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Estimation of daily global solar radiation based on different whitening applications using temperature in Mediterranean type greenhouses

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Abstract. The study aimed to estimate the daily global solar radiation (R_s) in Mediterranean-type greenhouses. Five different temperature-based R_s estimation models developed for open-field conditions were calibrated and validated in Mediterranean-type greenhouses in Almeria, Spain and Antalya, Türkiye, between August 26, 2013, and January 1, 2023, and between October 1, 2018, and 1 January 2023, respectively. Whitening applications were categorized according to greenhouse light transmissivity and classified as follows: without whitening or light-whitening, medium-whitening, and severe-whitening. Additionally, the best-performing model were compared with greenhouse plastic light transmissivity method. The estimation performance of the models was evaluated using the statistical indicators of the p-value of the slope, determination coefficient (R^2), Nash–Sutcliffe model efficiency coefficient (NSE), root mean square error (RMSE), mean absolute error (MAE), relative error (RE), and Willmott Index (d). Compared with the other models, the Bristow and Campbell model showed a slightly higher performance in all whitening applications. Although the light transmissivity coefficient method performed slightly better than the temperature-based R_s estimation model, there was no statistical difference in the performances of the estimation models. Temperature-based estimation models offer a highly viable alternative for individuals who rely on the light transmittance approach to estimate R_s in greenhouses. This method can prove particularly useful in areas where measuring R_s outside the greenhouse is not possible or where partial time measurements cannot be taken owing to equipment malfunctions. All calibrated models can be used to estimate solar radiation using temperature data from various Mediterranean countries with similar climates and greenhouse cultivation.

Keywords: calcium carbonate suspension, extraterrestrial radiation, modelling, short wave radiation, shadow powder.

HIGHLIGHTS

- R_s estimation models had high agreement and accuracy with measured R_s values of Mediterranean-type greenhouses.
- There was no statistical difference between the R_s estimation model and light transmission coefficient method.
- Calibrated models are good alternatives if R_s outside the greenhouse is unmeasured or malfunctioning.

1. INTRODUCTION

Greenhouse cultivation has become a widespread practice, with an area of 5.6 Mha worldwide, owing to its ability to reduce dependence on climate and increase income per unit area (Hickman, 2020). Recently, greenhouse cultivation has grown significantly, particularly in regions such as the Mediterranean Basin, where mild winter temperatures permit low-cost vegetable crop production (Pardossi et al., 2004; Baudoin et al., 2013). In such areas, greenhouse cultivation is generally carried out in low-cost greenhouses without heating and ventilation systems. Baudoin et al. (2013) reported that polyethylene plastic is widely used (90%) as a cover material in these greenhouses. Additionally, Büyüktaş et al. (2019) noted that farmers in the region tend to favor the use of polyethylene ultraviolet (UV) + infrared ray barrier (IR) + diffuser (DIF) + ethylene vinyl acetate (EVA)-added plastic cover material with a service life of 36 months. This material is typically replaced after three years of use. In greenhouse cultivation, light is a crucial and a limiting factor for most cultivated species, along with other factors such as temperature and relative humidity (Stanghellini and Heuvelink, 2007; Colantoni et al., 2018). Global solar radiation (R_s) is a fundamental driving variable for many plant physiological processes including evapotranspiration, photosynthesis, carbohydrate partitioning, and dry matter production (Woli and Paz, 2012). Previous studies demonstrated that R_s was correlated with various plant growth parameters such as leaf area index (Bergamaschi et al., 2010), yield (Palencia et al., 2013), fatty acid profile (Gauthier et al., 2017), CO_2 assimilation rate (Francesconi et al., 1997), stomatal conductance (Marini and Sowers, 2019), chlorophyll content (Mielke et al., 2010) and root oxygen uptake (Nieuwenhuizen, 1983).

R_s is crucial for plant metabolism, growth, and development as it directly affects the greenhouse climate. Inadequate levels of radiation can lead to reduced photosynthesis, premature senescence, and ultimately decreased yield. Conversely, excessive solar radiation can inhibit photosynthesis through a process called photoinhibition, resulting in permanent yield reduction (López-Martínez et al., 2019). Therefore, growers apply whitening techniques (calcium carbonate ($CaCO_3$) suspension) to prevent photoinhibition, ensure that plants receive optimal light conditions, and maintain a controlled greenhouse climate (de los Ángeles Moreno-Teruel et al., 2020).

In addition to other climatic parameters, R_s is considered a crucial input required by most crop models to effectively simulate crop response. This is because plant growth is dependent on several complex physiological processes that involve the utilization of R_s. Furthermore, R_s is an important input for estimating crop evapotranspiration (ET_c) (Allen et al., 1998).

In recent years, the number of outdoor climate stations has increased; however, their application in greenhouse environments remains limited. Moreover, measurement of R_s is limited, particularly in developing countries (Yıldırım et al., 2018). This inadequacy hinders the estimation of greenhouse climate using various empirical methods. Greenhouse cultivation activities in regions with a Mediterranean climate are generally carried out in low-technology greenhouses with the aim of achieving high production with minimal input costs (Pardossi et al., 2004; Baudoin et al., 2013). Consequently, growers in these regions often do not collect climate data beyond temperature and humidity, which are both easy and inexpensive to measure. When evaluating the sensor cost, the global solar radiation (R_s) sensor is among the most expensive sensors and has a short economic lifespan that is dependent on quality. Additionally, expertise is required to collect and evaluate the data generated by this sensor. When the R_s value outside the greenhouse is known, the R_s value inside the greenhouse can be estimated by using the plastic cover transmissivity coefficient (Valdés-Gómez et al., 2009; Chen et al., 2020). However, several researchers have reported that this coefficient is not fixed. Fernández et al. (2010) stated that the transmissivity of the cover in a Mediterranean type greenhouse varied between 48.1% and 60.8% during the period of whitening application, while this value was 60.9% on average during the period without whitening application. Valdés-Gómez et al. (2009) also stated that this value is 62% on average. Fernández et al. (2001) reported that whitening with calcium carbonate caused a decrease in light transmissivity with varying percentages depending on the amount applied (e.g., 10% reduction for 175 g/l, 30% reduction for 250 g/l, 60% reduction for 400 g/l, 90% reduction for 1000 g/l). Due to the fact that whitening is typically applied using simple equipment, such as spraying the greenhouse, the application is often not uniform. Jimenez et al. (2010) noted that the greenhouse's light transmittance coefficient, after whitening was applied, was not uniform across the entire spectrum and varies based on the time of day. In general, the density of an application can varies based on the experience of the individual performing the application. Consequently, different intensities of whitening are applied to regulate R_s within the greenhouse to the desired level, based on the specific crop variety and phenological conditions. Similarly, prior whitening applications may be partially or entirely removed to augment the transmissivity of light into the greenhouse. For this reason, Gallardo et al. (2014) categorized the application of whitening into three levels: light, moderate, and severe, to aid farmers in utilizing the light transmissivity coefficient. In countries with low technology, Mediterranean-type greenhouses, where global solar radiation values are generally not measured, it is crucial to estimate R_s using parameters that are easily measured.

