior and high storage capacity can provide an attractive alternative and/or augment such substrate heating systems.

In our study, the concept of temperature control with PCMs is applied to substrate heating system in a greenhouse. Melting PCM in passive TES units installed in the system store excess heat in the greenhouse during the day. During the night when heat is needed to keep the temperature of root zone at optimum levels, the PCM freezes to release the stored heat. Two different fatty acids are studied as PCMs in our system. Results from our field experiments in a greenhouse located in Adana, Turkey are presented here.

2. Materials and method

2.1. Location

The study greenhouse is located in Adana, Turkey (Latitude: 36.6N, Longitude: 35.2E) where a Mediterranean climate prevails. Greenhouses are quite common here with its mild winters and long insolation hours. The annual distribution of monthly average air temperatures and insolation periods for Adana are shown in Fig. 1. During most of November and March monthly average temperatures are around 19.5–8.4 °C and 22.2–10.7 °C. Such daily temperatures are high enough to grow plants without the need for heating in greenhouses. However, there may occur sudden drops in temperature at night-time when heating is necessary. Subzero temperatures present high risks for greenhouse producers.

2.2. Greenhouse

Field experiments were carried out in a section of a 500 m^2 glass covered greenhouse at Cukurova University, Department of Horticulture in Adana, Turkey. Soilless growing technique with drip irrigation was used in the greenhouse with ground-based system and crops in single rows. No heating or cooling was used during the tests. Measurements were done in the following two periods for the given plant varieties:

- *Period I:* November, 2009: Zucchini (*Cucurbite Pepo*)
- *Period II:* March, 2010: Pepper (*Capsicum Annum*)

Growth parameters of the plant varieties used in the tests are given in Table 1. These parameters are used to determine the optimum temperature levels necessary for each variety.

2.3. Phase change material

Based on the soil temperature levels required to avoid stress in the plants (Table 1), melting/freezing point of PCM was determined to be within the range of 10–15 °C. Two different fatty acids – oleic acid (OA; cis-9-octadecanoic acid), capric acid (CA; n-decanoic acid) and two paraffins (Rubitherm-RT2, Rubitherm-RT35) were selected to prepare PCMs in this range. OA and CA are among the most abundant fatty acids in nature. OA occurs naturally in olive oil and CA in coconut oil and palm oils. The purity of the fatty acids supplied by Merck were 65–88% for OA and 98% for CA. The properties of these materials as given by manufactures are shown in Table 2.

The mixtures of these selected materials are prepared to tailor the PCM according to the desired properties. The cooling curves of the prepared mixtures were obtained using a programmable thermostated bath with a heating/cooling rate of 1 °C/min. Temperature of the 10 ml samples in test tubes, placed in the bath were measured by T-type thermocouples with an accuracy of ±0.5 °C and recorded by a data logger (Agilent 34970A Model) at 15 s intervals. The freezing temperatures of the prepared PCMs determined from the cooling curves are listed in Table 3.

Based on these results, 40% OA–60% CA mixture and OA alone were selected as the PCMs for the greenhouse application. The cooling curves for the selected PCMs with freezing temperatures indicated by arrows are shown in Figs. 2 and 3. Fig. 2a and 3a are measured in the bath, while Fig. 2b and 3b are measured under outdoors temperature conditions. For OA–CA mixture, both measurements revealed a freezing temperature at 12.0 °C with a clear phase change plateau. For OA the freezing point in the bath was measured as 5.8 °C, but under outdoors conditions it was 12.0 °C.

This behavior can be explained with complex polymorphic structure of OA (γ and α forms). Solid–solid transformation from γ to α form occurs at around -3 °C and α form melts around

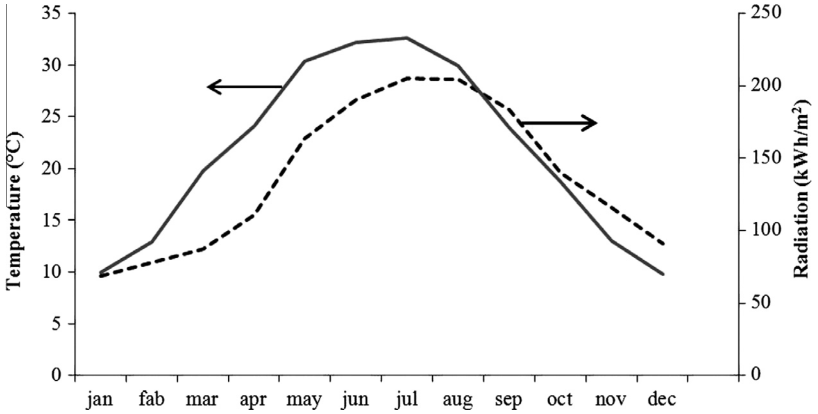

Fig. 1. Monthly average temperature and insolation hour distribution in Adana.

