TÜBİTAK

Turkish Journal of Agriculture and Forestry

Volume 50 | Number 1 Article 3

2-26-2026

Examining the effect of different polycarbonate greenhouse cover materials on tomatoyield and plant development with thermal imaging

CANDAN KORKMAZ

NEFİSE YASEMİN TEZCAN

Follow this and additional works at: https://journals.tubitak.gov.tr/agriculture

 Part of the Agriculture Commons, and the Forest Sciences Commons

Recommended Citation

KORKMAZ, C, & TEZCAN, N. Y (2026). Examining the effect of different polycarbonate greenhouse cover materials on tomatoyield and plant development with thermal imaging. *Turkish Journal of Agriculture and Forestry 50* (1): 13-31. https://doi.org/10.55730/1300-011X.3330



This work is licensed under a Creative Commons Attribution 4.0 International License.
This Research Article is brought to you for free and open access by TÜBİTAK Academic Journals. It has been accepted for inclusion in Turkish Journal of Agriculture and Forestry by an authorized editor of TÜBİTAK Academic Journals. For more information, please contact academic.publications@tubitak.gov.tr

TÜBİTAK

Turkish Journal of Agriculture and Forestry

http://journals.tubitak.gov.tr/agriculture/

Research Article

Turk J Agric For
(2026) 50: 13-31
doi:10.55730/1300-011X.3330
© Author

Examining the effect of different polycarbonate greenhouse cover materials on tomato yield and plant development with thermal imaging

Candan KORKMAZ[1,*], **Nefise Yasemin TEZCAN**[2]

[1]The Scientific and Technological Research Council of Türkiye, Ankara, Turkiye

[2]Department of Agricultural Structures and Irrigation, Faculty of Agriculture, Akdeniz University, Antalya, Turkiye

Received: 21.01.2025 • **Accepted/Published Online:** 18.07.2025 • **Final Version:** 26.02.2026

Abstract: In this study, the effects of different polycarbonate (PC) greenhouse covering materials on the environmental microclimate and plant growth were examined using three research greenhouses. Two types of PC covering materials were tested: the first greenhouse was covered with UV-additive PC (UV PC), the second greenhouse with UV+Infrared (IR) additive PC (UV+IR PC), and the third (control) greenhouse had UV-additive PC on the sidewalls and polyethylene (PE) covering material (UV PC+PE) on the roof. The measured fundamental parameters included total radiation transmittance, photosynthetically active radiation (PAR) transmittance, temperature, and relative humidity. Plant development was monitored and leaf temperatures were measured using a thermal camera at various points during the growing season. Tomatoes were cultivated in the greenhouses to evaluate the effects of the different covering materials on plant growth, development, yield, and fruit quality. Plant parameters assessed included height, stem diameter, leaf number, and yield, while fruit parameters analyzed were average fruit weight, diameter, soluble solids content (SSC), electrical conductivity (EC), pH of the fruit juice, and lycopene content. Additionally, plant canopy temperatures were monitored via a thermal camera. The initial total radiation transmittance values for the UV PC, UV+IR PC, and UV PC+PE were 49.4, 49.2, and 62.6%, respectively. By the end of the study, these values decreased by 25.1, 28.9, and 10.7%, respectively. Similarly, initial PAR transmittance values for the UV PC, UV+IR PC, and UV PC+PE were 54.7, 49.3, and 54.1%, respectively, with reductions of 27.2, 25.6, and 9.4%, respectively, observed at the end of the study. The highest total radiation and PAR transmittance throughout the study period were recorded in the PE-covered greenhouse. In terms of yield, the UV+IR PC greenhouse covering material produced the highest total yield across both growing seasons.

Key words: Thermal imaging, photosynthetically active radiation, radiation transmittance, environmental microclimate, polycarbonate

1. Introduction

The selection of greenhouse covering materials is influenced by various factors, with the primary ones being the type and amount of solar radiation, which have a direct impact on plant development. In addition, microclimatic factors such as air humidity and CO_2 concentration indirectly affect the choice of covering materials (Giacomelli et al., 1991). A key parameter to consider when selecting a material for greenhouse coverings is the material's thermal conductivity coefficient (W/m² K). Heating costs represent a significant portion of annual greenhouse operating expenses and materials with lower thermal conductivity can lead to substantial savings in heating costs (Çaylı et al., 2016). In recent years, PC materials, classified as rigid plastics, have gained popularity for use as greenhouse coverings as well as in a variety of other applications. Other criteria to consider when selecting greenhouse covering materials include total radiation transmissibility, long-wave radiation transmissibility, UV radiation transmissibility, ageing characteristics (time-dependent radiation transmissibility), condensation behavior on the inner surface relative to humidity, water vapor permeability, resistance to storms, hail and snowfall, mechanical properties, total heat transfer coefficient, chemical resistance, and manufacturing sizes/prices. Ideally, these materials should exhibit maximum transmissibility in the PAR spectrum and minimum transmissibility in the long-wavelength band (Choab et al., 2019).

Polycarbonate (PC) is a thermoplastic material known for its low specific gravity and high impact resistance. It also demonstrates a low condensation rate, excellent thermal insulation, heat stability, and oxidative stability. These properties make PC a highly valued commercial polymer, particularly because of its ease of processing. The use of polymeric materials, including PC, is steadily growing across various engineering disciplines, such as architecture, mechanical engineering, and agricultural

* Correspondence: candan.korkmaz@tubitak.gov.tr

Authors retain the copyright of their works. Upon acceptance, authors grant the journal a non-exclusive right of first publication and permission to distribute the article in all forms and media under the Creative Commons Attribution 4.0 International (CC BY 4.0) licence.

engineering (Fuina et al., 2019). Notably, PC is lightweight, easy to install, and capable of providing abundant natural light to indoor spaces. Its high thermal efficiency and ability to diffuse natural sunlight effectively make double-wall PC sheets a preferred choice for greenhouse coverings (Esen and Yuksel, 2014).

With the rise in urbanization and population density, challenges such as the reduction of water resources and arable land, erosion, food waste, and marine pollution have made expanding arable land to meet the growing population's food demands increasingly difficult. As a result, producers have turned to undercover cultivation methods to enhance productivity. Today, fruits and vegetables are valued not only for fulfilling nutritional needs but also for their rich content of vitamins, minerals, and antioxidants, which play a crucial role in protecting and improving health. Vegetables, in particular, exhibit protective and therapeutic effects on human health. Among the most widely cultivated and consumed vegetables globally are tomatoes. They are commonly consumed fresh or in processed forms, including ketchup, paste, sauces, and dried tomatoes. Additionally, products such as tomato juice, puree, and chopped tomatoes have become increasingly popular, further enhancing the significance of tomatoes over time.

Thermal imaging technology has proven to be highly effective in various agricultural applications, including plant physiology, irrigation planning, and yield prediction (Manickavasagan et al., 2005). Recent studies demonstrate the integration of multispectral cameras equipped with thermal imaging and environmental sensors for noninvasive precision agriculture analysis, effectively monitoring microclimatic parameters such as temperature, humidity, and CO_2 concentration (Scutelnic et al., 2024). Additionally, innovations in low-cost uncooled infrared cameras, enhanced by deep learning techniques, are expanding the accessibility and accuracy of thermal imaging in agricultural monitoring (Oz et al., 2025; Yun et al., 2024). For example, thermal cameras are utilized for preharvest assessments, land preparation (evaluating soil readiness for planting), irrigation management (developing irrigation models and measuring stomatal conductance), yield prediction (based on plant cover and ambient temperature relationships), harvesting (fruit detection and ripeness determination), and greenhouse monitoring (tracking growth stages and identifying heat losses). Moreover, they are invaluable tools for disease and pest detection, agricultural mechanization, and food quality analysis (Çamoğlu and Genç, 2013; Çaylı et al., 2016; Mercan et al., 2016; Smith et al., 1985; Stajnko et al., 2004).

While the use of thermal cameras and other remote sensing technologies in agriculture has been extensively studied in areas such as plant-soil-water interactions and plant disease detection, scientific research on the use of PC materials as greenhouse coverings in Türkiye remains limited. This study investigates the effects of PC materials with low specific gravity, reduced condensation rates, and superior thermal insulation properties—specifically UV PC and UV+IR PC as well as PE greenhouse coverings produced using CO-EX (multilayer) technology. The study evaluates their impact on the environmental microclimate, including total radiation and PAR transmissibility, interior greenhouse temperatures, and relative humidity, alongside plant development. Thermal cameras were employed to analyze these effects. The proposed PC and PE greenhouse coverings are particularly suitable for temperate and cold climates where thermal insulation and condensation control are critical to reducing heating costs and improving plant growth. Their effectiveness in hot climates, where cooling is more important than heating, may be limited and requires further study.

2. Materials and methods

2.1. Research area, characteristics of greenhouses used in the study and plant material

The study was conducted in three model PC greenhouses located at the Research and Application Area of the Faculty of Agriculture, Akdeniz University. The experimental area is located at 36°53′15″ north latitude and 30°38′53″ east longitude, with an average altitude of 54 m. The research area has a typical Mediterranean climate: hot, dry summers and mild, rainy winters. Each greenhouse had a ground area of approximately 28 m^2, with dimensions of 4.0 m in width, 7.0 m in length, 2.5 m in sidewall height and a total ridge height of 3.5 m. The long axes of the greenhouses were oriented east–west. Two of the research greenhouses featured a gable roof design: one covered with 8 mm UV-additive PC material and the other with 8 mm UV+IR-additive PC material. The third greenhouse had a gothic roof design, with the sidewalls covered in 8 mm UV-additive PC and the roof covered with single-layer PE material. This setup allowed for the investigation of the effects of PC material on the greenhouse frame structure and its selective use on sidewalls. The polycarbonate sheets used in this study were 8 mm thick, double-walled, transparent in color, and included antifog additives. These panels were designed to provide a diffuser effect and had high mechanical durability. The thermal conductivity of the PC sheets was 0.25 W/m K, and their light transmittance was approximately 76%. The IR-additive PC panel used in one of the greenhouses had identical physical and optical specifications.

No heating system was used during the study, as the PC covering materials provided sufficient insulation to maintain optimal internal temperatures. The model greenhouses were equipped solely with roof ventilation systems. The ratio of roof ventilation openings

to greenhouse floor area was approximately 26%. Additionally, no shading strategy was applied during the experiment, as the study was designed to investigate the direct effects of different cover materials under natural solar radiation conditions.

Measurements of temperature, humidity, radiation, and PAR began in February 2020 and continued through August 2021. Tomato (*Solanum lycopersicum* L.) cultivation was conducted during the spring growing seasons (March to June) of both 2019–2020 and 2020–2021 to evaluate the effects of different greenhouse cover materials on plant development, yield, and fruit quality parameters.

The experimental study was conducted over two separate production cycles. The first cycle began in October 2020 and ended in April 2021, followed by a short fallow period without cultivation. During this fallow phase, although no plant-based measurements were carried out, environmental parameters (temperature, humidity, radiation, and PAR) continued to be recorded. The second production cycle commenced in June 2021 and concluded in October 2021. This structure allowed for the analysis of both seasonal effects and the temporal performance of different covering materials.

