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Effects of polyethylene films with different UV-A transmittance on quality parameters and physiology of greenhouse-grown tomato

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Abstract: In this study, the effects of three different polyethylene (PE) greenhouse covering materials (CMs) with varying thicknesses and ultraviolet-A (UV-A) transmittance on greenhouse microclimate, plant growth, yield, fruit quality, and chlorophyll fluorescence parameters (Chl FPs) in tomatoes were investigated. The CMs used in the study were 180 µm thick ultraviolet (UV) + ethylene vinyl acetate (EVA) + long-wave infrared (IR) + light diffuser (LD) + antifog (AF) added PE (CM1), 160 µm thick PLUS UV + EVA + IR + LD + AF added PE (CM2), and 200 µm thick UV + EVA + IR + LD added PE (CM3). As Chl FPs, relative variable Chl fluorescence at 2 ms (Vj), relative variable Chl fluorescence at 30 ms (Vi), and estimated maximum quantum efficiency of photosystem II photochemistry (F_v/F_m) were taken into account. In addition, leaf temperatures were obtained by thermal images during the growing season. The thickness and IR efficiency rate of the CMs have significant effects on the average and minimum inside temperature values, and thus on related parameters in tomato, including plant height, yield, fruit juice pH, total soluble solids, fruit flesh firmness, fruit skin color, and leaf temperature. Plant development periods, rather than CM characteristics, affect F_v/F_m and V_j values. CM1 provided a significant yield increase in tomato cultivation under greenhouse conditions.

Key words: Covering material, polyethylene, ultraviolet-A, tomato, photosynthetically active radiation, thermal imaging

1. Introduction

Considering the unreliability of traditional farming methods, as well as the projected increase in food and energy demand due to global population growth, greenhouse structures have an important place in the sustainability of modern societies (Hassanien et al., 2018). In greenhouses, it is absolutely necessary to provide and maintain the optimum levels of growth factors such as air composition, light, humidity, and temperature (von Elsner et al., 2000). Solar radiation, which is the most important factor affecting plant growth, is significantly affected by the properties of the greenhouse covering material. For example, covering materials with low transmittance coefficients protect plants from overheating during the summer; however, this may result in insufficient photosynthetically active radiation (PAR) during the winter, increasing heating costs. Conversely, covering materials with high transmittance coefficients may allow sufficient PAR during the winter, but may lead to overheating during the summer, increasing the need for ventilation and energy consumption for active cooling methods. Therefore, the covering performance throughout the entire year should be taken into account in the selection of the appropriate covering material (Baxevanou et al., 2018). Consequently, the intensity of incoming solar radiation is an important parameter influencing the indoor climate as well as the photosynthetic activity of plants (von Elsner et al., 2000).

The radiation level inside a greenhouse is not only dependent on the transmittance of the covering material (CM), but also on the type and orientation of the greenhouse construction. Knowledge of the radiation transmissivity characteristics of a greenhouse CM is important when assessing the potential benefits of different materials because it is known that small differences in solar transmissivity can have a significant effect on crop growth (Papadakis et al., 2000). He et al. (2021) reported that a better understanding of greenhouse CMs, with a focus on energy-efficient CMs equipped in greenhouses, is an opportunity for better yield and higher nutrient content in vegetables in response to global climate challenges. They mentioned that interdisciplinary research on the application of novel covering materials in greenhouses and biological investigation of light-induced physiology and nutrient formation in vegetables may promote yield and health attributes for the protected cultivation of vegetables with energy use efficiency. Ahmadi et al. (2018)

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determined that the type of covering material used in greenhouses influenced the total carotenoid and lycopene contents of five tomato cultivars ($p < 0.05$). They suggest that the efficient transmission of solar energy could positively influence the biosynthesis of certain health-beneficial phytochemicals.

