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Effect of Thermal Screens on the Microclimate and Overall Heat Loss Coefficient in Plastic Tunnel Greenhouses

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Abstract: The objective of the present study was to evaluate the effects of thermal screens made of clear polyethylene (PE) and polyester material on the microclimate and overall heat loss coefficient in plastic tunnel greenhouses. The dimensions of the plastic tunnels were: width 6 m, length 20 m and height 3 m. Three different installations were used: (1) a single cover without a screen (as a control); (2) a single cover with a PE screen; and (3) a single cover with a polyester screen. The thermal screens made of PE with UV+IR additives and polyester materials were placed at a height of 2.5 m in the plastic tunnels, and supported with wires. Air temperature, relative humidity, wind speed, solar radiation and photosynthetically active radiation (PAR) were measured and recorded on a data-logger. In the plastic tunnels, the overall heat loss coefficient, heat input, the control factor for air-tightness, the rate of heat loss and the thermal screen effectiveness were calculated. The results showed that the polyester and PE screens were able to keep the air temperature inside the plastic tunnels 4.8 °C and 2.5 °C higher than that outside, respectively. Comparison of the calculated overall heat loss coefficients shows that the differences in the values between the plastic tunnels were large. The relationships between the overall heat loss coefficient and the wind speed, and the outside temperature were modeled, including the measured and calculated values. It was found that the thermal screen effectiveness was 16% and 19.8% for the PE and polyester screens, respectively.

Key Words: Plastic tunnel, Thermal screen, Overall heat loss coefficient

Plastik Tünel Seralarda Isı Perdelerinin Mikrokima ve Toplam Isı Kayıp Katsayısına Etkisi

Özet: Bu çalışmada, açık polietilen (PE) ve polyester malzemeden yapılmış ısı perdelerinin plastik tünel seralarda mikro-klima ve toplam ısı kayıp katsayısına etkisi incelenmiştir. Plastik tünel seralar 6 m genişlik, 20 m uzunluk ve 3 m yüksekliğindedir. Araştırmada üç farklı düzenleme yapılmıştır: (1) perdesiz tek katlı tünel (kontrol), (2) PE perdeli tek katlı tünel ve (3) polyester perdeli tek katlı tünel. UV + IR katkılı PE ve polyester malzemeden yapılmış ısı perdeleri, plastik tünel seralarda 2.5 m yükseklikte yerleştirilmiş ve tellerle desteklenmiştir. Hava sıcaklığı, bağıl nem, rüzgar hızı, güneş ışınımı ve fotosentez için etkin ışınım (PAR) değerleri ölçülmüş ve veri kaydedicide kaydedilmiştir. Plastik tünel seralarda; toplam ısı kayıp katsayısı, verilen ısı miktarı, hava sızdırmazlık için kontrol faktörü , ısı kayıp hızı ve ısı perdesi etkinliği hesaplanmıştır. Polyester ve PE perdeli seralarda, iç ortam sıcaklığının dış ortamdan 4.8 °C ve 2.5 °C daha yüksek olduğu belirlenmiştir. Plastik tünel seralarda toplam ısı kayıp katsayılarının önemli ölçüde farklı olduğu belirlenmiştir. Toplam ısı kayıp katsayısı ile rüzgar hızı ve dış ortam sıcaklığı arasındaki ilişkiler modellenmiştir. Perde etkinlik faktörü; PE perde için % 16, polyester perde için % 19.8 olarak belirlenmiştir.

Anahtar Sözcükler: Plastik tünel, Isı perdesi, Toplam ısı kayıp katsayısı

Introduction

The optimization of air temperature in greenhouses is of particular importance in relation to plant growth and development. In order to achieve optimum indoor conditions, it is necessary to heat the greenhouses, particularly during the cold seasons. Present fuel prices and projected increased prices have emphasized the need to reduce energy consumption for space heating. To overcome these problems it is of primary importance to utilize alternative heating technologies, with low cost, and efficient and dependable operation, such as the use of advanced cover materials and night thermal screens. Double glazing a greenhouse will reduce winter heat losses, but invariably causes a reduction in light transmission, thereby reducing the crop growth rate. An alternative approach is to introduce a moveable screen into the house. This can be drawn horizontally across at night, to reduce losses during this period. About a 40%

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saving in heat supply can be achieved in this way. During the day, the screen can be withdrawn, but a 4% light loss due to the rolled-up material is produced (Critten and Bailey, 2002).

Many energy conservation measures have been developed, or are at the development stage, to reduce the heat losses from a greenhouse. It is stressed that the most widespread system in use is undoubtedly an energy screen installation, especially a movable screen. When it is open during the daytime, it causes minimal disturbance to the light conditions in the interior of the greenhouse. When the screen is closed during the night it reduces heat flows from the interior of the greenhouse to the outside environment. In that way, heat conservation in the greenhouse interior is enabled and energy consumption is minimized (Kieboom, 1988). Thermal screens are generally regarded as being one of the most effective methods of energy conservation. A very wide range of screen material is available, such as polyethylene (PE), polyester, cloth or film. Nowadays, the most modern thermal screens are made of a combination of polyester and aluminum.

Comprehensive studies have been carried out concerning the energy conservation capacity of thermal screens by many researchers. The first trials during the 70s were usually with materials that were easily obtainable, such as transparent PE film, cloth or film that were developed for shading and darkening. As polyester absorbs a substantial amount of the heat and subsequently disperses much of it into the greenhouse, the screen temperature is always higher than the air temperature inside the greenhouse. The single layer screens, both film and woven, give the maximum savings, in the order of 21 to 45%. The differences from one material to another relate essentially to differences in the permeability to long-wave (infra-red) radiation. It appears that materials having good reflective properties allow 60% of the heat to be conserved (Zabeltitz, 1988). By adding an aluminum layer to the polyester strip, the radiation of heat is restricted. More aluminum applied to the screen material means greater energy conservation.

