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ORIGINAL PAPER

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EFFECT OF CLEAR AND DEFUSE GLASS COVERING MATERIALS ON FRUIT YIELD AND ENERGY EFFICIENCY OF GREENHOUSE CUCUMBER GROWN IN HOT CLIMATE

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ABSTRACT

Using proper greenhouse covering materials can provide a suitable environment for plant growth in Saudi Arabia. The effects of three different greenhouse covering materials, clear glass, polycarbonate and diffuse tempered glass were used to evaluate its effect on cucumber productivity, water and energy use efficiency. Results show that either water or light use efficiency was higher in compartments covered with diffused or clear glass than polycarbonate compartment. Inconsequence, fruit yield of cucumber plants/m^2 was significantly higher (58%) in clear and diffuse glass greenhouses as opposed to polycarbonate greenhouse. In term of the effect of cultivar or plant density, no significant differences on cucumber yield were found. Using of different covering materials did affect environmental data of greenhouses. Less light was transmitted through polycarbonate cover than clear or diffuse glass. The photosynthesis active radiation (PAR) was 996, 1703, 1690 mol/m^2/d, while the electricity consumption was 2.97, 3.44, and 2.88 kWh under polycarbonate, clear glass, and diffuse glass, respectively. Meanwhile, diffuse glass compartment revealed 16% lower of water consumption than other covering materials. In this respect, it could be concluded that using diffuse glass, as a greenhouse cover material, has a strong positive influence on crop productivity under Saudi Arabia climate.

Key words: *Cucumis sativus*, water use efficiency, light transmission, polycarbonate, greenhouse covering materials, yield

INTRODUCTION

Greenhouse industry for vegetable production aims to optimize environmental conditions within the greenhouse to achieve maximum yield through minimum production cost [Petropoulos et al. 2019]. The climate condition in Saudi Arabia demands greenhouses for year-round production cycle of the most needed vegetable crops. Alongside, under stress climate conditions, the scarcity of water is a limiting factor for agriculture in the region [Ministry of Water and Electricity 2013]. In a hot climate, plant production in the greenhouses might be affected by high solar radiation, resulting in temperatures that exceed favor-

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able conditions for the growth of most plants. This, in turn, increases the cooling load, leading to higher energy and water consumption [Montero 2006]. In the greenhouse, evaporative cooling is used to reduce greenhouse temperature during the long summer to maintain year-round vegetable production. However, evaporative cooling systems consume more water than do the plants and have high energy costs [Al-Helal 2001]. Proper greenhouse design and suitable covering materials would both exploit the external climatic conditions and create an adequate indoor microclimate [Abbouda et al. 2012].

Recently, wide ranges of covering materials with different properties have become available for greenhouse applications [Cocetta et al. 2017]. Polyethylene film is one of the most common greenhouses covering material in Saudi Arabia. It has a high transmittance for visible light (400–700 nm), which is the primary source of energy for photosynthesis [Kwon et al. 2017]. Besides, it is cheap, flexible, lightweight, easy to use, and characterized by a high thermal conductivity [Alsadon et al. 2016]. The greenhouse polyethylene cover has a short lifespan (less than three years) in harsh weather conditions such as high temperature, high solar intensity, dust, and strong wind, all of which occur in arid regions like Saudi Arabia [Abbouda et al. 2012].

