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

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ABSTRACT

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