Heat loss from the greenhouse at night is calculated with the overall heat loss coefficient (U). It represents the total energy loss per square meter of external area of the greenhouse for a difference of 1 °C between the inside and outside temperatures. As the value of U also depends on the external climatic conditions, it is always given in relation to the wind speed. The value of U is used for comparing the energy consumption of greenhouses having different technical equipment. U values are commonly used to determine the heating requirement of greenhouses. These commonly used values are overall values, which when used for estimating heat loss provide not only the conduction heat loss but also the heat loss due to direct thermal radiation exchange. The percentage of energy conservation achieved with thermal screens in greenhouses could be calculated by considering U values. The dependence of the overall heat loss coefficient on the wind speed is reduced by the use of thermal screens.

The objectives of the present study were: (1) to evaluate the effects of thermal screens made of clear PE and polyester material on the overall heat loss coefficient in plastic tunnel greenhouses; (2) to calculate the overall heat loss coefficients for plastic tunnels having different screen installation; (3) to determine the relationships between the overall heat loss coefficient and the wind speed and outside air temperature; (4) to compare the actual rate of heat loss from several different plastic tunnels, based on the overall heat loss coefficients; (5) to investigate the effects of thermal screens on the inside air temperature and air-tightness of plastic tunnels; and (6) to evaluate the effectiveness of thermal screens in heated tunnels.

Materials and Methods

Materials

Plastic Tunnel Greenhouses

The experiment was carried out during the 1998-1999 growing season in three plastic tunnel greenhouses installed in Tarsus in the Çukurova region. The latitude, longitude and altitude of Tarsus are, respectively, 37°N and 35°E, and 15 m above sea level. Plastic tunnels may be single or multi-span, and comprise a set of shallow generally circular arcs (steel tubes) over which is stretched a polyethylene sheet. Span width is similar to that of the traditional greenhouse. Tunnel length and the number of spans are of course optional. The experiments were carried out in three semi-cylindrical plastic tunnels that were aligned north south (Figure 1a). The plastic tunnel greenhouses, which consisted of galvanized steel tubes, have continuous side openings operated by a rolling mechanism. The openings in the sidewalls, which were created by rolling up or down the plastic film, were

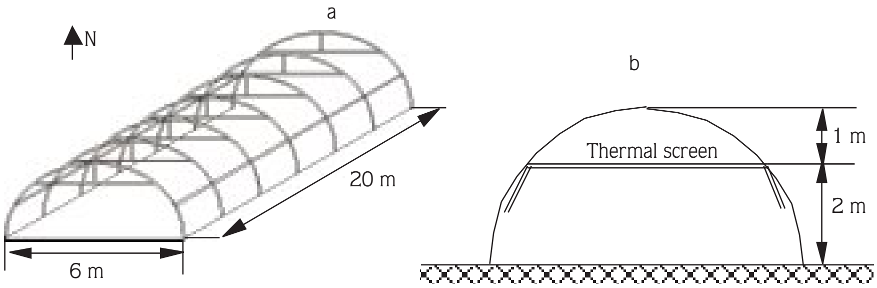

Figure 1. (a) Plastic tunnel greenhouse; (b) placement of the thermal screens in tunnels.

used for ventilation. The plastic tunnel greenhouses were covered with double skin PE material (thickness of 0.35 mm) that contains UV and IR stabilizers. The dimensions of the plastic tunnels were: width 6 m, length 20 m and height 3 m. In this research, three different installations were used to determine the effect of thermal screens on the overall heat loss coefficient: (1) a single cover without a screen (as a control); (2) a single cover with a PE screen; and (3) a single cover with a polyester screen.

The thermal screens made of PE with UV + IR additives and polyester materials were placed at a height of 2 m in the plastic tunnels, and supported with wires (Figure 1b). The thermal screens can be drawn horizontally to the side walls inside the plastic tunnels. To determine the energy conservation efficiencies of the screens, they were drawn at 17:00 and opened at 08:00 during the experimental period.

The plastic tunnels with thermal screens made of PE and polyester material were heated by two air heaters. The operation of the air heaters was controlled by ordinary commercial thermostats in response to the outside air temperature. The air heaters were activated when the outside air temperature dropped below the thermostat set-point (7 °C). The rates of fuel consumption over a given period were measured during the experimental period. The warm air from the air heaters was distributed by perforated PE ducts lying on the ground in the center of the plastic tunnels.

Measurements and Data Acquisition Unit

Air temperature, relative humidity, solar radiation and photosynthetically active radiation (PAR) were measured and recorded by a data-logger. The air temperature measurements were taken above and below the screen installations at heights of 2 m and 2.5 m in the center of each plastic tunnel. The air temperature sensors were placed at these heights in the center of each plastic tunnel. The air temperature measurement at the height of 2.5 m represents the air temperature above the thermal screen placements (i.e. between the screen and roof). Solar radiation and the PAR entering the plastic tunnels were also measured to determine the shading effect of the thermal screen installations in the plastic tunnels. Solar radiation and the PAR were measured at a height of 2 m in the plastic tunnels. The sensors were located 6 m apart in the plastic tunnels. Solar radiation and the PAR sensors were positioned in such a way that the incident solar radiation energy and the PAR were measured in the plastic tunnels. All climatic factors were measured at three locations: two sensors were placed in the inlet, at the middle and in the end of the plastic tunnels. Overall, six sensors were used to measure each of the climatic factors in each plastic tunnel. The average temperatures of the air in the plastic tunnels were determined by averaging the measurements of the sensors. The outside wind speed measurements were taken at a height of 6 m, near the plastic tunnels. The air temperature was measured at two locations at the inlet and outlet of the air heaters. Overall, four sensors were used to measure the air temperature at the inlet and outlet of the air heaters.