The "Seyran F1" tomato variety was planted in a single row, with 40 cm spacing between plants and 100 cm between rows. During both years of the study, all greenhouses received identical irrigation and fertilization programs. Irrigation was conducted via a drip irrigation system with a discharge rate of 4 L/h at an operating pressure of 1 atm, based on tensiometer readings. The average irrigation interval during the growing season was 2 days, with durations of 15–20 min per session. Fertilization during the growing period included chemical fertilizers containing N (ammonium nitrogen, nitrate nitrogen, urea nitrogen), P_2O_5 (phosphorus pentoxide), K_2O (potassium oxide), MgO (magnesium oxide), and SO_3 (sulfur trioxide). Microelements applied included Fe (iron), Zn (zinc), B (boron), Mn (manganese), and Cu (copper). In tomato plants, apical pruning (topping) was performed after the formation of six fruit clusters in order to cease vegetative growth and allow the plant to direct energy toward fruit development. Until the formation of the sixth cluster, plants were vertically trained up to approximately 1.80 m.

To assess plant responses to varying radiation values, six observation plants were selected from each greenhouse. These plants were monitored from transplanting to harvest, with measurements taken every 15 days, including plant height (cm), stem diameter (mm), and leaf number (leaves/plant). At harvest, additional parameters were evaluated, such as yield (t/ha) and several fruit quality metrics, including fruit size (classified by quality), average fruit weight (g), fruit diameter (mm), soluble solids content (SSC) (%), electrical conductivity (EC) (dS/m) and pH of fruit juice, and lycopene content (mg/kg).

2.2. Devices used for total radiation and PAR measurements in greenhouse cover materials

In this study, the total radiation transmittance of the greenhouse covering materials was measured using four pyranometers (Kipp & Zonen, Delft, Netherlands) sensitive to wavelengths between 300 and 2800 nm. Similarly, PAR transmittance was measured using four quantum sensors from (Kipp & Zonen; Delta-T Devices, Cambridge, UK) sensitive to wavelengths in the range of 400 to 700 nm. To eliminate shading effects from structural elements, three sensors were placed inside the greenhouses, while the fourth was positioned in the external environment.

The pyranometers and quantum sensors were positioned on stands at a height of 2.0 m, ensuring that they were not influenced by shading from the greenhouse roof elements and were placed in the central region, with the stands leveled at soil height to maintain horizontal alignment (Kittas et al., 2006). The pyranometers used in the study had a sensitivity ranging from 5 to 20 μV/W/m². The quantum sensors had a sensitivity range of 4 to 10 μV/μmol/m²/s.

The total radiation and PAR transmittance values were calculated using the following equations (Kittas et al., 1999):

$$Tt = \left(\frac{Ti}{To}\right) x100,$$

where T_t is total radiation transmittance of the greenhouse (%), T_i is total radiation measured inside the greenhouse (W/m²), and T_o is total radiation measured outside the greenhouse (W/m²).

$$Tp = \left(\frac{Pi}{Po}\right) x100,$$

where T_p is PAR transmittance of the greenhouse (%), P_i is PAR measured inside the greenhouse (mmol/m²s), P_o is PAR measured outside the greenhouse (mmol/m²s).

Measurements were conducted under clear (cloudless) sky conditions, within the time frame of 06:00 to 18:00 (Geoola et al., 1998; Geoola et al., 2004; Kittas et al., 2006). Five representative clear days per month, reflecting the monthly average, were selected for analysis based on sensor reliability. The average transmittance values from these days were considered as the monthly transmittance values (Cemek et al., 2006; Emekli et al., 2016). Time-dependent losses in total radiation and PAR transmittance of the greenhouse covering materials were calculated using the following equation (Emekli et al., 2016; Geoola et al., 1994; Geoola et al., 2004):

$$\text{Loss in transmittance} = \left(\frac{\text{Tnew} - \text{T}}{Tnew}\right) \times 100,$$

where T_{new} is radiation transmittance of the new covering material (%), T is radiation transmittance of the covering material after a specific period of time (%).

2.3. Devices used for temperature and relative humidity measurements

In this study, temperature and relative humidity measurements were conducted using four Testo-brand devices (Testo SE & Co. KGaA, Titisee-Neustadt, Germany) equipped with programmable and data logging capabilities. These devices have a temperature measurement range of −10 to 50 °C and can measure relative humidity levels from 0% to 100%. Three devices were placed inside the greenhouses, while the fourth was positioned in the external environment.

The devices used for temperature and relative humidity measurements were positioned at a height of 1.5 m on stands with a height of 2.0 m, ensuring they were unaffected by shading from the greenhouse roof components. The stands were centrally located within the greenhouse and horizontally leveled at soil level, following the recommendations of Barroso et al. (1999).

2.4. Devices used for thermal imaging

In this study, infrared thermal images were captured using a FLIR E53 thermal camera (Teledyne FLIR, Wilsonville, OR, USA). The temperature and relative humidity inside the greenhouse were recorded at the beginning and end of each thermal measurement session using data loggers positioned at a height of 1 m. This height was carefully selected to ensure that the material and canopy temperatures visible in the camera were not influenced by micrometeorological conditions (Thomson et al., 2012). All thermal images were uniformly captured from a distance of 1 m. At the time of image capture, temperature, relative humidity, emissivity value, and distance were input into the thermal camera to ensure accurate measurements. The emissivity value was set to 0.95 for both plant surfaces (Jones et al., 2002) and material surfaces (Meyers and Chawla, 2009). Measurement timing was determined based on established guidelines. In accordance with Allen et al. (2005), the period between 10:45 and 11:15 was used for calculating daily evaporation through instantaneous surface energy balance, using the crop coefficient approach. For plant surface temperature, Ehrler et al. (1978) and Jackson et al. (1977) recommended the standard measurement period between 13:00 and 14:00. To capture thermal images of material and canopy temperatures, considering the angle and intensity of sunlight, the period between 10:00 and 14:00 was selected, as this was when surface temperatures were highest (Çamoğlu and Genç, 2013; Tüne, 2016). In this study, high-resolution thermal images, acquired with three repetitions, were analyzed using FLIR Tools software (Teledyne FLIR). During the analysis, edge effects were removed from the thermal images and thermal temperature values were extracted for the remaining areas. This process ensured a homogeneous image across all thermal images analyzed, allowing for accurate surface temperature determination.

2.5. Statistical analysis

Descriptive statistics were calculated for the variables used in the study. The assumption of normality was tested using the Shapiro–Wilk test. Changes in the variables over time and across different types of covering materials were analyzed using repeated measures analysis of variance (rANOVA). When significant differences were detected, pairwise comparisons were conducted with Bonferroni correction. One-way analysis of variance (ANOVA) was applied to examine differences in EC, pH, soluble dry matter, and lycopene parameters among the varieties. For significant results, pairwise comparisons were performed using Duncan's test. Relationships between numerical data were evaluated using the Pearson correlation test.

All statistical analyses were conducted using SPSS version 23.0 (IBM, Armonk, NY, USA), with a significant level of $p < 0.05$, unless otherwise specified.

3. Results

The research findings obtained over the 19-month study period were evaluated under two main headings: (1) the temporal variation in the environmental microclimate associated with different greenhouse covering materials and (2) the effects of radiation transmissibility of these materials on plant development. For consistency, the starting month of the measurements (February 2020) was designated as the first month.

3.1. Temporal variation in total radiation transmissibility

The total radiation values for the greenhouse covering materials ranged as follows: 67.6–277.5 W/m² for the UV PC-coated material, 67.0–277.6 W/m² for the UV+IR PC-coated material, and 95.9–412 W/m² for the UV PC+PE-coated material. In the external environment during the same months, the total radiation values ranged from 160.5 to 733.6 W/m². The initial total radiation transmissibility values for the greenhouse covering materials were determined to be 49.4% for UV PC, 49.2% for UV+IR PC, and 62.6% for UV PC+PE (Figure 1). Upon further examination, it was observed that the transmissibility of the covering material in the UV PC+PE greenhouse (62.6%) was higher than that of the UV PC and UV+IR PC materials. This difference was attributed to the material's thickness: the UV PC+PE greenhouse's roof was 0.18 mm thick (PE), whereas the UV PC and UV+IR PC materials were 8 mm thick. As a result, solar radiation passing through the PE material traveled a much shorter distance (0.18 mm) compared to the PC materials (8 mm, approximately 44.4 times longer). At the end of the 19-month study period, the total radiation transmissibility of the greenhouse covering materials decreased by 25.1, 28.9, and 10.7% for the UV PC, UV+IR PC, and UV PC+PE greenhouses, respectively. These reductions were

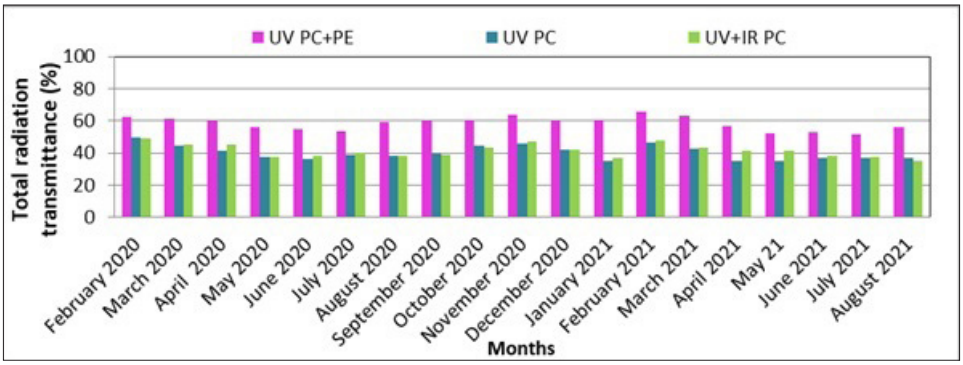

Figure 1. Time-dependent total radiation transmittance (%) of different greenhouse cover materials.

attributed to environmental conditions and material aging. The greater loss of transmissibility in the UV PC and UV+IR PC materials compared to the PE material was attributed to their higher sensitivity to environmental factors. Throughout the study period, it was determined that the UV PC+PE greenhouse covering material exhibited a higher total radiation value compared to the other greenhouse covering materials used in the study. Analyzing the total radiation values, it was found that the UV PC+PE covering material recorded the highest value, followed by the UV+IR PC material, while the UV PC material demonstrated the lowest total radiation value.

Figure 2 illustrates the changes in the total radiation transmissibility of different greenhouse covering materials depending on the time of day for typical summer days under both sunny and cloudy sky conditions. As seen in Figure 2, the transmissibility of the greenhouse covering materials varies throughout the day. Under clear sky conditions, the radiation transmissibility curve increases steadily from the morning hours, reaching its peak around midday (12:00) and then decreases towards the evening. During the summer months, solar energy is present in the external environment and greenhouses even during these times. Under cloudy sky conditions, the radiation transmissibility curve exhibits a sinusoidal pattern, reflecting fluctuations caused by varying cloud cover.

3.2. Temporal variation of photosynthetically active radiation (PAR) transmissibility

Throughout the study period, the photosynthetically active radiation (PAR) values for the greenhouse covering materials were as follows: 92.5–288.7 μmol/m²/s for the UV PC material, 87.5–266.0 μmol/m²/s for the UV+IR PC material, and 104.7–326.4 μmol/m²/s for the UV PC+PE. In comparison, the PAR values in the external environment ranged from 196.5 to 660.3 μmol/m²/s during the same period. Throughout the study period, the highest PAR value was recorded under the UV PC+PE greenhouse covering material, compared to the other covering materials used in the study. The initial PAR transmissibility values were determined to be 54.7% for UV PC, 49.3% for UV+IR PC, and 54.1% for the UV PC+PE greenhouse material (Figure 3). Due to the accumulation of dust and pollution on the external surfaces of the coverings, the PAR transmissibility of the UV PC and UV+IR PC materials began to decrease in the second month of the study, while the UV PC+PE material experienced a decline starting in the third month. By the seventh month, PAR transmissibility had decreased by 24.3% for the UV PC material, 20.9% for the UV+IR PC material, and 11.8% for the UV PC+PE material. At the end of the study period (19 months), these values further declined by 27.2%, 25.6%, and 9.4%, respectively, due to environmental factors and material aging. Throughout all the months examined, the UV PC+PE greenhouse covering material consistently exhibited higher PAR values compared to the UV PC and UV+IR PC materials, mirroring its superior performance in total radiation values. The temporal variation in PAR transmissibility under different greenhouse covering materials, based on time of day for typical summer days, under both sunny and cloudy sky conditions, is presented in Figure 4.

