Assessing the Effectiveness of Reflective and Diffusive Polyethylene Films as Greenhouse Covers in Arid Environments

Abdullah A. Al-Madani 1, Ibrahim M. Al-Helal 1,* and Abdullah A. Alsadon 2

1 Department of Agricultural Engineering, College of Food and Agriculture Sciences, King Saud University, P.O. Box 2460, Riyadh 11451, Saudi Arabia
2 Department of Plant Production, College of Food and Agriculture Sciences, King Saud University, P.O. Box 2460, Riyadh 11451, Saudi Arabia
* Correspondence: imhelal@ksu.edu.sa; Tel.: +966-504420213

Abstract: The application of diffusive and reflective polyethylene (PE) films as greenhouse coverings in arid climates presents an opportunity to improve the microclimate of the greenhouse and achieve consistent light distribution within the crop canopy. Nevertheless, there is still a lack of understanding regarding the properties of these covers and their impact on the microclimate and the growth parameters of crops. This study aimed to assess the impact of different covers on the diffusion of beam radiation during transmission, microclimatic parameters, and growth parameters of cucumbers in each of the greenhouses they covered. In the study, three PE covers were evaluated: a reflective cover (RC), a diffusive film (DC), and a locally produced cover (LPC) as the control treatment. The covers were installed on three identical, single-span, evaporatively cooled greenhouses named GH1/LPC, GH2/RC, and GH3/DC, which were utilized for cultivating cucumber crops. The results indicated that the diffusive nature of the tested films increased the ratio of diffuse to global solar radiation (D/G) from 0.22 outside the greenhouses to 0.49, 0.42, and 0.41 inside GH1/LPC, GH3/DC, and GH2/RC, respectively. Similarly, the ratio of diffuse to direct beam radiation (D/B) showed an increase, with values of 0.95, 0.70, and 0.68 inside GH1/LPC, GH3/DC, and GH2/RC, respectively, compared to the outside value of 0.28. The DC used in GH3 showed a favorable microclimate by reducing the air temperature and improving the relative humidity. Accordingly, the vegetative growth of the cucumbers was significantly improved in GH3/DC, followed by GH2/RC and GH1/LPC. The highest crop yield (p ≤ 0.05) of 12.3 kg/m² was achieved in GH3/DC, followed by 10.2 kg/m² in GH2/RC and 10.1 kg/m² in GH1/LPC. Interestingly, the LPC not only stood out as a low-cost option but also displayed excellent diffusive–radiative properties, and demonstrated reasonable growth development and productivity for the cucumber crops. Consequently, the LPC emerges as a practical and cost-effective greenhouse covering material for crop production in arid climates.

Keywords: greenhouse; plastic film cover; cucumber crop; solar radiation; beam; diffuse; near-infra-red (NIR) reflection

1. Introduction

In the Arabian Peninsula and in Saudi Arabia as well, the common weather conditions comprise intensive solar irradiance (up to 1200 W m⁻² around noon), elevated air temperatures (>45 °C in summer), and low relative humidity (below 15%) during most months of the year [1–3]. These weather conditions, along with the high salinity and scarcity of water resources in these regions, pose significant challenges for cultivating crops in open fields [3,4]. Therefore, greenhouse technology has become essential for crop production to provide a suitable environment for plant growth [1]. Because of the elevated ambient air temperature in summer, the air temperature inside greenhouses may exceed 50 °C, and therefore cooling the greenhouse air is extremely important for controlling the microclimate
to appropriate levels for plant growth [1,3,5]. Evaporative cooling (i.e., wet-pad and fan systems) and heat prevention are the common methods for cooling greenhouse air in summer. Evaporative cooling can work well in arid regions due to the low relative humidity of the air [2,3]. However, these systems are facing many challenges in the Arabian Peninsula due to the high salinity of its water resources. The high salinity of the cooling water leads to clogging in the pads (as they are affected by salt buildup on the pad surfaces), restricting the air flow rate and strongly reducing the cooling performance and the life time of the pads [5]. Shading is another heat prevention method, significantly cutting out solar radiation across the whole solar spectrum including photosynthetically active radiation (PAR: 400–700 nm), which is essential for plant growth. Therefore, studies have focused on using selective plastic films to cover greenhouses; these covers can transmit PAR and reflect the near-infra-red (NIR: 700–2500 nm) outside the greenhouse; then, the radiation heat load can be reduced before being transmitted into the greenhouse [6]. Since 2000, several attempts have been made by plastic-film manufacturers, locally or worldwide, to develop cover films able to reflect the NIR, and transmit the PAR [7,8]. In practice, NIR-reflecting films were used to cover greenhouses and reduced the air temperature inside the greenhouse by 2–3 °C at around noon and by 4–5 °C in the morning and afternoon [8–10]; however, the lifetime of these covers is very short (a few months) due to the NIR-reflective additives added to the polymers during the production processes of these films [5,7,10]. However, the cooling effect induced by these covers alone is insufficient in the hot summers of arid regions. Therefore, the implementation of evaporative cooling along with these covers is necessary to create a suitable environment for plant growth in greenhouses.

The most important property of greenhouse covers is the diffusive nature of the cover film, which makes the cover able to diffuse direct beam radiation during its transmission into the greenhouse. Diffuse radiation allows plants in the greenhouse to receive solar light (PAR) homogeneously from all sides [11,12]. Diffuse radiation in the greenhouse is of utmost importance to eliminate sunspots on the plant leaves and enhance the uniformity of the light (PAR) intercepted by plants and consequently stimulate photosynthesis [12–14]. In recent years, some companies have produced a range of polyethylene (PE) films having durable, NIR-reflective, and diffusive properties for covering greenhouses in hot and sunny regions [11,12]. Reflective film coverings reduce the solar heating load and decrease the temperature inside the greenhouse, and diffusive films are used for enhancing the diffuse radiation in the greenhouse.