Table 1
Growth parameters of the plants used in the tests [8].

Vegetable	Seed germination temperature (°C)	Optimum soil temperature (°C)	Optimum growth temperature (°C)	
			Day	Night
Zucchini (*CucurbitePepo*)	10	15.5	20–25	7–13
Pepper (*CapsicumAnnum*)	8–10	17	18–25	14–16

Table 2
Properties of materials selected to prepare PCMs as given by manufacture.

	Melting point (°C)	Molar mass (g/mol)	Density (g/cm^3)	Flash point (°C)
Oleic acid	16	282.46	0.89 (20 °C)	180
Capric acid	29–32	172.26	0.89 (20 °C)	150
RT2	2–5	–	0.77 (15 °C)	102
RT35	35	–	0.88	178

Table 3
Freezing temperatures of PCMs determined from cooling curves.

PCM	Freezing temperature (°C)
Oleic acid	5.8
10% RT35–90% RT2	16.6
15% RT35–85% RT2	16.5
20% RT35–80% RT2	15.7
40% oleic acid–60% capric acid	12.6
50% oleic acid–50% capric acid	18.4
60% oleic acid–40% capric acid	18.3
70% oleic acid–30% capric acid	18.1

13 °C [9]. The existence of two transformations and their possible overlapping leads to discrepancies in the phase change temperatures found in literature. Some of the melting temperatures of OA reported in literature are: 16.4 °C [10], 13.4 °C [11], 13.6 °C [9], 8.1 °C [12], 13.8 °C [13] and 5.3 °C [14].

Further thermal analysis of OA and OA–CA were made by Differential Scanning Calorimetry (Perkin Elmer Diamond Model) at 1 °C/min heating rate and 3 °C/min cooling rate. The DSC result for OA shown in Fig. 4 reveals a peak at 9.1 °C corresponding to the melting of OA with a heat effect of 70.1 J/g. For OA–CA a clear peak was not detected during melting (Fig. 5). Inoue et al. explains this behavior with a molecular compound formed by the interaction of OA and CA in the mixture [9]. The solid CA coexists with a liquid phase formed by the melting of mostly the molecular compound. The amount of the solid CA decreases with temperature and the melting completes around 16 °C. For freezing, the peak at 4 °C with a heat effect of 36.4 J/g can be clearly detected as shown in Fig. 5.

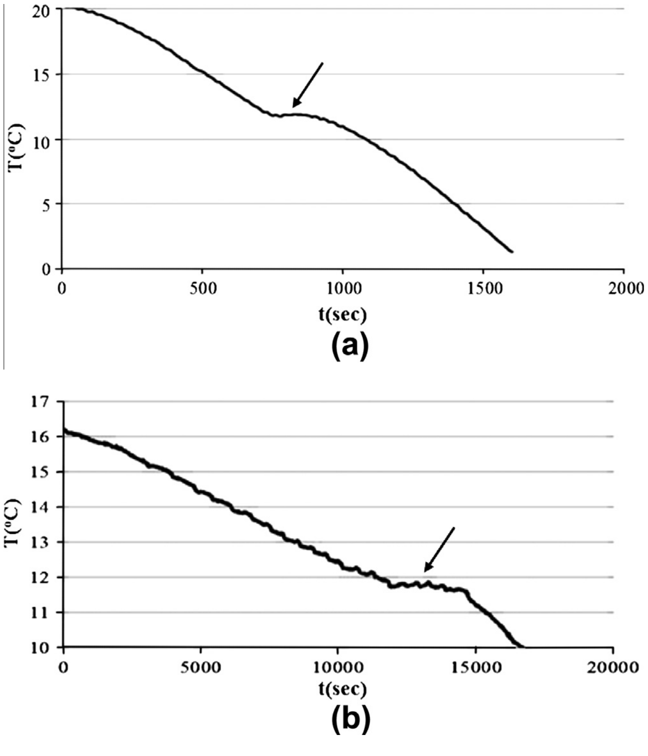

Fig. 2. Cooling curve of 40% oleic acid–60% capric acid mixture measured (a) in water bath (b) at outdoors conditions.

2.4. Substrate passive heating system

Crops were grown in single rows of plastic rectangular containers with dimensions of 0.80 m × 0.30 m × 0.20 m. The substrate used was 1:1 mixture of coco peat and perlite. PCMs were packed in plastic containers with dimensions of 0.16 m × 0.10 m × 0.03 m. 14 PCM units with a total mass of 2.6 kg for OA–CA and 4.4 kg for OA are placed on both sides of the containers as shown in Fig. 6.

