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The effects of plastic greenhouse covering on cucumber (*Cucumis sativus L.*) growth

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ABSTRACT

Cucumber (*Cucumis sativus L.*) is an important vegetable crop belonging to the cucurbit family. Cucumbers are grown under protected cultivation worldwide. The influence of greenhouse covering materials on cucumber physiological processes and yield were evaluated. Three greenhouses, each with 48 m^2, North–South direction and with wet-pad and fan cooling system were covered by either one of the 200 μm thickness plastic films; newly developed NIR-reflective film (C_1) and two commercial films (C_2 and C_3). The predicted equations of the photosynthetic rate (μmol CO_2 m^{-2} s^{-1}), transpiration (m mol H_2O m^{-2} s^{-1}), intercellular CO_2 concentration (μmol CO_2 mol^{-1}), stomatal conductance (mol H_2O m^{-2} s^{-1}) and leaf temperature were obtained by multiple regression analysis of the measured data. The average temperatures were 22.27 ± 2.06 °C, 23.80 ± 2.26 °C, 25.42 ± 2.41 °C and 31.12 ± 4.30 °C for films C_1, C_2, C_3 and outside respectively. The results revealed that vapour pressure deficit (VPD) under (C_1) was lower than that under C_2 and C_3 during the production period. The average of photosynthetic rate values were 16.61 ± 5.49, 15.51 ± 5.18 and 14.91 ± 4.78 μmol CO_2 m^{-2} s^{-1} for films C_1, C_2 and C_3, respectively. While, the transpiration rate and the intercellular CO_2 concentration under (C_1) were higher than those under C_2 and C_3 during the production period. Therefore, fruit and yield traits increased under C_1 followed by C_2 and then by C_3 of greenhouses covers. It can be concluded that the greenhouses plastic covering material has a great influence on the internal environmental conditions, physiological processes and productivity of cucumber plants.

1. Introduction

Ecological engineering is defined as "the design of sustainable ecosystems that integrate human society with its natural environment for the benefit of both" (Mitsch, 1993, 2012; Mitsch and Jørgensen, 2003, 2004). One of the goals of ecological engineering is the development of new sustainable ecosystems that have both human and ecological value (Mitsch and Jørgensen, 2004, Mitsch, 1998, 2012). The main purpose of a greenhouse construction is to provide an optimal level of microclimate conditions for plant growth, development, and productivity on a year-round basis or to extend the growing season (Ali, 2012). Cucumber (*Cucumis sativus L.*) is an important vegetable crop belonging to the cucurbit family. Cucumber fruit contain approximately 95% water, 3.6% carbohydrates, and 0.65% protein and are low in calories (150 kcal kg^{-1}). They are a good source of the following nutrients (in mg kg^{-1}): pantothenic acid (B_5) (0.026), vitamin C (0.28), and magnesium (1.3). Cucumbers are grown both as a source of pickles and to be eaten fresh (Lucier et al., 2007). Plant photosynthetic and other physiological properties are inherently programmed but largely governed by environmental conditions. Cucumber is a plant native to subtropical and temperate regions, and the optimum temperature ranges for growth and photosynthesis are generally regarded as 15–32 °C and 25–30 °C, respectively. Cucumber is affected by high temperatures, strong light, and water stress when cultivated from spring to fall compared to cultivation in the winter/spring period, resulting in a considerably shortened harvest period and a substantial decrease in yield and quality (Li et al., 2007a, 2007b). High temperatures can cause physiological injury to membrane lipids, carbon and nitrogen metabolism (Du and Tachibana, 1994; Zhou and Ye, 1999), photosynthesis (Li et al., 2007a; Sun et al., 2005; Tewari and Tripathy, 1998; Abd-el-baky et al., 2010) and root

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growth (Meng et al., 2003). It can also substantially reduce yield and quality (Meng et al., 2003). The negative effects of high temperature on yield are greater when the seedlings are smaller, and larger in the seedling stage than in the fruiting stage (Miao et al., 2000). Greenhouses provide better environmental conditions for plant growth and productivity (Elgood et al., 2010). Solar radiation of a given region is the first climatic factor to be considered before starting a protected cultivation project (Castilla, 2013). Kittas et al. (1999) noticed that the quality of the radiation allowed by covering materials to enter the greenhouse is important for evaluating its influence on plant's growth and development. Papadopoulos and Hao (1997) studied the effect of single-glass (glass), double inflated polyethylene film (D-poly), and a rigid twin acrylic (acrylic) panel, as greenhouse covers, on seedless cucumber growth and productivity. They found that plants in D-poly houses might have acclimated to the low light conditions by reducing specific leaf weight (SLW) and increasing their light interception efficiency. They concluded that under South Western Ontario, the D-poly greenhouse is strongly recommended, because there is no loss of productivity in comparison with a glass house. Abdel-Ghany et al. (2012) reviewed the effects of greenhouse cover type on the transmittance of photosynthetically active radiation (PAR), the reflectance or absorptance of near-infrared (NIR) and the greenhouse air temperature. They concluded that NIR-reflecting plastic films seem to be the most suitable, low cost and simple cover for greenhouses under arid conditions. The most common plastic materials used as agricultural films include low density polyethylene (LDPE), the copolymer of ethylene and vinyl-acetate (EVA) and polyvinyl chloride (PVC) (Castilla, 2013). Polyethylene films are flexible, transparent to thermal radiation and have been used extensively as greenhouse covering materials in many regions. Cemek et al. (2006) studied the effects of various polyethylene films as greenhouse covers on aubergine growth and productivity. They reported that plants under double layers of polyethylene showed faster growth and development with higher yield than plants under ultraviolet (UV) stabilised polyethylene, infrared (IR) absorbers polyethylene and single layer of polyethylene. The change in greenhouse cover materials and associated design has affected the greenhouse environment. About 5-20% loss of photosynthetically active radiation PAR in D-poly houses, in comparison to single-layered glass houses, has been shown by several researchers (Bauerle, 1981; Blom and Ingratta, 1985). The light transmission of acrylic may be lower (Stromme et al., 1986), similar (Ting and Giacomelli, 1987) or higher (Bredenbeck, 1985) than that of single glass depending on the composition, aging, and weathering of the acrylic panels and greenhouse structure. The improved insulation of D-poly and acrylic greenhouses has resulted in increased humidity and a higher 24-h average air temperature (Blom and Ingratta, 1985; Boulard et al., 1989; Cockshull, 1992; Papadopoulos and Hao, 1997). Changes in greenhouse microclimates may have significant effects on growth, development and productivity of crops (Cockshull, 1992). Net photosynthetic rates are reduced at low light levels and the loss of tomato yield was proportional to the loss of light (Challa and Schapendonk, 1984; Cockshull et al., 1992). Little attention has been paid to the interaction of environmental factors. Therefore, it is impossible to predict crop responses to different cover materials realistically based only on the effects of individual greenhouse environmental factors since the greenhouse cover materials will change several environmental factors simultaneously (Blom and Ingratta, 1985; Cockshull, 1992). Experimentation under simulated commercial conditions may lead to better understanding of the responses of greenhouse crops to the commercial use of various cover materials. Supplemental lighting increased leaf photosynthesis rates, plant growth and development, and fruit yield and quality of greenhouse crops (Blom and Ingratta, 1984; Blain et al., 1987; Hendriks, 1992), and has been suggested as an option for compensating the loss of light in double-layered energy saving greenhouses (Cockshull, 1992). In plant leaf cells, oxygen is produced during photosynthesis and used in respiration, and active oxygen species is also generated but is normally maintained at low levels with little negative effect (Alscher et al., 1997; Asada, 1999). When variations in temperature, light, and humidity go beyond the range required for normal growth and development in plants, excess generation and accumulation of active oxygen species is induced as oxidative stress (Foyer and Noctor, 2000; Monk et al., 1989; Neill et al., 2002). Active oxygen species is also involved in the physiological metabolism and life processes of plants, and is known to accelerate senescence (Li et al., 2004; McRae and Thompson, 1983; Ogweno et al., 2009; Xu et al., 2006) and inhibit photosynthesis (Asada and Takahashi, 1987; Powles, 1984; Guo et al., 2006). There is a lack of information about the local greenhouses covering materials. So, the objective of this study was to evaluate the effect of different plastic covering materials on the internal environmental parameters. These parameters include temperature, relative humidity and vapour pressure deficit (VPD). The effect of greenhouse covering on photosynthesis, other physiological properties and yield of cucumber fruits were also evaluated. The predicted equations of the photosynthetic, transpiration and other parameters were obtained by multiple regression analysis of the measured data.