Glass is also widely used as a greenhouse covering material because it is durable and has excellent mechanical characteristics. Besides, it transmits and holds solar radiation over a long period, with a lifespan of more than 20 years [Teitel et al. 2017]. These properties support glass as a nearly optimal choice for use as a greenhouse covering material. On the other hand, a glass sheet is heavy and requires a massive support frame [Giacomelli and Roberts 1993], which can significantly increase initial cost [Kwon et al. 2017]. Furthermore, light can be diffused by modern covering materials such as diffuse glass [Hemming et al. 2008]. Diffuse glass applied in the Netherlands showed an increase in tomato production of 7 to 9% [Dueck et al. 2012]. A large part of the solar radiation in Saudi Arabia is direct since the number of cloudy days is limited; so, the effect of diffuse covering should be even higher in Saudi Arabia than in Europe, where cloudy days are standard. In recent years, there have been advances in the polycarbonate industry that make polycarbonate equal or even better than glass as a greenhouse covering material. The main disadvantage of polycarbonate is its expensiveness relative to other covering materials. Briefly, different greenhouse covering materials have various effects on plant growth and yield. Although glasshouses improve production and control the microclimate around plants better, different types of glass and other materials have different effects on light interception [Ilić et al. 2017].

Cucumber (*Cucumis sativus L.*) is one of the most popular vegetables cultivated in greenhouses worldwide, and it is the second most cultivated crop under protected cultivation in Saudi Arabia [El-Wanis et al. 2012]. The cultivation area for greenhouse-grown cucumber has reached 2605 hectares, with productions of more than 236 tons per year [Ministry of Agriculture 2014]. Soilless culture has proven to be high water-efficient technology. This system is capable of both producing vegetables of superior quality [Abdelaziz and Pokluda 2007, Gruda 2009, Nejad and Ismaili 2014] under different water quality conditions [Abdelaziz and Abdeldaym 2018] and replacing soil cultivation in case of soil contamination in vegetable production systems [Lommen, 2007, Savvas et al. 2013, Savvas and Gruda 2018, Gruda 2019]. This study was designed to evaluate the effect of clear glass, diffuse glass, and polycarbonate covering materials on greenhouse climate condition, cucumber production, water and energy efficiency.

MATERIALS AND METHODS

Greenhouse and experimental site. Three different greenhouse compartments at the sustainable Agriculture Research and Development Center (Estidamah), King Saud University, Riyadh, Saudi Arabia (46°37' E longitude and 24°39' N latitude) were used. Each greenhouse has a length of 40 m from pad to fan and 12 m width. Three spans were placed with gutters of 37 m length, 19 cm wide and 70 cm height above the ground. The Hortimax computer system was used to operate fertilizers and drip irrigation applications. The nutrition recipe was prepared by Wageningen U.R. greenhouse Horticulture Center, Wageningen University, according to [Sonneveid and Voogt 2009]: NH_4 1.8, K 12.4, Ca 5.9, Mg 2.1, NO_3 23.5, SO_4 2.4, P 1.8, Fe 23.5, Mn 11.8, Cu 0.9, Mo 0.6 mol/kg, with

2.5 dS/m E.C. All greenhouse compartments were equipped with an automatically moving shading screen with a shading rate of 30% and an evaporative cooling system. Ventilators are controlled individually by the computer unit following air temperature inside each greenhouse.

Covering materials. Three different covering materials were used. The first compartment was covered by the conventional tempered glass (clear glass 4 mm) with the following properties: direct light 90%, hemispherical 82%, haze 0%. The second was covered by a double layer of polycarbonate (16 mm), with hemispherical 56%. The third was covered with modern diffuse tempered glass (diffuse glass 4 mm) with the following properties: direct light 91%, hemispherical 80%, haze 75%.

Greenhouse climate. Environmental data of each single greenhouse compartment was automatically recorded. Air temperature and relative humidity were measured by three separated sensors (Horitmax model MTV). One box was located 7 m apart from the pad, one in the center, and one 10 m apart from the wall where the fans are located to record greenhouse microclimate every 5 minutes during the day. Light intensity was measured by Photosynthetically Active Radiation (PAR) sensor from Vernier company (PAR range: 0 to 2000 μmol m^{-2} s^{-1}), placed at the height of the trellis. The compartments were equipped with drip irrigation systems serving every single plant with one dripper (4 l/h). Drain water was collected and pumped back to the central water preparation area while measuring the amount. Energy and water consumption were measured automatically using energy meter and water meters (Multi-Jet Water Meter from ARDA Company).