3.3. Internal and external temperature of the greenhouse under different covering materials

Throughout the study period, the average internal temperature values of the greenhouses ranged from 16.5 to 39.5 °C in the greenhouse covered with UV PC, from 16.4 to 39 °C in the greenhouse covered with UV+IR PC, and from 15.5 to 38.8 °C in the greenhouse covered with UV PC+PE. The average external temperature ranged from 10.9 to 32.4 °C during the studied months. Considering the cultivation under different greenhouse covering materials, it was found that the average internal temperature values were above 17 °C for all months except the 12th month, and the minimum, maximum, and average internal temperature values were in parallel (Figure 3). In the 12th month of the study, it can be said that heating was required for the greenhouses in the region. Furthermore, the highest average internal temperature values were recorded in the 7th month for the greenhouses with UV PC+PE and

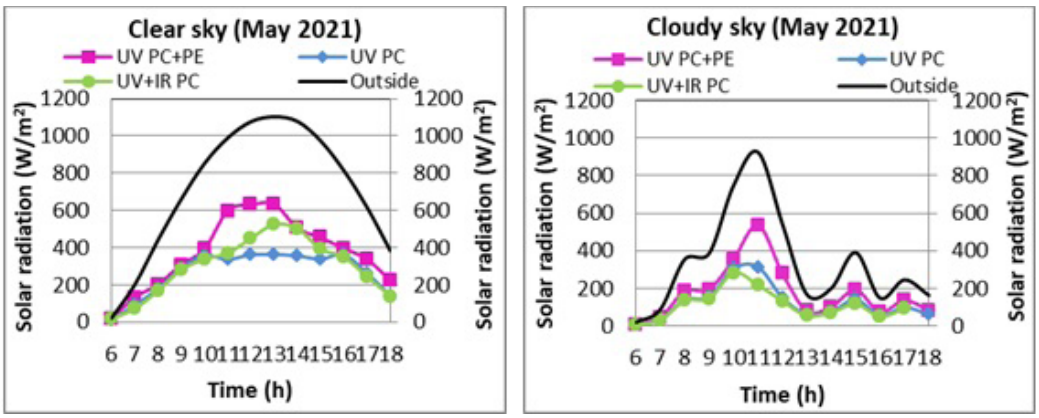

Figure 2. Temporal variation of the daily hourly average total radiation transmissibility of greenhouse covering materials on a typical summer day.

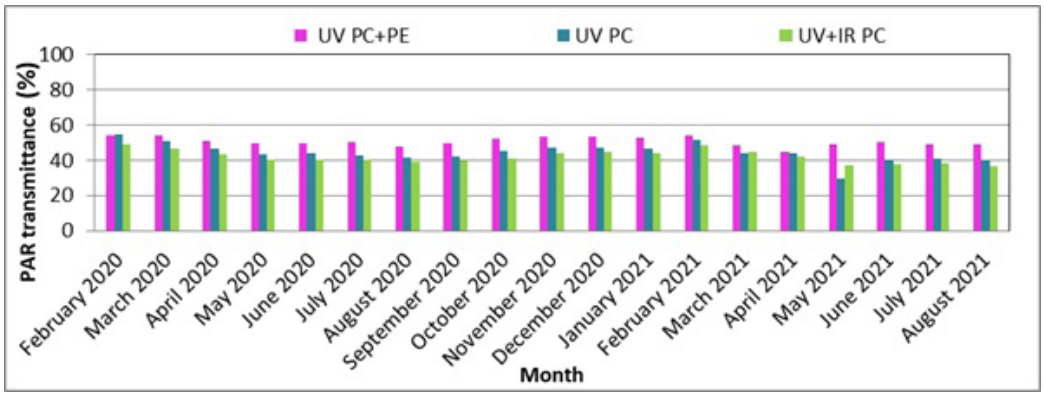

Figure 3. Time-dependent PAR transmittance (%) of different greenhouse covering materials.

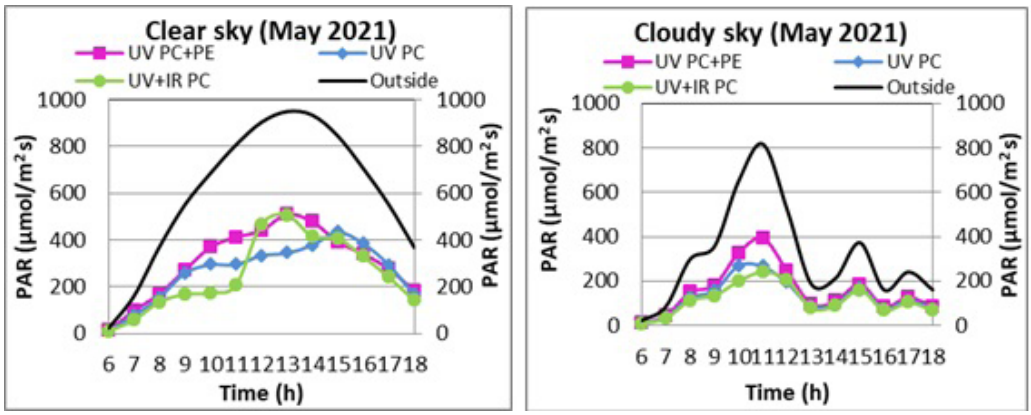

Figure 4. Temporal variation of daily hourly average PAR transmissibility of greenhouse covering materials on a typical summer day.

UV+IR PC covering materials and in the 19th month for the greenhouse covered with UV PC.

As shown in Figure 5, the internal temperature of the greenhouses was consistently higher than the external temperature across all months studied. In the greenhouses covered with UV PC and UV+IR PC materials, the average internal temperature was measured to be up to 10.5 °C higher than the external temperature, aligning with findings reported in the literature. The greenhouse covered with UV+IR PC material demonstrated higher and more

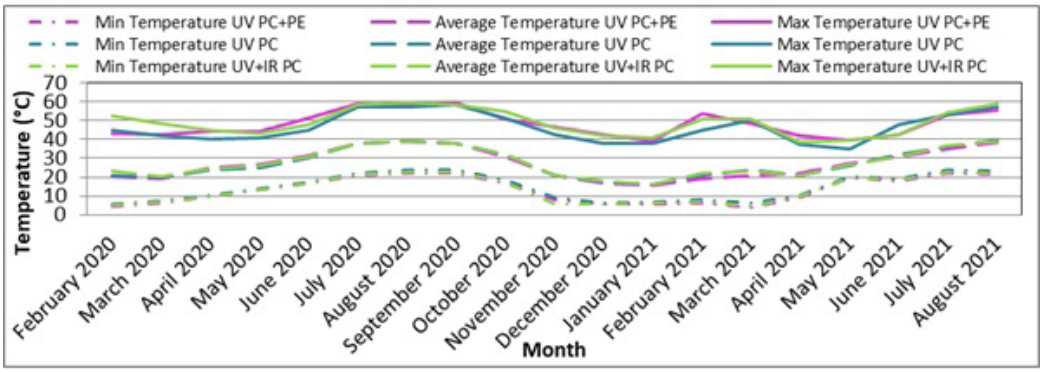

Figure 5. Minimum, maximum, and average internal temperature values of the greenhouse environment for the months studied in the research greenhouses.

stable internal temperature values compared with the other research greenhouses (UV PC and UV PC+PE), based on the studied months and times of the day.

In order to evaluate the effects of greenhouse covering materials on the internal microclimate from a seasonal perspective, the monthly average temperatures recorded during the 19-month experimental period were analyzed to identify the coldest and hottest months. Accordingly, the hottest month was determined as July 2021 (the 18th month of the study), while the coldest month was February 2020 (the 1st month of the study). Representative days were then selected from these months—16 July 2021, and 26 February 2020—for detailed analysis. To ensure a more meaningful comparison, not only the daytime hours (06:00–18:00), when solar radiation is typically higher, but the full 24-hour period was taken into account. This approach enabled a comprehensive comparison of the greenhouse microclimate under contrasting seasonal conditions.

During the hot day (16 July 2021), solar radiation (300–2800 nm) values fluctuated between 0 and 1095 W/m² outside, whereas inside they varied from 0 to 388 W/m² under UV PC, 0 to 500 W/m² under UV+IR PC, and 0 to 648.9 W/m² under UV PC+PE, respectively (Figure 6). The PAR radiation (400–700 nm) levels ranged from 0 to 926 µmol/m²s outdoors, and inside the greenhouses they ranged from 0 to 362 µmol/m²s under UV PC, 0 to 435.87 µmol/m²s under UV+IR PC, and 0 to 503.33 µmol/m²s under UV PC+PE, respectively (Figure 7). The outdoor air temperature ranged from 25.13 to 40.77 °C, whereas these values inside the greenhouses were ranged from 29.18 to 53.13 °C under UV PC, 28.2 to 54.3 °C under UV+IR PC, and 27.15 to 52.07 °C under UV PC+PE, respectively. Relative humidity varied ranged from 17.38 to 62.9% outdoors, while inside the greenhouses it ranged from 19.8 to 61.3% under UV PC, 14.02 to 63.0% under UV+IR PC, and 17.03 to 72.9% under UV PC+PE, respectively (Figure 8). On this day, the average solar radiation was 741.46 W/m² (between 06:00 and 18:00), while indoor averages were 262.12 W/m² under UV PC, 271.9 W/m² under UV+IR PC, and 368.2 W/m² under UV PC+PE. The average PAR values were 582.47 µmol/m²s outdoors, 243.65 µmol/m²s under UV PC, 233.22 µmol/m²s under UV+IR PC, and 287.43 µmol/m²s under UV PC+PE (between 06:00 and 18:00). The average outdoor air temperature was 32.1 °C and the average relative humidity was 32.7% (24-h averages). The average internal air temperatures were 38.82 °C under UV PC, 39.7 °C under UV+IR PC, and 38.69 °C under UV PC+PE. The average relative humidity values inside the greenhouses were 37.1% under UV PC, 33.47% under UV+IR PC, and 38.2% under UV PC+PE.