Fig. 1. The three greenhouses covered with C_2, C_1 and C_3 plastic films.

2. Materials and methods

2.1. Covering materials

Three plastic films, each with 200 μm thickness, were selected for the study. The first cover is NIR-reflective film (designated as C_1) produced at pilot scale at SABIC Polymer Research Center, College of Engineering, King Saud University for the purpose of reflecting some of the NIR radiation and transmitting most of the PAR into the greenhouse. The second two commercial films (designated as C_2 and C_3) were selected from the local market of Saudi Arabia (C_2) and Kuwait (C_3), respectively. Detailed description, the chemical formulations and the production procedures for the newly developed NIR-reflective film (C_1) were reported by Gulrez et al. (2013).

2.2. Greenhouses description

Three greenhouses (Fig. 1), each with 48 m^2, were built in a North-South direction with wet-pad and fan cooling system at the Educational Farm, King Saud University (Riyadh, Saudi Arabia, 46° 47′ E, longitude and 24° 39′ N, latitude) during winter and spring season 2012/2013.

Fig. 2. Photosynthetic properties instrument.

2.3. Plant materials

Cucumber seeds (*Cucumis sativus* L. cv. Sovana F1, Rijk Zwaan; The Netherlands) were germinated in Jiffy 7 pellets in controlled environment (24 °C ±1 day/ 18 °C ±1 night temperatures). At three true-leaf stage, seedlings were transplanted in the three greenhouses into 30 cm diameter pot containing a mixture of peat, sand and vermiculite (1:1:1) w/w. Fertilization and other cultural practices were applied as recommended in commercial cucumber production (Maynard and Hochmuth, 2007).

2.4. Data recoded

Three plants from each greenhouse were randomly selected at 15 days interval for the measurement of growth traits. Vegetative growth parameters (Alsadon et al., 2015) were measured. The yield traits (Fruit number, length and dry weight, total dry biomass and total yield) were recorded at each harvest time. The environmental parameters were measured outside and inside the three greenhouses; recorded at 1-min intervals, averaged every 10 min, and then every one hour and saved in a data logger (CR03000 Micrologger®, Campbell Scientific Inc). These parameters were air temperatures and relative humidity inside and outside the greenhouses. The vapour pressure deficit VPD was calculated from the measured temperature and relative humidity. The daily average (over 24-h period) of air temperature and relative humidity under C_1, C_2 and C_3 covers were measured during the period from 25 to 85 days from transplanting.

2.5. Photosynthesis system

An LI-6400 photosynthesis system (Li-Cor, Inc., Lincoln, NE) equipped with a standard 2 × 3 cm leaf corvette and a Li-Cor LI-6400-02B light source was used for gas exchange measurements (Fig. 2). Photosynthetic rate, transpiration, intercellular CO_2 concentration, conductance to H_2O and leaf temperature were also measured.

2.6. Experimental design and analysis

Randomized complete block design was applied with four replication. Each greenhouse was divided into 4 rows; distance between rows was 1 m, and the space between the containers in rows was 0.4 m. Plant density was 2.5 plants per m^2. Data were subjected to analysis of variance through SAS version 8.1 computer program (SAS Institute, 2008). Treatment means and correlation coefficients were calculated (Steel and Torrie, 1980).

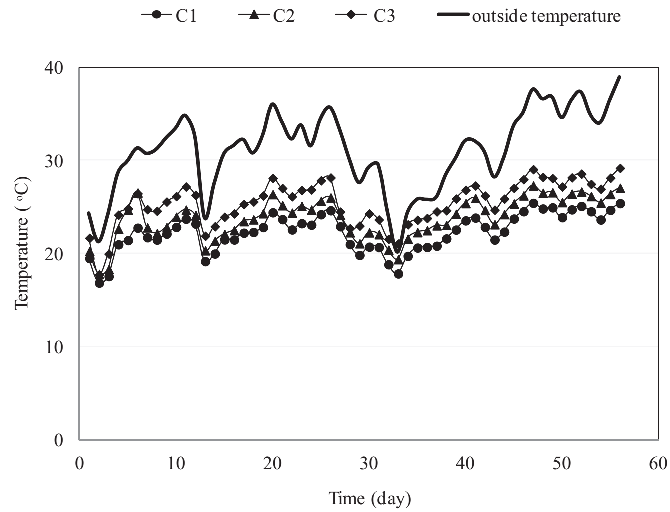

Fig. 3. Daily average (over 24-h period) for the air temperature inside the three greenhouses and at the outside during vegetative, flowering, and fruiting stages.

3. Results and discussion

3.1. The effect of covering materials on internal conditions

3.1.1. Air temperature

Fig. 3 represents the daily average (over 24-h period) for the air temperature inside the three greenhouses and at the outside during vegetative, flowering, and fruiting stages. At the day of transplanting, average temperatures were 19.49 °C, 20.25 °C, 21.67 °C and 24.35 °C for greenhouses covers C_1, C_2, C_3 and outside, respectively. While the average temperature at the 28th day after transplanting were 20.99 °C, 22.27 °C, 22.71 °C and 30.16 °C for greenhouses covers C_1, C_2, C_3 and outside, respectively. Additionally, at the end of the growing season, the average temperatures were 25.39 °C, 27.4 °C, 29.18 °C and 38.89 °C for greenhouses covers C_1, C_2, C_3 and outside, respectively. The average temperatures for the whole experimental period were 22.27 ± 2.06 °C, 23.80 ± 2.26 °C, 25.42 ± 2.41 °C and 31.12 ± 4.30 °C for greenhouses covers C_1, C_2, C_3 and outside, respectively. The air temperature under (C_1) was lower than those under C_2 and C_3 during the production period (Fig. 3). The temperature gradient increased with day times and the slope of this gradient increased with time. This finding supports the reports of Al-Helal and Alhamdan (2009) who indicated that the minimum temperature differences were observed at early morning, late afternoon and night. This phenomenon was observed by Farkas et al. (2001), who found the structural elements of 100 μm polyethylene plastic tunnels which have a large effect on the transmissivity of solar radiation and inside temperature.