Plant materials. Cucumber seeds (*Cucumis sativus L.*) of cultivars 'Alfrid' – F1 and 'Khassib' – F1, from Rijk & Zwaan Seed Company, were used. Two plants were grown in rockwool slabs with plant density four stems/m^2 and three stems/m^2, with 840 cucumber plants per greenhouse. The experiment was conducted in winter and spring cycles of 2017–2018. Seeds were sown in 15th and 8th of March and September, respectively, and seedlings were transplanted into rockwool slabs after 15 and 18 days, respectively, to the main greenhouses. Cultural practices were applied as recommended in commercial cucumber production [Maynard and Hochmuth 2007].

Yield and its components. Fruit harvesting was done twice a week, and the total yield per square meter was determined by collecting the weekly yield (kg/m^2) from each treatment. Twenty fruits were selected randomly from each replicate to measure fruit fresh weight. Fruit dry weight was estimated based on drying representative fruit samples to a constant weight at 70^{o}C in a laboratory ventilated oven.

Water and electric use efficiency. Water use efficiency (WUE) was calculated as the ratio of the total fruit yield, and the total water applied using the following equation: WUE (kg/m^3) = total yield (kg/m^2)/ water applied (m^3/m^2), [Zotarelli et al. 2009]. Similarly, the electric consumption (kWh/m^2) for each greenhouse was calculated.

Statistical analysis. Combined analysis of variance of the data was computed after running Bartelet test according to Snedecor and Cochran [1994] for all tested parameters. The data was statistically analyzed using the Statistical Analysis System (SAS), and treatment means were compared using the LSD test at a 0.05 property level, according to Steel and Torrie [1980].

RESULTS

Greenhouse climate. Data in Table 1 show no variance in term of air temperature between the three different greenhouse covering materials. Moreover, a slight increase in relative humidity was found with polycarbonate cover materials than diffuse or clear glass greenhouse. Notably, clear and diffuse glass presented higher values of photosynthetic active radiation (1690 and 1703 mol/m^2) in comparison to polycarbonate (996 mol/m^2).

Yield and its components. The interaction between cultivars, number of branches/m^2 and the three covering materials on yield and its components were significantly differed (Table 2). Cultivar Alfrid presented the highest number of fruits and total yield (95, 8.1 kg/m^2) under clear glass/4 branches·m^{-2}, respectively, while the lowest number of fruits and total yield (54.4, 4.2 kg/m^2) was obtained by cultivar Khassib/3 branches·m^{-2} under polycarbonate. In term of fruit fresh weight, cultivar 'Alfrid' showed the highest fruit fresh weight (88 g) with diffuse glass/3 branches·m^{-2}. In comparison, cultivar Khassib resulted in the lowest fruit fresh weight (73 g) under poly-

Table 1. Average air temperature, relative humidity and total photosynthetic active radiation (PAR) inside the greenhouse under different covering materials

Temperature (Cº)			Relative humidity (%)			PAR (mol/m^2/d)		
polycarbonate	diffuse glass	clear glass	polycarbonate	diffuse glass	clear glass	polycarbonate	diffuse glass	clear glass
22–23	23–24	23–24	74–75	70–71	71–72	996	1690	1703

Table 2. Effect of different greenhouse cover materials on number of fruits, total yield, fruit fresh and dry weight of cucumber during the two growing cycles