Greenhouse crop-growers typically choose covers based on several factors, including the specific light requirements of the crop, the prevailing climatic conditions, and the availability of covers in the market [11]. In Saudi Arabia, diffusive and reflective covers are commercially available on the market. Considering the advantages they offer, it is crucial to thoroughly evaluate the utilization of these covers for greenhouses, and their impact on the microclimate, growth parameters, and plant productivity. This is particularly important when considering the operation of these covers under extremely harsh climatic conditions.

Numerous studies have been conducted to investigate the effect of diffusive and/or reflective greenhouse covers on crop yield, morphology, and productivity [11–14]. However, it is important to note that most of these studies have focused on examining these covers under climatic conditions that differ significantly from an arid climate. In the previous studies, the diffuse radiation in the greenhouse is usually estimated as the diffuse incident radiation multiplied by the cover transmittance to diffuse radiation [15–22]. However, these studies have neglected the diffusion effect of the covering materials on the solar beam’s radiation. Recently, most of the newly developed cover films diffuse a considerable amount of beam radiation during transmission. This means that the fraction of diffuse radiation in the greenhouse is much higher than that outside the greenhouse. An extensive survey of the literature revealed that studies describing the characteristics of solar radiation transmitted through plastic-film covering materials under arid climatic conditions are still limited. Some studies assumed that a portion of the incident beam radiation on the cover film is diffused during transmission, resulting in diffused beams, while the remaining portion is directly
transmitted as direct beam radiation [23–25]. A recent study characterized the various components of solar beam radiation transmitting through the covers of small greenhouse models in an arid environment [26]. These components included the transmitted portion from the incident atmospheric diffuse radiation, the portion of the direct beams that were diffused during transmission, and the remaining portion of the direct beams that were transmitted directly without diffusion [26]. However, this study [26] was conducted on small-scale, crop-free, and uncooled greenhouse models. Therefore, the present study aimed to examine diffusive and reflective covers in real evaporatively cooled planted greenhouses operating under arid conditions.

The primary focus of this study was to assess the impact of three selective covers on the greenhouse microclimate, the level of diffuse radiation, and the growth parameters and productivity of cucumber crops (Cucumis sativus L.) in an arid climate. The choice to include the cucumber crop in this study was based on its significance as a vital vegetable crop, extensively cultivated in greenhouses across the Arabian Peninsula and globally. Three types of covers that are commercially available and used in Saudi Arabia were selected for evaluation: a locally produced cover, serving as the control treatment (referred to as the LPC); a diffusive cover (referred to as the DC); and a reflective cover (referred to as the RC), as specified by the manufacturers. The LPC was used as the control treatment because recently this type of film has become widely used in the harsh environment of Saudi Arabia instead of imported covers.

2. Materials and Methods

2.1. Determining Solar Radiation Components

The common method for measuring the radiative properties of a plastic film related to diffuse solar radiation is to expose the film and the measuring devices (pyranometers) to diffuse solar radiation by preventing the direct-beam component from reaching both the film and the pyranometers [24]. However, to accurately measure both the direct beam and diffuse radiation components of the global solar radiation, two pyranometers are employed simultaneously. One is used to measure the global radiation \( G \) and the other is shaded using an opaque disk (32 cm in diameter [26]) to measure the diffuse component \( D \) at the same time [24]. The opaque disk prevents a portion of the diffuse radiation from reaching the pyranometer. Therefore, correction factors \( F > 1 \) are used to compensate for the prevented portion of diffuse radiation outside \( F_o \) and inside \( F_i \) the greenhouse. The average values of these factors were experimentally determined by Al-Helal et al. [26] to be 1.95 for \( F_o \) outside the greenhouse, and to be 2.05, 2.17, and 2.31 for \( F_i \) in greenhouses covered with the diffusive film (DC), the reflective film (RC), and the locally produced film (LPC) as the control treatment, respectively.

Thus, for the measured global \( (G_o) \) and diffuse \( (D_o) \) radiation outside the greenhouse, the direct-beam component \( (B_o) \) was given as

\[
B_o = G_o - F_o D_o
\]  

(1)

The direct-beam component that was transmitted into the three greenhouses covered with the three films tested was given as

\[
B_i = G_i - F_i D_i
\]  

(2)

where the subscript \( i \) represents the measured parameters in the greenhouse covered with the diffusive film (DC), the reflective film (RC), and the control treatment film (LPC). During the transmission of solar beam radiation through a greenhouse cover, a portion of the direct beam \( B_o \) is diffused forward during its transmission through the cover. So, the measured diffuse radiation in the greenhouse \( (F_i D_i) \) will include this portion and may become higher than that measured outside the greenhouse \( (F_o D_o) \). Under global radiation conditions, the ratio of the measured parameters \( (F_i D_i / F_o D_o) \) gives an apparent transmittance \( \tau_D \) of a greenhouse cover to diffuse solar radiation \( \tau_D > 1 \) for the diffusive covers. However,
the true transmittance of a cover to diffuse solar radiation ($\tau_D = D_i/D_o < 1$) is usually estimated by exposing the cover and the measuring devices totally to diffuse radiation and measuring the values of $D_i$ and $D_o$ under such conditions. The diffusive power of a plastic film is defined as the ability of the film to convert the solar beam into diffuse radiation during transmission. The diffusive power ($\sigma$) of each film tested was estimated according to [26] as follows:

$$\sigma = \left( \frac{F_i D_i - \tau_D D_o}{G_i - \tau_D D_o} \right) \times 100 \quad (3)$$

The term $\tau_D D_o$ in Equation (3) is the transmitted portion of the sky diffuse radiation outside the greenhouse.