Tomato is the most produced and consumed vegetable in the world. It is important for human health due to its lycopene content, and it is one of the most important vegetables because of its use in many forms in the food industry (paste, canned, ketchup, dried tomatoes, etc.). Tomato production in the world was 186.8 million tons in 2020. Türkiye, with 13.2 million tons, ranked third after China and India[1].

Stress in plants affects plant growth parameters such as leaf water potential, stomatal conductance, chlorophyll content, and photosynthesis rate (Peñuelas et al., 1993). However, the data obtained by measuring the parameters in question on individual plucked leaves are point-based and may not provide information about the entire area. Making these measurements on a large number of leaves requires a lot of labor and also causes damage to the plants (Meyer et al., 1985). Instead of these techniques, stress factors can be quickly determined with less effort and without damaging the plant by using remote sensing methods (Çamoğlu and Genç, 2013). Thermal imaging is a noncontact technique used to convert the radiation pattern of an object into a visible image called a thermogram or thermal image (Agerskans, 1975). A thermal camera is a device that detects temperature patterns in the infrared wavelength spectrum (900–14,000 nm) without direct contact with the object to be measured. The imaging technique that enables the detection of the temperature distribution occurring on the measured object surface is called "thermography". In this measurement technique, each 0.1 °C increase in temperature is indicated by a different color. In thermal images, cold and warm areas are shown in blue and red, respectively (Çalışan and Türkoğlu, 2011). Potential uses of thermal remote sensing in agriculture include nursery and greenhouse monitoring, irrigation scheduling, soil salinity, and plant disease detection, estimating fruit yield, evaluating the maturity of fruit, and bruise detection in fruit and vegetables (Ishimwe et al., 2014). However, limited research has focused on the effects of greenhouse CMs using this technique.

It is hypothesized that the properties of the greenhouse CM (thickness, additives, transmittance at different wavelengths, etc.) affect the greenhouse microclimate and plant development. With developing technology, many properties of greenhouse covering materials are being improved in terms of sustainability, environmental impact, and efficiency. In this study, the effects of greenhouse CMs with different film thicknesses and ultraviolet-A (UV-A) transmittance on microclimate, tomato plant growth, yield, and chlorophyll fluorescence parameters were investigated in autumn tomato cultivation. Additionally, the effects of different greenhouse CMs on leaf temperature were determined with a thermal camera.

2. Materials and methods

2.1. Study area and plant material

The experiment was conducted at Akdeniz University Research and Application Field in Antalya Province, Türkiye, under three polyethylene (PE)-covered greenhouses. The experimental area is located at latitude 36°53'15"N and longitude 30°38'53"E, with an average altitude of 54 m. The research area has a typical Mediterranean climate: hot and dry summers with mild and rainy winters.

The experimental soils are classified as Entisols formed on massive travertine with shallow soil depth in the profile and a clay loam texture (Sarı et al., 1993). Some physical properties of the experimental soils are given in Table 1.

The Tayfun F1 tomato variety was used as plant material in the study, and tomato seedlings were transplanted into the soil in the experimental greenhouses using a double-row planting system on 5 September 2023. The distance between narrow rows was 50 cm, and between wide rows, it was 70 cm. The distance between tomato seedlings in each row was 60 cm. There were three replications in each experimental greenhouse. Harvesting started 93 days after seedling transplanting (DAS), on 7 December 2023.

2.2. Experimental greenhouses and covering materials

The experiment was carried out as a completely randomized design in three independent greenhouses oriented in a north-south direction. The model greenhouses have geometrical characteristics of 3.0 m side wall height, 4.5 m ridge height, 10 m width, and 27 m length. The frame of the greenhouses was made of galvanized steel and aluminum profiles. Natural ventilation openings were located on both the roof and side walls. The ratio of total natural ventilation openings (side + roof walls) to the greenhouse floor area was 40%.