Greenhouse cover	Cultivar	Branches/m^2	Number of fruits/m^2	Total yield (kg/m^2)	Fruit fresh weight (g)	Fruit dry weight (%)
Polycarbonate	Alfrid	3	61.9 d	4.8 d	77 d	3.4 ab
	Alfrid	4	61.4 d	4.9 d	78 de	2.5 de
	Khassib	3	54.4 d	4.2 d	77 de	2.3 e
	Khassib	4	60.1 d	4.6 d	73 e	2.9abcde
Diffuse glass	Alfrid	3	85.2 bc	7.5 ab	88 a	3.0 abcd
	Alfrid	4	86.3 abc	7.6 ab	87 ab	3.4 a
	Khassib	3	83.2 bc	7.1 bc	85 abc	2.6 cde
	Khassib	4	83.5 bc	6.8 bc	81 cd	3.5 a
Clear glass	Alfrid	3	84.9 bc	7.3abc	86 abc	3.5 a
	Alfrid	4	95.0 a	8.1 a	84 abc	2.7 bcde
	Khassib	3	78.2 c	6.50 c	83abcd	3.2 abc
	Khassib	4	87.7 ab	7.2abc	82 bcd	2.8abcde
LSD			9.04	0.87	5.73	0.68

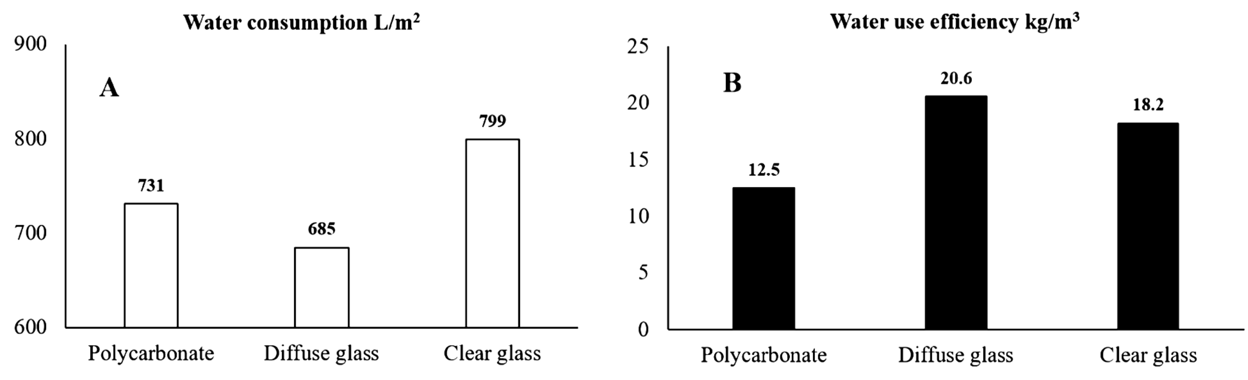

Fig. 1. Water consumption and water use efficiency of cucumber plants grown under different three greenhouse covering materials during the two growing cycles

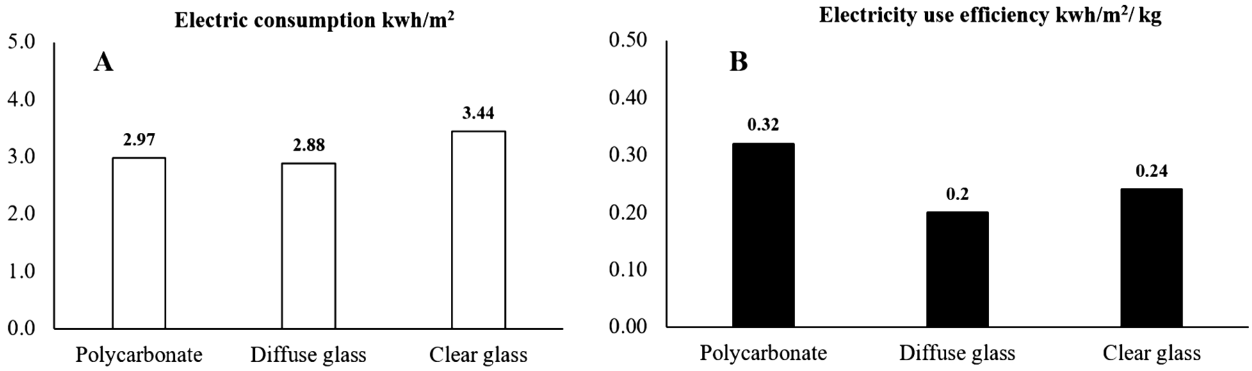

Fig. 2. Electricity consumption and electricity use efficiency of cucumber plants grown under different three greenhouse covering materials during the two growing cycles