3.1.2. Relative humidity

At the day of transplanting, the average of relative humidity values were 96.78%, 59.82%, 56.66% and 51.31% for greenhouses covers C_1, C_2, C_3 and outside, respectively. While the average relative humidity values at the 28th day after transplanting were 79.88%, 62.50%, 68.51% and 80.53% for greenhouses covers C_1, C_2, C_3 and outside, respectively. Fig. 4 shows the daily average (over 24-h period) for the relative humidity inside the three greenhouses and at the outside during vegetative, flowering, and fruiting stages. Additionally, at the end of the growing season, the average values were 42.15%, 50.20%, 43.57% and 28.25% for greenhouses covers C_1, C_2, C_3 and outside, respectively. The average relative

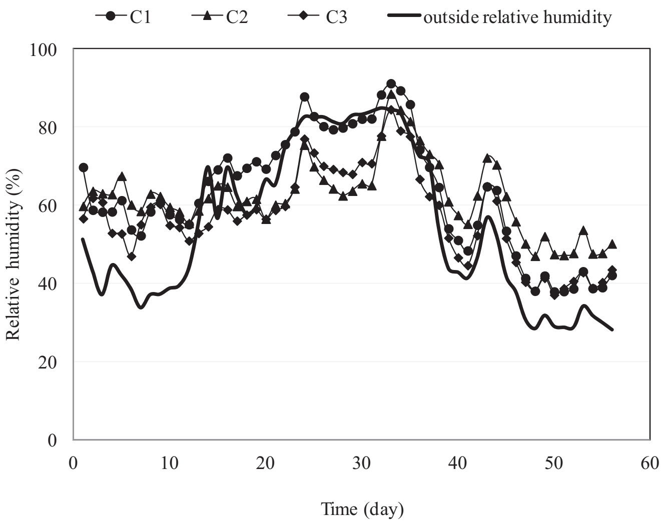

Fig. 4. Daily average (over 24-h period) for the relative humidity inside the three greenhouses and at the outside during vegetative, flowering, and fruiting stages.

humidity values for the whole experimental period were 63.05 ± 15.52%, 62.20 ± 9.27%, 57.19 ± 11.79% and 54.63 ± 19.67% for greenhouses covers C_1, C_2, C_3 and outside, respectively. Because the three greenhouses were evaporatively cooled (using wet pads and fans systems), the effect of the three films covers (C_1, C_2 and C_3) on the relative humidity in the greenhouses was not clearly evident.

3.1.3. Vapour pressure deficit (VPD)

At the day of transplanting, the average values of VPD were 0.68, 0.95, 1.12 and 1.48 kPa for greenhouses covers C_1, C_2, C_3 and outside, respectively. While the average of VPD values at the 28th day after transplanting were 0.5, 1.01, 0.87 and 0.83 kPa for greenhouses covers C_1, C_2, C_3 and outside, respectively. Additionally, at the end of the test the average values of VPD were 1.88, 1.78, 2.28 and 4.99 kPa for greenhouses covers C_1, C_2, C_3 and outside, respectively. The average VPD values for the whole experimental period were 1.034 ± 0.52, 1.14 ± 0.38, 1.43 ± 0.53 and 2.20 ± 1.26 kPa for greenhouses covers C_1, C_2, C_3 and outside, respectively. The air VPD under (C_1) was lower than those under C_2 and C_3 during the production period (Fig. 5). The temperature gradient increased with day

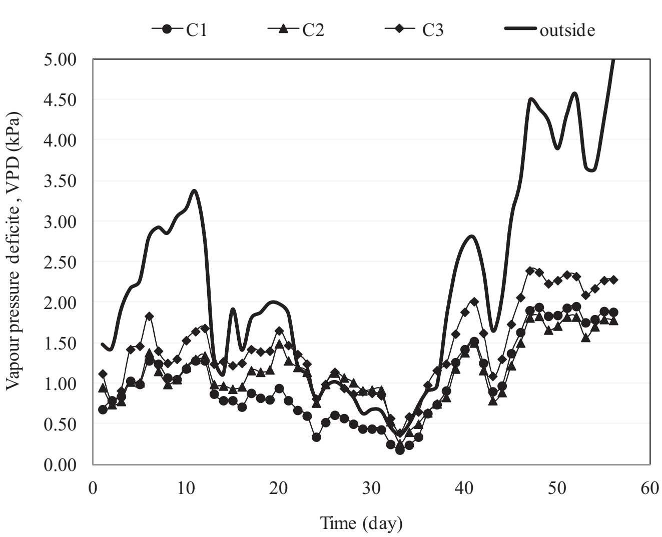

Fig. 5. Daily average (over 24-h period) for theVPD) inside the three greenhouses and at the outside during vegetative, flowering, and fruiting stages.

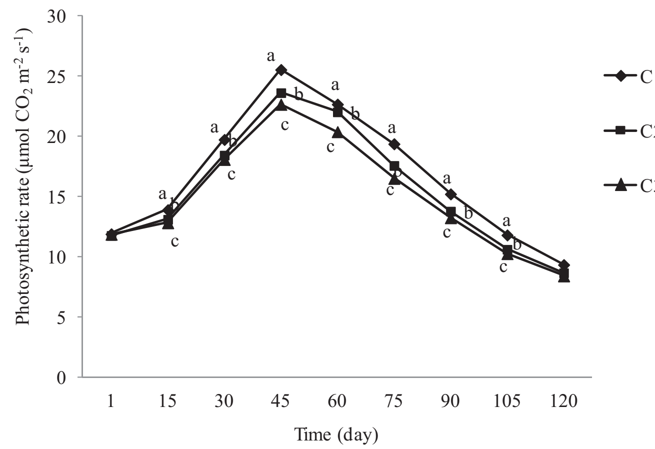

Fig. 6. Photosynthetic rate (μmol CO_2 $m^{-2}s^{-1}$) of cucumber plants.

