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Use of flat plate solar collectors and parabolic trough concentrators for greenhouse soil disinfestation

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Abstract

The aim of the present work was to investigate the use of low and medium temperature active solar energy systems for the disinfestation of greenhouse soils. Four flat plate solar collectors (low-temperature solar thermal energy devices) and six parabolic trough concentrators (medium-temperature solar thermal energy devices) were used to heat water, which, via a buried heat exchange system, was used to heat the soil of greenhouse plots. These treatments were compared to no solar (control) and solarized (using a 50 µm-thick transparent polyethylene sheet) plots. Experiments performed in the summers of 2004 and 2005 showed that: 1) the temperatures reached and the energy accumulated in the soil - and therefore the disinfestation capacity - were greater with either of the active solar treatments (40-60ºC and 10.222.438–18.102.054 J, respectively) than with solarization (< 40ºC and 6.628.760 J, respectively) and 2) the temperatures reached using the parabolic trough concentrators (50 - 60ºC) were higher than those achieved with the flat plate solar collectors (40-50ºC). The soil temperatures reached suggest these systems could be used to disinfest greenhouse soils.

Additional key words: soil heating, soil treatment, solarization.

Resumen

Desinfestación de suelos de invernadero con colectores solares planos y concentradores cilíndrico-parabólicos

El objetivo de este trabajo fue investigar el uso de sistemas de energía solar activa de baja y media temperatura en la desinfestación de suelos de invernadero. Se usaron cuatro paneles solares planos y seis concentradores cilíndrico-parabólicos para calentar agua, la cual, a través de un intercambiador de calor enterrado, aumentó la temperatura del suelo de los bancales de un invernadero. Estos tratamientos se compararon con un bancal testigo y otro solarizado con una lámina de polietileno transparente de 50 µm. Los resultados de los ensayos realizados durante los veranos de 2004 y 2005 demuestran que: 1) las temperaturas alcanzadas y la energía acumulada en el suelo y, por tanto, la capacidad de desinfestación del sistema como consecuencia de los tratamientos solares activos (40-60ºC y 10.222.438–18.102.054 J, respectivamente) fueron superiores a las del suelo sometido a solarización (< 40ºC y 6.628.760 J, respectivamente) y 2) las temperaturas alcanzadas usando concentradores cilíndrico-parabólicos (50-60ºC) fueron superiores a las obtenidas con paneles solares planos (40-50ºC). Las temperaturas obtenidas en el suelo sugieren que estos sistemas pueden usarse eficientemente para la desinfestación de suelos de invernadero.

Palabras clave adicionales: calentamiento del suelo, solarización, tratamiento del suelo.

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Abbreviations used: LDR (light-dependent resistors).

Introduction

Agricultural applications of solar energy technology first began to appear in the second half of the 20th century with the aim of reducing the consumption of fossil fuels, limiting atmospheric pollution, and bringing down production costs (Solar Energy Society, 1965). Following the 1973 energy crisis, research efforts to improve the performance of solar technology were intensified (Casanova, 1993). In October 1978, the European Economic Community initiated a project looking into the possible applications of solar energy in European agriculture, concluding that its most viable uses were the provision of hot water for washing, heating livestock sheds, use in greenhouses and in the drying of crops (Di Vecchia *et al*., 1981).

Since 1977 the use of passive solar thermal energy (solar energy captured without the help of mechanical systems) for the control of soil pathogens has spread widely, a consequence of the development of the soil solarization method. This simply entails the spreading of a transparent plastic sheet, exposed to the sun, over a moist, uncultivated soil. This causes a change in the energy balance of the soil, leading to an increase in temperature of between 7 and 10ºC over that reached in control soil (Katan *et al*., 1976; Katan, 1981). Several authors report that such pathogen control is effective if maintained for one or two months (Martínez *et al*., 1986; Cenis, 1991; Soriano *et al*., 1998).