Greenhouse air temperature is correlated with R_s, with little or no time lag (Nieuwenhuizen, 1983). Numerous studies have attempted to estimate global solar radiation (R_s) using temperature values in outdoor conditions (Bristow and Campbell, 1984; Hargreaves and Samani, 1985, 1982; Donatelli and Campbell, 1998; Goodin et al., 1999; Chen et al., 2004). Hargreaves and Samani (1982) reported that R_s is related to extraterrestrial radiation (R_a) and relative sunshine duration (n/N) and that R_s can be estimated using these parameters. Hargreaves (1981) and Hargreaves and Samani (1982) established a correlation between daily temperature range (ΔT_1) and relative sunshine duration. Moreover, they proposed an empirical coefficient fitted to R_s/R_a versus temperature data, which served as the initial basis for other R_s estimation models (Hargreaves and Samani, 1985). Bristow and Campbell (1984) modified the definition of daily temperature range to account for the potential influence of large-scale hot or cold air masses that may move through the study area, because the maximum temperature may rise due to the hot air mass on the day of measurement. Because this phenomenon occurs after the measurement of the minimum temperature value, it causes the maximum and minimum air temperature differences to be high. Therefore, it is considered that the prediction models overestimate the value of R_s (Bristow and Campbell 1984). The opposite situation occurs in the case of a cold air mass, and underestimation of the incoming radiation would result in these conditions. Thus, Bristow and Campbell (1984) used the difference between the maximum air temperature and average minimum temperature values for two consecutive days to determine the daily temperature range. Donatelli and Campbell (1998) improved this model by incorporating a summer-night air temperature factor, as the ristow and Campbell model underestimated the value of R_s in the July-August period for the Northern Hemisphere and the January-February period for the Southern Hemisphere (Grillone et al., 2012). Goodin et al. (1999) added an additional R_a parameter to the Bristow and Campbell model and validated its reliability outside of the calibration region. Additionally, several researchers (Hunt et al. 1998; Chen et al. 2004) have modified these models and achieved a high level of accuracy in estimating the R_s value under outdoor conditions. However, despite the development and modification of these models for outdoor conditions, there are currently no calibrated or modified models for greenhouse conditions.

The primary aim of current study was to calibrate and validate six temperature-based models (namely, Hargreaves, Bristow and Campbell, Donatelli and Campbell, Chen, and Goodin) originally designed for outdoor conditions to estimate Rs in low-tech plastic greenhouses with a Mediterranean climate. Additionally, temperature-based prediction models were compared with the greenhouse light transmissivity coefficient method to determine the optimal approach under the prevailing conditions.

2. MATERIALS AND METHODS

2.1 Experimental sites

The study was carried out in two regions, at the University of Almeria (UAL) Experimental Farm in Almeria (SE Spain, 36°51'N latitude, 2°16'W longitude; 92 m above sea level) and Akdeniz University (AU) Experimental Farm in Antalya (TR Türkiye, 36°53'N latitude, 30°38'E longitude;12 m above sea level) in plastic greenhouses.

2.1.1 Experimental greenhouse in Almeria

The dimensions of the greenhouse in Almeria were 32 m (four tunnels of 8 m) width and 45 m length with ridge and gutter heights of 5.7 and 4.5 meters, respectively. The greenhouse was covered with a 200 µm polyethylene film featuring UV, IR, EVA, and AD additives and possessed a 36-month strength. The plastic coverings of the greenhouse were replaced three times on 08/03/2013, 09/03/2016, and 17/12/2019, respectively.

Climatic parameters, including air temperature, relative humidity (RH), and incident solar radiation were

Table 1. Crop varieties and corresponding growing periods cultivated within the research greenhouse in Almeria.

Crop Variety	Growing Period*
Cucumber	05/09/2013 - 22/11/2013
Pepper	04/03/2014 - 28/05/2014
Pepper	12/08/2014 - 29/01/2015
Pepper	19/07/2016 - 24/03/2017
Cucumber	30/03/2017 - 22/06/2017
Pepper	21/07/2017 - 20/02/2018
Cucumber	24/04/2018 - 03/07/2018
Pepper	27/02/2020 - 11/06/2020
Pepper	22/07/2020 - 28/01/2021
Melon	26/02/2021 - 08/06/2021
Pepper	16/07/2021 - 15/03/2022
Pepper	11/07/2022 - 16/03/2023

*The growth periods listed in the table include the start and end dates.

monitored inside the greenhouse at 5-minute intervals. The temperature and humidity were measured using temperature and humidity sensors (Model 43502, R.M. Young Company, Michigan, USA) and the solar radiation was measured using a pyranometer (model SKS 1110, Skye Instruments, Llandrindod Wells, Wales, United Kingdom) situated in the central area of the greenhouse at a height of 1.5 m above the ground. All monitored data were collected and stored using a data logger (model CR10X, Campbell Scientific, Inc., Utah, USA). Meteorological data outside the greenhouse were obtained from the Agricultural and Fisheries Research and Training Institute (IFAPA) meteorological station located at 36°50'N latitude and 2°24'W longitude. The distance between both sites was 10.1 km. Climate data collected both inside and outside the greenhouse were used in the study, covering the period from August 26, 2013, to January 1, 2023.

Indoor climatic data were interrupted between 18 November 2014 to 17 December 2014, between 6 June 2016 to 12 July 2016 and between 4 June 2019 to 23 February 2020, due to greenhouse maintenance activities. Table 1 shows the crops grown in the research greenhouse of Almeria, including their respective growing periods.

2.1.2 Experimental greenhouse in Antalya

The dimensions of the greenhouse in Antalya were 9.6 meters in width and 25 meters in length, with ridge and gutter heights of 6.0 and 4.0 meters, respectively. The greenhouse was covered with a 180 µm polyethylene film featuring UV, IR, EVA, and AD additives and possessed a 36-month strength. The plastic coverings of the greenhouse were replaced twice on July 11, 2018, and February 20, 2021.

Table 2. Crop varieties and corresponding growing periods cultivated within the research greenhouse in Antalya.

Crop Variety	Growing Period*
Grass	01/08/2018 - 01/01/2021
Tomato	27/02/2021 - 24/06/2021
Tomato	08/09/2021 - 24/01/2022
Tomato	24/02/2022 - 22/06/2022
Grass	15/07/2022 – 01/01/2023

*The growth periods listed in the table include the start and end dates.