2.2. Specification of the Selected Covers

For the study, three types of greenhouse covers were selected. Two of these covers were supplied by PLASTIKA KRITIS S.A. (Iraklion Crete, Greece). The first cover was a PE-EVA diffusing film (DC), designed with pearl-based pigments to effectively diffuse radiation. The second cover was a PE-LLDPE reflective film (RC), containing tiny aluminum particles that reflect the NIR solar spectrum. Both films were equipped with an anti-drip additive, and their optical properties were measured after removing this additive from the film’s surface, as indicated in the supplier’s data sheet. The third film used in the study was a PE-LD film, locally produced by Napco Modern Plastic Products Company—Sack Division Ltd., (Dammam, Saudi Arabia). This film incorporates various additives such as UV stabilizers, antioxidants, plasticizers, etc. However, the specific chemical compositions of these films are treated as confidential information by the suppliers. A summary of the available information about these films is provided in Table 1.

| Table 1. Physical and radiative properties of the selected films as they were supplied by the producers. |
|----------------------------------|---------------------------------|---------------------------------|
| Film Properties as Supplied by the Producers | Polyethylene-EVA, Diffusive Cover (DC) | Polyethylene-LLDPE, Reflective Cover (RC) | Polyethylene-LD, Locally Produced Cover (LPC) |
| Film thickness (µm) | 180 | 200 | 200 |
| Diffusive power, $\sigma$ (%) | 60 | - | - |
| Photosynthetically active radiation transmittance, $\tau_{PAR}$ (%) | 87–88 | 78–80 | 75–80 |
| Near-infra-red transmittance, $\tau_{NIR}$ (%) | <17 | - | - |
| Working temperature (°C) | N/A * | N/A | 50–80 |
| Expected lifetime (year) | 4–5 | 4–5 | 2–3 |
| Price (USD/m²) | 0.75 | 0.75 | 0.46 |

* not applicable.

Apart from the supplier’s information (i.e., as it was inaccurate in most cases), in order to provide accurate scientific information about the selected covers, prior to deploying the covers on the greenhouses, the spectral radiative properties of these covers were measured at around noon, on a sunny day, using a Black-Comet (Stellar Net Inc., Tampa, FL, USA) spectrophotometer, scanning between 200 and 2700 nm at 0.5 nm intervals over the UV–VIS–IR spectrum range. The measured spectral transmittance ($\tau_\lambda$) and reflectance ($\rho_\lambda$) are depicted in Figure 1a, b, respectively. For each cover, the measured data were integrated over 200–2700 nm to obtain the global reflectance ($\rho_g$); integrated over 400–700 nm to obtain the transmittance to the photosynthetically active radiation, PAR ($\tau_{PAR}$); and integrated over 700–2700 nm to obtain the transmittance to near-infra-red radiation, NIR ($\tau_{NIR}$). The results of these integrations are illustrated in Table 2 for the three greenhouses. In addition, the diffusive power of each cover was estimated using Equation (3) and these results are included in Table 2. The radiative properties of the covers in Table 1 are usually measured by the producers in their laboratories; and the specific measuring procedures are kept confidential. However, the measured radiative properties of the tested covers during our
experiment under natural weather conditions, as outlined in Table 2, displayed certain variations.

Table 2. Radiation transmittance in the three greenhouses covered with the LPC, RC, and DC.

<table>
<thead>
<tr>
<th>Greenhouse</th>
<th>PAR Transmittance $\tau_{\text{PAR}}$ (%)</th>
<th>NIR Transmittance $\tau_{\text{NIR}}$ (%)</th>
<th>Global Reflectance $\rho_g$ (%)</th>
<th>Diffusive Power $\sigma$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>GH1/LPC</td>
<td>46.2</td>
<td>59.0</td>
<td>13.5</td>
<td>43</td>
</tr>
<tr>
<td>GH2/RC</td>
<td>45</td>
<td>47.8</td>
<td>18.5</td>
<td>33</td>
</tr>
<tr>
<td>GH3/DC</td>
<td>39.8</td>
<td>57.4</td>
<td>12.5</td>
<td>34</td>
</tr>
</tbody>
</table>

2.3. Description of the Greenhouses

The experiment was conducted at the Agricultural Research and Experiment Station, Agriculture Engineering Department, King Saud University (Riyadh, Saudi Arabia, 46°47’ E, longitude and 24°39’ N, latitude). This experiment utilized three identical greenhouses, namely GH1, GH2, and GH3, each with a floor surface area of 48 m². All three greenhouses were equipped with wet-pad and fan cooling systems and were oriented in the east–west direction (Figure 2). GH1 was covered with the locally produced film and was considered as the control treatment; hereafter, it will be referred to as GH1/LPC. GH2 was covered with the reflective film, RC, and designated as GH2/RC. GH3 was covered with the diffusive film, DC, and referred to as GH3/DC.

Figure 2. Photograph of the three greenhouses (GH1 covered with LPC, GH2 covered with RC, and GH3 covered with DC) used for this study.
2.4. Plant Material

Cucumber seeds (*Cucumis Sativus* L. cv. Sovana F1, Rijk Zwaan, De Lier, The Netherlands) were germinated under a controlled environment (24 °C ± 1 daytime/18 °C ± 1 nighttime temperatures) in Jiffy 7 pellets. Seedlings at the three true-leaf stages were transferred into pots with a diameter of 30 cm in all three greenhouses. The pots were filled with a mixture consisting of peat, sand, and vermiculite in equal proportions (1:1:1, w/w). Fertilization and other cultural practices were implemented following the recommendations outlined in commercial cucumber production, as reported in [27]. The experiment was conducted from 25 April 2019 (transplanting) to 25 August 2019 (harvesting).

2.5. Experimental Design and Statistical Design

A randomized complete block design with four replications was employed for the experiment. Each greenhouse was divided into four rows, with a spacing of 1 m between the rows and a distance of 0.4 m between the containers in each row (Figure 3). The plant density was set at 2.5 plants per square meter. The data obtained for the different measurements were subjected to analysis of variance. Duncan’s multiple range test via SAS (version 6.12; SAS Institute, Cary, NC, USA) was used to compare mean differences among the experimental treatments at a significance level of \( p \leq 0.05 \).