The air temperatures outside and inside the plastic tunnels were measured with 2 kΩ hermetically sealed thermistors (TM1, Delta-T Devices Ltd., Cambridge, UK). The range of the thermistors was –20 to +80 °C and the accuracy was ± 0.2 °C over 0-70 °C. The sensors consisted of a stainless steel clad thermistor probe with a 5 m cable. The sensors was mounted in an open-cylindrical probe made from a material that has a low affinity for water and that fits inside a cylindrical louvered radiation screen made of anodized aluminum, which protects the sensor against solar radiation and rain. The relative humidity sensor (%RH, Delta-T Devices Ltd.), of cracked chromium oxide, alters its capacitance in response to changes in relative humidity. Its response is claimed to be linear to within 2% over the range 0 to 95% relative humidity. The output of the relative humidity sensor is 1 mV per % of relative humidity. Solar radiation energy was measured in the 400-1000 nm wavelength range. The sensing element is a blue-enhanced precision silicon photodiode, with good stability characteristics (ESR, Delta-T Devices Ltd.). The spectral response is filtered to give a flat, uniform response to solar energy, independent of wavelength, from 400 to 1000 nm. The output of the solar radiation sensor is 10.8 mV per kW m^{-2} of total solar radiation. The PAR was determined by measuring the flux of photons in the 400 to 700 nm wavelength range with quantum sensors. The output of the PAR sensor (QSR, Delta-T Devices Ltd.) is 10 mV per mmol m^{-2} s^{-1}. Wind speed was measured with a Vector A100 anemometer, which had an accuracy of 1% ± 0.1 m s^{-1} (AN1, Delta-T Devices Ltd.). The anemometer had a range of 0.3-75 m s^{-1}. To determine the rate of heat input from the air heaters to the plastic tunnels, the flow rate of the airflow was measured with an anemometer (OMEGA HHF7-P1) with a range of 0.5-3.5 m s^{-1}, and the accuracy of ±1%. The calibration of all sensors and the logger was completed successfully at the beginning of the experiment.

A data-logger was used for taking and storing readings from the sensors (Delta Logger, Delta-T Devices Ltd.). The recorded data were stored in the memory for output to a printer or to a computer for storage on disk. Data can be retrieved from the logger and the current readings of the sensors can be examined without interrupting the logging process. Readings can be taken at regular intervals, which may be different for each channel. To optimize the use of the logger's memory, timed readings taken on a channel over specified periods can be recorded as single values, representing the average, maximum or minimum reading for the period. A personal computer was also used to monitor, record and check the parameters. The time interval for data recording was every 15 min with data acquisition every minute for integrated measurements.

Methods

The overall heat loss coefficient (U) in the greenhouses can be determined by limiting heat transfer to convection and radiation if the heat transfer rate, surface area, and inside and outside temperatures are known or measured. This procedure does not require the separation of the convection and radiation components. The values of U in the plastic tunnels were calculated from the following equation:

$$U = Q_i / A_c\,(T_i - T_o) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

where U is the overall heat loss coefficient in W m^{-2} $°C^{-1}$, Q_i is the rate of the heat input from the heater in W, A_c is the area of tunnel cover in m^2, T_i is the inside (under the thermal screens) air temperature in °C, and T_o is the outside air temperature in °C.

The value of U depends in particular on the external ambient conditions (principally on wind speed). Since the values of U in greenhouses are always given in relation to wind speed, the relationships between the values of U and wind speed, and the outside air temperature were modeled, including the measured and calculated values.

The heat input from the air heaters was obtained by measuring the airflow rate across the heaters and their inlet and outlet air temperatures. Thus, the rate of the heat input from the air heaters, Qi, was calculated from following equation:

$$Q_i = V.\rho.c_p(T_{oh}-T_{ih}) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (2)$$

where V is the air flow rate in m^3 s^{-1}, ρ is the density of air in kg m^{-3}, c_p is the specific heat of air at constant pressure in kJ $kg^{-1}°C^{-1}$, T_{oh} is the air temperature at the outlet of the air heater in °C, and T_{ih} is the air temperature at the inlet of the air heater in °C.

The air-tightness between the heated space and unheated section of the greenhouse has a considerable effect on the possible conservation of energy and it was checked by the use of a control factor, F_a, which was determined from the following expression (Zabeltitz, 1988):

$$F_a = (T_a - T_o)/(T_i - T_o) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (3)$$

where T_a is the air temperature between the thermal screen and roof in the tunnels in °C.

The rate of heat loss from the plastic tunnels, Q_l (W m^{-2}), was calculated from the following equation:

$$Q_l = U.A_c(T_i - T_o) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (4)$$

The thermal screen effectiveness (TSE) evaluated according to Chandra and Albright (1980) was as follows:

$$TSE = [(Q_{lus}-Q_{ls})/Q_{lus}] \quad (5)$$

where Q_{lus} is the heat loss from the unscreened tunnel in W m^{-2}, and Q_{ls} is the heat loss from the screened tunnel in W m^{-2}, calculated using equation (4).

Results and Discussion

The efficiency of thermal screens in plastic tunnels was investigated in particular for the coldest days during the experimental period. The air temperatures in the plastic tunnels were compared to the outside air temperatures as an important measure of the effectiveness of the screens.