The climate inside the greenhouse was monitored with a meteorology station located in the center of the greenhouse at a height of 1.5 m above the ground at 5-minute intervals. The meteorological station was equipped with various sensors, including an air temperature (PT100 1/3 Class B, Pessl Instruments, Weiz, Austria), relative humidity (Rotronic hygrometer IN-1, Pessl Instruments, Weiz, Austria), pyranometer (LI-200SZ, Pessl Instruments, Weiz, Austria) and net radiation with all its components (CNR4, Kipp&Zonen, Delft, Netherlands). Net radiation data were collected using a model CR1000X data logger (Campbell Scientific, Inc., Utah, USA), while all other recorded data were collected using an iMETOS 3.3 data logger (Pessl Instruments, Weiz, Austria). The climatic data outside the greenhouse were obtained from the station of Turkish State Meteorological Service, located at latitude 36° 53' N and longitude 30° 38' E. Distance between both sites is 0.3 km. Indoor greenhouse climate data were collected between October 1, 2018, and January 1, 2023, for a period of four years and three months. The solar radiation sensor located outside the greenhouse began collecting data on February 26, 2019, and finished on January 1, 2023. Data could not be collected outside the greenhouse between April 10, 2019 - April 22, 2019, and October 1, 2020 - October 30, 2020 due to sensor failure. Table 2 shows the crops grown in the research greenhouse of Antalya, including their respective growing periods.

2.2 Whitening application and data selection

During the research, whitening was applied at different doses and rates according to the crop species grown in both research greenhouses, the growing season, and the phenological period of the crop. Simi-

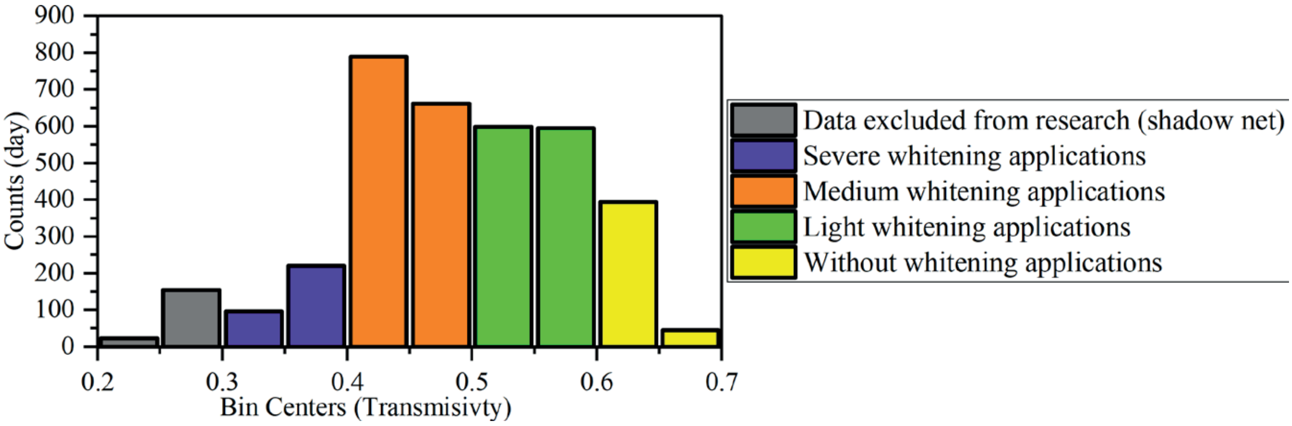

Figure 1. Histogram plot of transmissivity values in the dataset used in the experiment.

larly, the whitening density was reduced by washing to increase the intensity of the light entering the greenhouse. In addition, the whitening of the greenhouse cover was naturally washed away by precipitation. For this reason, the ratio of $R_{s\text{-indoor}}$ (solar radiation values inside the greenhouse) to $R_{s\text{-outdoor}}$ (solar radiation values outside the greenhouse) was used instead of the applied doses while selecting the data. The data between 12 August 2014 to 19 August 2014, 10 May 2016 to 17 July 2016, 13 July 2017 to 01 August 2017, and 05 May 2022 to 17 May 2022 were not included in the research conducted in the Almeria research greenhouse, as shade nets were extended during these periods. The $R_{s\text{-indoor}}/R_{s\text{-outdoor}}$ and $R_{s\text{-indoor}}/R_a$ ratios were used to eliminate erroneous data caused by sensor malfunctions during research. A histogram plot of the transmissivity values in the dataset used for the experiment was used to the classify the whitening application (Figure 1).

In the study, the classification of whitening applications was based on transmissivity values, where values between 0.6-0.7 indicated "without whitening", values between 0.5-0.6 indicated "light whitening", values between 0.4-0.5 indicated "medium whitening", and values between 0.3-0.4 indicated "severe whitening". The extraterrestrial radiation (R_a) was calculated using the method described by Allen et al. (1998).

2.3 Overview of the models

Table 3 summarizes the five different models that were calibrated and validated to estimate R_s based on temperature.

The unknown parameters (a, b, and c) for the greenhouse conditions of the models listed in Table 3 were determined using MS Excel Solver. The calibration and validation of the models for each whitening application class were conducted using data from odd and even days, respectively.

Table 3. Temperature-based solar radiation estimation models used under greenhouse conditions.

Model	Equation
HS (Hargreaves and Samani, 1985)	$R_s = a\sqrt{\Delta T_1}\,R_a$
BC (Bristow and Campbell, 1984)	$R_s = a\left(1 - exp(-b\,\Delta T_2{}^{c})\right)R_a$
DC (Donatelli and Campbell, 1998)	$R_s = a\left(1 - exp\left(-b\dfrac{\Delta T_2{}^{c}}{\Delta T_m}\right)\right)R_a$
CH (Chen et al., 2004)	$R_s = \ (a\,ln\,\Delta T_1 + b)\,R_a$
GO (Goodin et al., 1999)	$R_s = a\left(1 - exp\left(-b\dfrac{\Delta T_2{}^{c}}{R_a}\right)\right)R_a$

Abbreviations: R_s, global solar radiation (MJ m^{-2} day^{-1}); R_a, extraterrestrial radiation (MJ m^{-2} day^{-1}); Alt, altitude (m); ΔT_1, difference between daily maximum (T_{max}) and minimum (T_{min}) air temperatures (°C); ΔT_2, the difference between the maximum air temperature and the average of the minimum temperatures for two consecutive days (°C); ΔT_m, average monthly temperature (°C), a, b and c: models coefficients.

2.4 Evaluation of the performances of the models and statistical analysis

In current study, firstly, all models were calibrated for each whitening application, and the coefficients of each model were determined for greenhouse conditions. Then, the performance of the models was evaluated using these coefficients in the validation dataset. Finally, the best temperature-based R_s model was compared with the R_s estimated using the light transmissivity coefficient method ($R_{s\text{-}Tr}$) and measured R_s values ($R_{s\text{-measured}}$). In the light transmissivity coefficient method, 0.65, 0.55, 0.45 and 0.35 coefficients were used for no whitening, light, medium and severe, respectively.