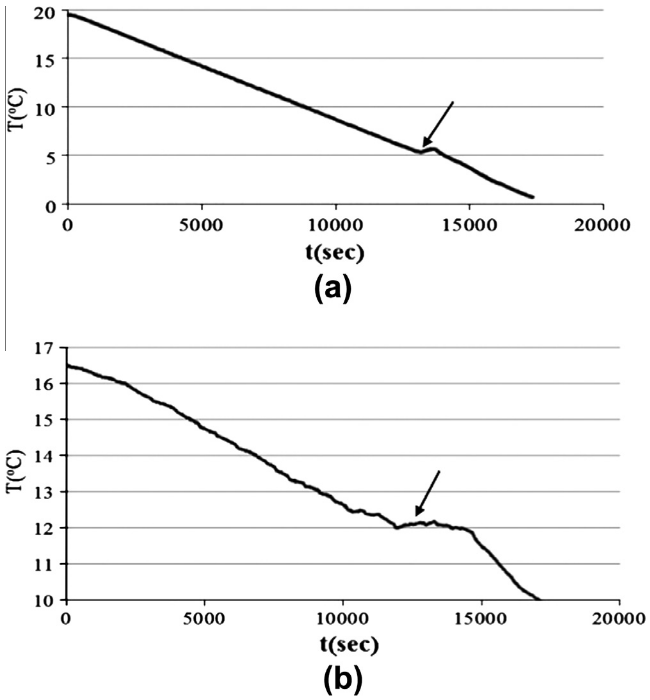

Fig. 3. Cooling curve of oleic acid measured (a) in water bath (b) at outdoors conditions.

Temperatures in the substrate (near root zone of the plant), in the PCM and air at plant level were measured for the container with PCM and at the control container without PCM (Fig. 6a and b). In addition, ambient temperatures inside and outside the greenhouse were recorded. For air measurements 105T-L type sensors, for PCM and substrate temperatures T type sensors were used. All measurements were recorded with a Campbell data logger at 15 min intervals.

2.5. Thermal energy storage effectiveness

Thermal energy in the forms of sensible (Q_s) and latent heat (Q_L) is stored by PCMs. Q_s and Q_L are calculated according to the following equations:

$$Q_L = m\Delta H_L \tag{1}$$

$$Q_S = mCp_s(T_m - T_i) + mCp_l(T_f - T_m) \tag{2}$$

where m (kg) is the mass, ΔH_L (kJ/kg) is the latent heat, $Cp_{,s}$ (kJ/kg K) is the heat capacity in solid phase, Cp_l (kJ/kg K) is the heat capacity in liquid phase, T_m (K) is the melting temperature, T_i (K) is the initial temperature and T_f (K) is the final temperature of the PCM. Total energy stored by PCM units, Q_T is the sum of latent and sensible effects given by the following equation:

$$Q_T = Q_L + Q_S \tag{3}$$

For a given period, passive heating effect, Q_{PE} (kJ) of the PCM is defined as the difference in energy of the substrate in the control container and the container with PCM, and is calculated according to the following equation:

$$Q_{PE} = m_s Cp_{sb}(T_{sf,PCM} - T_{si,PCM}) - m_s Cp_{sb}(T_{sf,c} - T_{si,c}) \tag{4}$$

where m_S (kg) is the mass and Cp_{Sb} (kJ/kg K) is the heat capacity of substrate. $T_{sf,PCM}$ (K) is final substrate temperature of container with PCM, $T_{sf,c}$ (K) is final substrate temperature of control container and $T_{si,PCM}$ (K) is initial substrate temperature of container with PCM, $T_{si,c}$ (K) is initial substrate temperature of control container.

The thermal energy storage effectiveness η is defined by the ratio given in the following equation:

$$\eta = \frac{Q_{PE}}{Q_T} \times 100 \tag{5}$$

3. Results and discussion

PCM based passive root zone temperature control system developed here was tested in a greenhouse without any heating in Adana, Turkey during the months March, 2010 and November, 2009. During these months, greenhouses do not usually require heating in Adana where mild Mediterranean climate prevails. However, hourly mean ambient temperature distribution for Adana given in Fig. 7 shows that, there were significant number of hours below the level of optimum plant growth temperature in November and March indicated by the dashed line. Just a few hours below optimum conditions can place the plants under stress and decrease the quality of the crops. Therefore, a heating system that can control the temperature passively can particularly be very useful when