Effects of Thermal Screens on the Microclimate in Plastic Tunnels

The change in air temperature in the plastic tunnels during the day and night is shown as a function of time in Figure 2. As seen in Figure 2a, the highest air temperature was recorded in the PE screened tunnel when the thermal screens were not drawn in the plastic tunnels during the daytime. The air temperature in the PE screened tunnel varied between 19.9 °C and 31.3 °C, whereas the outside air temperature ranged from 10.1 to 13.5 °C . The air temperature in the polyester screened tunnel was lower than that in the PE screened tunnel during the experimental period, since the polyester screen reflected the solar radiation entering the plastic tunnel. The air temperature in the polyester screened tunnel and unscreened tunnel varied between 21.2 °C and 28.5 °C,and 18.2 °C and 28.3 °C, respectively (Figure 2a). It was calculated that the average daily temperature was 27.34 °C, 25.52 °C and 24.84 °C in the PE screened tunnel, polyester screened tunnel and unscreened tunnel, respectively. In this period, to determine the passive heating effects of the thermal screens, the screens were drawn at nighttime. However, the air heaters in the plastic tunnels were not used over this period. The highest air temperature was recorded in the polyester screened tunnel, as shown in Figure 2b. While the air temperature difference between inside and outside the polyester screened tunnel was only 1.8 °C at 20:00 in the evening, the air temperature difference reached 4.8 °C at 06:00 in the early morning. The average air temperature differences between the inside and outside of the PE screened tunnel, polyester screened tunnel and unscreened tunnel were 3.33 °C, 1.91 °C and 0.33 °C for the period of time covered by Figure 2b. The results showed that the polyester screen was able to keep the air temperature inside the polyester screened tunnel 4.8 °C higher than that outside. Under these conditions, the polyester screen provided a heating effect of 4.8 °C . This good performance was due to the high air-tightness effect of the polyester screen, which was calculated using equation (3).

It was found that the maximum heating effect of the PE screen was only 2.5 °C during the experimental period. Thus, the heating effect of the PE screen was lower than that of the polyester screen. The PE screen did not substantially increase the average daily temperature in the PE screened tunnel. This result is due to the fact that the transmittance of the polyester screen for long-wave (infra-red) radiation is normally low. The difference in the heating effect between the PE and polyester screen relates essentially to the difference in transmittance for long-wave radiation. In other words, the heating effect of the thermal screens used in this

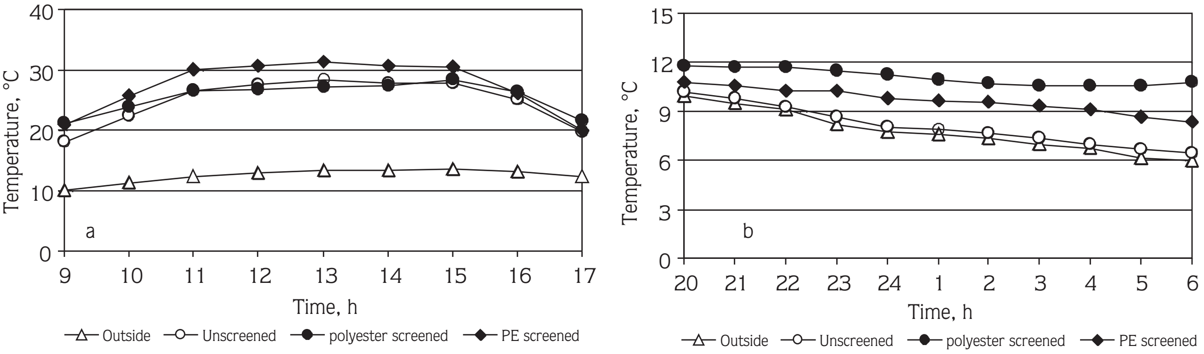

Figure 2. Changes in air temperature as a function of time: (a) daytime; (b) nighttime.

experiment was strongly affected by the transmittance for long-wave radiation, emissivity and the air-tightness of the screen materials. The heating effect of the PE and polyester screen increased as the outside air temperature dropped during the night.