A scatter plot was generated by applying linear regression to the relationship between the estimated and measured data to visualize the distribution of the data around the 1/1 line. The estimation performance of the models was evaluated using statistical indicators using the p-value of the slope, determination coefficient (R^2) (Eq-1), Nash–Sutcliffe model efficiency coefficient (NSE) (Eq-2), root mean square error (RMSE) (Eq-3), mean absolute error (MAE) (Eq-4), relative error (RE) (Eq-5) and Willmott Index (d) (Eq-6).

$$R^2 = \frac{\left[\sum_{i=1}^{n}\left(X_i - \overline{X_i}\right)\left(Y_i - \overline{Y_i}\right)\right]^2}{\sum_{i=1}^{n}\left(X_i - \overline{X_i}\right)^2 \sum_{i=1}^{n}\left(Y_i - \overline{Y_i}\right)^2} \tag{1}$$

$$NSE = 1 - \frac{\sum_{i=1}^{n}(X_i - Y_i)^2}{\sum_{i=n}^{n}\left(X_i - \overline{X_i}\right)^2} \tag{2}$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(X_i - Y_i)^2}{n}} \tag{3}$$

$$MAE = \frac{\sum_{i=1}^{n}|X_i - Y_i|}{n} \tag{4}$$

$$RE = \frac{RMSE}{\overline{Y_i}} \tag{5}$$

$$d = 1 - \frac{\sum_{i=1}^{n}(X_i - Y_i)^2}{\sum_{i=n}^{n}\left(\left|X_i - \overline{Y_i}\right| + \left|Y_i - \overline{Y_i}\right|\right)^2} \tag{6}$$

Where n is number of observations, X_i is estimated R_s, Y_i is measured R_s and $\bar{X}_i$ is mean value of estimated R_s, $\bar{Y}_i$ is mean value of measured R_s.

R^2, NSE, and d values equal to 1, and RMSE, RE, and MBE values equal to 0 indicate the best possible regression relationship. Climatic data from Almeria and Antalya were compared using two-sample t-tests. Also, some climatic data (monthly average minimum temperature, mean temperature, maximum temperature, sunshine hours, and extraterrestrial radiation) related to the temperature-based R_s estimation models of six different greenhouse regions (Alger, Algeria; Almeria, Spain; Antalya, Türkiye; Bizerte, Tunisia; Kalamata, Greece; Siracusa, Italy) at similar latitudes were obtained from CLIMWAT 2.0 (Muñoz and Grieser, 2006). The aim of this was to determine the climatic similarities or differences between these regions using one-way ANOVA. The results of this statistical analysis are provided in the Supplementary Material (Figure S1). All statistical analyses were performed using SPSS Statistics Base v23 (SPSS Inc., Chicago, IL, USA) and figures were prepared using OriginPro v2023a (OriginLab Corporation, MA, USA).

3. RESULTS

3.1 Climatic analogies between Almeria and Antalya

The relationship between the monthly average solar radiation and sunshine duration data outside the greenhouse for Almeria and Antalya and the extraterrestrial radiation data of the two regions is shown in Figure 2.

The distribution of external solar radiation throughout the year showed great similarities between Almeria and Antalya (Figure 2). The annual average sunshine durations of Almeria and Antalya were 8.15 and 8.23 hour, respectively. Almeria had 0.08-hour shorter sunshine duration (p=0.38). The longest sunshine duration in both regions occurred in July. The annual average solar radiation of Almeria (17.7 MJ m^{-2} day^{-1}) was 0.5 MJ m^{-2} day^{-1} lower than Antalya (18.24 MJ m^{-2} day^{-1}) (p=0.65). There was a strong relationship between extraterrestrial radiation in Antalya and Almeria (R^2=0.999, RMSE=0.014, RE=0.0005).

Figure 3 showed the temperature, relative humidity, and precipitation data for Antalya and Almeria, with the significance level of the two-way test analysis of variance represented by “p”.

There were no significant differences in the maximum, mean and minimum air temperatures (p=0.28, 0.33 and 0.49, respectively) between Antalya and Almeria (Figure 3a). In both regions, the air temperature showed an increasing trend between January and August, whereas it decreased in the following months. In contrast to air temperature, there was a significant difference in the monthly average relative humidity (p<0.05) and precipitation values (p<0.001) between the two regions (Figure 3b). Almeria and Antalya received a seasonal total of 200 and 1058 mm of precipitation, respectively.

3.2 Calibration of models

Table 4 shows the coefficients of the calibrated models used for estimating solar radiation values inside the greenhouse categorized under different whitening application conditions.

The scatterplot in Figure 4, which is a 1/1 plot, shows the correlation between the solar radiation within

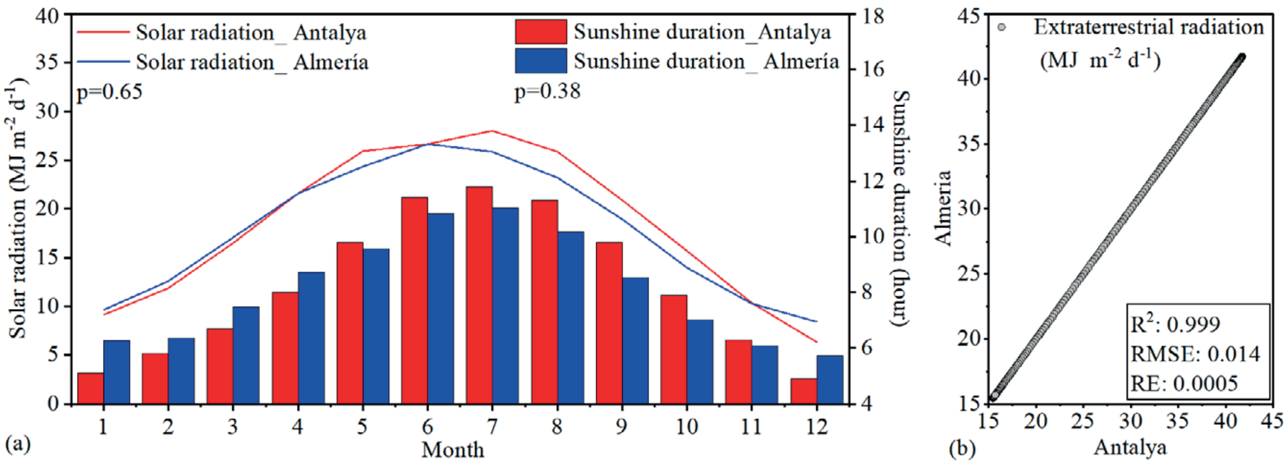

Figure 2. Monthly average solar radiation and sunshine duration data for Almeria and Antalya outside the greenhouse (a) and the relationship between the extraterrestrial radiation data of the two regions (b). *p is the significance level of the two-sample t-test; R^2 is the determination coefficient; RMSE is the root mean square error; RE is the relative error.*