times and the slope of this gradient increased with time. Changes in greenhouse microclimate may have significant effects on growth, development and productivity of crops (Cockshull, 1992). Net photosynthetic rates are reduced at low light levels and the loss of tomato yield was proportional to the loss of light (Challa and Schapendonk, 1984; Cockshull et al., 1992). Continuous VPD can induce calcium deficiency and leaf area reduction in greenhouse tomato (Bakker, 1990; Holder and Cockshull, 1990). Low VPD in day time increased early tomato yield, but the final yield was reduced by low VPD regardless of day or night (Bakker, 1990). The mean fruit quality and keeping quality were also reduced under low VPD (Bakker, 1990; Holder and Cockshull, 1990). Early vegetative growth and yield of cucumber were enhanced by either low day or night VPD, and final total yield was negatively related to day time VPD (Bakker et al., 1987). High temperature stimulated plant growth and increased the early yield of various greenhouse vegetables (Van Holsteijn, 1987). While covering materials will change several environmental factors simultaneously (Blom and Ingratta, 1985; Cockshull, 1992). Ludlow and Jarvis (1971), Running (1976), Sanford and Jarvis (1986), and Warkentin et al. (1992) described response curves for *Picea sitchensis* that drop precipitously as VPD increases above 0.5 kPa. Kaufmann's (1976) curve for *Picea engelmannii* shows a similar response. Darlington et al. (1997) reported that seedlings of *Picea mariana*, a species that is closely related to and can hybridize with *Picea rubens* in the sympatric portions of their ranges (Gordon, 1976), showed no significant difference in biomass accumulation when grown in 0.3–0.8 kPa and 2.0–2.5 kPa VPD regimes. Although gas exchange rates were not measured by Darlington et al. (1997), their results are indicative of a relatively high threshold for the VPD response or a response curve with a low slope.

3.2. Photosynthetic system

3.2.1. Photosynthetic rate

The photosynthetic rate values at the day of transplanting were 11.9, 11.77 and 11.86 μmol CO_2 m^{-2} s^{-1} for greenhouses covers C_1, C_2 and C_3, respectively. All covering materials induced a pronounced increase in photosynthetic rate with day times till the 45th day and then decreased gradually (Fig. 6). The photosynthetic rates at the end of the growing season were 9.34, 8.67 and 8.4186 μmol CO_2 m^{-2} s^{-1} for greenhouses covers C_1, C_2 and C_3, respectively. Additionally, the average photosynthetic rate values for the whole experimental period were 16.61 ± 5.49, 15.51 ± 5.18 and 14.91 ± 4.78 μmol CO_2 m^{-2} s^{-1} for films C_1, C_2 and C_3, respectively. The results illustrated that photosynthetic rate under (C_1) was higher than those under C_2 and C_3 during the production

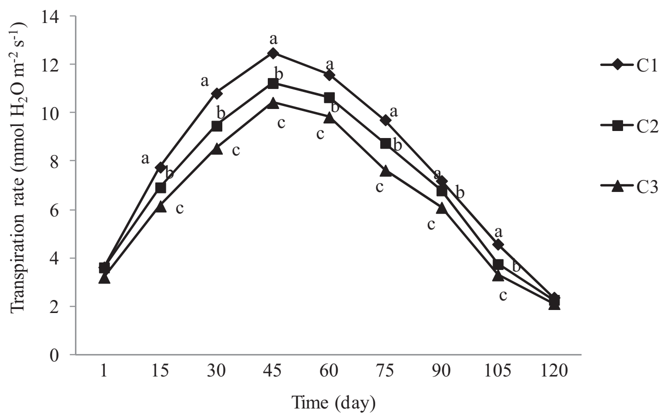

Fig. 7. Transpiration rate (mmol H_2O $m^{-2}s^{-1}$) for cucmber plants.

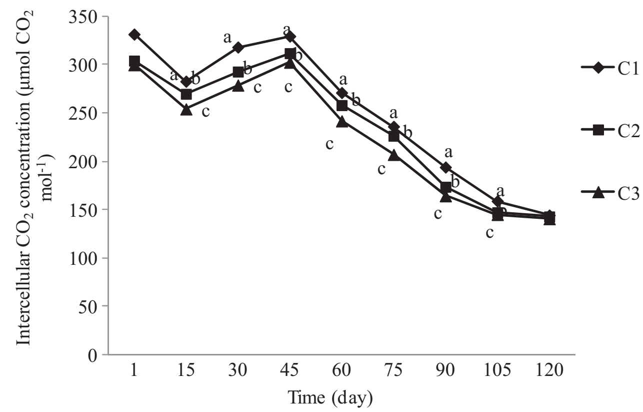

Fig. 8. Intercellular CO_2 concentration (μmol CO_2 mol^{-1}) for cucumber leaves.

period. The curves increased gradually till the 45th day and then decreased gradually. This means that the maximum photosynthetic rate was obtained at that day. It is shown that the temperature gradient increased with day times and the slope of this gradient increases with time. The CO_2 fixed reaction is an enzyme reaction strongly controlled by temperature (Tewari and Tripathy, 1998). The reduction of photosynthetic rate after 45 days could be attributed to increased senescence and photorespiration, reduced CO_2 solubility, and increased diffusion resistance. In addition, significant inhibition of photosynthesis and damage to the CO_2 fixed reaction mechanism might be due to the high temperature stress (Baker, 1991; Havaux, 1996; Crafts-Brandner and Salvucci, 2004; Li et al., 2007a, 2007b), Xu et al., 2014). This implies that inhibition of photosynthesis and damage to the mechanism of photosynthesis through large amounts of active oxygen species brought about by high temperature stress is one process, which is also inferred from the results of this experiment in which there was an increased amount of active oxygen due to high temperatures (Asada and Takahashi, 1987; Monk et al., 1989; Guo et al., 2006). On the other hand, increasing temperature also appeared to affect independently of its effects on photosynthesis (Mansfield, 1985; Weiler et al., 1982; Wilkinson and Davies, 1997).

3.2.2. Transpiration

The values of transpiration rate for the plants under different covering films and production times found for the transpiration at the day of transplanting were 3.62, 3.60 and 3.20 m mol H_2O m^{-2} s^{-1} for greenhouses covers C_1, C_2 and C_3, respectively (Fig. 7). However, at the end of the growing season, the average values of transpiration rate were 2.36, 2.26 and 2.11 m mol H_2O m^{-2} s^{-1} for greenhouses covers C_1, C_2 and C_3, respectively. Additionally, the average transpiration rate values for the whole experimental period were 7.79 ± 3.66, 7.05 ± 3.26 and 6.36 ± 3.01 m mol H_2O m^{-2} s^{-1} for greenhouses covers C_1, C_2 and C_3, respectively. The results illustrated that transpiration rate under (C_1) was higher than those under C_2 and C_3 during the production period. The transpiration rate increased with increasing day time till the 45th day and then decreased gradually (Fig. 7). This means that the maximum transpiration rate was obtained at that day.