Figure 3 shows the variation of relative humidity as a function of time inside the plastic tunnels. When the thermal screens are opened during the daytime (Figure 3a), the air relative humidity inside the polyester screened tunnel ranged from 48% to 57.2%, whereas the outside air relative humidity was in the range 64.6-76.4%. The air relative humidity inside the polyester screened tunnel dropped from 56.8% (at 09:00) to 48% (at 15:00). On the other hand, the air relative humidity inside the PE screened tunnel varied between 47.3% and 64.8% when the thermal screens were opened during the daytime. For the period covered by Figure 3a, the average daily relative humidity inside the polyester and PE screened tunnels was 51.8% and 53.3%, respectively. The average daily relative humidity of the outside air was 68.2% during the experimental period. The average daily relative humidity difference between outside and inside the polyester and PE screened tunnels was 16.8% and 15.3%, respectively. This means that the air relative humidity inside the polyester and PE screened tunnels was lower than that of the outside. Most plants grow best within a fairly restricted range, typically 70% to 85% relative humidity for many species. Low humidity increases the evaporative demand on the plant to the extent that moisture stress can occur, even when there is an ample supply of water to the roots. The variation of relative humidity in the plastic tunnels is given in Figure 3b as a function of time when the thermal screens were drawn at nighttime. The air relative humidity inside the PE screened tunnel varied between 91% and 96 %, whereas the air relative humidity inside the polyester screened tunnel ranged from 78% to 81% for the night (Figure 3b). The average nightly relative humidity inside the polyester and PE screened tunnels, and unscreened tunnel was 79.8%, 93.7% and 91.7%, respectively. However, the average nightly relative humidity of the outside air was 89% during the experimental period. It was found that the average nightly relative humidity inside the PE screened tunnel was 5.2% higher than that outside when the PE screen was drawn at nighttime. This means that the humidifying effect of the PE screen in the plastic tunnel was 5.2%. This result was due to the fact that the rate of air exchange was reduced inside the PE screened tunnel by the PE screen, and therefore the dew-point temperature of the air was increased. The rate of air exchange depends on the design of the greenhouse, the covering material, its method of attachment and the speed and direction of the wind. Bailey (1978) found that the rate of air exchange was reduced 38% by the polyester screen inside a glasshouse. When the rate of the air leakage is very low, the temperature of the thermal screen will control the dew-point temperature, and therefore air will condensate below the screen. Since the temperature of the thermal screen was higher than that of the covering material, the air relative humidity below the PE screen was high. Thus, the air relative humidity below the thermal screens depends on the air tightness of the screens, and when the rate of the air leakage is very low, the temperature of the thermal screen will be a limiting factor. In this experiment, the humidifying effect of the PE screen was lower in comparison with the results (10–15%) obtained by Sims (1977). Bailey (1978) also found that air relative humidity inside the glasshouse where tomato plants were grown increased by up to 10-15% by means of an aluminized polyester screen. On the other hand, the average nightly relative humidity inside the polyester screened tunnel was lower 10.4% than the outside. This result was due to the air-tightness value of the polyester screen, which was calculated using equation (3). The air relative humidity below the thermal screens depends on the air tightness of the screens. The average nightly air-tightness value inside the polyester and PE screened tunnels was 0.72 and 0.57, respectively. Since the average nightly air tightness value inside the polyester screened tunnel was higher than that of the PE screened tunnel, the average nightly relative humidity inside the polyester screened tunnel was lower than that of the PE screened one. In other words, the air relative humidity inside the plastic tunnels increased as the control factor of the air tightness increased during the experimental period. Due to the air tightness of the PE screen, the air relative humidity inside the PE screened tunnel reached levels unfavorable for normal crop development, unless specific measures are taken to prevent this. Garzoli (1989) also reported that energy efficient greenhouses frequently have unacceptabley high levels of relative humidity for two reasons: (1) being tightly sealed, there is only a very small exchange of humid greenhouse air with dry outside air; and (2) double or multiple glazing results in the inner

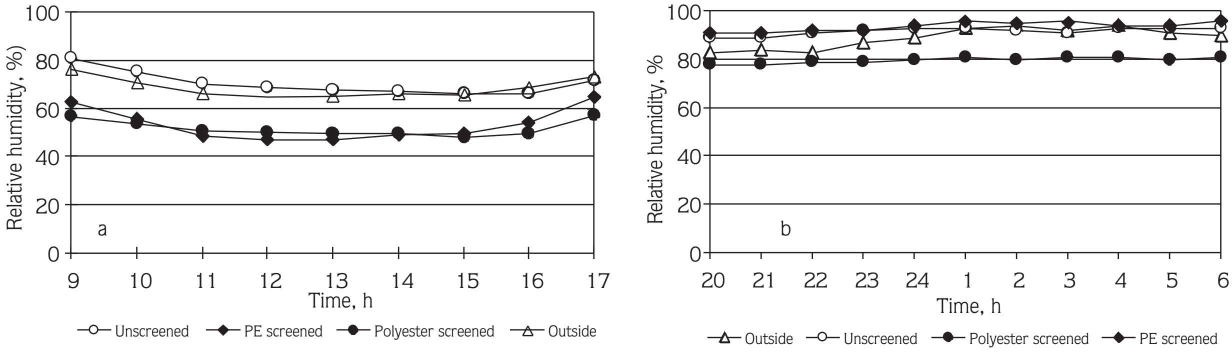

Figure 3. Changes in relative humidity as a function of time: (a) daytime; (b) nighttime.

cover surface being relatively warm; there is reduced condensation on the cover and thus reduced extraction of moisture from the greenhouse air. High relative humidity, approaching saturation, can seriously depress the evaporative demand on the plant and inhibit the uptake of nutrients, particularly calcium. Of greater concern to most growers are the disease and fungal problems that are often associated with high air relative humidity.

The variation in the control factor for air tightness as a function of time in the screened plastic tunnels is given in Figure 4 when the thermal screens are drawn during the night. The air-tightness value implies the degree of reduction of the air temperature above the thermal screen in relation to the air temperature below the screen. It also depends on the wind speed. The average wind speed and the outside temperature were 1.28 m s^{-1} and 7.35 °C respectively during the night (Figure 4). The air-tightness value varied between 0.55 and 0.81 for the polyester screened tunnel during the experimental period. For the polyester screened tunnel, while the air-tightness value was 0.55 at 21:00, it reached 0.81 at 05:00. This means that the air-tightness efficiency of the polyester screen was good in the evening, and then it fell in the early morning. While the average nightly temperature difference between below and above the polyester screen was 1.9 °C, the average nightly air-tightness value for the polyester screened tunnel was 0.72 during the night (Figure 4). Meyer (1981) found that the air-tightness value was 0.52 for the thermal screen made of aluminized polyester (non-woven material). In this experiment, the air-tightness value was higher than the result obtained by Meyer (1981) due to the driving mechanism of the screen. The driving system for collecting and stretching the screen material is a very important part of thermal screen installations. It has a considerable influence on air tightness or the possible conservation of energy. In the present study, the driving system of the thermal screen installation did not stretch the screen material tightly. Therefore, the air-tightness value was higher than previous results.

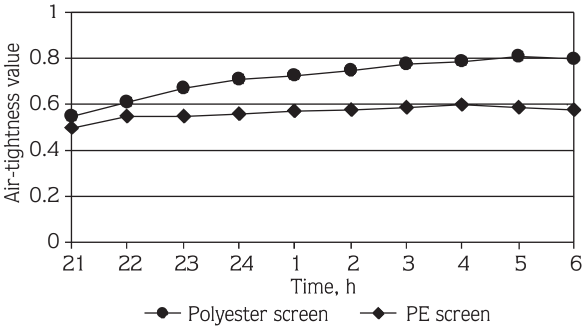

Figure 4. Changes in the control factor for air tightness as a function of time.