carbonate cover material/4 branches·m^{-2}. Moreover, fruit dry weight percentage of both cultivars declared the best significant value under diffuse and clear glass compartments (3.5%). On the contrast, the lowest dry fruit weight percentage for both cultivars was obtained under polycarbonate cover material (2.5% g).

Water and energy use. Diffuse glasshouse presented lower water and electric consumption (685 L/m^2 and 2.88 kWh/m^2). Particularly, compartments covered with clear glass found to consume more water and electric (799 L/m^2 and 3.44 kw/m^2) if compared to polycarbonate (731 L/m^2 and 2.97 kWh/m^2), respectively (Fig. 1–2). On the other hand, diffuse glasshouse presented higher water use efficiency (20.6 kg/m^3) for cucumber followed by clear glass (18.2 kg/m^3) than polycarbonate (12.5 kg/m^3). According to electrical use efficiency, polycarbonate compartment displayed higher efficiency value (0.32 kWh/m^2/kg), followed by clear and diffuse glass cover materials (0.24 and 0.20 kWh/m^2/kg), respectively.

DISCUSSION

Climate management inside the greenhouse plays a significant role in improving crop production, mainly under hot climate conditions [Villarreal-Guerrero et al. 2012]. High radiation during spring and summer generates microclimate of high temperature and low vapour pressure deficit inside the greenhouses [Jimenez et al. 2010]. To overcome this phenomenon, it is common to coat polyethylene greenhouse roof with $CaCO_3$ (whitewash) to reduce the intensity of transmitted radiation into the greenhouse to improve microclimate conditions [Kittas et al. 2003]. Using of polyethylene film covering whitewashed during the warm seasons' blocks out the infrared range which decrease greenhouse air temperature and considered as low-cost cooling system [Mashonhowa et al. 2010, Nikolaou et al. 2018]. Therefore, using the appropriate greenhouse covering materials are limited factor for cost effective production in arid and semi-arid regions since fresh fruit and vegetable consumption are continuously increasing [FAOSTAT 2016]. To have an efficient climate within the greenhouse environment, new covering materials have been experienced during the last decades [Ilić et al. 2017]. In this respect, this work was conducted to study the effect of three different greenhouse cover materials; polycarbonate, diffuse and clear glass, on production of two cucumber cultivars grown under Saudi Arabia climate.

According to the impact of the three used covering materials on greenhouse climate, temperature and humidity found to be similar under all tested covering materials as they were controlled by an automatic evaporative cooling system. Our results show that total photosynthetic active radiation (PAR) inside the greenhouse under the three covering materials were vary, depending on type of each single used cover material. Diffuse and clear glass compartments showed higher PAR values than polycarbonate (Table 1). Interestingly, light transmitted by polycarbonate was 41% less than clear glass, while light transmitted by diffuse glass was almost the same as clear glass. In this concern, Papadakis et al. (2000) reported that using polycarbonate (4–16 mm), as covering material, reduced light transmissivity coefficient for PAR by 7–14% than glass covering material (4–5 mm). It is worthy to mention that quality of the radiation allowed by covering materials to pass into the greenhouse is vital for growth and crop development [Kittas et al. 1999]. Likewise, Castilla [2013] explained that solar radiation is the first climatic factor to be taken into consideration before establishing a greenhouse project. The same author reported that light transmission of polycarbonate is strongly affected by polycarbonate thickness, and light transmission decreased from 87% to 74% then 64% when increasing polycarbonate thickness from 0.8 to 6 then 16mm, respectively. Thus, the wide-ranging effects of covering materials are generally related to the reduced light availability to the plants [Fan et al. 2013]. Notably, fruit yield per square matter in the greenhouse that covered by clear or diffuse glass was parallel but still higher than cucumber yield produced in polycarbonate compartment (Table 2). This result indicates that using either clear or diffuse glass covers led to 30% higher cucumber fruit yield than did polycarbonate. This trend could be explained based on the fact that diffuse and/or clear glass covers increased light transmittance (41%) than polycarbonate. In connection, Papadakis et al. [2000] reported that decreasing PAR transmittance of a greenhouse cover by 1% results in a yield reduction of 1%. Also, Marcelis et al. [2004] showed that 1% more light gives between 0.7 and 1% higher production of cucumber.