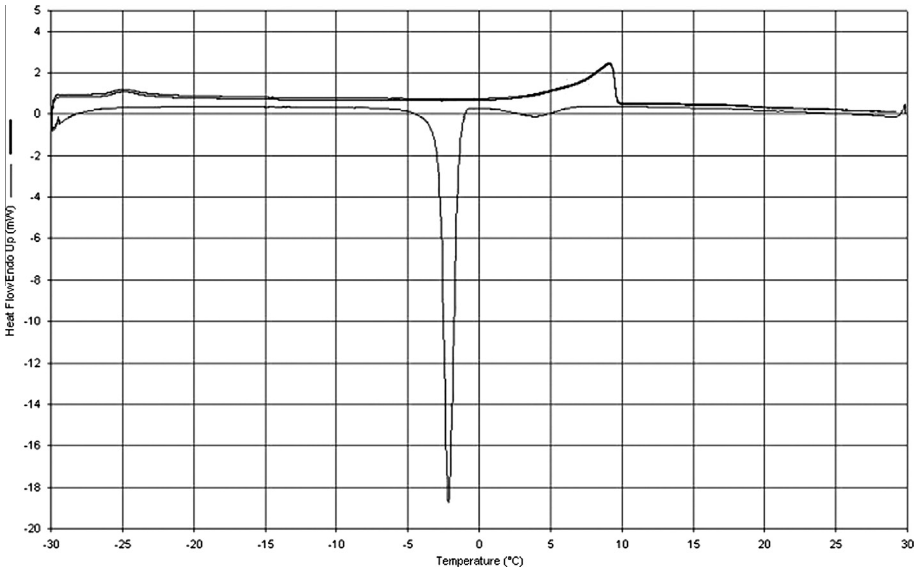

Fig. 4. DSC curve of oleic acid.

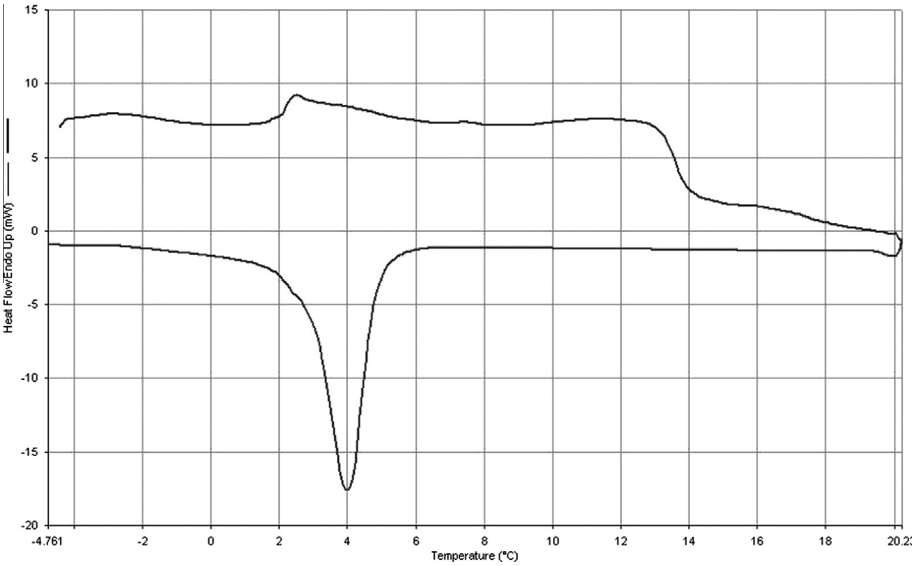

Fig. 5. DSC curve of 40% oleic acid–60% capric acid mixture.