During the cold day (26 February 2020), solar radiation (300–2800 nm) fluctuated between 0 and 862.93 W/m² outside, whereas inside it ranged from 0 to 506.4 W/m² under UV PC, 0 to 455.8 W/m² under UV+IR PC, and 0 to 565.5 W/m² under UV PC+PE, respectively (Figure 9). Similarly, the PAR radiation (400–700 nm) values outdoors varied between 0 and 781.6 µmol/m²s, while indoor values ranged from 0 to 481.3 µmol/m²s under UV PC, 0 to 393.5 µmol/m²s under UV+IR PC, and 0 to 410.6 µmol/m²s under UV PC+PE, respectively (Figure 10). The outdoor air temperature ranged from 4.8 to 19.0 °C, whereas inside the greenhouses it ranged from 6.3 to 45.0 °C under UV PC, 5.5 to 51.0 °C under UV+IR PC, and 5.2 to 41.5 °C under UV PC+PE, respectively. Relative humidity varied between 37.1 and 84.3% outdoors, while indoor values ranged from 17.8 to 74.1% under UV PC, 21.6 to 77.6% under UV+IR PC, and 30.2 to 99.9% under UV PC+PE, respectively (Figure 11). On this day, the average solar radiation was 444.1 W/m² (between 06:00 and 18:00), while indoor averages were 216.8 W/m² under UV PC, 218.7 W/m² under UV+IR PC, and 255.9 W/m² under UV PC+PE. The average PAR values were 407.4 µmol/m²s outdoors, 220.72 µmol/m²s under UV PC, 189.09 µmol/m²s under UV+IR PC, and 204.67 µmol/m²s under UV PC+PE (between 06:00 and 18:00). The average outdoor

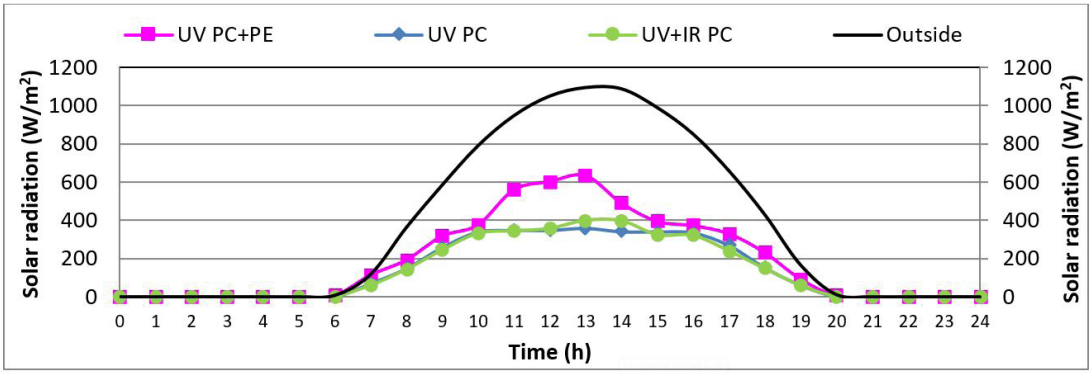

Figure 6. Temporal variation of the daily hourly average total radiation transmissibility of greenhouse covering materials on the hottest summer day, 16 July 2021.

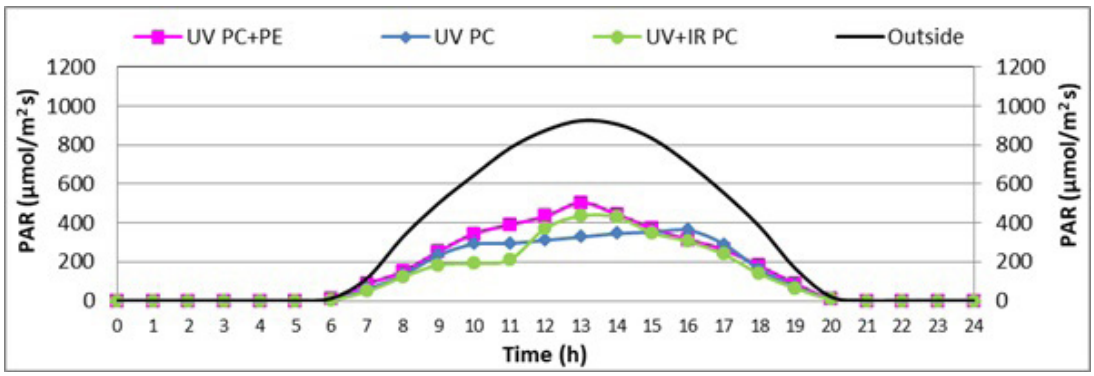

Figure 7. Temporal variation of the daily hourly average PAR transmissibility of greenhouse covering materials on the hottest summer day, 16 July 2021.

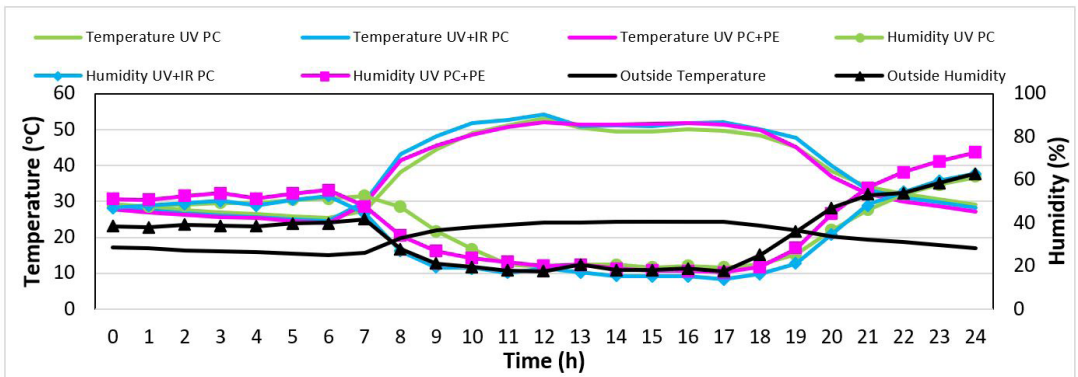

Figure 8. Time-dependent variation of the daily hourly average temperature and humidity values of greenhouse cover materials on the hottest summer day, 16 July 2021.

air temperature was 11.9 °C and the average relative humidity was 64.9% (24-h averages). The average internal air temperatures were 21.7 °C under UV PC, 23.7 °C under UV+IR PC, and 20.3 °C under UV PC+PE. The average relative humidity values inside the greenhouses were 50.8% under UV PC, 52.1% under UV+IR PC, and 71.0% under UV PC+PE.

The analysis revealed that, on the cold day (26 February 2020), indoor temperatures were low, humidity levels were high, and solar radiation values were minimal (Figures 9 and 11). Conversely, on the hot day (16 July 2021), solar radiation peaked, resulting in increased temperatures and reduced humidity inside the greenhouse (Figures 6 and 8). These patterns, supported by the corresponding graphs,

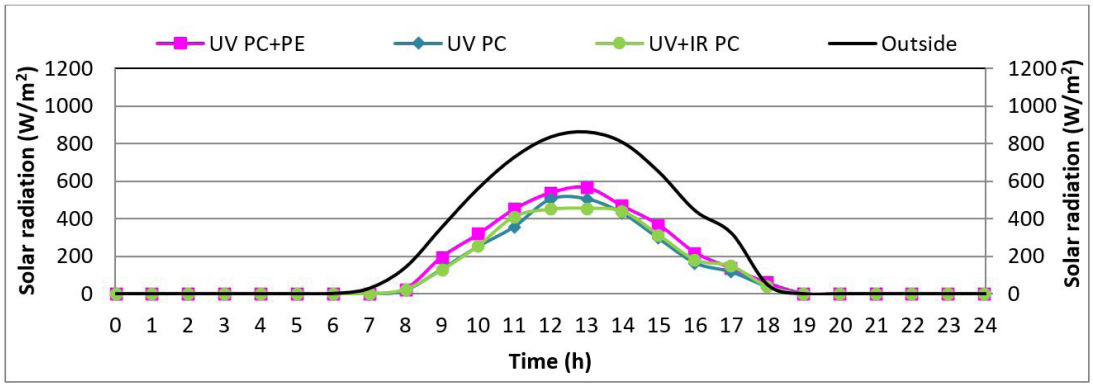

Figure 9. Temporal variation of the daily hourly average total radiation transmissibility of greenhouse covering materials on the coldest day, 26 February 2020.

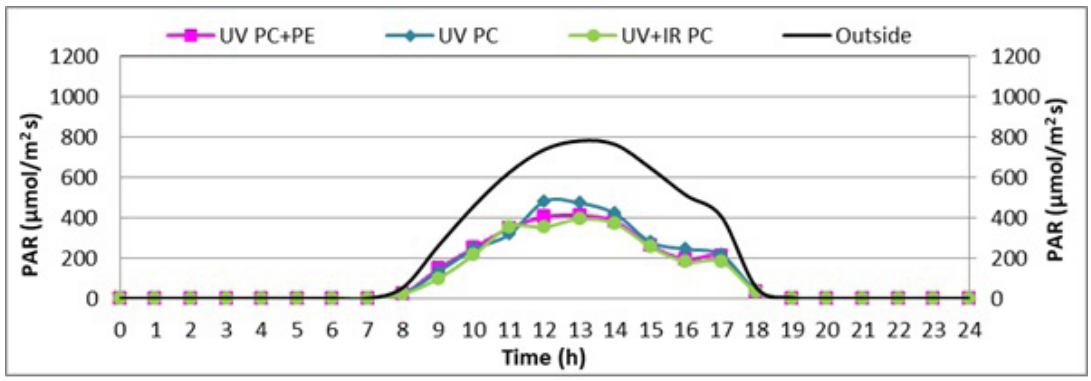

Figure 10. Temporal variation of the daily hourly average PAR transmissibility of greenhouse covering materials on the coldest day, 26 February 2020.

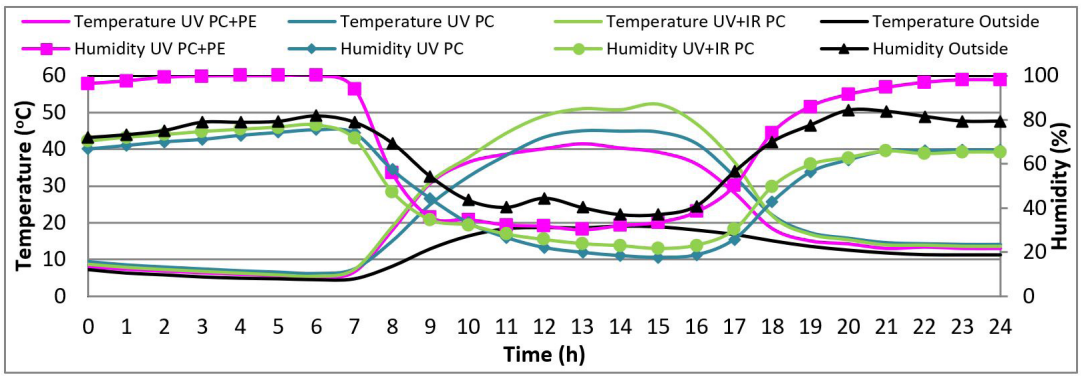

Figure 11. Time-dependent variation of the daily hourly average temperature and humidity values of greenhouse cover materials on the coldest day, 26 February 2020.

clearly demonstrate how different greenhouse covering materials respond to seasonal changes and influence internal environmental conditions.