3.2.3. Intercellular CO_2 concentration

The values found for the intercellular CO_2 concentration at the day of transplanting were 331.33, 304 and 299.67 μmol CO_2 mol^{-1} for greenhouses covers C_1, C_2 and C_3, respectively. While, at the end of the growing season, the average values of intercellular CO_2 concentration were 144.33, 143.14 and 140.67 μmol CO_2 mol^{-1} for greenhouses covers C_1, C_2 and C_3, respectively. Additionally, the average intercellular CO_2 concentration values for

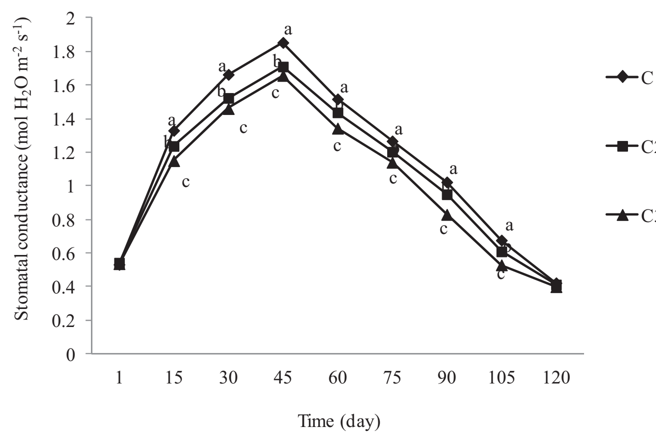

Fig. 9. Stomatal conductance (mol H_2O m^{-2} s^{-1}) for plants.

the whole experimental period were 251.7 ± 72.28, 236.3 ± 66.77 and 225.9 ± 64.29 μmol CO_2 mol^{-1} for greenhouses covers C_1, C_2 and C_3 respectively. The results illustrated that intercellular CO_2 concentration under C_1 was higher than those under C_2 and C_3 during the production period. The intercellular CO_2 concentration increased with increasing plant age time till the 45th day and then it decreased with increasing time (Fig. 8). This means that the maximum intercellular CO_2 concentration was obtained at that day. Under high temperatures, the Rubisco CO_2 fixation reaction decreases while the oxygenation reaction in photorespiration becomes relatively large because the reduction of CO_2 solubility in plant leaf cells becomes greater than that of O_2, and CO_2

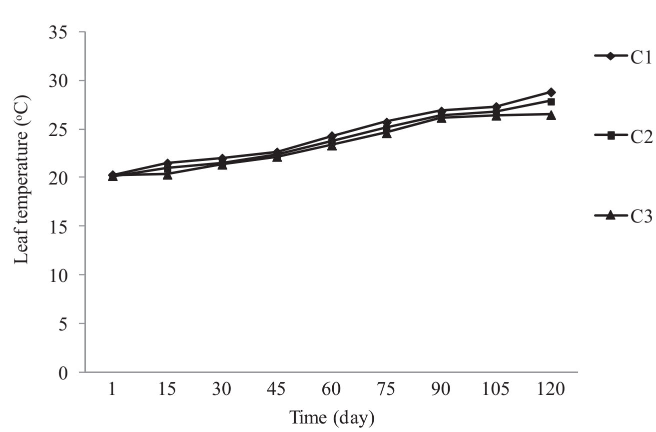

Fig. 10. Leaf temperatures of cucumber fruit plants.

Table 1
Fruit and yield traits of cucumber plants grown under different plastic films. Data taken at 60 days from transplanting.

Type of plastic film	No fruits/ plant	Fruit length (cm)	DW fruits (g)	Total dry biomass (g)	Yield /plant (g)	Yield/m^2 (g)
C_1	49.89 a	16.7 a	236.67 a	285.23 a	6383 a	15958 a
C_2	45.98 b	15.6 b	201.35 b	241.48 b	5501 b	13753 b
C_3	44.67 c	14.5 c	194.57 c	230.78 c	5137 c	12842 c
LSD at 0.05	1.05	0.79	4.26	6.981	104.5	259.7

Means in each column followed by different letters are significantly different (LSD at 0.05). Total biomass represents dry weight of leaves, shoots and fruits).

diffusion resistance increases (Dai et al., 1992). Injury caused by the mechanism of the CO_2 fixation reaction due to high temperatures also causes a reduction in the CO_2 fixation reaction (Chaitanya et al., 2001). The CO_2 fixed reaction is an enzyme reaction strongly controlled by temperature (Tewari and Tripathy, 1998). This was caused by increased senescence and photorespiration, reduced CO_2 solubility, and increased diffusion resistance, as well as significant inhibition of photosynthesis and damage to the CO_2 fixed reaction mechanism due to the long period with high temperature stress (Baker, 1991; Havaux, 1996; Crafts-Brandner and Salvucci, 2004). This implies that inhibition of photosynthesis and damage to the mechanism of photosynthesis through large amounts of active oxygen species brought about by high temperature stress is one process, which is also inferred from the results of this experiment (Fig. 8) in which there was an increased amount of active oxygen due to high temperatures (Asada and Takahashi, 1987; Monk et al., 1989; Guo et al., 2006).

3.2.4. Stomatal conductance

The conductance to water of cucumber leaves increased with increasing plants age to the 45th day and then decreased gradually (Fig. 9). The values found for the conductance parameter at the starting day were 0.53, 0.54 and 0.54 mol H_2O m^{-2} s^{-1} for greenhouses covers C_1, C_2 and C_3, respectively. While, at the end of the growing season, the values of conductance were 0.42, 0.41 and 0.40 mol H_2O m^{-2} s^{-1} for films C_1, C_2 and C_3, respectively. Additionally, the average conductance values for the whole experimental period were 1.14 ± 0.51, 1.07 ± 0.47 and 1.01 ± 0.45 mol H_2O m^{-2} s^{-1} for greenhouses covers C_1, C_2 and C_3, respectively. The results illustrated that conductance under (C_1) was higher than those under C_2 and C_3 during the production period. The maximum conductance values were obtained at the 45th day. Stomatal conductance is controlled by the aperture of stomatal pores (instantaneous response) and by the number and size of stomata in the leaf on the long term response (Farquhar and Sharkey, 1982; Iino et al., 1985; Lawson, 2009; Zeiger et al., 2002). In addition, cucumber plants grown under different B:R ratios (long term response), show greater stomata density and larger stomata (Hogewoning et al., 2010; Savvides et al., 2012; Van Ieperen et al., 2012). On the other hand, stomatal response to change in air current of the leaf boundary layer can be conjectured to relate to changes in the intercellular CO_2 concentration and the transpirational water loss of the leaf.

3.2.5. Leaf temperature

The values for the leaf temperature at the day of transplanting were 20.3, 20.13 and 20.2 °C for films C_1, C_2 and C_3, respectively (Fig. 10) while, at the end of growing season, the values of leaf temperature were 28.8, 27.83 and 26.47 °C for greenhouses covers C_1, C_2 and C_3, respectively. Additionally, the average leaf temperature values for all experiment period were 24.37 ± 2.95, 23.86 ± 2.79 and 23.45 ± 2.57 °C for greenhouses covers C_1, C_2 and C_3, respectively. The results illustrated that leaf temperature under C_1 was higher than those under C_2 and C_3 during the production period. The leaf temperature increased gradually which means that the maximum leaf temperatures were obtained at the end of growing season at the 120th day while the minimum leaf temperatures were obtained at the first day (Fig. 10).