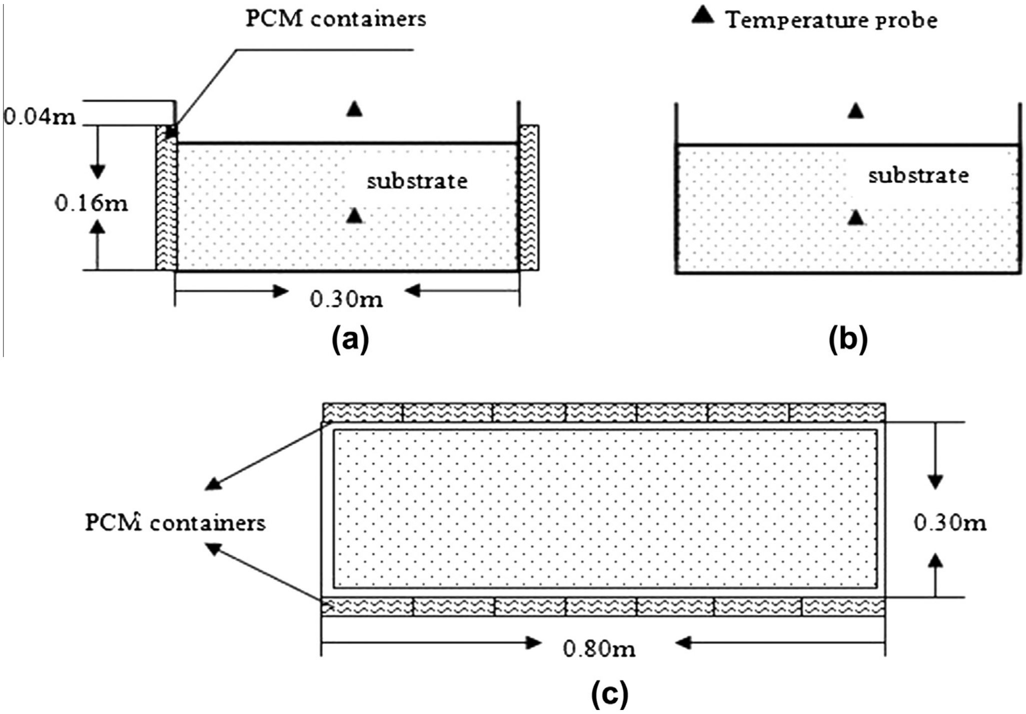

Fig. 6. Schematic diagram of the experimental set up (a) Lateral section of container with PCM, (b) Lateral section reference container and (c) Top view of container with PCM.

temperature drops below optimum conditions in the periods when heating is not employed.

The temperature measurements during the first period of November 14–23, 2009 are shown in Fig. 8. The inside (T_{in}) and outside (T_{out}) greenhouse temperatures during this period is below 10 °C at nighttime with minimum values dropping to 3.4 °C and 3.2 °C. Fig. 9 shows the temperature distributions for substrate with and without PCM (OA–CA) together with T_{in} and T_{out}. Substrate temperature of the container with PCM (T_{s1}) is higher than substrate temperature of the control container (T_{cs})during most of the nights as given in Fig. 9. The largest difference is obtained in the encircled region on the night of November 17th, which is the coldest day during this measurement period.

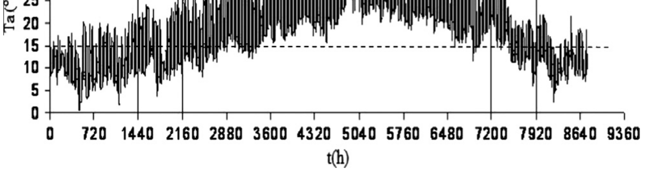

Fig. 7. Hourly mean ambient temperature distribution for Adana.

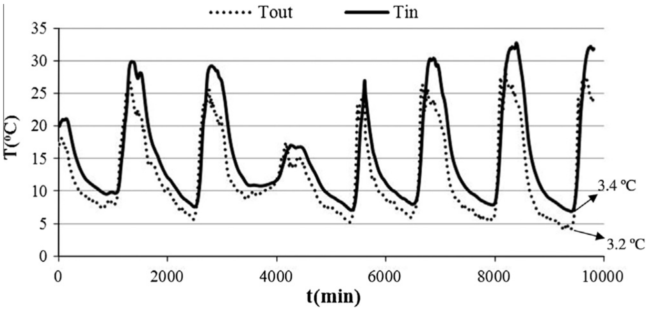

Fig. 8. Temperature and humidity measurements inside and outside greenhouse between November 14 and 23, 2009 (··· T_{out}, — T_{in}).

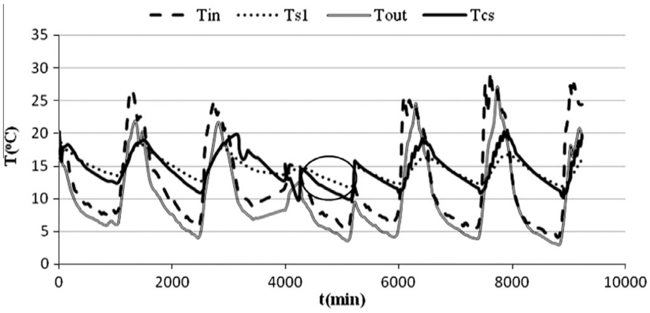

Fig. 9. Temperature measurements in PCM based passive heating system in the first period (November 14–23, 2009). The encircled region corresponds to November 17th (– – T_{in}, ······ T_{s1}, ═══ T_{out}, ▬▬ T_{cs}).