Active low-temperature solar energy (captured using mechanical systems; T <100ºC) can also be used in pathogen control. For example, flat plate solar collectors have been successfully used to control different soil pathogens in container medium from nurseries in Brazil (Armond *et al*., 1990; Ghini and Bettiol, 1991; Ghini *et al*., 1992; Ghini, 1993). Active medium-temperature solar energy (T=100-250ºC), however, has not been used directly in pathogen control.

The aim of the present work was to investigate the use of low —and medium— temperature active solar energy systems for the disinfestation of greenhouse soils. For this, four flat plate solar collectors (low-temperature solar thermal energy devices) and six parabolic trough concentrators (medium-temperature solar thermal energy devices) were constructed on mobile structures and placed next to a greenhouse. The soil temperatures achieved and the energy accumulated in the soil by solarization and these active solar energy treatments were compared. Since the efficiency of pathogen control depends on the soil temperature reached (which depends on its energy balance) and exposure time (Katan, 1981; Pullman *et al*., 1981), soil energy accumulation was used as an indicator of disinfestation capacity (Soriano *et al*., 2006). Finally, the energy performance of these two systems was compared, and the effect of insulating investigated.

Material and methods

This work was performed in a greenhouse (3.1 m wide, 15.2 m long and 2.2 m maximum height) at the *Escuela Universitaria de Ingeniería Técnica Agrícola de Ciudad Real* (The University School of Agricultural Technology of Ciudad Real) (Spain), part of the University of Castilla-La Mancha. This greenhouse was supplied with a source of drinking quality water, 220 V electricity, and a nebulization cooling system that avoided ambient temperatures of over 38±0.5ºC being reached. The interior of the greenhouse was divided into 16 plots (width 0.95 m, length 1.6 m, depth 0.27 m), of which six were used. The soil was removed from these plots and a layer of expanded polyurethane placed at the bottom of each (*i.e.,* at a depth of 0.27 m). Grill-type heat exchangers (made from 12 mm diameter/120 mm-long copper pipes placed 87 mm apart) were placed on top of four of these polyurethane layers. The removed soil was then replaced after mixing.

The active solar energy systems consisted of four flat plate solar collectors and six parabolic trough concentrators installed along the south face of the greenhouse (Fig. 1). These installations required the connection of different subsystems: a solar energy capture subsystem, a fluid distribution subsystem, and a control subsystem (IDAE, 1992). The heat-transporting fluid was water.

Solar energy capture subsystem

This was composed of the flat plate solar collectors or parabolic trough concentrators themselves. The design of these units followed criteria that would permit ease of construction and assembly, ease of use, and energetic and agronomic efficiency (Montero, 1987; Mezquida and Martínez, 1991; López and González, 1995).

The flat plate solar collectors were mounted on a south-facing metallic structure held at an angle of 45º. Four wheels mounted on the underside allowed the entire structure to be mobile; the apparatus could be

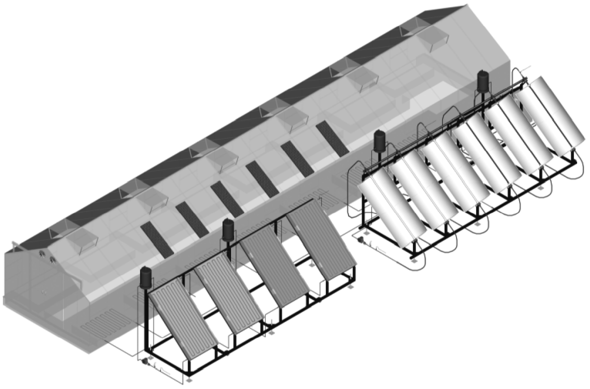

Figure 1. Location of the solar energy installations. The flat plate solar collectors on the left have one glass cover, while those on the right have two (insulated). The parabolic trough concentrators on the left are insulated, those on the right are not.

fixed at any point using pins. The flat plate solar collectors were composed of a 1 m-wide x 2 m-high and 0.15 m-deep stainless steel frame insulated with a layer of fibre glass (thermal conductivity 0.125 kJ/h·m·ºC), a 1 m-wide x 2 m-high absorbent surface made of galvanised steel plate with a grill of matt black-painted copper tubes (12 mm diameter) in serpentine form welded to it, and one or two transparent glass covers (0.005 m-thick tempered glass with a low iron content) with an anti-reflective surface fixed to a longitudinal flange (part of the frame) by four lateral, metallic clamps. Two of the flat plate solar collector, connected in series, had a single glass cover (Fig. 1, left) while the other two (also connected in series) had a double cover (*i.e.,* greater insulation) (Fig. 1, right).