2.6. Experimental Measurements in the Greenhouses

To assess the growth traits, four cucumber plants from each greenhouse were randomly chosen at 15-day intervals. Vegetative growth parameters (i.e., the number of leaves per plant, leaf area, plant height, leaf dry and fresh weights, stem diameter, and stem dry and fresh weights) were measured using the techniques outlined in [9]. Yield traits, such as the number of fruits, length and dry weights of the fruits, total dry biomass, and total yield, were recorded at each harvesting time for evaluation [9]. Furthermore, the meteorological parameters were measured outside and inside the three greenhouses. The air temperatures and relative humidity inside and outside each greenhouse (\( T_i, \text{RH}_i, T_o, \text{RH}_o \)) were measured with DMA033 thermo-hygrometers (LSI Lastem, Milan, Italy), with each having a Pt 100 output for temperature and 0–1 V dc for RH; an operating temperature range of \(-5\) to \(60\) °C; an accuracy of \(\pm 2\%\) over the whole range of RH; and \(\pm 0.1\) °C accuracy of temperature measurement. Eight CMP3 pyranometers (Kipp & Zonen Inc., Sterling, VA, USA) were used, each having a time response of 18 s, a maximum error of \(\pm 2\%\), a sensitivity of \(5-20\) \(\mu\)V/W m\(^{-2}\), a working temperature range of \(-40\) °C to \(+80\) °C, and a wavelength...
range of 310–2800 nm. Four of them were shaded with black-painted wooden disks, 32 cm in diameter (shaded pyranometers); we installed one outside and one inside each greenhouse for measuring the diffuse radiation outside \((D_o)\) and inside \((D_i)\). Manual tracking was applied every 20 min to the shaded pyranometers to keep the sensors always in the shade. The remaining four pyranometers were used to measure the global solar radiation outside and inside each greenhouse \((G_o\) and \(G_i)\). Four LI-190SA quantum sensors (LI-COR Inc., Lincoln, NE, USA) were used to measure PAR outside and inside each greenhouse \((PAR_o\) and \(PAR_i)\). The quantum sensors had a time response of 10 µs with a maximum error of ±1%, a sensitivity of 5 µA per 1000 µmol m\(^{-2}\) s\(^{-1}\), a working temperature range of −40 to +65 °C, and a wavelength range of 400–700 nm. The measurements were 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., Logan, UT, USA). The measuring devices had been calibrated before use by their suppliers.

3. Results and Discussion

3.1. Radiation Components in the Greenhouses

Utilizing diffusive plastic films as greenhouse covers offers several advantages compared to conventional covering films. This is primarily due to the ability of diffusive covers to scatter a portion of the beam radiation during transmission. The presence of increased diffuse radiation within the greenhouse environment helps mitigate the harmful effects of direct sunspots on plant leaves. Moreover, it allows plants in the greenhouse to receive diffuse solar radiation from various directions, thereby promoting photosynthesis and facilitating optimal crop growth. The global and diffuse radiation fluxes outside \((G_o\) and \(D_o)\) and inside \((G_i\) and \(D_i)\) of the three greenhouses (GH1/LPC, GH2/RC, and GH3/DC) were measured simultaneously during the experiment. The direct-beam components outside \((B_o)\) and inside the three greenhouses \((B_i)\) were estimated using Equations (1) and (2). For simplicity, the results from one summer day (29 June 2019) were selected to be presented. The diffuse radiation terms were corrected using the correction factors (Section 2.1) for the outside \((F_oD_o)\) and inside \((F_iD_i)\) components. The corrected diffuse radiation fluxes outside and inside the three greenhouses are illustrated in Figure 4a, and the direct-beam components \((B_o\) and \(B_i)\) were calculated and are depicted in Figure 4b. Figure 4a shows that the three covers significantly enhanced the diffuse radiation inside the greenhouses compared to the outside diffuse radiation \((F_iD_i \gg F_oD_o)\). The locally produced cover (GH1/LPC) showed the highest diffusive power, followed by the diffusive cover (GH3/DC), and then the reflective cover (GH2/RC). For comparison, the daily integrals for the diffuse radiation fluxes \((F_oD_o\) and \(F_iD_i)\) in Figure 4a), for the direct beam radiation fluxes \((B_o\) and \(B_i)\) in Figure 4b), and for the global radiation fluxes \((G_o\) and \(G_i)\) were calculated in MJ m\(^{-2}\) (or in kWh m\(^{-2}\)). For the selected day, the outside diffuse \((F_oD_o)\) and direct beam \((B_o)\) radiation components were 4.8 and 16.8 MJ m\(^{-2}\) (1.33 and 4.66 kWh m\(^{-2}\)), whereas the inside components \((F_iD_i\) and \(B_i)\) were 7.9 and 8.3 MJ m\(^{-2}\) (2.2 and 2.3 kWh m\(^{-2}\)) in GH1/LPC; 6.1 and 8.9 MJ m\(^{-2}\) (1.7 and 2.47 kWh m\(^{-2}\)) in GH3/DC; and 5.8 and 8.3 MJ m\(^{-2}\) (1.6 and 2.3 kWh m\(^{-2}\)) in GH2/RC. The ratio of diffuse to global solar radiation is usually defined as the diffuse index either outside \((F_oD_o/G_o)\) or inside \((F_iD_i/G_i)\) the greenhouse. The daily integrals for the diffuse and global radiation components outside and inside the three greenhouses were calculated. According to the diffusive power of the tested covers, σ (Table 2), the diffuse index percentage increased from 22.2% outside the greenhouse to 49% in GH1/LPC, 41% in GH2/RC, and 42% in GH3/DC, respectively. Even though the diffusive film cover (DC) was designed mainly for the purpose of diffusion, the locally produced cover (LPC) showed a higher performance than the RC and DC in terms of their diffusion characteristics. This makes the LPC a promising option to serve effectively for crop production in greenhouses.
integrals for the diffuse radiation fluxes ($F_{oDo}$ and $F_{iDi}$ in Figure 4a), for the direct beam radiation fluxes ($B_o$ and $B_i$ in Figure 4b), and for the global radiation fluxes ($G_o$ and $G_i$) were calculated in MJ m$^{-2}$ (or in kWh m$^{-2}$). For the selected day, the outside diffuse ($F_{oDo}$) and direct beam ($B_o$) radiation components were 4.8 and 16.8 MJ m$^{-2}$ (1.33 and 4.66 kWh m$^{-2}$), whereas the inside components ($F_{iDi}$ and $B_i$) were 7.9 and 8.3 MJ m$^{-2}$ (2.2 and 2.3 kWh m$^{-2}$) in GH1/LPC; 6.1 and 8.9 MJ m$^{-2}$ (1.7 and 2.47 kWh m$^{-2}$) in GH3/DC; and 5.8 and 8.3 MJ m$^{-2}$ (1.6 and 2.3 kWh m$^{-2}$) in GH2/RC. The ratio of diffuse to global solar radiation is usually defined as the diffuse index either outside ($F_{oDo}/G_o$) or inside ($F_{iDi}/G_i$) the greenhouse.