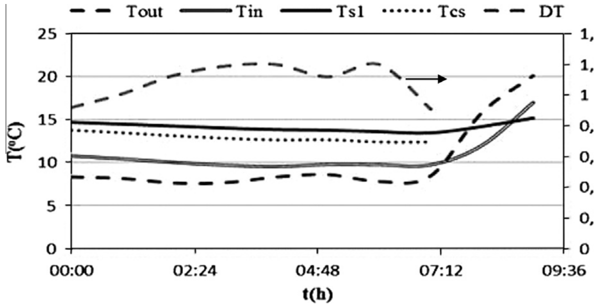

Fig. 11. Minimum temperature difference between control container and container with OA–CA on November 14th (– – T_{out}, ═══ T_{in}, ▬▬ T_{s1}, ······ T_{cs}, – – DT).

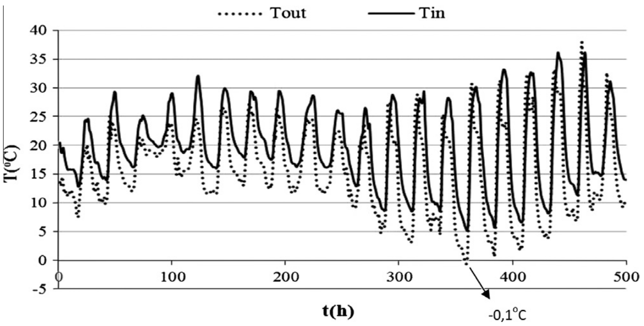

Fig. 12. Temperature and humidity measurements inside and outside greenhouse between March 6 and 26, 2010 (······ T_{out}, ▬▬ T_{in}).

Further investigation of the effect of PCM for a 24 h period on November 17th is done by evaluating the temperature difference (ΔT) of the substrate in container with PCM and in control container. As seen in Fig. 10, the maximum difference of 1.9 °C was seen in the morning, when inside temperature was the lowest. T_{s1} was kept within optimum temperature range, which was accomplished by the heat given off, when PCM freezes at this time interval. But for the control, T_{cs} drops to 10 °C towards morning.

On a warmer day – November 14th, the lowest ΔT that can be attained was 1.2 °C (Fig. 11). The night time temperatures were not as low as for November 17th, therefore the PCM was less effective.

Inside and outside temperature in the greenhouse for the second period of March 6–26, 2010 are shown in Fig. 12. The lowest outside temperature of −0.1 °C was seen during this period. During March a second container with oleic acid as PCM was added to the system. Fig. 13 compares substrate temperatures for container with OA, T_{s2}, with OA–CA, T_{s1} and for control, T_{cs}. The encircled day of March 20th in Fig. 13 is enlarged in Fig. 14 for a more detailed analysis. Fig. 14 compares the substrate temperature and ΔT, temperature difference of substrate with respect to control. The highest ΔT for OA–CA of 2.4 °C and OA of 1.1 °C were obtained on this day. The largest effect seen here is due to the sub-zero air temperatures observed. This shows that the PCM system is more effective at lower outside temperatures.

The temperatures of PCMs were also recorded to investigate their freezing behavior in the greenhouse environment. Fig. 15 shows cooling curves at night-time on March 22nd. The OA–CA

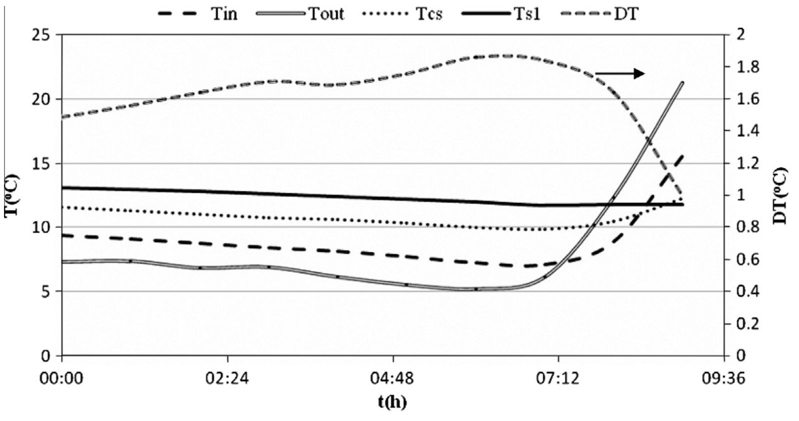

Fig. 10. Maximum temperature difference between control container and container with OA–CA on November 17th (– – T_{in}, ═══ T_{out}, ······ T_{cs}, ▬▬ T_{s1}, ‒ ‒ ‒ ‒ DT).