The parabolic trough concentrators were mounted on another mobile metallic structure and also faced south at an angle of 45º. A chain belt allowed all the concentrators to be turned to face the sun; this belt meshed with cogs mounted at the end of the heat-pipe absorber of each installation. The entire system was driven by an oleodynamic piston. Each concentrator was comprised of a reflective surface made from a stainless steel sheet (0.003 m thick, 2 m long, 1 m wide) placed over an aluminium frame in the form of a parabola ($x^2 = 73.096732\, y$). The absorbent surface was a matt black-painted cylindrical tube made of galvanised steel (internal diameter 3.57 cm) fixed by an aluminium support along the concentrator's focal line. The six parabolic trough concentrators were connected as two sets of three in series. The heat-pipe absorber of the first set was not insulated (Fig. 1, right), while that of the other set was insulated using by a Pyrex tube (0.005 mm thick, internal diameter 4.5 cm).

Distribution subsystem

Four distribution subsystems were required, one for each installation. Each was comprised of a 45 W centrifugal pump run by photovoltaic power, rigid copper or flexible rubber distribution tubes (internal diameters 12 mm), the above-mentioned heat exchanger set at a depth of 25 cm in the soil, and an open expansion vessel at the highest point of the installation.

Control subsystems

Three control subsystems were employed. The first controlled temperature in each installation. This electronic subsystem allowed the water circulation pumps to be automatically switched on and off according to the temperature recorded by a sensor located on the energy capturing surface of either the flat plate solar collectors or parabolic trough concentrators. The second controlled the orientation of the concentrators over the day. This was run by a computer, programmed *ad hoc*, which analysed the signals received from two associated light-dependent resistors (LDR) (forming a Wheatstone bridge) (Porras *et al*., 1989; Baquerizo *et al*., 2003) placed on the sides of the first parabolic trough concentrator. Finally, the third subsystem allowed the electronic monitoring of soil moisture in all experiments, thus ensuring, via an irrigation system, that all the plots had the same moisture level over the treatment period (Porras *et al*., 2007).

The active solar power installations worked following the system shown in Fig. 2. When the temperature control subsystem was switched on (at about 08:00 h solar time), the pump began to push water through the flat

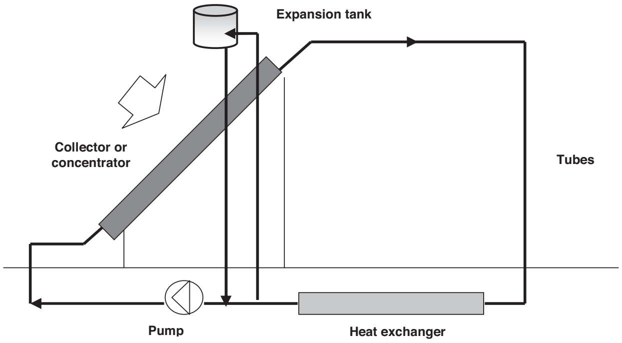

Figure 2. Functioning of collector and distribution subsystems for the flat plate solar collectors and parabolic trough concentrators installations.

plate solar collectors or parabolic trough concentrators, where the water was heated before passing through the heat exchanger in the soil, thus heating the latter. The soil temperature was recorded every half hour in each plot at depths of 5, 10 and 25 cm using a datalogger designed for the purpose; the mean was then calculated. The exiting water (now at a lower temperature) passed on to the expansion tank, and from there to the pump to circulate once again. This process was repeated until the temperature control subsystem deactivated the pump and stopped circulation at about 15.00 h (solar time).