The air-tightness value varied between 0.5 and 0.6 for the PE screened tunnel during the night (Figure 4). While the average nightly temperature difference between below and above the PE screen was 1 °C, the average nightly air-tightness value for the PE screened tunnel was 0.57 during the experimental period. For the PE screened tunnel, better air-tightness values were obtained in relation to increases in the outside temperature compared with the polyester screened tunnel. Meyer (1981) found that the air-tightness value was 0.46 for a thermal screen made of clear PE film. Öztürk (1991) found that the air-tightness value was

0.49 for a PE screened plastic house. The air-tightness value for the PE screened tunnel was higher than the results obtained by Meyer (1981) and Öztürk (1991), due to the reason related to the driving system mentioned above. Figure 5 represents the relationships between the air-tightness value and the outside temperature for the polyester and PE screened tunnels. As expected, the air-tightness value for the polyester and PE screened tunnels decreased as the outside temperature increased. In other words, the air-tightness efficiency of the PE and polyester screens decreased as the outside temperature decreased.

Figure 6 shows the changes in solar radiation and PAR as a function of time in the plastic tunnels when the thermal screens are opened during the daytime. The outside solar radiation varied between 42 W m^{-2} and 366 W m^{-2} during the day (Figure 6a). The outside solar radiation was 366 W m^{-2} at 13:00; it fell to 40 W m^{-2} at 15:00 in the early evening. The solar radiation transmitted into the unscreened tunnel and PE and polyester screened tunnels was in the range of 39-305 W m^{-2}, 32-247 W m^{-2} and 25-103 W m^{-2} respectively for the period covered by Figure 6a. The average daily solar radiation transmitted into the unscreened tunnel and, PE and polyester screened tunnels was 208 W m^{-2}, 169 W m^{-2} and 84 W m^{-2} respectively during the experimental period. As shown in Figure 6a, an average of 63.86% of the outside solar radiation entered the PE screened tunnel, whereas an average of 78.84% of the outside solar radiation was transmitted into the unscreened tunnel. This result is in agreement with Weimann (1989), who investigated the characteristics of light transmission, heat consumption and condensation processes in different film greenhouses. She found that the light transmission into the single film, double film, single film with aluminized polyester screen, and double film with aluminized polyester screen greenhouses was 60%, 54%, 54% and 49%, respectively. Due to the shading effect of the PE screen, 19% less solar radiation was transmitted into the PE screened tunnel compared with the unscreened tunnel. Similar results were obtained by Öztürk (1991). He found that 20% less solar radiation was transmitted into a screened plastic house compared with an unscreened one. However, Lommerse (1989) found that the overall light transmission before and after

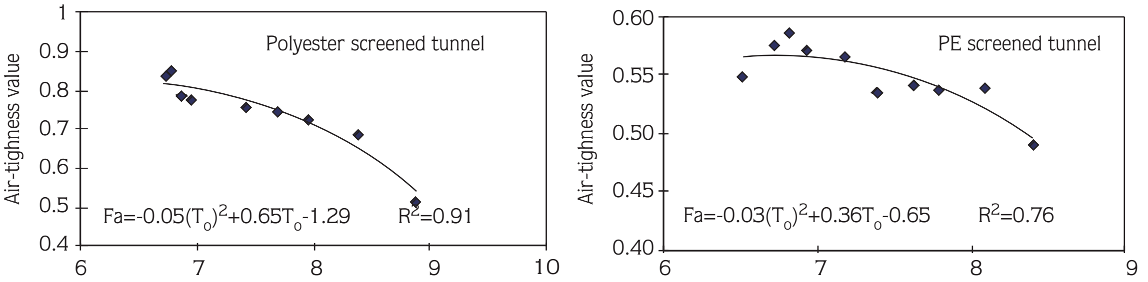

Figure 5. The relationships between air tightness and outside temperature.

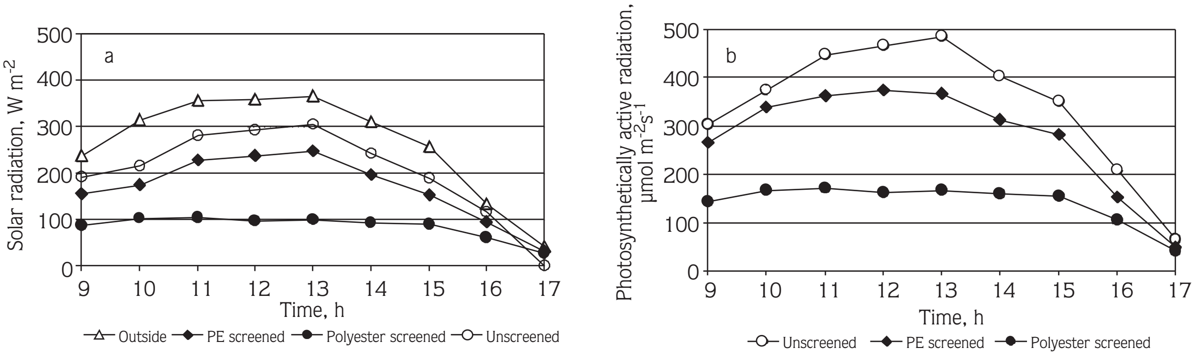

Figure 6. Changes in (a) solar radiation and (b) photosynthetically active radiation.

thermal screen installation was 68% and 65%, respectively. Polyester screen installation in the screened tunnel reduced solar radiation by an average of 50% more than the PE screened one, although the screens were opened during the daytime. An average of 31.9% of the outside solar radiation was transmitted into the polyester screened tunnel since the screen installation shaded the solar radiation entering the polyester screened tunnel.