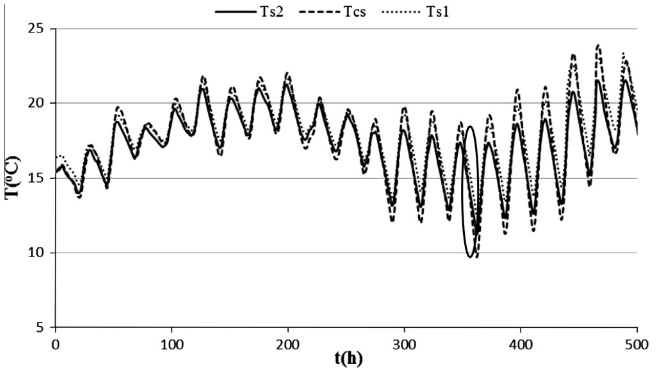

Fig. 13. Substrate temperature measurements in control container (T_{cs}), container with OA–CA (T_{s1}) and container with OA (T_{s2}) between March 6 and 26. The encircled day corresponds to March 20th (▬ T_{s2}, - - - T_{cs}, ······ T_{s1}).

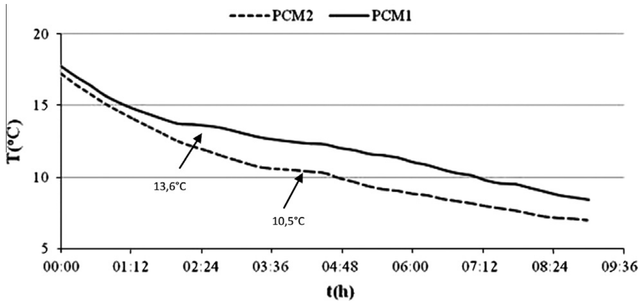

Fig. 15. PCM cooling curves under greenhouse conditions on March 22nd (PCM1: 40% OA–60% CA mixture, PCM2: OA) (- - - PCM2, ▬ PCM1).

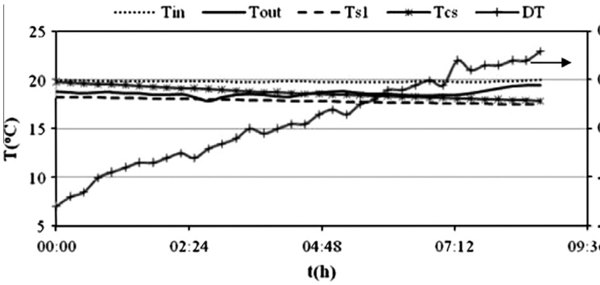

Fig. 16. Minimum temperature difference between control container (T_{cs}) and container with OA–CA (T_{s1}) on March 9th (······ T_{in}, ▬ T_{out}, – – – T_{s1}, —✱— T_{cs}, —+— DT).

was expected to freeze at 12 °C according to laboratory measurements. The phase change starts at 13.6 °C for OA–CA. Whereas, for OA, starts freezing at 10.5 °C. The temperature levels during this period were in general higher than the freezing point of OA, which prevents recovery of stored heat. This explains why OA–CA is more effective than OA.

The minimum ΔT's of around 0.1 °C were seen on March 9th for OA–CA and March 7th for OA (Figs. 16 and 17). The inside temperatures during this period is around 20 °C and is sufficient for plant growth. At these temperature levels, PCM is a liquid and therefore no effect is seen.

The passive PCM system storage effectiveness, η and passive heating effect of PCM, Q_{PE} calculated from Eqs. (4) and (5) are given in Table 4.

The OA–CA has the highest storage effectiveness of 64.3% and therefore has higher impact on control of substrate temperature. This was also confirmed by the temperature measurement discussions. Oleic acid with latent heat twice as much as OA–CA, has the highest total stored heat of 247.6 kJ. But, as discussed above, storage capacity of oleic acid could not be completely recovered because temperature level in the greenhouse was not low enough. For both PCMs, 40–80% of the stored heat was lost to the surroundings and not transferred to the substrate effectively. This can be explained with low thermal conductivity of plastic containers used for PCMs and insufficient contact surface with the substrate containers.

The average annual energy consumption of greenhouses in Mediterranean climate, which require about 90 days of heating, is estimated as 150 kW. 0.055 L/m^2 of Fuel-Oil (No:6) or 0.1 kg/m^2 of coal is necessary to meet this demand daily [15]. During this study, energy consumption for heating has been avoided by using the passive PCM based system that has been developed. In November and March test periods, the system was used for 28 days and saved approximately 47 kW of energy. For the greenhouse of 500 m^2, the economic savings will be $280 for coal (unit price $0.2/kg) and $1155 for Fuel-Oil (unit price $1.5/L) in 28 days. The economic benefit resulting from improved plant quality and yield as a result of better growthconditions provided by the PCM based temperature control system has not been evaluated.