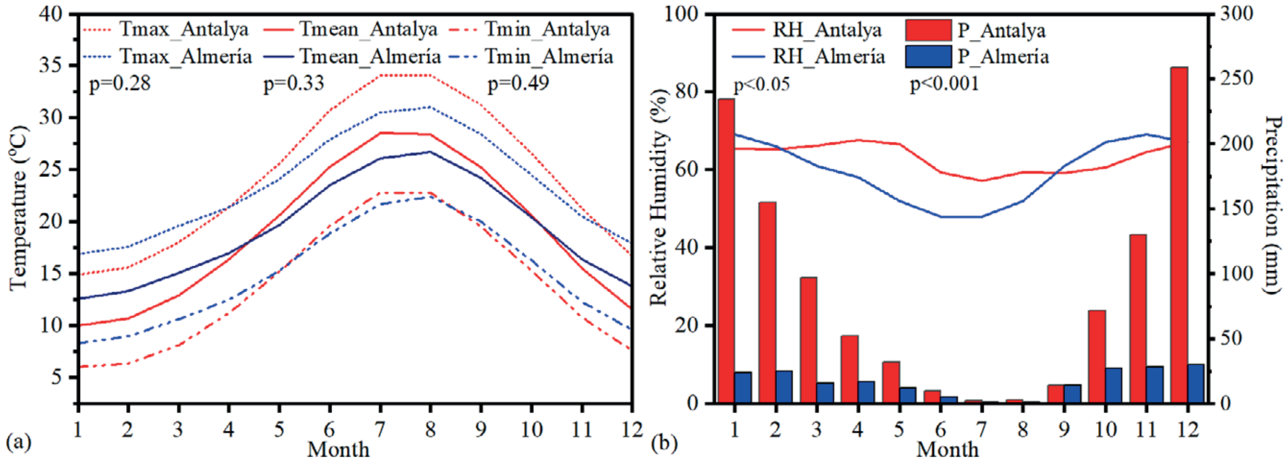

Figure 3. Maximum, mean and minimum temperature (a), relative humidity and precipitation data (b) of Antalya and Almeria. *T_{max} is the maximum temperature, T_{mean} is the mean temperature, T_{min} is the minimum temperature, RH is the relative humidity, P is precipitation and p is the significance level of the two-sample t-test.*

the greenhouse calculated using the calibrated models and the values measured by the sensors. The calibration performance of the models for the four whitening applications is listed in Table 5.

The calibration performance of the solar radiation estimation models for greenhouses was remarkably similar to one another within each whitening application. The relationship between the estimated and measured R_s values was highly significant in all calibrated models and whitening applications (p<0.001) (Figure 4). Similarly, the coefficients of determination of the relationship between the measured and estimated R_s values in each calibrated model ranged from 0.960-0.981 and were remarkably close to each other. Despite this, in certain models and whitening applications, the intensities of both the measured and estimated R_s values, as represented by the dark colors, were more closely aligned with the 1/1 line. Table 5 gave more details on these differences between calibrated models. The estimation performance of the calibrated models varied depending on the whitening application used. In all models, except for the NSE indicator of HA, the highest NSE, d, and lowest RMSE, MAE, and RE values proved that the best calibration performance was in the medium whitening application. All calibrated models had the lowest estimation performance in severe whit-

Table 4. Coefficients of models calibrated to estimate solar radiation inside the greenhouse for different whitening applications.

Whitening application	Model	Equation coefficient		
		a	b	c
Without whitening	Hargreaves (HA)	0.0866		
	Bristow and Campbell (BC)	0.4593	0.3565	0.5593
	Donatelli and Campbell (DC)	0.4163	1.2769	1.2587
	Chen (CH)	0.0803	0.1496	
	Goodin (GO)	0.3921	0.5108	2.0664
Light	Hargreaves (HA)	0.0812		
	Bristow and Campbell (BC)	0.4497	0.2023	0.7055
	Donatelli and Campbell (DC)	0.3871	0.4105	1.6478
	Chen (CH)	0.1005	0.0628	
	Goodin (GO)	0.3622	0.0148	3.3984
Medium	Hargreaves (HA)	0.0702		
	Bristow and Campbell (BC)	0.3307	0.3329	0.7002
	Donatelli and Campbell (DC)	0.3147	1.1624	1.3779
	Chen (CH)	0.0495	0.1591	
	Goodin (GO)	0.3064	2.8110	1.4448
Severe	Hargreaves (HA)	0.0577		
	Bristow and Campbell (BC)	0.2363	0.7958	0.5062
	Donatelli and Campbell (DC)	0.2305	5.3442	0.8858
	Chen (CH)	0.0210	0.1700	
	Goodin (GO)	0.2514	25.1243	0.4428

ening application. Among the calibrated models without whitening application conditions, the BC model exhibited the best performance (NSE: 0.79, RMSE: 1.93, RE: 0.18), whereas the HA model had the lowest performance (NSE: 0.74, RMSE: 2.10, RE: 0.19). The calibrated BC and CH models showed the best estimation performance in the light whitening application, with the HA and GO models showing relatively weak performance. Among the models used in the medium whitening application, the BC, DC, and CH models were nearly identical in their superior estimation performance relative to the other models. The performances of all calibrated models, except for HA, were closely matched to each other in the severe whitening application, with HA exhibiting the lowest level of performance.

3.3 Validation of models

The distribution of solar radiation estimated from different models (HA, BC, DC, CH and GO) and measured solar radiation values in different greenhouse whitening applications for the validation data are shown in Figure 5, while the results of the statistical indicators for these models are given in Table 6.

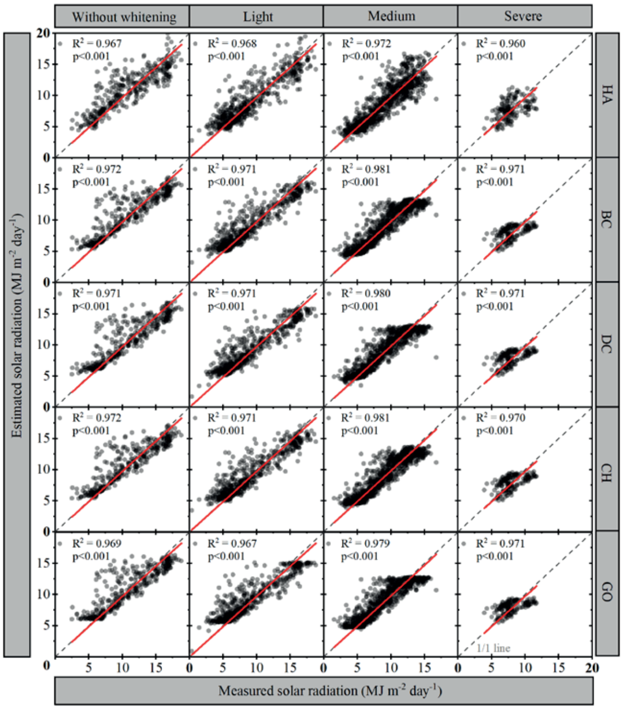

Figure 4. Relationship between estimated solar radiation from different models (HA, BC, DC, CH and GO) and measured solar radiation, at different greenhouse whitening applications for calibration data. *HA, Hargreaves; BC, Bristow and Campbell; DC, Donatelli and Campbell; CH, Chen; GO, Goodin.* R^2 *is the determination coefficient. p is the significance of regressions.*