When the thermal screens were not drawn during the daytime, the PAR transmitting into the screened plastic tunnels was also reduced, depending on the effect of the screen installations in reducing solar radiation. As shown in Figure 6b, the PAR transmitted into the screened plastic tunnels was lower than that of the unscreened one because of the shading effects of the screen installations inside the screened plastic tunnels. The PAR transmitted into the unscreened tunnel and PE and polyester screened tunnels was in the range 67-486 µmol m^{-2} s^{-1}, 49-374 µmol m^{-2} s^{-1} and 42-171 µmol m^{-2} s^{-1} respectively for the period covered by Figure 6b. The average daily PAR transmitted into the unscreened tunnel and PE and polyester screened tunnels was 345 µmol m^{-2} s^{-1}, 279 µmol m^{-2} s^{-1} and 141 µmol m^{-2} s^{-1} respectively during the experimental period. Therefore, 19.21% less PAR was transmitted into the PE screened tunnel compared with the unscreened one, due to the shading effect of the PE screen installations. This result is in agreement with Başçetinçelik et al. (1993), who investigated the effects of a double covered roof and thermal screens on internal solar radiation and tomato plant growth in plastic houses. According to their results, 20% less PAR was transmitted into the PE screened plastic house compared to the unscreened one. However, in the present experiment 59% less PAR was transmitted into the polyester screened tunnel compared with the unscreened one. The reduction in solar radiation and PAR levels in energy efficient greenhouses is an inevitable consequence of double or multiple glazing systems. Studies also confirmed the frequently quoted relationship between light and yield: a 1% reduction results in a 1% yield, when taken over a complete season (Bailey, 1989).

Effect of Thermal Screens on Heat Loss in Plastic Tunnel Greenhouses

If the total heat transfer of the greenhouse is expressed by the overall heat loss coefficient (U), then it is possible to express the influence of the thermal screen installation in different weather conditions. U values were calculated by equation (1), and then the relationships between these coefficients, and the wind speed and the outside temperature were determined. The U values were calculated from the average temperature values recorded during the experimental period. The average values of U and the other climatic factors are given in Table 1. Since the rate of heat loss from the plastic tunnels increased with the wind speed, the calculated values of U also rose considerably. For the polyester screened tunnel, the relationships between U and the wind speed (v, m s^{-1}), and the outside temperature (T_o, °C) were obtained as follows: $U = 2.63 + 0.18v$ ($R^2 = 0.063$) (Figure 7a); $U = 2.5 + 0.09T_o$ ($R^2 = 0.29$) (Figure 7b). Connellan et al. (1988) determined the relationship between U and the wind speed for a well-sealed greenhouse to be $U = 2.99 + 0.13v$. It can be seen that the derived relationship for U obtained in the present research is similar to that reported by Connellan et al. (1988).

As shown in Table 1, the average value of U for the unscreened plastic tunnel was higher than that for the PE screened one, due to the greater heat loss from the

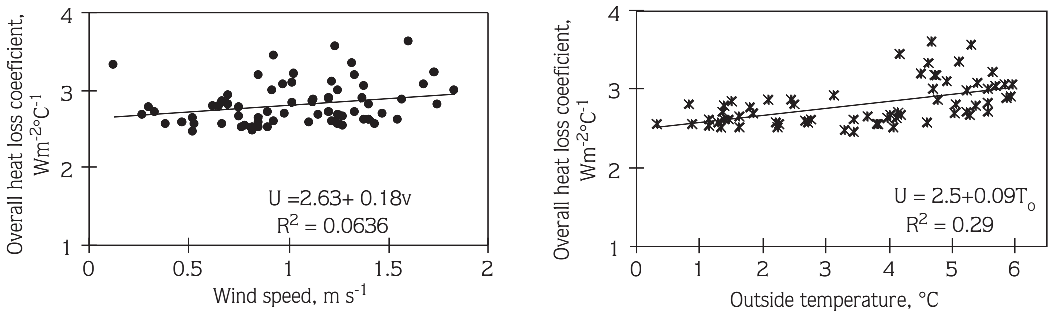

Figure 7. The relationship between the overall heat loss coefficient (a) and the wind speed; (b) and outside temperature.

Table 1. The average values of the overall heat loss coefficient and climate parameters.

Plastic tunnels	Wind speed (v; m s^{-1})	Temperature (°C)		Overall heat loss coefficient (W m^{-2} °C^{-1})	Heat loss (W m^{-2})	Effectiveness (%)
		Outside	Inside			
Polyester screened tunnel	0.41	4	26.85	2.78	86.2	19.8
PE screened tunnel	1.1	6.56	-	3.48	75.1	16
Unscreened tunnel	0.93	4.7	23.37	3.65	69.1	-

former. Calculation of the U values indicated that the U values differed between the unscreened and PE screened tunnels. However, the difference was not great. As expected, considerably higher U values were obtained for the unscreened tunnel. For the PE screened tunnel, the relationships between U and the wind speed, and the outside temperature were obtained as follows: $U = 2.82 + 0.06v$ ($R^2 = 0.12$); $U = 3.10 + 0.02T_o$ ($R^2 = 0.33$). In the present experiment, the calculated U values were lower than those obtained by Mihara and Hayashi (1979). They reported the following relationships between U and the wind speed for PVC greenhouses with a PVC screen and PE screen, respectively: $U = 2.91 + 0.14v$; $U = 3.15 + 0.17v$.