4. Conclusions and recommendations

A promising and new PCM based root zone temperature control system was field tested for two different plants in this study. The system was tried under mild climate conditions of Adana, Turkey

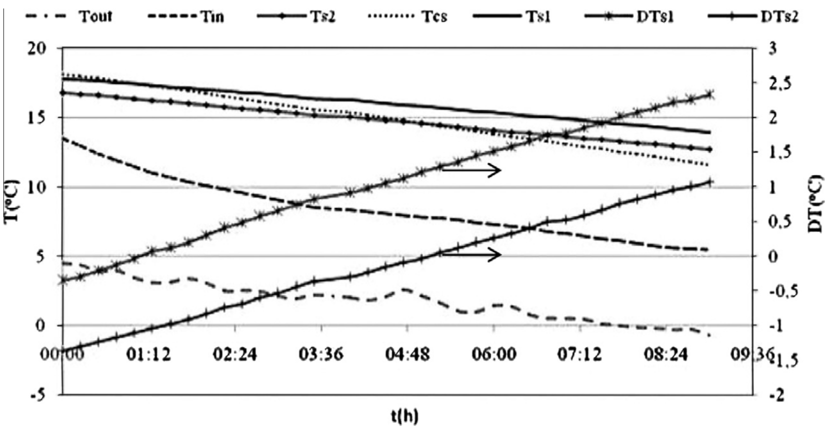

Fig. 14. Maximum differences of substrate temperatures between control container and container of OA–CA and OA on March 20th (– · – T_{out}, - - - T_{in}, —◆— T_{s2}, ······ T_{cs}, ▬ T_{s1}, —✱— DT_{s1}, —+— DT_{s2}).

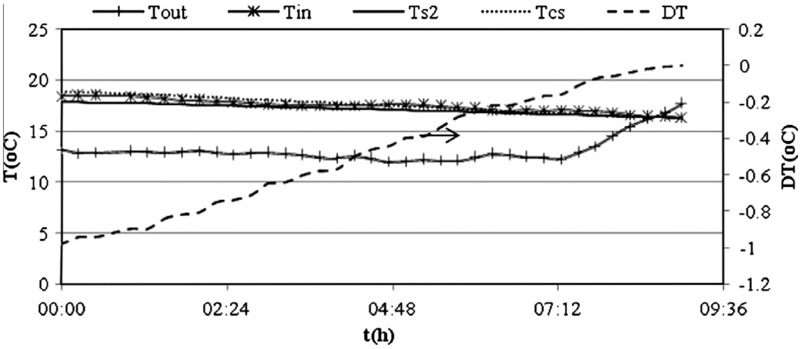

Fig. 17. Minimum temperature difference between control container (T_{cs}) and container with OA (T_{s2}) on March 7th (—+— T_{out}, —✱— T_{in}, ▬ T_{s2}, •••••• T_{cs}, •••••••••• DT).

Table 4
Thermal energy storage effectiveness of PCM.[a]

Date	PCM	ΔT_{max} (°C)	Q_T (kJ)	Q_{PE} (kJ)	η%
November 17, 2009	1	1.9	66.5	33.9[b]	43.5
March 20, 2010	1	2.4	83.04	40.0[c]	64.3
March 20, 2010	2	1.9	247.6	57.8[c]	21.6

[a] PCM1: 40% oleic acid–60% capric acid mixture, PCM2: oleic acid.
[b] Calculated for the period between 00:00 and 07:00 h.
[c] Calculated for the period between 00:00 and 09:30 h.

for zucchini and pepper plants. Oleic acid (OA) and 40% oleic acid (OA)–60% capric acid (CA) mixtures were identified as two PCMs suitable for optimum temperature requirements of these plants. In the test period of November 2009, night-time temperature of the substrate in the PCM container was always kept higher than that of the control container by 1.9–1.2 °C. OA–CA mixture used as PCM here has shown to be suitable for temperature control. In March 2010, the differences between the PCM container and control for OA were in the range of 1.1–0.2 °C. For OA–CA mixture the highest temperature difference was 2.4 °C. The temperature differences attained by PCMs here result in better growth parameters. A maximum storageeffectiveness of 64.3% was obtained for OA–CA on March 20th. Our results indicate that temperatures within the root zone can be better controlled using a passive PCM system. Further investigations on different PCMs having better thermal properties, and different container shapes and sizes are recommended for future. Such variations may further enhance heat transfer and storage effectiveness of thermal energy storage units. A demonstration project for an entire greenhouse is also recommended to evaluate the environmental and economic benefits of utilizing PCMs in greenhouses. Furthermore, new studies to determine the theoretical potential of using a similar PCM system for different climate conditions and for many other plant varieties are anticipated.

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