The relationship between the measured and estimated solar radiation inside the greenhouse was significant during the validation process ($p<0.001$) (Figure 5). In all models and whitening applications, the determination coefficients of the relationship between the estimated and measured greenhouse solar radiation values showed good agreement ($R^2>0.960$). The BC model had the highest R^2 value (0.982) in the medium whitening treatment and the HA model had the lowest R^2 value (0.960) in the severe whitening treatment. The statistical indicators in Table 6 showed that the highest estimation performances in the validation stage as well as in the calibration stage were obtained with the medium whitening application in all models except for the NSE of HA. Compared with other whitening applications, all models showed higher prediction performance in light and medium whitening applications. The DC model had the highest NSE (0.78) and the lowest RMSE (1.93) in the without whitening application (Table 6). The validation performances of BC (NSE: 0.77, RMSE:1.97) and CH (NSE: 0.77, RMSE:1.96) models were remarkably close to those of the DC model. The estimation accuracies of the BC, DC and CH mod-

Table 5. Statistical indicators of calibration for greenhouse conditions of five R_s estimation models for different whitening applications.

Whitening application	Model	Statistical indicators				
		NSE	RMSE	MAE	RE	d
Without whitening	HA	0.74	2.10	1.61	0.19	0.92
	BC	0.79	1.93	1.42	0.18	0.93
	DC	0.78	1.93	1.43	0.18	0.93
	CH	0.78	1.92	1.40	0.18	0.93
	GO	0.76	1.99	1.49	0.18	0.93
Light	HA	0.81	1.78	1.36	0.20	0.94
	BC	0.83	1.69	1.25	0.18	0.95
	DC	0.83	1.70	1.25	0.18	0.94
	CH	0.83	1.69	1.25	0.18	0.95
	GO	0.81	1.78	1.30	0.19	0.94
Medium	HA	0.77	1.60	1.21	0.18	0.94
	BC	0.84	1.31	0.98	0.15	0.95
	DC	0.84	1.33	0.98	0.15	0.95
	CH	0.84	1.31	0.98	0.15	0.96
	GO	0.83	1.36	1.01	0.15	0.95
Severe	HA	0.00	1.62	1.37	0.21	0.68
	BC	0.26	1.39	1.21	0.18	0.70
	DC	0.26	1.39	1.21	0.18	0.69
	CH	0.27	1.39	1.21	0.18	0.70
	GO	0.28	1.38	1.15	0.17	0.65

Abbreviations: HA, Hargreaves; BC, Bristow and Campbell; DC, Donatelli and Campbell; CH, Chen and GO, Goodin. NSE, Nash–Sutcliffe model efficiency coefficient; RMSE, root mean square error; RE, relative error; MBE, mean bias error; d, Willmott Index.

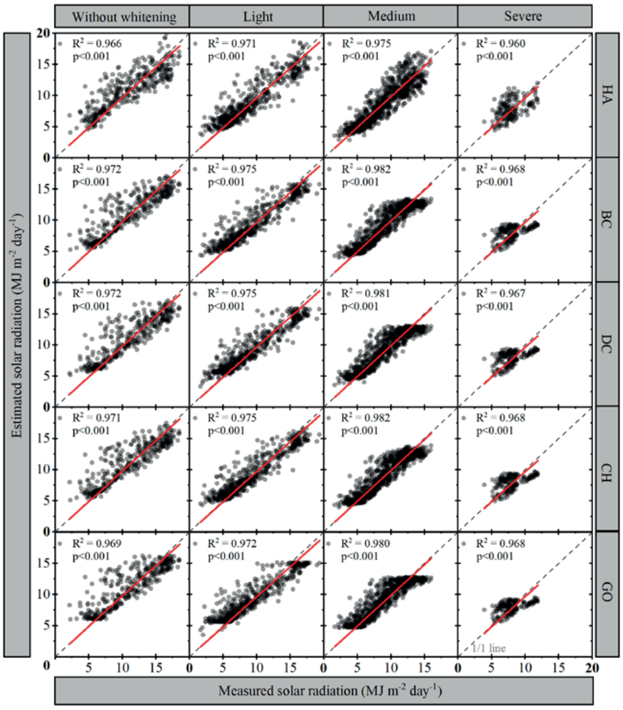

Figure 5. Relationship between estimated solar radiation from different models (HA, BC, DC, CH and GO), and measured solar radiation, at different greenhouse whitening applications for validation data. *HA, Hargreaves; BC, Bristow and Campbell; DC, Donatelli and Campbell; CH, Chen; GO, Goodin.* R^2 *is the determination coefficient. p is the significance of regression.*

els in light whitening applications were slightly better than those of the other models. The HA model showed low validation performance in both Medium and Severe whitening applications. In the validation stage, similar to the calibration stage, all models had lower estimation performance in the severe whitening application than in the other whitening applications. Furthermore, in the validation phase, the BC model showed better performance than the other models in the severe whitening application. All models demonstrated adequate performance in predicting in-greenhouse solar radiation, despite the slight differences observed in their validation results.

3.4 Comparison of the temperature-based method and the light transmissivity coefficient method

The relationships and distributions among the Bristow and Campbell model ($R_{s\text{-}BC}$), greenhouse light transmissivity coefficient ($R_{s\text{-}Tr}$), and measured ($R_{s\text{-}measured}$) solar radiation values, in various whitening applications are shown in Figure 6, and the statistical indicators of these relationships are listed in Table 7.

There was a significant relationship between the estimated with $R_{s\text{-}BC}$ and $R_{s\text{-}Tr}$ and $R_{s\text{-}measured}$ in all the whitening applications ($p<0.001$) (Figure 6). The regression analysis between the estimation methods and $R_{s\text{-}measured}$ showed that $R_{s\text{-}Tr}$ had a greater coefficient of determination than $R_{s\text{-}BC}$ for each whitening application. Nonetheless, a significant relationship was observed between the estimation methods in all whitening applications ($p<0.001$, $R^2>0.967$). The scatter plot showed that the data points in the $R_{s\text{-}Tr}$ method were distributed closer to the 1/1 line compared to the $R_{s\text{-}BC}$ model, which implied a lower error rate. Moreover, the NSE, RMSE, MAE, RE and d values of the relationship between the estimation methods ($R_{s\text{-}BC}$ and $R_{s\text{-}Tr}$) and the $R_{s\text{-}measured}$ were remarkably similar (Table 7). However, compared with $R_{s\text{-}BC}$, the $R_{s\text{-}Tr}$ method displayed superior NSE and d (higher), as well as RMSE, MAE, and RE (lower) in all whitening applications. As with all temperature-based R_s estimation models, the estimation performance of the $R_{s\text{-}Tr}$ method for R_s inside the greenhouse showed a slight relative decrease under severe whitening application.

Table 6. Statistical indicators of validation for greenhouse conditions of five R_s estimation models for different whitening applications.