3.3. Crop yield

Fruit number, length and dry weight increased for plants grown under C_1 film with significant differences from both C_2 and C_3 covered plants (Table 1). Total dry biomass and yield followed similar manner. The crop yield values were 15.958, 13.753 and 12.842 kg m^{-2} for greenhouses covers C_1, C_2 and C_3, respectively while the yield per plant values were 6.383, 5.501 and 5.137 kg for greenhouses covers C_1, C_2 and C_3, respectively. Additionally, the cucumber fruit lengths were 16.7, 15.6 and 14.5 cm for greenhouses films C_1, C_2 and C_3, respectively. In general, the results indicated that fruit and yield traits increased under C_1 followed by C_2 and then by C_3 films. Daily transmission of solar radiation and temperature has been optimal for cucumber growth and development under C_1 cover as compared to C_2 and C_3 film. Using C_1 film lead

Table 2
The constants *a*, *b* and *c* and coefficient of determination for photosynthetic properties under different greenhouses covering.

Properties	Covering materials	Constants *a*	*b*	*c*	R^2
Photosynthetic rate (μmol CO_2 m^{-2} s^{-1})	C_1	−0.789	7.344	−0.11	0.844
	C_2	−0.707	6.502	0.471	0.829
	C_3	−0.628	5.681	1.446	0.815
Transpiration rate (μmol CO_2 m^{-2} s^{-1})	C_1	−0.854	8.152	−4.611	0.831
	C_2	−0.791	7.535	−4.275	0.818
	C_3	−0.749	7.121	−4.146	0.789
Intercellular CO_2 concentration (CO_2 mol^{-1})	C_1	−5.690	39.511	222.83	0.854
	C_2	−4.923	31.815	227.05	0.842
	C_3	−4.536	28.874	219.26	0.819
Stomatal conductance (mol H_2O m^{-2} s^{-1})	C_1	−0.069	0.620	0.240	0.864
	C_2	−0.063	0.559	0.277	0.862
	C_3	−0.059	0.522	0.272	0.841

to 16.03% increase in productivity as compared with C_2 film and 24.3% increase in comparison with C_3 film. Many researchers indicated that temperature and relative humidity inside greenhouses were depend on covering materials and resulting in higher plant yield (Papadopoulos and Hao, 1997; Bakker et al., 1987; Acock et al., 1976; Stromme et al., 1986). Results from the present study support this conclusion. While, high humidity levels resulted in an increased photosynthetic rate (Acock et al., 1976; Bunce, 1984), fresh and dry weight, stem length and leaf area, and final total cucumber yield was positively related to daytime humidity, when the other variables are kept constant (Bakker et al., 1987).

3.4. Regression analysis

Regression analysis was conducted to find a relation between the studied parameters for different covering films and plant age periods. The following equation shows the most appropriate form of the relationship between each characteristic and period of time.

$$Y = aX_2 + bX + c$$

The equation was from the regression analysis of the measured data. Table 2 illustrates the values of the constants a, 3b and c of the predicting equation and coefficient of determination of the measured parameters.

4. Summary and conclusions

Results show that the covering materials affect the internal environmental conditions such as temperature, relative humidity and VPD. In addition, the photosynthetic and physiological processes of cucumber leaves are influenced by several factors (i.e. the environmental conditions such as temperature, relative humidity and VPD and plants age). The average temperatures for the whole experimental period were $22.27 \pm 2.06\,^{\circ}$C, $23.80 \pm 2.26\,^{\circ}$C, $25.42 \pm 2.41\,^{\circ}$C and $31.12 \pm 4.30\,^{\circ}$C for greenhouses covers C_1, C_2, C_3 and outside, respectively while air temperature under C_1 was lower than those under C_2 and C_3 during the production period. In addition, VPD under C_1 was lower than those under C_2 and C_3 during the production period. The average of photosynthetic rate values were 16.61 ± 5.49, 15.51 ± 5.18 and 14.91 ± 4.78 μmol CO_2 m^{-2} s^{-1} for films C_1, C_2 and C_3, respectively. The transpiration rate as well as intercellular CO_2 concentration under (C_1) were higher than those under C_2 and C_3 during the production period. Therefore, fruit and yield traits increased under C_1 followed by C_2 and then by C_3 film. Using film C_1 lead to increase the productivity to 16.03% in comparison with C_2 film and 24.3% in comparison with C_3 film. In conclusion, the greenhouses covering material have a great influence on the internal conditions, physiological processes and productivity of cucumber plants.