The daily integrals for the diffuse and global radiation components outside and inside the three greenhouses were calculated. According to the diffuse power of the tested covers, $\sigma$ (Table 2), the diffuse index percentage increased from 22.2% outside the greenhouse to 49% in GH1/LPC, 41% in GH2/RC, and 42% in GH3/DC, respectively. Even though the diffuse film cover (DC) was designed mainly for the purpose of diffusion, the locally produced cover (LPC) showed a higher performance than the RC and DC in terms of their diffusion characteristics. This makes the LPC a promising option to serve effectively for crop production in greenhouses.

For further understanding the difference between the true and apparent transmittances of a cover to diffuse radiation, the well-known true transmittance ($\tau_D$) of the cover to diffuse solar radiation was defined as the ratio between the inside and outside diffuse radiation when exposing the whole system to a diffuse radiation environment: ($\tau_D < 1$). However, the apparent transmittance ($\bar{\tau}_D$) was estimated as $F_{iDi}/F_{oDo}$ measured when exposing the system (the greenhouses and the measuring devices) to natural global solar radiation. Determining $\bar{\tau}_D$ shows the ability of the cover to diffuse direct beams during transmission. Values of $\bar{\tau}_D$ were estimated for the three greenhouses and the time course is illustrated in Figure 5 to describe the apparent transmittances of the three greenhouses to the atmospheric diffuse (incident) radiation and that generated during transmission. By definition, the apparent transmittances ($\bar{\tau}_D$) of the three greenhouses are higher than one, because each cover converted a portion of solar beams to diffuse radiation during transmission. In Figure 5, GH1/LPC shows a high capability to diffuse direct beam radiation, followed by
GH3/DC and GH2/RC. The value of $\tau_D$ depends mainly on the chemical composition and the type of additives that were added to the polymers during the production of each cover. The RC was characterized by the producer as an NIR-reflective cover, and it also showed diffusion property values very close to those of the DC (Figure 5). The locally produced cover (LPC) exhibited a notable diffusive effect, which might be attributed to the inclusion of additives during the manufacturing process. These additives might serve as light diffusers, contributing to the enhanced diffusive power of this cover. In additions, these covers are specifically designed to withstand the challenging weather conditions typically found in arid regions. Based on the data in Figure 5, the daily integrals of the apparent transmittance ($\tau_D$) were estimated to be 1.62, 1.27, and 1.19 for GH1/LPC, GH3/DC, and GH2/RC, respectively, compared to the true transmittance ($\tau_D$) values of 0.77, 0.76, and 0.65 reported in [26] for the same plastic films.

For comparison, the operation of wet-pad–fan systems were identical in the three tested identical greenhouses; all of them operated if the inside air temperature $T_i \geq 25$ °C. During the cultivation season, the daily averages of the outside air temperature $T_o$ and relative humidity ($RH_o$) and those inside the three greenhouses ($T_i$ and $RH_i$) were determined for the day- and nighttime periods, separately. Figure 6a reveals the daily average variations of $T_o$ and $T_i$ inside the three greenhouses GH1/LPC, GH2/RC, and GH3/DC during the daytime periods. Similarly, Figure 6b represents the daily average variations of these temperatures during the nighttime periods. During the daytime (Figure 6a), the evaporative cooling combined with the effect of the cover helped maintain $T_i$ within the range of 35–37 °C in both GH1/LPC and GH2/RC. Notably, both covers exhibited a similar effect in this regard. However, the DC in GH3/DC could maintain $T_i$ at 3–5 °C lower than GH1/LPC and GH2/RC during the growing season. During the nighttime (Figure 5b), the LPC and RC showed also a similar effect, and the DC in GH3/DC maintained $T_i$ at 1–3 °C lower than GH1/LPC and GH2/RC during the growing season. This means that the DC could provide the best cooling effect in GH3/DC, better than the LPC and RC. However, when referring to the $\tau_{NIR}$ values in Table 2, it appears that the lowest NIR heating load should have been entered GH2/RC, and the most effective cooling effect should have been observed in the case of RC in GH2/RC, rather than DC in GH3/DC. This may be attributed to the cooling performance of the wet pads in the cooling systems; even though the three cooling systems were similar, the working performance of the wet pads were different due
to the accumulation of salts on each pad surface being different among the three cooling systems. In addition, several other factors can affect the wet pads’ performance such as dust accumulation, the pad location, the flow rate of the cooling water and its uniformity on the pad surface, etc.