Whitening application	Model	Statistical indicators				
		NSE	RMSE	MAE	RE	d
Without whitening	HA	0.73	2.12	1.67	0.19	0.91
	BC	0.77	1.97	1.45	0.18	0.93
	DC	0.78	1.93	1.43	0.18	0.93
	CH	0.77	1.96	1.45	0.18	0.93
	GO	0.75	2.05	1.53	0.19	0.92
Light	HA	0.83	1.68	1.29	0.19	0.95
	BC	0.86	1.57	1.17	0.17	0.95
	DC	0.85	1.56	1.18	0.17	0.95
	CH	0.85	1.59	1.20	0.17	0.95
	GO	0.84	1.64	1.24	0.18	0.95
Medium	HA	0.80	1.47	1.14	0.17	0.95
	BC	0.86	1.25	0.96	0.14	0.96
	DC	0.85	1.27	0.96	0.14	0.96
	CH	0.85	1.25	0.96	0.14	0.96
	GO	0.84	1.31	0.99	0.15	0.95
Severe	HA	0.07	1.63	1.37	0.21	0.71
	BC	0.29	1.46	1.26	0.18	0.68
	DC	0.25	1.46	1.26	0.19	0.68
	CH	0.26	1.45	1.26	0.18	0.69
	GO	0.28	1.43	1.19	0.18	0.65

Abbreviations: HA, Hargreaves; BC, Bristow and Campbell; DC, Donatelli and Campbell; CH, Chen and GO, Goodin. NSE, Nash–Sutcliffe model efficiency coefficient; RMSE, root mean square error; RE, relative error; MBE, mean bias error; d, Willmott Index.

Table 7. Statistical indicators of the relationships between the two different R_s estimation methods for greenhouse conditions among themselves and with measured values.

Whitening application	Model	Statistical indicators				
		NSE	RMSE	MAE	RE	d
Without whitening	$R_{s\text{-measured}} - R_{s\text{-Tr}}$	0.84	1.61	1.06	0.13	0.96
	$R_{s\text{-measured}} - R_{s\text{-BC}}$	0.77	1.96	1.46	0.17	0.93
	$R_{s\text{-BC}}$ - $R_{s\text{-Tr}}$	0.44	2.51	1.91	0.21	0.89
Light	$R_{s\text{-measured}} - R_{s\text{-Tr}}$	0.90	1.32	1.06	0.13	0.97
	$R_{s\text{-measured}} - R_{s\text{-BC}}$	0.84	1.65	1.23	0.18	0.95
	$R_{s\text{-BC}}$ - $R_{s\text{-Tr}}$	0.64	2.03	1.63	0.20	0.93
Medium	$R_{s\text{-measured}} - R_{s\text{-Tr}}$	0.93	0.90	0.64	0.10	0.98
	$R_{s\text{-measured}} - R_{s\text{-BC}}$	0.85	1.29	0.97	0.15	0.96
	$R_{s\text{-BC}}$ - $R_{s\text{-Tr}}$	0.84	1.22	0.85	0.14	0.96
Severe	$R_{s\text{-measured}} - R_{s\text{-Tr}}$	0.50	1.17	0.96	0.14	0.85
	$R_{s\text{-measured}} - R_{s\text{-BC}}$	0.26	1.43	1.24	0.18	0.69
	$R_{s\text{-BC}}$ - $R_{s\text{-Tr}}$	0.32	0.92	0.76	0.11	0.86

Abbreviations: $R_{s\text{-measured}}$, measured solar radiation inside the greenhouse; $R_{s\text{-Tr}}$, greenhouse solar radiation calculated using the light transmissivity coefficient; $R_{s\text{-BC}}$, Bristow and Campbell solar radiation estimation model calibrated for greenhouse conditions; NSE, Nash–Sutcliffe model efficiency coefficient; RMSE, root mean square error; RE, relative error; MBE, mean bias error; d, Willmott Index.

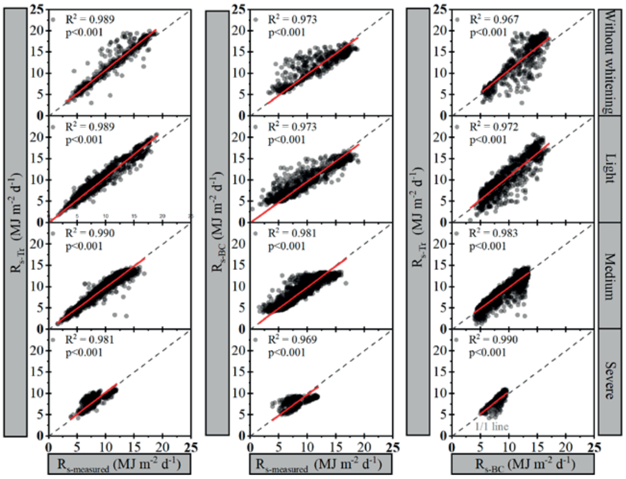

Figure 6. Relationships between the R_s values of the Bristow and Campbell model ($R_{s\text{-BC}}$) and the light transmissivity coefficient method ($R_{s\text{-Tr}}$) with the measured R_s ($R_{s\text{-measured}}$) in greenhouse under various whitening applications. *R^2 is the determination coefficient and p is the significance of the regressions.*

4. DISCUSSION

The average annual solar radiation value of Almeria is 0.53 MJ m^{-2} day^{-1} less than that of Antalya. Specifically, from December to April, the values of solar radiation outside the greenhouse were relatively higher in Almeria than in Antalya. However, in the remaining months, the solar radiation values were slightly lower in Almeria. This trend was closely related to the clear-sky index. According to Zhang et al. (2022), the solar radiation received at different regions of the same latitude can vary owing to the presence of varying amounts of water vapor and other aerosols in the atmosphere.

Despite the similarities between the two regions in climatic parameters such as air temperature, solar radiation, and relative humidity, there was a difference in the average annual and monthly precipitation values. Antalya is located at the base of the Taurus Mountains, which can affect a city's weather patterns and create a rain shadow effect, resulting in higher precipitation levels (Atalay et al., 2014). In contrast, the precipitation levels in Almeria are constrained, largely because of the influence of the Sierra Nevada Mountains, which act as a barrier that impedes the majority of moisture from the Atlantic Ocean. Additionally, dry and hot winds originating from North African continent further exacerbate this limitation (Frot et al., 2002). The amount of precipitation that falls in Antalya between December and April accounts for 70.4% of the total annual precipitation, resulting in a slightly higher sunshine duration and external greenhouse solar radiation in Almeria during these months.

Given the proximity in latitude between Antalya and Almeria, the climatic parameters that directly influence the temperature-based estimation model for R_s (maximum temperature, minimum temperature, solar radiation, extraterrestrial radiation, and sunshine duration) show significant similarities between the two regions. Based on these similarities, it is hypothesized that the R_s estimation models calibrated in this study for greenhouse cultivation in these regions can also be applied to other Mediterranean regions with similar latitudes and climatic conditions, and greenhouse activities. Moreover, the minimum temperature, mean temperature, maximum temperature, sunshine hours, and extraterrestrial radiation parameters were statistically similar among the six greenhouse regions (Alger, Algeria; Almeria, Spain; Antalya, Türkiye; Bizerte, Tunisia; Kalamata, Greece; Siracusa, Italy) supports this hypothesis.