Assays involving six soil heating treatments were performed during the summers of 2004 and 2005: 1) no solar treatment (control), 2) solarization using a 50 µm-thick transparent polyethylene sheet (solarization), 3) soil heating using water warmed by flat plate solar collectors with a single glass cover (single collectors), 4) soil heating using water warmed by flat plate solar collectors with two glass covers (double or insulated collectors), 5) soil heating using water warmed by parabolic trough concentrators with a non-insulated heat-pipe absorber (non-insulated concentrators), and 6) soil heating using water warmed by parabolic trough concentrators with an insulated heat-pipe absorber (insulated concentrators).

Trials commenced on 1st July and ended 30th September. The greenhouse soil was kept without vegetation and with a moisture level of 15-16%.

Data were analysed using the multiple range test. Significance was set at $P<0.05$.

Results and discussion

Figure 3 shows the mean daily soil temperatures recorded over the summers of 2004 and 2005.

The temperature reached in the solarized soil was higher than that reached in the control soil, but lower than that reached in the soils heated by the active solar energy systems. The highest mean temperature reached in the solarized soil was never greater than 40ºC, unlike that mentioned in the literature (Katan, 1981; Martínez *et al.*, 1986; Cenis, 1989; Ghini *et al.,* 1993; Frápolli *et al.*, 1994; Hasing *et al.*, 2004; Singh *et al.*, 2004). This was a consequence of the ambient temperature never surpassing 38ºC, the recorded temperature being a mean of those registered at the three depths stated above, the size of the plots ensuring a notable edge effect, and the irrigation that maintained the soil moisture level.

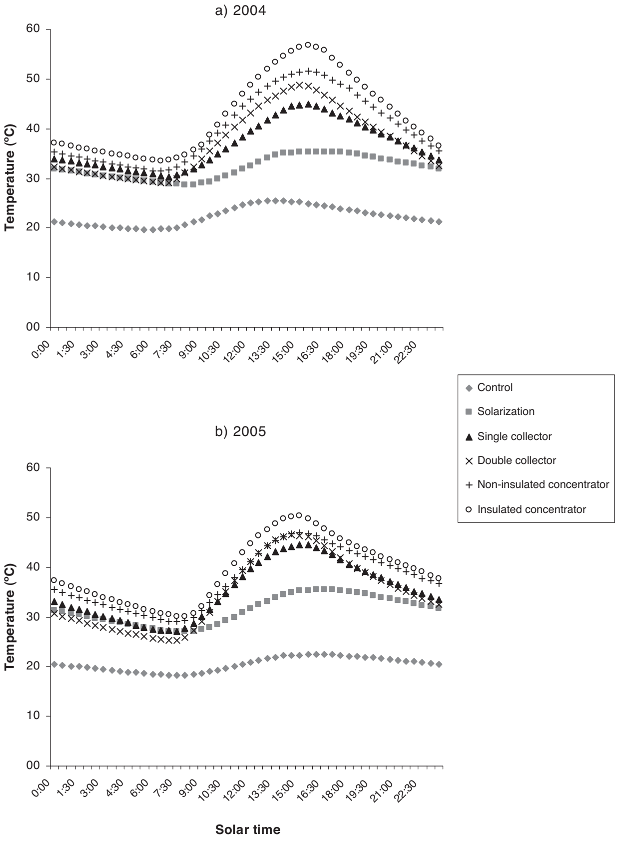

Figure 3. Mean daily soil temperatures achieved under the different treatment conditions in the summer of a) 2004 and b) 2005.

The maximum mean daily soil temperature obtained with the parabolic trough concentrators was between 50 and 60ºC; with the flat solar plate collectors it was 40-50ºC. A clear difference was seen between the July and August temperatures achieved and those of September with both systems. For example, in July 2004 the maximum mean daily temperature was 52.9ºC in the soil heated with the flat plate solar collectors with a double glass cover, and 59.2ºC in the soil heated by the insulated parabolic trough concentrators, compared to 44.5 ºC and 52.3ºC in September respectively. These temperatures were similar to those reported by Ghini *et al.* (1992).