3.4. Internal and external relative humidity values under different greenhouse covering materials

Throughout the 19-month study period, the average internal relative humidity values ranged from 27.9% to 91.3% in the greenhouse covered with UV PC material, 28.5% to 79.2% in the greenhouse covered with UV+IR PC material, and 32.9% to 82.5% in the greenhouse with UV PC+PE material. Among the studied months, the lowest average internal relative humidity values for all three greenhouse covering materials were observed in the 19th month, while the highest values were recorded in the

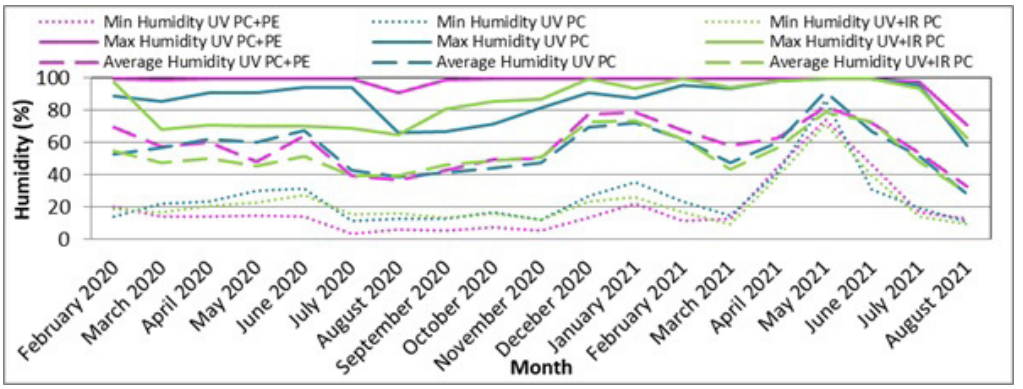

Figure 12. The minimum, maximum, and average relative humidity values of the indoor environment in the research greenhouses for the months studied.

16th month. During the same period, the external average relative humidity values ranged from 36.3% to 90.9% (Figure 12).

In this study, days representing the summer season were selected to evaluate UV PC, UV+IR PC, and UV PC+PE greenhouse cover materials and the time-dependent variations of indoor temperature and relative humidity values under clear sky conditions are presented in Figure 13.

3.5. Monitoring environmental conditions inside the greenhouse with a thermal camera

Canopy and roof temperatures were monitored using a thermal camera in greenhouses covered with three different materials.

3.5.1. Canopy temperatures

Canopy temperatures measured with a thermal camera during the plant growth period (March–June) in both years (2020–2021) of the study changed as follows. For the UV PC+PE greenhouse covering material, canopy temperatures ranged from 34.7 to 43.5 °C in the first year and 21.1 to 26.3 °C in the second year. For the UV PC greenhouse covering material, canopy temperatures ranged from 36.1 to 39.1 °C in the first year and 20.7 to 29.1 °C in the second year. For the UV+IR PC greenhouse covering material, canopy temperatures ranged from 36.8 to 40.4 °C in the first year and 19.4 to 31.8 °C in the second year. Variance analysis of the canopy temperatures obtained under different covering materials during both growing years revealed no statistically significant differences ($p < 0.05$). Additionally, a Pearson correlation test was conducted to assess the relationship between canopy temperature and outside temperature on the measurement days. The results indicated a strong correlation between canopy temperature and outside temperature during both growing years (Figures 14 and 15).

3.5.2. Roof temperatures

Roof temperatures measured with a thermal camera during the study period (February 2020–August 2021) changed as follows. For the UV PC+PE greenhouse covering material, roof temperatures ranged from 10.5 to 38.9 °C. For the UV PC greenhouse covering material, roof temperatures ranged from 21.0 to 51.8 °C. For the UV+IR PC greenhouse covering material, roof temperatures ranged from 23.7 to 59.0 °C. The lowest roof temperatures for all three greenhouses were recorded in the 13th month of the study (February 2021), while the highest temperatures were observed in the 18th month (July 2021).

Variance analysis of the roof temperatures obtained under different covering materials during the study period revealed statistically significant differences ($p < 0.05$). Additionally, a Pearson correlation test was conducted to assess the relationship between roof temperature and outside temperature on the measurement days. The results showed a strong correlation between roof temperature and outside temperature (Figure 16).

3.6. Effect of different greenhouse covering materials' radiation transmittance on plant growth

The effects of different greenhouse covering materials on various plant growth parameters, yield, and fruit quality parameters were examined under the assumption that irrigation, fertilization, and cultural practices remained constant. The results are summarized sequentially in Table. The variance analysis results for tomato plant heights under different covering materials showed statistically significant differences at the end of both study years. According to the Duncan's test results, the average plant heights for tomatoes grown in greenhouses covered with UV PC, UV+IR PC, and UV PC+PE materials were as follows: 80.0, 83.1, and 77.8 cm, respectively, in the first year and 84.7, 89.3, and 82.5 cm in the second year. The effect of different greenhouse covering materials on tomato plant stem diameters was statistically insignificant

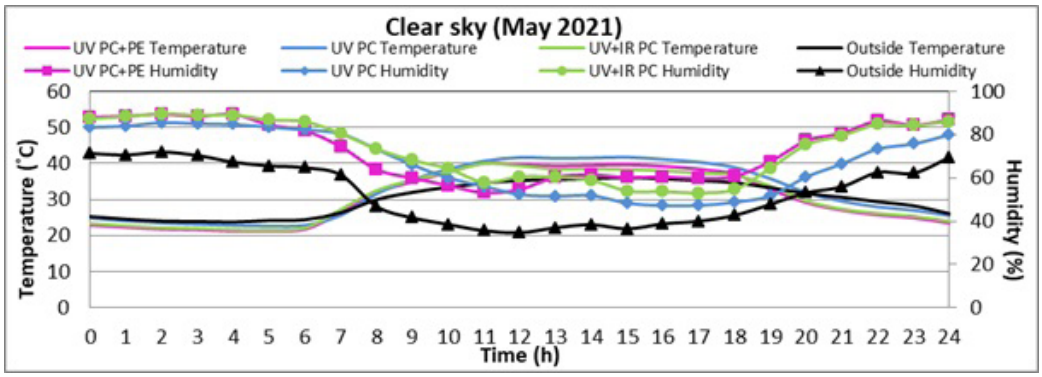

Figure 13. Time-dependent variation of the daily hourly average temperature and humidity values of greenhouse cover materials on a typical summer day.

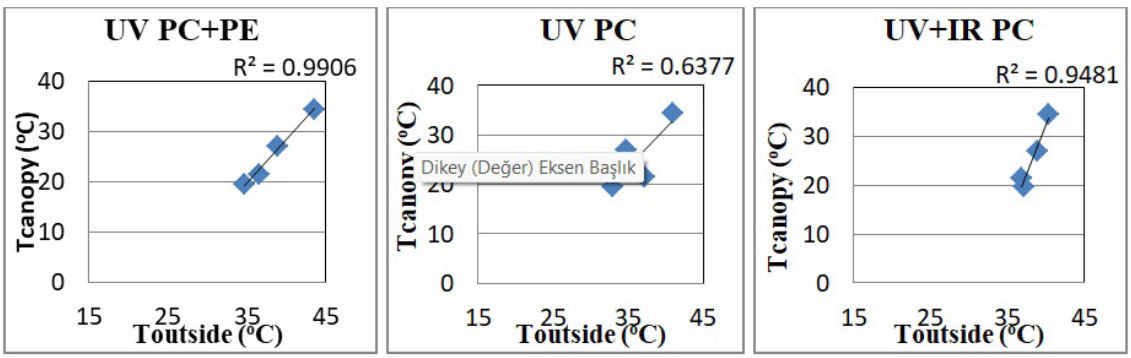

Figure 14. The relationship between the canopy temperature values obtained with the thermal camera and the outside temperature values in the research greenhouses during the first year.

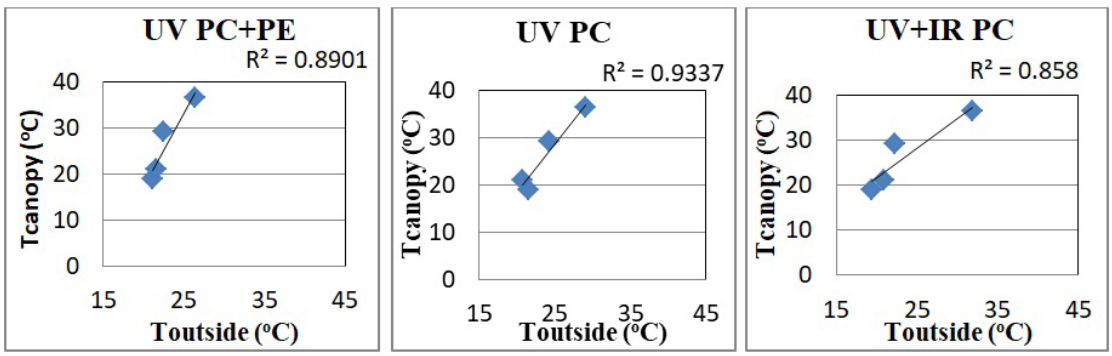

Figure 15. The relationship between the canopy temperature values obtained with the thermal camera and the outside temperature values in the research greenhouses during the second year.

in the first year but significant in the second year. The Duncan's test results for stem diameters measured on day 70 of the study were as follows: in the first year, 10.85, 11.83, and 11.01 mm, respectively, and in the second year, 11.07, 11.92, and 11.15 mm for UV PC, UV+IR PC, and UV PC+PE materials (Table). The effect of different greenhouse covering materials on the number of tomato leaves was also statistically insignificant in the first year but significant in the second year. The average number of leaves for tomato plants grown under UV PC, UV+IR PC, and UV PC+PE materials was as follows: in the first year, 17.50, 17.00, and 16.58 leaves/plant, and in the second year, 17.47, 17.97, and 16.61 leaves/plant. Yield results under different covering materials were statistically significant in both study years. The total yields for the UV PC, UV+IR PC, and UV PC+PE greenhouses were 102.0, 103.0, and

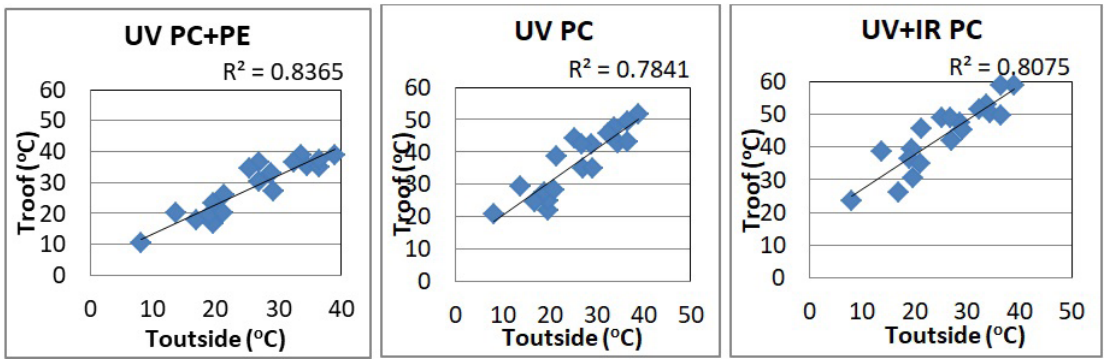

Figure 16. Relationship between roof temperatures obtained with the thermal camera and outside temperatures for the measured months in the research greenhouses.

Table. Effect of different greenhouse covering materials' radiation transmittance on plant growth.