The amount of solar radiation that reaches greenhouse plastic cover is closely related to various atmospheric factors, such as sunshine duration, cloud cover, and weather phenomena such as precipitation and fog (Díaz-Torres et al., 2017; Matuszko, 2012; Tuononen et al., 2019). However, the amount of solar radiation that penetrates the interior of a greenhouse is influenced by a number of additional factors, including the thickness of the greenhouse cover material, any additives present in the material, and the presence of whitening, among other parameters (Cabrera et al., 2009; Fernández et al., 2010). Hence, to apply temperature-based models that are adjusted for Mediterranean-style low-tech greenhouse conditions to greenhouse regions situated at close latitudes, the characteristics of the greenhouses in this region should be similar.

During both the calibration and validation phases, all R_s estimation models showed a high level of agreement ($p<0.001$) with the measured R_s values in all whitening applications. During the assessment of the R_s estimation models, minor variations were observed in their estimation capabilities, although these were not statistically significant. These small differences were identified by analyzing various statistical indicators, including R^2, NSE, RMSE, MBE, RE, and d. The estimation models performed similarly in terms of RMSE, MAE, and RE for all whitening applications during both calibration and validation stages. However, differences were observed in the NSE and d indicators for the severe whitening application as compared to the other whitening applications owing to a slight deviation in the distribution of the points from the 1/1 line. This deviation can be attributed to the reduction in light transmissivity of the greenhouse, ranging from 30% to 40%, owing to the severe whitening application, which caused a change in the behavior of the maximum and minimum temperature differences in the greenhouse. During severe whitening application, there was a significant decrease in solar radiation reaching the greenhouse on cloudy days. However, the maximum and minimum temperature differences in the greenhouse did not decrease at the same rate, which caused a higher level of error compared to other whitening applications.

In the present study, the estimation performance of the $R_{s\text{-}BC}$ model was lower than that of the $R_{s\text{-}Tr}$ method. In addition, the data exhibited a wider and more distant distribution around the 1/1 line, indicating a higher error rate in the $R_{s\text{-}BC}$ model. The primary explanation for this is that temperature-based estimation approaches depend on the difference between the maximum and minimum temperatures, and the impact of cloud and precipitation records on the maximum and minimum temperatures varies (Dai et al., 1999; Pyrgou et al., 2019). In particular, there was a larger fluctuation in the maximum temperature values than in the minimum temperature values. Upon examining the hourly temperature data, the maximum temperature was observed to occur at noon and the minimum temperature occurred at sunrise (data not shown). Cloud density affects on the amount of energy that penetrates a greenhouse, leading to a reduction in the maximum temperature. Conversely, during the coldest hours of the day, increased cloud density results in an increase in minimum temperature values within the greenhouse (Pyrgou et al., 2019). This led to greater daily oscillations in the maximum temperature values than in the minimum temperature values.

The degree of light transmissivity in a greenhouse is strongly affected by the choice of the cover material (Tantau et al., 2012). However, in current study, it was determined that the use of greenhouse covers with similar characteristics, which are widely used in the Mediterranean region, in both regions did not have a significant effect on the results. The high estimation performance observed in the model when using pooled data indicates that the age of greenhouse cover does not have a significant impact on the predictive ability of the model. Tantau et al. (2012) had already pointed out that there was no conclusive evidence on how aging affects the light transmittance of materials.

The temperature-based models used to estimate the R_s values may not be appropriate for greenhouses with heating systems. This is because these models are dependent on temperature, and any additional energy source that alters the greenhouse temperature diminishes the accuracy of the R_s estimation. On the Mediterranean coast, producers typically do not use heating systems in their greenhouses, because the average daily temperature usually remains above 7 °C. In rare cases of extremely cold weather, producers may apply simple heating measures to sustain their production (Baytorun and Zaimoglu, 2018). Therefore, this temperature-based estimation models can be reliably employed in unheated greenhouses throughout the growing season in the Mediterranean region, with the exception of a few days.

The results revealed that all calibrated models exhibited a high level of accuracy in estimating the daily global solar radiation (R_s) using daily temperature data in a Mediterranean-type greenhouse. In terms of performance under various whitening applications, the BC, DC, and CH models displayed slightly better estimation sensitivities than the other models. Nevertheless, this finding does not necessarily indicate the unsuitability of HA and GO models for estimating R_s under greenhouse conditions. Notably, all calibrated models demonstrated high estimation performance and had similar performances, with negligible differences. For this reason, all calibrated models can be used in important greenhouse cultivation regions located between 36.5-37.5 ° N latitudes (Algeria, Greece, Italy, Spain, Türkiye, Tunisia).

The light transmissivity method is commonly used in specific regions to estimate indoor solar radiation (Fernández et al., 2010; Gallardo et al., 2016; Zhang et al., 2020). If data cannot be obtained from the solar radiation sensor for any reason, all the calibrated models can be used to estimate R_s. Indeed, in the present study, solar radiation values outside of a greenhouse could not be collected for a limited period owing to sensor failure.

5. CONCLUSIONS

The aim of current study was to calibrate and validate five different models used for estimating daily global solar radiation (R_s) under various whitening applications for Mediterranean type greenhouses. The results demonstrated that all calibrated models were effective in estimating the solar radiation inside the greenhouse. The method of estimating solar radiation (R_s) within the greenhouse using the light transmissivity coefficient showed slightly superior performance compared to the models calibrated with temperature data. Consequently, in situations where R_s data for outside the greenhouse are unavailable, any of the calibrated models can be used for R_s estimation. In this context, calibrated models serve as useful tools for regional farmers, consultants, and researchers.

SUPPLEMENTAL MATERIAL

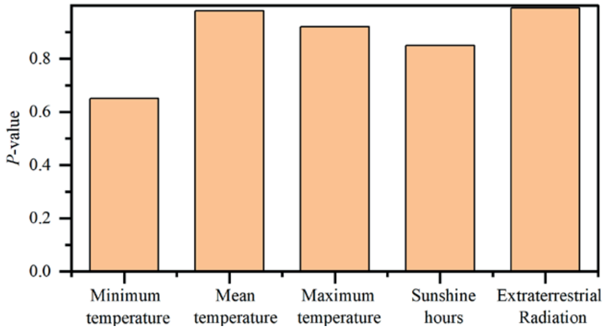

Figure S1. The *p* values of some climatic variables (minimum temperature, mean temperature, maximum temperature, sunshine hours, and extraterrestrial radiation) among the six Mediterranean greenhouse regions (Alger, Algeria; Almeria, Spain; Antalya, Türkiye; Bizerte, Tunisia; Kalamata, Greece; Siracusa, Italy).

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