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References

Abd-El-Baky, H.M., Ali, S.A., ElHaddad, Z.A., El Ansary, M., 2010. Some environmental parameters affecting sweet pepper growth and productivity under different greenhouse forms in hot and humid climatic conditions. J. Soil Sci. Agric. Eng. 1 (3), 225–247.
Abdel-Ghany, A.M., Al-Helal, I.M., Alzahrani, S.M., Alsadon, A.A., Ali, I.M., Elleithy, R.M., 2012. Covering materials incorporating radiation-preventing techniques to meet greenhouse cooling challenges in arid regions: a review. Scientific World J. 2012, http://dx.doi.org/10.1100/2012/906360.
Acock, B., Charles-Edwards, D.A., Hand, D.W., 1976. An analysis of some effects of humidity on photosynthesis by a tomato canopy under winter light conditions and a range of carbon dioxide concentrations. J. Exp. Bot. 27, 933–941.
Al-Helal, I.M., Alhamdan, A.M., 2009. Effect of arid environment on radiative properties of greenhouse polyethylene cover. Solar Energy 83, 790–798.
Ali, S.A., 2012. Modeling of some solar radiation available at different orientations of greenhouses. Misr J. Agric. Eng. 29 (3), 1181–1196.
Alsadon, A.A., Al-Helal, I.M., Ibrahim, A.A., Abdel-Ghany, A.M., Al-Zaharani, S.M., Gulrez, S.K.H., 2015. Growth analysis responses of cucumber crops under arid environment greenhouses covered with plastic films. J. Animal Plant. Sci. (under review).
Alscher, R.G., Donahue, J.L., Cramer, C.L., 1997. Reactive oxygen species and antioxidants. Am. Acta Hortic. I70, 69–80.
Asada, K., 1999. The water–water cycle in chloroplasts: scavenging of active oxygens and dissipation of excess photons. Annu. Rev. Plant Physiol. Plant Mol. Biol. 50, 601–639.
Asada, K., Takahashi, M., 1987. Production and scavenging of active oxygen in photosynthesis. In: Kyle, D.J., Osmond, C.B., Arntzen, C.J. (Eds.), Photoinhibition. Elsevier, Amsterdam, pp. 227–288.
Baker, N.R., 1991. A possible role for photosystem II in environmenta1 perturbations of photosynthesis. Physiol. Plant. 81, 563–570.
Bakker, J.C., 1990. Effects of day and night humidity on yield and fruit quality of greenhouse tomatoes (*Lycopersicon esculentum* Mill). J. Hortic. Sci. 62, 363–370.
Bakker, J.C., Welles, G.W.H., Van Uffelen, J.A.M., 1987. The effect of day and night humidity on yield and quality of glasshouse cucumbers. J. Hortic. Sci. 62, 363–370.
Bauerle, W.L., 1981. Exolite acrylic for glazing greenhouses. Proc. Natl. Agric. Plastics Congress 2 (2), 225–234.
Blain, J., Gosselin, A., Trudel, M.J., 1987. Influence of HPS supplementary lighting on growth and yield of greenhouse cucumbers. HortScience 22, 36–38.
Blom, T.J., Ingratta, F.J., 1984. The effect of high pressure sodium lighting on the production of tomatoes, cucumbers and roses. Acta Hortic. 148, 905–914.
Blom, T.J., Ingratta, F.J., 1985. The use of polyethylene film as greenhouse glazing in North America. Acta Hortic. I70, 69–80.
Boulard, T., Baille, H., Lagier, J., Mermier, M., Vanderschmitt, E., 1989. Water vapour transfer in a plastic house equipped with a dehumidification heat pump. J. Agric. Eng. Res. 44, 191–204.
Bredenbeck, H., 1985. Influence of different glazing materials on the light transmissivity of greenhouses. Acta Hortic. 170, 111–117.
Bunce, J.A., 1984. Effects of humidity on photosynthesis. J. Exp. Bot. 35, 1245–1251.
Castilla, N. 2013. Greenhouse Technology and Management, 2nd Edition. (Translated by E. J. Baeza). CABI. Croydon, UK. P. 335.
Cemek, B., Demir, Y., Uzun, S., Ceyhan, V., 2006. The effects of different greenhouse covering materials on energy requirement, growth and yield of aubergine. Energy 31, 1780–1788.
Chaitanya, K.V., Sundar, D., Reddy, A.R., 2001. Mulberry leaf metabolism under high temperature stress. Biol. Plant. 44, 379–384.
Challa, H., Schapendonk, A.H.C.M., 1984. Quantification of effects of light reduction in greenhouses on yield. Acta Hortic. 148, 501–510.
Cockshull, K.E., 1992. Crop environments. Acta Hortic. 312, 77–85.
Cockshull, K.E., Graves, C.J., Cave, C.R.J., 1992. The influence of shading on yield of glasshouse tomatoes. J. Hortic. Sci. 67, 11–24.
Crafts-Brandner, S.J., Salvucci, M.E., 2004. Analyzing the impact of high temperature and CO_2 on net photosynthesis: biochemical mechanisms, models and genomics. Field Crops Res. 90, 75–85.
Dai, Z., Edwards, G.E., Ku, M.S.B., 1992. Control of photosynthesis and stomatal conductance in *Ricinus communis L* (castor bean) by leaf to air vapor pressure deficit. Plant Physiol. 99, 1426–1434.
Darlington, A.B., Halinska, A., Dat, J.F., Blake, T.J., 1997. Effects of increasing saturation vapor pressure deficit on growth and ABA levels in black spruce and jack pine. Trees 11, 223–228.
Du, Y.C., Tachibana, S., 1994. Effect of supra optimal root temperature on the growth, root respiration and sugar content of cucumber plants. Sci. Hortic. 58, 289–301.
Elgood, Z., Robertson, W.D., Schiff, S.L., Elgood, R., 2010. Nitrate removal and greenhouse gas production in a stream-bed denitrifying bioreactor. Ecol. Eng. 36 (11), 1575–1580.
Farkas, I., Weihb, P., Biroí, A., Laube, W., Eitzinger, J., Woí jcicki, A., 2001. Modeling of radiative PAR transfer in a tunnel greenhouse. Math. Comput. Simul. 56, 357–368.
Farquhar, G.D., Sharkey, T.D., 1982. Stomatal conductance and photosynthesis. Ann. Rev. Plant Physiol. 33, 317–345.
Foyer, C.H., Noctor, G., 2000. Leaves in the dark see the light. Science 284, 5414–5416.
Gordon, A.G., 1976. The taxonomy and genetics of *Picea rubens* and its relationship to *Picea mariana*. Can. J. Bot. 54, 781–813.
Gulrez, S.K. H., Abdel-Ghany, A.M., Al-Helal, I.M., Al-Zaharani, S.M., Alsadon, A.A., 2013. Evaluation of PE films having NIR-reflective additives for greenhouse applications in arid regions. Advances in Materials Science and Engineering. Volume 2013, Article ID 575081, 8 pages. http://dx.doi.org/10.1155/2013/575081.
Guo, Y.P., Zhou, H.F., Zhang, L.C., 2006. Photosynthetic characteristics and protective mechanisms against photooxidation during high temperature stress in two citrus species. Sci. Hortic. 108, 260–267.
Havaux, M., 1996. Short-term responses of photosystem I to heat stress. Photosynth. Res. 47, 85–97.
Hendriks, J., 1992. Supplementary lighting for greenhouses. Acta Hortic. 312, 65–76.

Hogewoning, S.W., Trouwborst, G., Maljaars, H., Poorter, H., van Ieperen, W., Harbinson, J., 2010. Blue light dose-responses of leaf photosynthesis, morphology, and chemical composition of *Cucumis sativus* grown under different combinations of red and blue light. J. Exp. Bot. 61, 3107–3117.

Holder, R., Cockshull, K.E., 1990. Effects of humidity on the growth and yield of glasshouse tomatoes. J. Hortic. Sci 65, 31–39.

Iino, M., Ogawa, T., Zeiger, E., 1985. Kinetic properties of the blue-light response of stomata. Proc. Natl. Acad. Sci. 82, 8019–8023.

Kaufmann, M.R., 1976. Stomatal response of Engelmann spruce to humidity, light, and water stress. Plant Physiol. 57, 898–901.

Kittas, C., Baille, A., Giaglaras, P., 1999. Influence of covering material and shading on the spectral distribution of light in greenhouses. J. Ag. Eng. Res. 73, 341–351.

Lawson, T., 2009. Guard cell photosynthesis and stomatal function. New Phytol. 181, 13–34.

Li, J., Chang, Y., Yu, J., 2007a. Changes of some photosynthetic properties and photosystem II photochemical activities in cucumber seedlings under high temperature stress. Plant Physiol. Commun. 43, 1085–1088 (in Chinese with English abstract).

Li, J., Yu, J., Chang, Y., Xu, X., Nie, S., 2007b. Influences of high temperature stress on membrane permeability and activity of cell defense enzymes in leaves of cucumber seedlings. J. Changjiang Vegetables 9, 59–61 (in Chinese with English abstract).