Parameter	Year	Greenhouse covering material			p > F	*Mean*
		UV PC+PE	UV PC	UV+IR PC		
Plant height (cm)	1	*77.77 ± 0.972b*£	*80.02 ± 0.972b*	*83.08 ± 0.972a*	***	*80.43*
	2	*82.50 ± 3.47c*£	*84.67 ± 3.47b*	*89.31 ± 3.47a*	***	*85.49*
Stem diameter (mm)	1	*8.16 ± 0.028a*£	*8.16 ± 0.028a*	*8.26 ± 0.028a*	ns.	*8.19*
	2	*8.18 ± 0.067b*£	*8.21 ± 0.067b*	*8.31 ± 0.067a*	***	*8.23*
Yield (t/ha)	1	*74.4c*£	*102.0b*	*133.0a*	***	*103.1*
	2	*69.8c*£	*97.1b*	*118.4a*	***	*95.1*
Number of leaves (leaves/plant)	1	*16.58 ± 0.281a*£	*17.50 ± 0.281a*	*17.00 ± 0.281a*	ns.	*17.03*
	2	*16.61 ± 0.688b*£	*17.47 ± 0.688a*	*17.97 ± 0.688a*	***	*17.35*
Soluble solids content (SSC)	1	*5.0%a*£	*4.7%a*	*4.8%a*	ns.	*4.83*
	2	*5.2%a*£	*4.8%b*	*4.7%b*	***	*4.90*
EC	1	*2.8b*£	*3.3a*	*2.7b*	***	*2.93*
	2	*2.8b*£	*3.4a*	*2.7c*	***	*2.97*
pH	1	*4.42a*£	*4.39a*	*4.42a*	ns.	*4.41*
	2	*4.44a*£	*4.38b*	*4.42a*	***	*4.41*
Fruit diameter (mm)	1	*49.7b*£	*51.5b*	*65.4a*	***	*55.53*
	2	*49.7b*£	*51.7b*	*65.2a*	***	*55.53*
Average fruit weight (g)	1	*95.9b*£	*99.5b*	*129.8a*	***	*108.40*
	2	*90.1b*£	*94.7b*	*115.6a*	***	*100.13*
Lycopene content	1	*92.9b*£	*108.2a*	*105.9a*	***	*102.33*
	2	*76.1b*£	*91.9a*	*94.3a*	***	*87.43*

ŧ: The section in italics represents the average of six plants for each value.
£: The section in italics indicates the comparison of means (horizontally across rows) at a 5% significance level according to Duncan's test. *Different letters indicate statistically significant differences ($p < 0.05$).
***: Significant at the 0.5% probability level. ns: statistically nonsignificant.

74.4 t/ha, respectively, in the first year and 97.1, 118.4, and 69.8 t/ha in the second year. The highest yield was consistently observed in greenhouses covered with UV+IR PC, aligning with findings in the literature. Furthermore, the yields in the UV PC and UV+IR PC greenhouses were higher than those in the UV PC+PE greenhouses in both years. A statistically significant difference was observed in average fruit weight between the research greenhouses in both years. Average fruit weights were 99.5, 129.8, and 95.9 g in the first year and 94.7, 115.6, and 90.1 g in the second year for the UV PC, UV+IR PC, and UV PC+PE greenhouses, respectively. Similarly, significant differences were noted in fruit diameter, with values of 51.5, 65.4, and 49.7 mm in the first year and 51.7, 65.2, and 49.7 mm in the second year for the UV PC, UV+IR PC, and UV PC+PE greenhouses, respectively. The soluble solids content of tomato fruit juice was statistically insignificant in the first year but significant in the second year. SSC values for the UV PC, UV+IR PC, and UV PC+PE greenhouses were 4.7, 4.8, and 5.0% in the first year and 4.8, 4.7, and 5.2% in the second year, respectively. The effect of greenhouse covering materials on the EC values of tomato fruit juice was statistically significant in both years. EC values were 3.3, 2.7, and 2.8 dS/m in the first year and 3.4, 2.7, and 2.8 dS/m in the second year for the UV PC, UV+IR PC, and UV PC+PE greenhouses, respectively. For pH, no significant differences were found in the first year; however, differences were significant in the second year. The pH values were 4.39, 4.42, and 4.42 in the first year and 4.38, 4.42, and 4.44 in the second year for the UV PC, UV+IR PC, and UV PC+PE greenhouses, respectively. The lycopene content of tomato fruits was measured using a spectrophotometric method. Statistically significant differences were observed in both years. Lycopene levels in the UV PC, UV+IR PC, and UV PC+PE greenhouses were 108.2, 105.9, and 92.9 mg/kg in the first year and 91.9, 94.3, and 76.1 mg/kg in the second year, respectively.

4. Discussion

The aim of this study was to determine the effect of different additive-containing PC materials on the microclimate and plant development within greenhouses, utilizing thermal cameras. The study investigated the impact of greenhouse covering materials on microclimatic parameters such as total radiation and PAR transmittance, internal and external temperatures, and relative humidity, alongside their effects on plant development.

The initial total radiation transmittance values for UV PC, UV+IR PC, and UV PC+PE greenhouse covering materials were 49.4%, 49.2% and 62.6%, respectively. After the 19-month study, these values decreased due to environmental conditions and material aging by 25.1%, 28.9% and 10.7%, respectively. These results align with previous studies, such as Papadakis et al. (2000) and Serrano and Monero (2020), which reported lower transmittance for PC materials compared to PE and other materials. Tuchinda et al. (2006) reported that the radiation transmittance of glass materials was 90%, 40–62%, and 20–57% for UV, visible, and infrared radiation, respectively. Mastekbayeva and Kumar (2000) found that the radiation transmittance of PE greenhouse covering material was 87.9% initially (in April), which decreased to 75.8% after 30 days due to dust accumulation. Emekli (2014) reported that the total radiation transmittance values of PE greenhouse covering materials were initially 92.7 and 83.6% respectively, but decreased by 7.3% and 13.2% after 24 months due to environmental conditions and aging. Mashonjowa et al. (2010) observed that the total radiation transmittance of LDPE material ranged between 55% and 74% over a 6-month period. Mintorogo (2007) reported that the radiation transmittance of PC covering materials was 43 and 40% respectively. In addition, Zhang et al. (2022) highlighted that material degradation in PC sheets was accelerated by UV exposure in arid climates, which supports the observed higher degradation in the UV-only PC greenhouses. The results obtained in our study are consistent with the literature.

The initial PAR transmittance values for UV PC, UV+IR PC, and UV PC+PE materials were 54.7%, 49.3% and 54.1%, respectively. Over the 19 months, these values decreased by 27.2%, 25.6% and 9.4%, consistent with findings from Al-Helal and Alhamdan (2009) and Kwon et al. (2017), who noted reductions in PAR transmittance due to dust accumulation and aging. Mashonjowa et al. (2010) reported that the PAR transmittance of LDPE material varied between 53% and 75%. Emekli (2014) observed that the PAR transmittance values of PE greenhouse covering materials were 80.1 and 83.0%, respectively, at the onset of the study and these values decreased by 6.2 and 4.9%, respectively, by the conclusion of the study. The results obtained in our study are consistent with the literature.

The average internal temperature ranged as follows: 16.5 to 39.5 °C for UV PC, 16.4 to 39.0 °C for UV+IR PC, and 15.5 to 38.8 °C for UV PC+PE. The greenhouse covered with UV+IR PC exhibited higher and more stable internal temperatures due to its IR additive, which retained infrared radiation. These findings align with İkizler (2019), who reported that infrared (IR) additive materials used in greenhouses are made with fine Kaolin (China clay) particles (0.001 mm in size), which reflect infrared rays and help the greenhouse warm up and cool down gradually, thus maintaining higher and more stable internal temperatures. Mogharreb and Abbaspour-Fard (2019) reported that in a PC greenhouse, while the maximum side temperature reached 35 °C, the indoor temperature of the greenhouse could reach up to 45 °C.

In our study, considering the cultivation in greenhouses covered with UV PC and UV+IR PC materials, it was observed that the average indoor temperature was 10.5 °C higher than the outside temperature, which is consistent with the literature. Emekli (2014) reported that, in PE greenhouse covering materials, the average indoor temperature ranged between 10.9 and 37.9 °C and 10.9 and 38.2 °C, respectively. In our study, the measured average indoor temperature in greenhouses covered with UV PC+PE material was found to be consistent with the literature.

Although direct measurements of condensation on the inner surfaces of the greenhouse covering materials were not conducted, condensation formation was monitored through continuous visual observations during the study period. This observational approach aligns with recent findings reported by Stanghellini et al. (2012), who highlighted the relevance of visual monitoring for condensation assessment in greenhouses. Furthermore, Ferreira Filho et al. (2017) and Zheng et al. (2020) also documented the effects of condensation on microclimate and light transmittance using similar noninvasive observational methods. Thermal imaging data collected in our study further provided indirect evidence of condensation effects by showing variations in canopy and roof temperatures correlated with humidity fluctuations, as supported by previous studies using thermal imaging for moisture detection in building and greenhouse environments (Al-Qazweeni and Kamal, 2013; Ferreira Filho et al., 2017). In future work, quantitative image processing techniques such as pixel intensity thresholding or thermal variance mapping could be employed to objectively evaluate condensation dynamics. Thus, although quantitative condensation data was not captured, the combined observational and indirect evidence strengthens the interpretation of microclimate variations under different cover materials.

Relative humidity within the greenhouses ranged from 27.9% to 91.3% for UV PC, 28.5% to 79.2% for UV+IR PC, and 32.9% to 82.5% for UV PC+PE-covered greenhouses. These values align with the literature, such as Öztürk (2008), which emphasized the importance of maintaining relative humidity between 50% and 80% for optimal plant development. Dayıoğlu (2013) reported that, in a double-layer PC (4 mm) greenhouse, the relative humidity values of the plant's top and bottom sides on a typical summer day ranged from 19.9–67.3% and 25.9–72.1%, respectively. Emekli (2014) reported that, for PE greenhouse covering materials, the relative humidity values ranged from 27.4–77.6% to 26.0–78.2%. The results obtained in our study are consistent with the literature.

Canopy temperatures and roof temperatures in greenhouses covered with UV PC, UV+IR PC, and UV PC+PE materials were monitored with a thermal camera and correlations between the measurement temperatures and external temperatures from the sensors were determined. In addition to measuring roof surface temperatures, the thermal imaging analysis also included canopy temperature measurements in all three greenhouses. These values were compared to the internal air temperature to evaluate the thermal response of the plant microenvironment. The roof was selected as a key measurement surface because the incoming solar radiation enters the greenhouse primarily through the roof panels. All three greenhouses had a roof inclination of 26°, allowing direct sunlight to enter without shading, thus making roof temperature a reliable indicator of cover material performance. This design choice minimized shadowing artifacts during thermal analysis and increased the accuracy of roof surface temperature data, which is critical when comparing material emissivity. In both years of the study, a strong relationship was found between the canopy temperature and roof temperature with the external temperature. Saka (2012) reported a correlation between planting densities and the light entering the canopy. In a study conducted in the same region, Karaca (2020) measured the average spring tomato canopy temperature in a PE greenhouse using an infrared thermometer, which was 23.4 °C. Nicacias (2009) measured the canopy temperature values of two different tomato varieties under greenhouse conditions between November and January. However, in our study, the examination of the relationship between canopy temperature and outside temperature in the PC greenhouse covering material has not been previously addressed in the literature. Therefore, the data obtained in this field in the study creates and increases the originality of the study.