The energy accumulated in the greenhouse soil under each system is defined by the expression:

$$E = E_s + E_a = m_s \cdot c_s \cdot \Delta t + m_a \cdot c_a \cdot \Delta t \qquad [1]$$

where E = the total energy accumulated (J), E_s = the energy accumulated by the soil (J), E_a = the energy accumulated by the water in the soil (J), m_s = the mass of the soil (g), m_a= the mass of the water in the soil (g), c_s = the specific heat of the soil (in this case 1.06 J/g·ºC),

c_a= the specific heat of the water (J/g·ºC), and Δt = the variation in temperature (ºC). Δt depends on the thermal treatment provided, and was calculated as the difference between the mean soil temperature recorded each half hour, and the mean for the preceding half hour.

Every day during July, August and September of 2004 and 2005, expression [1] was used to calculate the energy accumulated between 08:00 h and 15:00 h (both solar time) as the sum of the energy accumulated every half hour. For each month the mean daily energy accumulation was calculated (*i.e.*, the mean of each day's energy accumulation value). The mean summertime energy accumulation was determined as the mean for that accumulated in July, August and September. Theoretically, the disinfestation capacity should increase the more energy is accumulated per day.

Since the energy capturing surface of the flat plate solar collectors and parabolic trough concentrators was different (2 m^2 of capturing surface per panel in the former, and 1.68 m^2 in the latter), the results recorded for each treatment were adjusted to allow comparisons between energy capturing surfaces of the same size.

Figure 4 shows the energy accumulated in the soil under the different treatments. In both 2004 and 2005 the amount of energy accumulated by either of the active solar energy systems (insulated and non-insulated) was significantly greater than that accumulated by solarization (a mean 1.9 times higher for the flat plate solar collector systems, and 2.6 times higher for the parabolic trough concentrator systems). Further, the parabolic trough concentrators (insulated and non-insulated together) accumulated a mean 1.3 times more energy in the soil than the flat plate solar collectors (insulated and non-insulated together). The insulation of both systems (i.e., the double glass cover or the Pyrex tube around the heat pipe absorber) led to significant increases in soil energy accumulation over that achieved by the corresponding non-insulated systems (1.3 times for the flat plate solar collectors and 1.2 times for the cylindrical parabolic concentrators).

For the active solar energy installations, the energy performance of each treatment was calculated using equation [2] to allow comparisons between the different active solar power installations from a technological viewpoint:

$$\eta(\%) = \frac{energy_{accumulated}}{energy_{received}} 100 \qquad [2]$$

i.e., the daily energy accumulated in the soil per m^2 of energy capturing surface, as a consequence of the treatment, from 8:00 - 15:00 h, divided by the energy provided daily by the sun [J/m^2] over those same hours (data supplied by the Spanish *Instituto Nacional de Meteorología*). Figure 5 shows the results obtained for 2004 and 2005.

The energy performance of the insulated parabolic trough concentrators was significantly greater than that of their non-insulated counterparts, although both these showed a significantly better performance than the flat plate solar collector systems with either single or double covers (a mean 1.3 times better). The energy performance of these active solar energy systems is influenced by their shape, which determines the amount of solar energy absorbed, and by the amount of radiation that falls upon them. For the same amount of solar radiation