![Figure 6. Daily average air temperatures outside and inside GH1/LPC, GH2/RC, and GH3/DC during the growing season in the daytime (a) and the nighttime (b).](image)

The evaporative cooling systems in GH1/LPC, GH2/RC, and GH3/DC operated continuously during the daytime. However, during the nighttime, they were only active for a brief duration in GH1/LPC and GH2/RC. In contrast, the evaporative cooling system in GH3/DC did not operate at all during the nighttime. Therefore, the accumulative water and electric energy consumption for cooling were low in GH3/DC, being recorded at 48.7 m$^3$ and 826 kWh (per season) compared to 54 m$^3$ and 841 kWh in GH2/RC and 59.5 m$^3$ and 865 kWh in GH1/LPC. Even though the reduction in the inside greenhouse air temperature was relatively small, the results of the present study are in accordance with results reported in previous studies. For example, in the summer in southern Spain, a reflecting PE film covering a greenhouse showed a maximum reduction of about 4–5 °C in the $T_i$ values around noon [28]. In another study in the same climate, a reflective film cover reduced the inside greenhouse air temperature ($T_i$) by about 3 °C, at around noon, compared to a conventional PE cover [29]. Also, a reflective film used to cover a greenhouse model reduced $T_i$ by 2 °C at noon compared to the model covered with a conventional PE film in [30].
In arid climates, the common relative humidity is very low, averaging around 10–15% throughout both the daytime and nighttime (Figure 7a,b). Therefore, an evaporative cooling system is essential to keep the relative humidity in greenhouses at a desired level for plant growth. However, the cooling efficiency of these systems deteriorates rapidly due to the high salinity of the cooling water used. The salinity leads to clogging of the cooling pads and subsequent reduction in airflow rate, resulting in a decrease in overall efficiency. Due to this reason, the cooling system combined with the selective covers used in this study increased $RH_i$ from about 10% to 30–45% during the daytime (Figure 7a). On the other hand, during the nighttime (Figure 7b), the covering materials maintained $RH_i$ in the range of 50–70% during the growing season even without operating the cooling system (with the exhaust fans operating only). This assures the fact that in arid climates, growers should carefully select their greenhouse-covering materials to provide a better microclimate for crop growth requirements. Basically, the relative humidity of the inside greenhouse air ($RH_i$) increases with decreases in the inside air temperature ($T_i$); thus, during daytime, the $RH_i$ values in GH3/DC were slightly higher (2–3%) compared to the $RH_i$ values in GH1/LPC, and GH2/RC maintained $RH_i$ values 5–7% lower than those in GH1/LPC and GH3/DC during most of the growing season.

![Figure 7](image-url)

**Figure 7.** Daily averages of the air’s relative humidity outside and inside GH1/LPC, GH2/RC, and GH3/DC during the growing season in the daytime (a) and the nighttime (b).
Global solar radiation transmitted into the greenhouse \( (G_{i}) \) is the main source of heat energy; about 70% of \( G_{i} \) is transformed into sensible heat used to warm up the greenhouse air \[31\]. To show the effect of the selected covers on the values of \( G_{i} \), the daily integrals of \( G_{o} \) and \( G_{i} \) in the three greenhouses (GH1/LPC, GH2/RC, and GH3/DC) were determined (in MJ m\(^{-2}\)) and are depicted in Figure 8a for the growing season. Similarly, the daily integrals of the photosynthetically active radiation (PAR) outside and inside the greenhouses were determined (in mole m\(^{-2}\)) and are depicted in Figure 8b. In Figure 8a, \( G_{i} \) in GH1/LPC was the highest and in GH3/DC was the lowest depending on the cover’s transmittance to the global solar irradiance; consequently, the inside air temperature \( (T_{i}) \) followed similar trends (Figure 6a), and the inside relative humidity \( (RH_{i}) \) followed opposite trends (Figure 7a). In Figure 8b, PAR\(_{i} \) in GH1/LPC was the highest, and that in GH3/DC was the lowest, as in the case of \( G_{i} \). High levels of PAR\(_{i} \) would enhance photosynthesis and stimulate crop growth and production. However, the PAR\(_{i} \) levels in all the three greenhouses not only meet but also exceed the requirements for crop growth, ranging from those suitable for indoor and ornamental plants (optimum PAR of 5 mole m\(^{-2}\) day\(^{-1}\)) to those necessary of rice and wheat crops (optimum PAR of 17–23 mole m\(^{-2}\) day\(^{-1}\)) \[32\].

"Figure 8. Daily integrals of (a) the global solar irradiance outside \( (G_{o}) \) and inside \( (G_{i}) \) the three greenhouses, GH1/LPC, GH2/RC, and GH3/DC, and (b) the photosynthetically active radiation outside \( (PAR_{o}) \) and inside \( (PAR_{i}) \) the three greenhouses."

3.3. Crop Growth Parameters in the Three Greenhouses

The average values of the stem length (cm) and fresh and dry weights of the stem (gm) were estimated (as an average value per plant) in the three greenhouses (GH1/LPC, GH2/RC, and GH3/DC) and are illustrated in Table 3. In GH3/DC, the length, fresh weight, and dry weight of the stems were significantly higher ($p \leq 0.05$) than those in GH1/LPC by about 9%, 18%, and 27%, respectively; and higher than those in GH2/RC by 5%, 15%, and 14%, respectively. In addition, measurements of the average leaf area per plant (in cm$^2$) and the average fresh and dry weights of the leaves (in grams) were conducted for the three greenhouses. The corresponding results are presented in Table 4. In GH3/DC, the area, fresh weight, and dry weight of the leaves are significantly higher ($p \leq 0.05$) than those in GH1/LPC by about 18%, 12%, and 18.5%, respectively; and higher than those in GH2/RC by about 12%, 5%, and 11%, respectively. The data in Tables 3 and 4 indicate that the diffusive cover (DC) significantly improved ($p \leq 0.05$) the vegetative growth of the cucumber crops, which was reflected in their biomass, followed by the reflective cover (RC) and the locally produced cover (LPC), in that order.