Thermal radiation is most commonly detected using infrared thermal imaging systems equipped with current electronic technologies. According to Wien's law, the majority of electromagnetic waves emitted by objects fall within the infrared region of the electromagnetic spectrum and correspond to thermal radiation. Thermal cameras estimate an object's temperature by analyzing the amount of infrared radiation it emits. However, these cameras typically cannot measure the emissivity of the object directly. Consequently, an object with a low temperature but high emissivity may appear to have a higher temperature than an object with a higher temperature but lower emissivity. This phenomenon, while seemingly contradictory, is expected, as thermal cameras measure the object's "apparent temperature." In this study, considering the roof covering materials—UV PC+PE, UV PC, and UV+IR PC—it was observed that the UV+IR PC material retained incoming heat more effectively due to its IR additive, suggesting a lower emissivity. This interpretation

is reinforced by previous studies (e.g., Espi et al., 2006), which demonstrated that infrared additives in greenhouse films can significantly modify thermal radiation properties and improve energy retention by altering the emissivity of the surface. As a result, the apparent temperature of the UV+IR PC material, which had lower emissivity but higher actual temperature, appeared higher compared with the other two materials. Rasheed et al. (2017) reported thermal conductivity (heat transfer coefficient) values for polyethylene and polycarbonate greenhouse covering materials that align closely with the results obtained in the present study. However, to the best of our knowledge, an in-depth analysis of the relationship between roof surface temperature and ambient outdoor temperature specifically for PC-covered greenhouses remains lacking in the existing literature. Therefore, the data obtained in this field in the study creates and increases the originality of the study.

The study revealed statistically significant differences in plant height between the greenhouses in both study years. Tomatoes grown in UV+IR PC greenhouses exhibited the highest plant heights due to the more balanced microclimatic conditions. Similarly, significant differences were found in leaf number at the end of the second year, reflecting the positive impact of UV+IR PC materials on plant growth.

Total yield varied significantly among the covering materials. Yields for UV PC, UV+IR PC, and UV PC+PE materials were 102.0, 103.0, and 74.4 t/ha in the first year and 97.1, 118.4, and 69.8 t/ha in the second year, respectively. These results indicate that UV+IR PC materials significantly outperformed others in enhancing yield, consistent with Shakir and Geboloğlu (2023). Emekli (2014) reported the tomato plant yield under PE material as 109.4 and 104.1 t/ha in the first year and 134.4 and 106.9 t/ha in the second year. Öztekin et al. (2015) reported the tomato plant yield in a PE greenhouse as 105.8 t/ha. Birgin (2021) reported the control group tomato plant yield under PE material as 78.3 t/ha at the end of the study. Özdemir and Özer (2015) reported the tomato plant yield in a PE greenhouse as 94 and 104 t/ha. The results obtained in our study are consistent with the literature.

Statistically significant differences were observed in average fruit weight and diameter, with UV+IR PC greenhouses producing larger and heavier fruits in both years. Soluble solids content showed no significant differences in the first year but became significant in the second year. EC values differed significantly in both years, with UV+IR PC materials showing lower EC values compared to UV PC and UV PC+PE materials. Lycopene content was significantly influenced by the covering materials. Lycopene levels for the UV PC, UV+IR PC, and UV PC+PE greenhouses were 108.2, 105.9, and 92.9 mg/kg in the first year and 91.9, 94.3, and 76.1 mg/kg in the second year. The higher lycopene content in PC-covered greenhouses aligns with Aktaş and Hor (2024), who reported similar values for PC materials. These values align with the literature, such as Gök (2018), who reported that the lycopene content of tomatoes grown under PE greenhouse covering material ranged from 48.2 to 85.9 mg/kg. In our study, lycopene contents exceeded these values under PC-based covers, indicating a potential link between light spectrum modulation and secondary metabolite synthesis, which merits further biochemical investigation. Kumcuoğlu et al. (2011) examined the lycopene content in tomato paste at different temperatures using ultrasound, and the highest lycopene content was reported as 87.33 ppm. Türüt (2016) examined the lycopene content in all tomato products and found the values ranged from 88.56 to 550.30 mg/kg. In a study by Kuti and Konuru (2005), the lycopene content of cluster and round tomatoes grown in PE greenhouses was found to be higher (30.3 mg/kg) compared with those grown in the field (25.2 mg/kg). However, they also found that the lycopene content in cherry tomato varieties grown in the field (91.9 mg/kg) was higher than in those grown in PE greenhouses (56.1 mg/kg). Toor et al. (2006) reported that the lycopene content in PE greenhouses ranged from 19 to 73 mg per 100 g of dry matter. In this study, the lycopene content found under PE greenhouse covering material is significantly lower than that found in studies by Kuti and Konuru (2005) and Toor et al. (2006). However, the lycopene content found in this study under PC greenhouse covering material is consistent with the findings of Aktaş and Hor (2024). Higher lycopene levels observed in this study compared to some previous studies are attributed to the unique combination of greenhouse covering materials, climate conditions, and the plant variety used. The use of PC sidewalls in PE greenhouses also contributed to the observed differences in lycopene content.

5. Conclusion

The use of greenhouse covering materials is essential for increasing yield, extending the production period and reducing the need for insecticides, herbicides, and water evaporation. This study aimed to examine the temporal changes in the effects of PC materials (UV PC and UV+IR PC) and PE greenhouse covering materials (UV PC+PE) on the environmental microclimate, and their impact on plant development and indoor environmental conditions monitored via thermal cameras. Notably, the use of thermal cameras to monitor indoor environmental conditions has not been extensively investigated in scientific studies in Türkiye, making this study a significant contribution to the field.

The findings indicated that greenhouses covered with PC materials (UV PC and UV+IR PC) outperformed those with PE materials (UV PC+PE) in almost all studied parameters. Although greenhouses with UV PC+PE covering material demonstrated higher total radiation and PAR values, higher yields were achieved in greenhouses with PC coverings, with the highest yield observed in the greenhouse covered with UV+IR PC material. Furthermore, the greenhouse with UV+IR PC material provided a more balanced indoor environment, attributed to the IR additive, which retained infrared radiation and moderated temperature fluctuations.

Based on these results, it is recommended that producers select PC materials (UV PC and UV+IR PC) as greenhouse covering materials to optimize yield and environmental conditions. Additionally, based on our observations during the experimental period, the incidence of diseases and pests in PC greenhouses (UV PC and UV+IR PC) was significantly lower compared with the UV PC+PE greenhouse, resulting in a reduced need for agricultural chemicals. This suggests that this condition contributes to a reduction in agricultural pollution during production. Future studies should explore additional combinations of covering materials, such as sidewall PE and roof UV PC or sidewall UV PC and roof UV+IR PC, to further understand their effects on greenhouse cultivation. Moreover, investigating the impact of PC greenhouse covering materials with different additives on plant development across a wider variety of fruit and vegetable species is strongly recommended. Additionally, the observed increase in lycopene content under PC covers suggests a potential influence of light spectrum modulation on secondary metabolite synthesis, which should be further explored through detailed biochemical studies. It is recommended that studies be conducted on disease and pest management, various irrigation issues and plant water consumption in the context of climate change, global warming, and sustainability.

Acknowledgment

The present study is derived from the doctoral thesis titled "Determination of the Effects of Different Polycarbonate Greenhouse Covering Materials on Environmental Microclimate and Plant Development Using Thermal Cameras" by Candan KORKMAZ, completed at the Department of Agricultural Structures and Irrigation, Institute of Science, Akdeniz University. Furthermore, the research was supported by the Akdeniz University Scientific Research Projects Management Unit under project number FDK-2019-5042. The authors also wish to thank Işık Plastik Corporation for the model greenhouses and their covering material.

Author contributions

Candan KORKMAZ: Writing – review and editing, qriting – original draft, visualization, validation, software, resources, methodology, investigation, formal analysis, conceptualization. Nefise Yasemin TEZCAN: Writing – review and editing, supervision, project administration, funding acquisition.

References

Aktaş H, Hor Y (2024). The effect of mycorrhiza and *Trichoderma* inoculation on plant growth, yield, and fruit quality in soilless tomato (*Solanum lycopersicum*) cultivation. AgriTR Science 6 (1): 19-32 (in Turkish).

Al-Helal IM, Alhamdan AM (2009). Effect of arid environment on radiative properties of greenhouse polyethylene cover. Solar Energy 83 (6): 790-798. https://doi.org/10.1016/j.solener.2008.11.008

Allen RG, Tasumi M, Morse A, Trezza R (2005). A Landsat-based energy balance and evapotranspiration model in Western US water rights regulation and planning. Irrigation and Drainage Systems 19 (3-4): 251-268. https://doi.org/10.1007/s10795-005-5187-z

Al-Qazweeni JS, Kamal HA (2013). Infrared imaging of roof systems for moisture detection. In: Güneş O, Akkaya Y (editors). Nondestructive Testing of Materials and Structures. RILEM Bookseries. Volume 6. Dordrecht, Netherlands: Springer, pp. 805-809. https://doi.org/10.1007/978-94-007-0723-8_115

Barroso MR, Meneses JF, Mexia JT (1999). Comparison between greenhouse type and their effects on two lettuce cultivars yield and *Botrytis* incidence. Acta Horticulturae 491: 137-142. https://doi.org/10.17660/ActaHortic.1999.491.19

Birgin Ö (2021). Effects of foliar application of calcium on tomato plant under drought stress in greenhouse conditions. MSc, Şırnak University, Şırnak, Türkiye.

Cemek B, Demir Y, Uzun S, Ceyhan V (2006). The effects of different greenhouse covering materials on energy requirement, growth and yield of aubergine. Energy 31 (12): 1780-1788. https://doi.org/10.1016/j.energy.2005.08.004

Choab N, Allouhi A, El Maakoul A, Kousksou T, Saadeddine S et al. (2019). Review on greenhouse microclimate and application: design parameters, thermal modeling and simulation, climate controlling technologies. Solar Energy 191: 109-137. https://doi.org/10.1016/j.solener.2019.08.042

Çamoğlu G, Genç L (2013). Kızılötesi termal görüntüleri ve hiperspektral yansıma verilerini kullanarak taze fasulyede su stresinin belirlenmesi. Ankara, Türkiye: TÜBİTAK 111O874 Project Final Report (in Turkish with an abstract in English).

Çaylı A, Akyüz A, Baytorun AN, Üstün S, Boyacı S (2016). Determination of structural problems causing heat loss with the thermal camera in greenhouses. Kahramanmaraş Sütçü İmam Üniversitesi Tarım ve Doğa Bilimleri Dergisi 19 (1): 5-14 (in Turkish with an abstract in English).

Dayıoğlu MA (2013). Design of wireless data acquisition system based on bluetooth for greenhouses: prototype and implementation. Tarım Makinaları Bilimi Dergisi (Journal of Agricultural Machinery Science) 9 (2): 117-125 (in Turkish with an abstract in English).

Ehrler WL, Idso SB, Jackson RD, Reginato RJ (1978). Diurnal changes in plant water potential and canopy temperature of wheat as affected by drought. Agronomy Journal 70 (6): 999-1004. https://doi.org/10.2134/agronj1978.00021962007000060027x

Emekli NY (2014). Time based changings on some physical and mechanical properties of different polyethylene coverings used as greenhouse covering material and light transmittance effect on crop growing under Antalya conditions. PhD Thesis, Akdeniz University, Antalya, Türkiye.