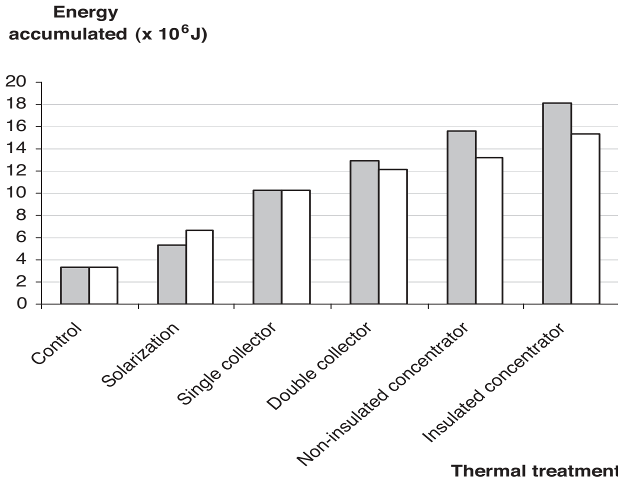

Figure 4. Energy accumulated in the soil (J) in summer 2004 (dark) and in summer 2005 (white) by the different treatments.

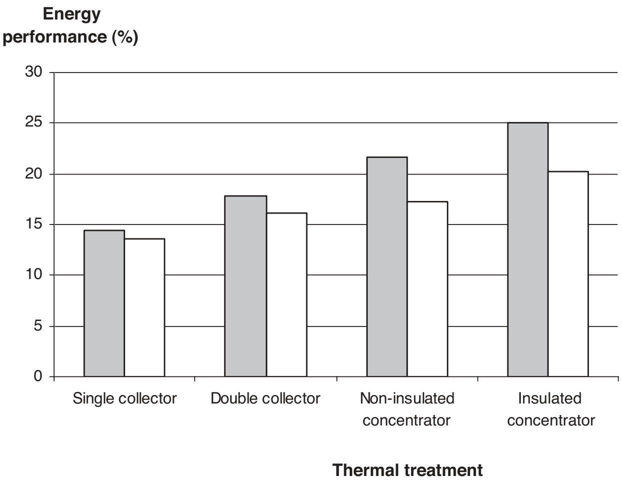

Figure 5. Energy performance (%) of the different treatments in summer 2004 (dark) and summer 2005 (white).

received, a better or worse energy performance depends on the energy captured and losses by conduction, convection and radiation. From this point of view, the parabolic trough concentrator system reduces the area from which losses occur in relation to the energy capturing area; at high temperatures the performance of solar concentrators can therefore be better than that of flat plate solar collectors (Ajona, 1997).

During the summer of 2005 the energy performance of the insulated and non-insulated parabolic trough concentrators diminished with respect to 2004, a consequence of the poor durability of the materials used for the reflective surface. Dirt, the action of atmospheric agents and cleaning materials reduced the solar energy that could be concentrated (Morris, 1980; Cachorro, 1993; Fend *et al.*, 2003).

Insulation of the parabolic trough concentrators increased the temperatures reached in the soil, the amount of energy accumulated and the performance of the installation. It is normal for the heat-pipe absorber of parabolic trough concentrators to be covered by glass (Ajona, 1997). Flat plate solar collectors, however, usually only have a single cover (no insulation) although they may provide options for the use of a second. Mezquida and Martínez (1991) indicate that in Southern Europe it is neither necessary nor indeed a good idea to use double glass covers. In fact, the Andalusian Regional Government (Junta de Andalucía, 1991) prohibited the installation of double cover panels for hot water production. However, other authors report advantages with double covers when ambient temperatures are very high (Portillo, 1985; De Andrés *et al.*, 1991; Xiaowu and Ben, 2005). In the present work, double covers were associated with the higher soil temperatures, energy accumulation and energy performance, although with an added economic cost.

Conclusions

Solar energy can be used to thermally treat greenhouse soils. Passive solarization increased the temperature and energy accumulated compared to the control system, although less than so that with either form of active solar energy examined.

The soil temperatures achieved with the flat solar collectors and especially the parabolic trough concentrators were high, which should ensure a disinfestation effect. The soils heated by the flat plate solar collectors accumulated less energy than those heated by the parabolic trough concentrators. The insulation of either system increased the amount of energy accumulated in the soil, and therefore the soil disinfestation capacity. The flat plate solar collector systems showed a better energy performance than the parabolic trough concentrator systems.

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