### Table 3. Stem lengths (cm) and fresh and dry weights of the stems (gm) estimated in the three greenhouses *.

<table>
<thead>
<tr>
<th>Greenhouse</th>
<th>Stem Length (cm)</th>
<th>Fresh Weight (gm)</th>
<th>Dry Weight (gm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>GH1/LPC</td>
<td>199.80 ± 1.31 c</td>
<td>189.27 ± 0.64 c</td>
<td>26.30 ± 0.36 c</td>
</tr>
<tr>
<td>GH2/RC</td>
<td>205.25 ± 1.11 b</td>
<td>195.25 ± 2.78 b</td>
<td>29.35 ± 0.20 b</td>
</tr>
<tr>
<td>GH3/DC</td>
<td>214.75 ± 1.17 a</td>
<td>224.75 ± 1.65 a</td>
<td>33.52 ± 0.42 a</td>
</tr>
</tbody>
</table>

* Means followed by different letters in the same column are significantly different at the $p \leq 0.05$ level, according to Duncan’s multiple range test. Each data point represents the mean of four replicates ± standards error of the mean.

### Table 4. Leaf areas (cm$^2$) and fresh and dry weights of the leaves (gm) in the three greenhouses *.

<table>
<thead>
<tr>
<th>Greenhouse</th>
<th>Leaf Area (cm$^2$)</th>
<th>Fresh Weight (gm)</th>
<th>Dry Weight (gm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>GH1/LPC</td>
<td>5790.0 ± 5.70 c</td>
<td>549.25 ± 2.01 c</td>
<td>51.70 ± 0.35 c</td>
</tr>
<tr>
<td>GH2/RC</td>
<td>6146.0 ± 8.52 b</td>
<td>589.00 ± 3.02 b</td>
<td>55.17 ± 0.13 b</td>
</tr>
<tr>
<td>GH3/DC</td>
<td>6867.8 ± 6.41 a</td>
<td>616.75 ± 1.65 a</td>
<td>61.27 ± 0.34 a</td>
</tr>
</tbody>
</table>

* Means followed by different letters in the same column are significantly different at the $p \leq 0.05$ level, according to Duncan’s multiple range test. Each data point represents the mean of four replicates ± standards error of the mean.

3.4. Crop Yield in the Three Greenhouses

Among the three greenhouses tested, the vegetative growth, total dry biomass, and crop yield followed a similar manner as affected by the microclimatic conditions that were generated based on the type of cover and its radiative properties. The number of fruits (per m$^2$), the fruit length, and the fresh and dry weights of the fruits increased for plants grown in GH3/DC, with significant differences ($p \leq 0.05$) from both those grown in GH1/LPC and those grown in GH2/RC (Table 5). The fruit length, diameter, and fresh and dry weights were 9%, 7.6%, 13%, and 11.8% higher ($p \leq 0.05$) than those in GH1/LPC, and 6%, 11%, 6%, and 8% higher than those in GH2/RC. Additionally, the number of fruits in GH3/DC was 108.5, which was 8% higher ($p \leq 0.05$) than that in GH1/LPC and 14% higher than that in GH2/RC. The crop yield values were 12.3, 10.2, and 10.1 kg m$^{-2}$ for GH3/DC, GH2/RC, and GH1/LPC, respectively.
Table 5. Yield parameters for the cucumber crops in the three greenhouses *.

<table>
<thead>
<tr>
<th>Greenhouse</th>
<th>Fruit Length (cm)</th>
<th>Fruit Diameter (cm)</th>
<th>Fresh Weight (gm)</th>
<th>Dry Weight (gm)</th>
<th>Number of Fruits</th>
</tr>
</thead>
<tbody>
<tr>
<td>GH1/LPC</td>
<td>14.22 ± 0.13 c</td>
<td>2.90 ± 0.08 c</td>
<td>100.5 ± 1.32 c</td>
<td>6.17 ± 0.04 c</td>
<td>100.5 ± 1.40 c</td>
</tr>
<tr>
<td>GH2/RC</td>
<td>14.55 ± 0.10 b</td>
<td>2.80 ± 0.04 b</td>
<td>106.7 ± 0.85 b</td>
<td>6.30 ± 0.04 b</td>
<td>95.5 ± 0.64 b</td>
</tr>
<tr>
<td>GH3/DC</td>
<td>15.50 ± 0.23 a</td>
<td>3.12 ± 0.09 a</td>
<td>113.5 ± 0.85 a</td>
<td>6.90 ± 0.08 a</td>
<td>108.5 ± 0.85 a</td>
</tr>
</tbody>
</table>

* Means followed by different letters in the same column are significantly different at the $p \leq 0.05$ level, according to Duncan’s multiple range test. Each data point represents the mean of four replicates ± standards error of the mean.

The presented results indicated that the growth and yield traits increased in GH3/DC, followed by GH2/RC and then by GH1/LPC. This is because during the growing season, the daily averages of the inside air temperature ($T_i$) and relative humidity ($RH_i$) were optimal for cucumber growth and development in GH3/DC as compared to those in GH1/LPC and GH2/RC. Even though the PAR transmittance and the diffusive power of the locally produced cover (LPC) were higher than those of the other two covers (DC and RC), the crop growth behavior and productivity depended mainly on $T_i$ and $RH_i$. The relatively low $T_i$ and high $RH_i$ in GH3/DC (Figures 6a, b and 7a, b) led to a 22% increase in productivity as compared with GH1/LPC and a 20% increase in comparison with GH2/RC. It is important to note that the PAR$_i$ levels in all of the three greenhouses were sufficient to support the growth and development of cucumber crops, as shown in Figure 8b. Finally, under the same climatic conditions, the quality, quantity, and productivity of the plants in each greenhouse depended on a combination of different factors, such as the inside air temperature and relative humidity ($T_i$, $RH_i$), photosynthetically active radiation (PAR$_i$), diffuse radiation ($D_i$), ventilation rate, pathogenic activity, etc. These factors together depended mainly on the radiative and thermophysical properties of the covering material and on the performance of the evaporative cooling system. In addition, the price and the service life of the tested covers are different (Table 1); therefore, it is quite difficult to evaluate the financial impact of these covers at the moment.