Emekli NY, Büyüktaş K, Başçetinçelik A (2016). Changes of the light transmittance of the LDPE films during the service life for greenhouse application. Journal of Building Engineering 6: 126-132. https://doi.org/10.1016/j.jobe.2016.02.013

Esen M, Yuksel T (2014). Experimental evaluation of using various renewable energy sources for heating a greenhouse. Energy and Buildings 65: 340-351. https://doi.org/10.1016/j.enbuild.2013.06.018

Espi E, Salmerón A, Fontecha A, García-Alonso Y, Real AI (2006). New ultrathermic films for greenhouse covers. Journal of Plastic Film & Sheeting 22 (1): 59-68. https://doi.org/10.1177/8756087906062764

Ferreira Filho AC, Leal PAM, Meneses JF (2017). Evaluation of condensation and energy consumption during the night in heated rose greenhouses. Acta Horticulturae 1170: 263-268. https://doi.org/10.17660/ActaHortic.2017.1170.31

Fuina S, Marano GC, Scarascia-Mugnozza G (2019). Polycarbonate laminates thermo-mechanical behaviour under different operating temperatures. Polymer Testing 76: 344-349. https://doi.org/10.1016/j.polymertesting.2019.03.031

Geoola F, Kashti Y, Levi A, Brickman R (2004). Quality evaluation of anti-drop properties of greenhouse cladding materials. Polymer Testing 23 (7): 755-761. https://doi.org/10.1016/j.polymertesting.2004.04.006

Geoola F, Kashti Y, Peiper UM (1998). A model greenhouse for testing the role of condensation, dust and dirt on the solar radiation transmissivity of greenhouse cladding materials. Journal of Agricultural Engineering Research 71 (4): 339-346. https://doi.org/10.1006/jaer.1998.0333

Geoola F, Peiper UM, Geoola F (1994). Outdoor testing of the condensation characteristics of plastic film covering materials using a model greenhouse. Journal of Agricultural Engineering Research 57 (3): 167-172. https://doi.org/10.1006/jaer.1994.1016

Giacomelli GA, Ting KC, Fang W (1991). Wavelength specific transmission of polyethylene film greenhouse glazing. Plasticulture 13: 17-22.

Gök A (2018). Determining influences of genes heredity and environmental variance to level of lycopene on tomato (*Solanum lycopersicum*) crops. MSc, Süleyman Demirel University, Isparta, Türkiye.

İkizler C (2019). Using possibilities of reinforced greenhouse covering materials in greenhouse cultivation: the case of Bursa. MSc, Bursa Uludağ University, Bursa, Türkiye.

Jackson RD, Reginato RJ, Idso SB (1977). Wheat canopy temperature: a practical tool for evaluating water requirements. Water Resources Research 13 (3): 651-656. https://doi.org/10.1029/WR013i003p00651

Jones HG, Stoll M, Santos T, De Sousa C, Chaves MM et al. (2002). Use of infrared thermography for monitoring stomatal closure in the field: Application to grapevine. Journal of Experimental Botany 53 (378): 2249-2260. https://doi.org/10.1093/jxb/erf083

Karaca C (2020). Evapotranspiration of crops widely grown in greenhouses using the energy balance method. PhD, Akdeniz University, Antalya, Türkiye.

Kittas C, Baille A, Giaglaras P (1999). Influence of covering material and shading on the spectral distribution of light in greenhouses. Journal of Agricultural Engineering Research 73 (4): 341-351. https://doi.org/10.1006/jaer.1999.0420

Kittas C, Tchamitchian M, Katsoulas N, Karaiskou P, Papaioannou C (2006). Effect of two UV-absorbing greenhouse-covering films on growth and yield of an eggplant soilless crop. Scientia Horticulturae 110 (1): 30-37. https://doi.org/10.1016/j.scienta.2006.06.018

Kumcuoğlu S, Yılmaz T, Tavman Ş (2011). Ultrasound assisted extraction of lycopene from tomato paste processing wastes. Akademik Gıda 9 (6): 23-28 (in Turkish with an abstract in English).

Kuti JO, Konuru HB (2005). Effects of genotype and cultivation environment on lycopene content in red-ripe tomatoes. Journal of the Science of Food and Agriculture 85 (12): 2021-2026. https://doi.org/10.1002/jsfa.2205

Kwon JK, Khoshimkhujaev B, Lee JH, Yu IH, Park KS et al. (2017). Growth and yield of tomato and cucumber plants in polycarbonate or glass greenhouses. Horticultural Science & Technology 35 (1): 79-87. https://doi.org/10.12972/kjhst.20170009

Manickavasagan A, Jayas DS, White NDG, Paliwal J (2005). Applications of thermal imaging in agriculture: a review. In: Proceedings of the CSAE/SCGR 2005 Meeting; Winnipeg, MB, Canada.

Mashonjowa E, Ronsse F, Mhizha T, Milford JR, Lemeur R et al. (2010). The effects of whitening and dust accumulation on the microclimate and canopy behaviour of rose plants (rosa hybrida) in a greenhouse in Zimbabwe. Solar Energy 84 (1): 10-23. https://doi.org/10.1016/j.solener.2009.09.004

Mastekbayeva GA, Kumar S (2000). Effect of dust on the transmittance of low density polyethylene glazing in a tropical climate. Solar Energy 68 (2): 135-141. https://doi.org/10.1016/S0038-092X(99)00069-9

Mercan Y, Karataş BS, Tüne C (2016). Solution and determination of possible problems in the greenhouses with thermal camera. In: 13th National Culture and Technology Congress; Antalya, Türkiye. p. 400 (in Turkish with an abstract in English).

Meyers MA, Chawla KK (2009). Mechanical Behavior of Materials. Cambridge, UK: Cambridge University Press.

Mintorogo DS (2007). The aquatic-polycarbonate skylight for Surabaya Indonesia. Dimensi: Journal of Architecture and Built Environment 35 (1): 100-106. https://doi.org/10.9744/dimensi.35.1.100-106

Mogharreb MM, Abbaspour-Fard MH (2019). Experimental study on the effect of a novel water injected polycarbonate shading on light transmittance and greenhouse interior conditions. Energy for Sustainable Development 52: 26-32. https://doi.org/10.1016/j.esd.2019.07.002

Nicacias MM (2009). Evaluating the effect of moisture stress on tomato using nondestructive remote sensing techniques. MSc, University of Limpopo, Limpopo, South Africa.

Oz N, Sochen N, Mendlovic D, Klapp I (2025). End-to-end pipeline for simultaneous temperature estimation and super-resolution of low-cost uncooled infrared camera frames for precision agriculture applications. Computers and Electronics in Agriculture 238: 110765. https://doi.org/10.1016/j.compag.2025.110765

Özdemir A, Özer H (2015). Effect of leaf pruning on yield and quality of organically grown grape tomato (*Solanum lycopersicum* L.). Anadolu Tarım Bilimleri Dergisi 30 (1): 1-6 (in Turkish with an abstract in English). https://doi.org/10.7161/anajas.2015.30.1.1-6

Öztekin GB, Tüzel Y, Ece M (2015). Effects of nitrogen-fixing bacteria use on plant growth, yield and fruit quality of tomatoes grown in greenhouse conditions. Journal of the Institute of Science & Technology – Iğdır Üniversitesi Fen Bilimleri Enstitüsü Dergisi 5 (1): 21-27 (in Turkish with an abstract in English).

Öztürk HH (2008). Sera İklimlendirme Tekniği. İstanbul, Türkiye: Hasad Publications (in Turkish).

Papadakis G, Briassoulis D, Scarascia Mugnozza G, Vox G, Feuilloley P et al. (2000). Review Paper (SE—Structures and Environment): radiometric and thermal properties of, and testing methods for, greenhouse covering materials. Journal of Agricultural Engineering Research 77 (1): 7-38. https://doi.org/10.1006/jaer.2000.0525

Rasheed A, Lee JW, Lee HW (2017). Development of a model to calculate the overall heat transfer coefficient of greenhouse covers. Spanish Journal of Agricultural Research 15 (4): 4. https://doi.org/10.5424/sjar/2017154-10777

Saka AK (2012). The effects of different planting systems and distances on the growth, development, yield and fruit quality of first season organic tomato (*Solanum lycopersicum* L.) and cucumber (*Cucumis sativus* L.) grown in greenhouses. MSc, Ondokuz Mayıs University, Samsun, Türkiye.

Scutelnic D, Muradore R, Daffara C (2024). A multispectral camera in the VIS–NIR equipped with thermal imaging and environmental sensors for non-invasive analysis in precision agriculture. HardwareX 20: e00596. https://doi.org/10.1016/j.ohx.2024.e00596

Serrano MA, Moreno JC (2020). Spectral transmission of solar radiation by plastic and glass materials. Journal of Photochemistry and Photobiology B: Biology 208: 111894. https://doi.org/10.1016/j.jphotobiol.2020.111894

Shakir ZR, Geboloğlu N (2023). Effect of salinity and different calcium doses on yield and quality of tomato. Turkish Journal of Agriculture-Food Science and Technology 11 (11): 2179-2184 (in Turkish with an abstract in English). https://doi.org/10.24925/turjaf.v11i11.2179-2184.6428

Smith RCG, Barrs HD, Steiner JL, Stapper M (1985). Relationship between wheat yield and foliage temperature: theory and its application to infrared measurements. Agricultural and Forest Meteorology 36 (2): 129-143. https://doi.org/10.1016/0168-1923(85)90005-X

Stajnko D, Lakota M, Hočevar M (2004). Estimation of number and diameter of apple fruits in an orchard during the growing season by thermal imaging. Computer and Electronics in Agriculture 42 (1): 31-42. https://doi.org/10.1016/S0168-1699(03)00086-3

Stanghellini C, Bruins MA, Mohammadkhani V, Swinkels GLAM, Sonneveld PJ (2012). Effect of condensation on light transmission and energy budget of seven greenhouse cover materials. Acta Horticulturae 952: 249-254. https://doi.org/10.17660/ActaHortic.2012.952.30

Thomson SJ, Ouellet-Plamondon CM, DeFauw SL, Huang Y, Fisher DK et al. (2012). Potential and challenges in use of thermal imaging for humid region irrigation system management. Journal of Agricultural Science 4 (4): 103-116. http://dx.doi.org/10.5539/jas.v4n4p103

Toor RK, Savage GP, Lister CE (2006). Seasonal variations in the antioxidant composition of greenhouse grown tomatoes. Journal of Food Composition and Analysis 19 (1): 1-10. https://doi.org/10.1016/j.jfca.2004.11.008

Tuchinda C, Srivannaboon S, Lim HW (2006). Photoprotection by window glass, automobile glass, and sunglasses. Journal of the American Academy of Dermatology 54 (5): 845-854. https://doi.org/10.1016/j.jaad.2005.11.1082

Tüne C (2016). The determination of water stress on cotton by using infra-red thermal images under different irrigation management system circumstances. MSc, Adnan Menderes University, Aydın, Türkiye.

Türüt N (2016). The effect of processing technologies on lycopene in tomatoes (*Lycopersicum esculentum* L.). MSc, İstanbul Aydın University, İstanbul, Türkiye.

Yun H, Lo S, Diepenbrock CH, Bailey BN, Earles JM (2024). VisTA-SR: improving the accuracy and resolution of low-cost thermal imaging cameras for agriculture. In: Proceedings of the IEEE/CVF Conference on Computer Vision and Pattern Recognition; Seattle, WA, USA. pp. 5470-5479.

Zhang D-S, Gu X-H, Liu S-W, Liu Y, Zhou Q-Y et al. (2022). Study on properties of regenerated fluorinated polyurethane rigid foam prepared by degrading waste polyurethane. Sustainability 14 (23): 15685. https://doi.org/10.3390/su142315685

Zheng L, Zhang Q, Zheng K, Zhao S, Wang P et al. (2020). Effects of diffuse light on microclimate of solar greenhouse, and photosynthesis and yield of greenhouse-grown tomatoes. HortScience 55 (10): 1605-1613. https://doi.org/10.21273/HORTSCI15241-20