For the unscreened tunnel, the relationships between U and the wind speed, and the outside temperature were $U = 3.55 + 0.11v$ ($R^2 = 0.22$); $U = 3.40 + 0.05T_o$ ($R^2 = 0.35$). Comparison of the calculated U values shows a large difference in the U values between the unscreened and polyester screened tunnels. This result is due to the fact that the dependence of the U values on the wind speed was reduced by the use of thermal screens. The calculated U values for the unscreened tunnel were lower compared with the results of Hellickson (1978) and Mihara and Hayashi (1979). Hellickson (1978) calculated U to be 5.3055 W $m^{-2}C^{-1}$ for a PE greenhouse cover. However, for the PVC greenhouse the following relationship was obtained by Mihara and Hayashi (1979): $U = 4.87 + 0.54v$. Bailey (1983) reported that the relationship between U and the wind speed was $U = 5.2 + 0.4v$ from measurements at night in a 2000 m^2 commercial house (Critten and Bailey, 1989). The dependence of U on the wind speed is very much reduced by the use of the thermal screens. The reduction in U obtained with a transparent screen has been reported to be 38% (Meyer, 1981). When the calculated U values for different greenhouses are compared with U values reported in the literature, differences are seen due to the parameters having a significant effect on the overall heat loss coefficient. Burek et al. (1989) reported that the parameters having a significant effect on the overall heat loss coefficient were as follows: 1) the thermal conductance of the cover material; (2) the conductive heat transfer coefficient from the greenhouse air to the cover and ground; (3) the transmittance of the cover to, and emittance of the ground of, long-wave thermal radiation; (4) the ratio of the total cover area to the ground area; (5) the set-point temperature; and (6) the ventilation rate per unit ground area.

The rate of heat loss per m^2 of floor area of the plastic tunnels was obtained by integrating values of q obtained when equation (4) was used with hourly values of inside and outside temperatures. The values of U obtained in the present experiment were used to compare the rates of heat loss from the plastic tunnels. The effects of the thermal screen on the rate of heat losses were evaluated by equation (5). Figure 8 shows the rate of heat losses per m^2 of floor area from the plastic tunnels. The rate of heat losses per m^2 of floor area was 86.2 W m^{-2}, 75.1 W m^{-2} and 69.1 W m^{-2} for the unscreened tunnel and PE and polyester screened tunnels, respectively. Comparison of

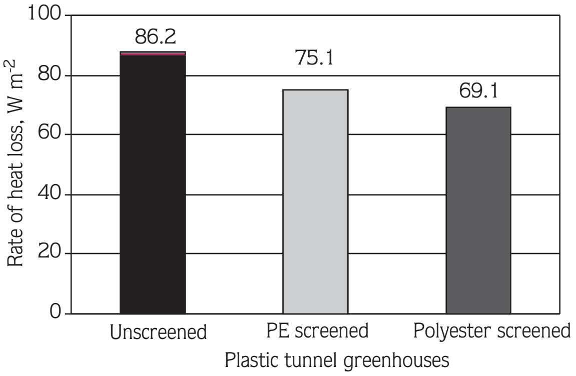

Figure 8. Rate of heat loss in the plastic tunnel greenhouses.

the rate of heat losses per m^2 of floor area shows that the difference in the rate of heat loss between the PE and polyester screened tunnels was not great. The rate of heat loss was calculated to be 16% and 19.8% lower than that from the unscreened tunnel for the PE and polyester screened tunnels, respectively. In other words, it was found that the thermal screen effectiveness was 16% and 19.8% for the PE and polyester screens, respectively. The effect of the PE and polyester screens on the rate of heat loss changed according to the properties of the screen materials.

Therefore, more energy conservation was obtained with screens made of polyester materials than with those made of PE. The calculated screen effectiveness for the PE screen in the present experiment was lower compared with the results of Meijer (1980), who found that the thermal screen effectiveness for a PE screen was 25%. Roberts et al. (1981) reported that the thermal screen effectiveness ranged from 22% to 58%, depending on the thermal screen materials. However, the values of the thermal screen effectiveness are in agreement with Kieboom (1988), who reported that possible energy saving depending on the screen materials was between 10% and 70%.

Conclusion

Energy conservation techniques have been developed to reduce the heat loss from greenhouses or plastic tunnels because of rising energy prices. Thermal screens have gained increasing importance among the measures to protect crops against extreme weather conditions and to regulate cultivation. To reduce energy consumption for greenhouse heating, thermal screens are used in nearly all conditions of greenhouse production in the world. The performance of a given thermal screen system is influenced by several interrelated parameters, including the size of the greenhouse, the cover material, the type of cultivation, the desired day and night temperature of the inside air, and the external ambient conditions. In this study, it was found that the maximum heating effect of polyester and PE screens was 4.8 °C and 2.5 °C respectively in the plastic tunnel greenhouses during the experimental period.

During the night, when the screen is closed in the greenhouse the energy conservation of the thermal screen varies depending on the type of material used. The energy conservation efficiency of polyester screens is higher than that of PE screens. In the present study, the thermal screen effectiveness of polyester and PE screens was 19.8% and 16%, respectively. Proper sealing of the screen to prevent air exchange between the enclosed space and the roof space is most important. If the screen system does not close tightly, the amount of energy saving at night may be reduced. On the other hand, when the screens are completely opened, daytime solar radiation in the greenhouses is reduced, because of the shading effect of the screen installation. Polyester screen installation in the tunnel greenhouse was reduced solar radiation by an average of 50% more than the PE screened one, although the screens were opened during the daytime. This problem is solved by using suppler screen materials and by operating the screen installation efficiently. Loss of light caused by the parked screen is a source of some concern when light levels are low. It is essential that the space taken up by the screen when folded be reduced to a minimum in order to limit light loss.

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