4. Conclusions and Recommendation

This study evaluated three greenhouse covers under real arid weather conditions in the Arabian Peninsula to explore the effect of difference covering materials on greenhouse microclimates, diffuse radiation enhancement, and the growth parameters and yield of the cucumber crop. These covers comprised a locally produced film (LPC), used to cover GH1/LPC and used as the control treatment, a reflective film (RC), used to cover GH2/RC, and a diffusive film (DC), used to cover GH3/DC. Based on the presented results, the main conclusion is summarized as follows:

- In addition to the sky diffuse radiation transmitted into the greenhouses, the three covers diffused a portion of the direct beam radiation during transmission. Accordingly, the ratio of diffuse to direct beam radiation decreased from 0.28 outside the greenhouses ($D_o/B_o$) to 0.95, 0.70, and 0.68 in GH1/LPC, GH3/DC, and GH2/RC, respectively. The LPC showed a higher diffusive power and PAR transmittance compared to the other covers tested.

- Even though the reflective cover (RC) was designed mainly for cooling the greenhouse environment, the diffusive cover (DC) showed better performance in terms of lowering $T_i$ and enhancing $RH_i$ than the RC and LPC, and the LPC and RC showed nearly the same effects on $T_i$ and $RH_i$. In the extremely hot climate, the evaporative cooling system controlled the microclimate in the summer rather than the covering material.

- The diffusive cover (DC) in GH3 improved the crop growth development and significantly increased ($p \leq 0.05$) the crop productivity by 20–21% compared with the productivity of GH1/LPC and GH2/RC. This cover is expected to serve effectively in arid climates.

- The locally produced cover (LPC) showed the highest diffusion capability, which is a very important property for promoting crop growth and development.
the conversion of direct beam radiation into diffuse radiation within the greenhouse
did not result in a cooling effect. Therefore, further research is needed to enhance the
NIR-reflectivity of this cover. Improving the cooling effect of the LPC would make it
an excellent alternative for greenhouse applications in arid climates.

- Due to the dependency of greenhouse productivity on the combination of several
  construction-related, thermophysical, and microclimatic parameters, separate research
  is needed to evaluate the financial impacts of these covers individually.

published version of the manuscript.

**Funding:** The authors would like to express their gratitude to the “King Abdulaziz City for Science and Technology” in Saudi Arabia for funding this research (grant number: 1-18-04-001-0012).

**Data Availability Statement:** Data are available upon request.

**Conflicts of Interest:** The authors declare no conflicts of interest.

**Nomenclature**

- $B_o$: direct solar beam radiation outside the greenhouse (W m$^{-2}$);
- $B_i$: direct beam radiation transmitted into the greenhouse (W m$^{-2}$);
- $D/G$: ratio of diffuse to global solar radiation inside or outside the greenhouse;
- $DC$: diffusive cover;
- $D_o$: atmospheric diffuse radiation outside the greenhouse (W m$^{-2}$);
- $D_i$: atmospheric diffuse radiation inside the greenhouse (W m$^{-2}$);
- $F_o$: correction factor of the shaded pyranometer outside the greenhouse (-);
- $F_{LPC}$: correction factor of the shaded pyranometer in GH1/LPC (-);
- $F_{RC}$: correction factor of the shaded pyranometer in GH2/RC (-);
- $F_{DC}$: correction factor of the shaded pyranometer in GH3/DC (-);
- $G_o$: global solar radiation flux outside the greenhouse (W m$^{-2}$);
- $G_i$: global solar radiation flux inside the greenhouse (W m$^{-2}$);
- GH1/LPC: greenhouse number 1, covered with the LPC film;
- GH2/RC: greenhouse number 2, covered with the RC film;
- GH3/DC: greenhouse number 3, covered with the DC film;
- LPC: locally produced cover, used as a control;
- PAR: photosynthetically active radiation (400-700 nm) (W m$^{-2}$);
- $RC$: reflective cover;
- $RH_i$: relative humidity of the air inside the greenhouse (%);
- $RH_o$: relative humidity of the air outside the greenhouse (%);
- $T_i$: air temperature inside the greenhouse (°C);
- $T_o$: air temperature outside the greenhouse (°C);
- $\rho_g$: total reflectance of the cover film to global solar radiation (%);
- $\tau_D$: true transmittance of the cover to diffuse radiation;
- $\tau_{D'}$: apparent transmittance of the cover to diffuse radiation;
- $\tau_g$: total transmittance of the cover film to global solar radiation;
- $\tau_{PAR}$: total transmittance of the cover to PAR (-);
- $\tau_{NIR}$: total transmittance to of the cover to NIR (-).
References


2. Hesham, A.A.; Tong, Y.X.; Yang, Q.C.; Al-Faraj, A.A.; Abdel-Ghany, A.M. Spatial distribution of air temperature and relative humidity in the greenhouse as affected by external shading in arid climates. J. Integr. Agric. 2019, 18, 2869–2882. [CrossRef]


18. Graefe, J.; Sandmann, M. Shortwave radiation transfer through a plant canopy covered by single and double layers of plastic. Agric. Forest Meteorol. 2015, 201, 196–208. [CrossRef]


Disclaimer/Publisher’s Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.