Meanwhile, Kwon et al. [2017] reported no significant difference in cucumber and tomato yields when using polycarbonate (3 mm) or glass (4 mm) greenhouse covers since both transmitted the same quantity of light. Hemming et al. [2008] said that cucumber yield was improved by diffuse light because of its higher photosynthesis in the middle leaf layers as compared with clear glass. Previous reports are in harmony with our results since either clear or diffuse glass covers resulted in higher fresh weight of cucumber fruits than polycarbonate. Petropoulos et al. [2019] reported that the significant effect of cover material might be attributed partly to different properties of light diffusion and transmission of infrared radiation which resulted in the different total number of fruit clusters per plant. This explaining outfit our results since no difference in term of total yield under different cultivars or plant distance were found.

As shown in Table 2, both ‘Alfrid’ and ‘Khassib’ cultivars behaved similarly under each single cover materials. A similar trend was previously reported by Pratta et al. [2011], who found that fruit weight is depended on genotype than growth conditions. Meanwhile, an increasing number of branches could decrease the average fruit size, which increases ununiform fruit weight [Peil and Gálvez 2004]. Another explanation that the tested plant density under our condition was not quite enough to accumulate significant fruit yield through the plant crop cycle. Therefore, according to our outcomes, it could be concluded that loss of light has been a significant concern, in polycarbonate compartment, since low photosynthesis rates may reduce the yield of growing cucumber plants; in other words, that makes polycarbonate is restricted by its lower transmittance compared to glass.

The main effect of greenhouse coverings materials on water and electric consumption for cucumber growth are presented in Figures (1 and 2). Diffuse glass compartment presented the lowest water and electric consumption during cucumber growth, followed by polycarbonate and clear glass compartments. This result could be described according to the ability of clear glasshouse to increase the compartment temperature, that requires more water and electricity consumption for cooling.

This conclusion was reported by Al-Helal [2001], who mentioned that evaporative cooling systems consume more water than do the plants and have high energy costs. Besides, the structure of clear glasshouse has one wall connected to the outside climate while for another compartment, the sidewall was entirely inside the greenhouse, that decreases the outside transmitted light. On the contrast, increasing energy cause a decrease in water and electric use efficiency to produce one kilogram of cucumber per square meter. In this respect, an expected decrease in electric use efficiency of diffuse glasshouse than clear glass was found. However, the lowest water use efficiency of polycarbonate was expected since it is transmitting less light and needs lower cooling. In this respect, it may be confirmed that diffuse glass and clear glass greenhouses were more efficient than the polycarbonate greenhouse in term of saving energy.

CONCLUSION

Greenhouse covering materials has a significant influence on the inside environmental conditions and cucumber productivity. In general, high light transmissivity caused by diffuse and clear glass cover materials increased cucumber fruit yield up to 50% more than polycarbonate cover material. Results show no differences between cultivars under clear and diffuse glass coverings in terms of cucumber plant yield. It is assumed that, due to the high light intensity in Saudi Arabia, light does not limit photosynthesis. On the contrast, water and energy usage are more efficient when the greenhouse is covered by a material with higher transmissivity, either diffuse or glass cover materials.

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