Li, J., Zhao, X., Matsui, S., Maezawa, S., 2004. Changes in antioxidative levels in aging cucumber (*Cucumis sativus L.*) leaves. J. Japan Soc. Hort. Sci. 73, 491–495 (in Japanese with English abstract).

Lucier, G., Jerardo, A., 2007. Vegetables and Melons Outlook/VGS-319. Economic Research Service. USDA.

Ludlow, M.M., Jarvis, P.G., 1971. Photosynthesis in Sitka spruce (*Picea sitchensis* (Bong.) Carr.) I. General characteristics. J. Appl. Ecol. 8, 925–953.

Mansfield, T.A., 1985. Porosity at a price: The control of stomatal conductance in relation to photosynthesis. In: Barber, J., Baker, N.L. (Eds.), Photosynthetic Mechanisms and the Environment. Elsevier Science Publishers, New York, pp. p419–p452.

Maynard, D.N., Hochmuth, G.J., 2007. Knott's Handbook for Vegetable Growers. John Wiley & Sons, Inc, Hoboken, NJ, USA, pp. 630.

McRae, D.G., Thompson, J.E., 1983. Senescence-dependent changes in superoxide onion production by illuminated chloroplasts from bean leaves. Planta 158, 185–193.

Meng, L., Qin, Z., Li, S., 2003. Effect of high temperature stress on the root of cucumber seedling. Acta Hortic. Sin. 30 694 (in Chinese with English abstract).

Miao, M., Li, Q., Cao, B., Chen, X., 2000. Effect of temperature on reproductive growth and yield formation of *Cucumis sativus L.* Acta Hortic. Sin. 27, 412–417 (in Chinese with English abstract).

Mitsch, W.J., Jørgensen, S., 2003. Ecological engineering: a field whose time has come. Ecol Eng 20, 363–377.

Mitsch, W.J., 1993. Ecological engineering—a cooperative role with the planetary life-support systems. Environ. Sci. Technol. 27, 438–445.

Mitsch, W.J., 1998. Ecological engineering—the seven-year itch. Ecol. Eng. 10, 119–138, 7.

Mitsch, W.J., 2012. What is ecological engineering? Ecol. Eng. 45, 5–12.

Mitsch, W.J., Jørgensen, S.E., 2004. Ecological Engineering and Ecosystem Restoration. John Wiley & Sons, Inc, New York, pp. 411.

Monk, L.S., Fagerstedt, K.V., Crawford, R.M.M., 1989. Oxygen toxicity and superoxide dismutase as an antioxidant in physiological stress. Physiol. Plant. 76, 456–459.

Neill, S.J., Desikan, R., Clarke, A., Hurst, R.D., Hancock, J.T., 2002. Hydrogen peroxide and nitric oxide as signaling molecules in plants. J. Exp. Bot. 53, 1237–1247.

Ogweno, J.O., Song, X.S., Hu, W.H., Shi, K., Zhou, Y.H., Yu, J.Q., 2009. Detached leaves of tomato differ in their photosynthetic physiological response to moderate high and low temperature stress. Sci. Hortic. 123, 17–22.

Papadopoulos, A.P., Hao, X., 1997. Effects of the greenhouse covers on seedless cucumber growth, productivity, and energy use. Sci. Hortic. 68, 113–123.

Powles, S.B., 1984. Photoinhibition of photosynthesis induced by visible light. Ann. Rev. Plant Physiol. 35, 15–44.

Running, S.W., 1976. Environmental control of leaf water conductance in conifers. Can. J. For. Res. 6, 104–112.

Sanford, A.P., Jarvis, P.G., 1986. Stomatal responses to humidity in selected conifers. Tree Physiol. 2, 89–103.

SAS., 2008. Statistical Analysis System. SAS Institute, Inc., Cary, NC, USA.

Savvides, A., Fanourakis, D., van Ieperen, W., 2012. Co-ordination of hydraulic and-stomatal conductances across light qualities in cucumber leaves. J. Exp. Bot. 63, 1135–1143.

Steel, R.G.D., Torrie, J.H., 1980. Principles and Procedures of Statistics. McGraw-Hill, New York., USA., pp. 633.

Stromme, E., Sebesta, Z., Reiersen, D., 1986. Experience with, double acrylic cladding for tomatoes in Norway. Tag. -Ber., Akad. Landwirtsch. -Wiss. DDR Berlin 238, 167–172.

Sun, Y., Fan, A., Xu, W., 2005. Effects of oxalate on photosynthetic apparatus and xanthophyll cycle in leaves of cucumber seedlings under high temperature stress. Sci. Agric. Sin. 38, 1774–1779 (in Chinese with English abstract).

Tewari, A.K., Tripathy, B.C., 1998. Temperature-stress-induced impairment of chlorophyll biosynthetic reactions in cucumber and wheat. Plant Physiol. 177, 851–858.

Ting, K.C., Giacomelli, G.A., 1987. Solar photosynthetically active radiation transmission through greenhouse glazing. Energy Agric. 6, 121–132.

Van Holsteijn, G.P.A., 1987. Small differences in temperature, great differences in yield. Groenten Fruit 43, 45–48.

Van Ieperen, W., Savvides, A., Fanourakis, D., 2012. Red and blue light effects during growth on hydraulic and stomatal conductance in leaves of young cucumber plants. Acta Hortic. 956, 223–230.

Warkentin, D.L., Overhulser, D.L., Gara, R.I., Hinckley, T.M., 1992. Relationships between weather patterns Sitka spruce (Picea sitchensis) stress, and possible tip weevil (Pissodes strobi) infestation levels. Can. J. For. Res. 22, 667–673.

Weiler, E.W., Schnabl, H., Hornberg, C., 1982. Stress-related levels of abscisic acid in guard cell protoplasts of *Vicia faba* L. Planta 154, 24–28.

Wilkinson, S., Davies, W.J., 1997. Xylem sap pH increase: a drought signal received at the apoplastic face of the guard cell that involves the suppression of saturable abscisic acid uptake by the epidermal symplast. Plant Physiol. 113, 559–573.

Xu, S., Li, J., Zhang, X., Wei, H., Cui, L., 2006. Effects of heat acclimation pretreatment on changes of membrane lipid peroxidation, antioxidant metabolites, and ultra structure of chloroplasts in two cool-season turf grass species under heat stress. Environ. Exp. Bot. 56, 274–285.

Xu, X., Zou, X., Cao, L., Zhamangulova, N., Zhao, Y., Tang, D., Liu, D., 2014. Seasonal and spatial dynamics of greenhouse gas emissions under various vegetation covers in a coastal saline wetland in southeast China. Ecol. Eng. 73, 469–477.

Zeiger, E., Talbott, L.D., Frechilla, S., Srivastava, A., Zhu, J., 2002. The guard cell chloroplast: a perspective for the twenty-first century. New Phytol. 153, 415–424.

Zhou, L., Ye, C., 1999. Effects of high temperature stress on metabolism of nitrogen and carbohydrates in seedlings of cucumber. J. Fujian Agric. Univ. 28, 289–293 (in Chinese with English abstract).