Each greenhouse was covered with a different CM produced using Co-Ex Extruder (CO-EX) technology (layered plastic) as follows: (i) the first greenhouse covering material (CM1) is 180 μm thick and UV + ethylene vinyl acetate (EVA) + IR + light diffuser (LD) + antifog (AF) added PE (Plastika Kritis S.A., Heraklion, Crete, Greece); (ii) the second greenhouse covering material (CM2) is 160 μm thick and PLUS UV + EVA + IR + LD + AF added PE (İmece Plastic Trade Inc. Co. Ltd. , Antalya, Türkiye);

[1] Food and Agriculture Organization of the United Nations (2021). FAOSTAT. Crops and livestock products [online]. Website www.fao.org/faostat/en/#data/QC [accessed 17 June 2021].

Table 1. Some physical and chemical characteristics of the experimental soil.

Depth (cm)	pH	$CaCO_3$ (%)	Soil content (%)			Texture	Field capacity (%)	Wilting point (%)
			Sand	Silt	Clay			
0–15	7.8	30.6	52	38	10	SC	15.5	7.8
15–30	7.7	30.5	68	28	4	SCL	12.9	5.9

and (iii) the third greenhouse covering material (CM3) is 200 µm thick and UV + EVA + IR + LD added PE (İmece Plastic Trade Inc. Co. Ltd.). The radiation transmittance test results for these three PE CMs are given in Table 2.

The UV light transmittance tests on five sample replications were carried out using a Shimadzu UV-2600 Plus spectrophotometer (Shimadzu Corporation, Kyoto, Japan) at the laboratory of İmece Plastic Trade Inc. Co. Ltd. in Antalya, Türkiye. The tests were performed according to TS EN 13206:2017 + A1 Plastics — Thermoplastic covering films for use in agriculture and horticulture (or its equivalent EN 13206:2017 + A1:2020) (Turkish Standards Institution, 2020) (Table 2). Infrared (IR) effectiveness of the covering materials was 86.9%, 91.9%, and 90.0% for CM1, CM2, and CM3, respectively (Turkish Standards Institution, 1998).

2.3. Cultural practices, measurements, and analyses

The experiment was conducted under greenhouse conditions in the fall of 2023–2024. A drip irrigation system with 1 atm operating pressure and a 4 L/h dripper discharge rate was used in each greenhouse. Irrigation was generally performed 3 days a week (Monday, Thursday, and Sunday) for 15 min. Throughout the experimental period, a total of 200 kg N/ha + 150 kg P_2O_5/ha + 150 kg K_2O/ha was applied to each greenhouse through the drip irrigation system eight times at 7-day intervals. Water and fertilizer were applied equally to all greenhouses during the experimental period using a drip irrigation system. Weed control was performed by hand whenever required. Depending on disease symptoms, pesticides or herbicides were applied.

The PAR (µmol/m^2/s) values were recorded using a quantum sensor (model PQS 1, Kipp and Zonen, Delft, Netherlands) for a wavelength range of 400–700 nm. The sensors were placed 2.0 m aboveground in the center of each greenhouse and under the external atmospheric conditions (on the meteorological instrument shield) (Kittas et al., 2006). The air temperature (°C) and relative humidity (%) values were recorded using temperature and relative humidity sensors (model 175-H2, Testo SE and Co. KGaA, Lenzkirch, Germany). These sensors were placed 1.5 m aboveground in the center of each greenhouse and under the external atmospheric conditions (on the meteorological instrument shield) (Barroso et al., 1999).

PAR transmittance values of PE greenhouse CMs at different wavelengths were determined by the following equation (Kittas et al., 1999):

$$\tau_p = \frac{P_i}{P_o} \times 100, \quad (1)$$

where τ_p is the PAR transmittance of the greenhouse CM (%); P_i is the PAR entering the greenhouse through the CM (mol/m^2/s); and P_o is the PAR outside the greenhouse (mol/m^2/s).

The PAR transmittance of PE greenhouse CMs was determined under open sky conditions, taking into account the period from 06:00 AM to 06:00 PM (Geoola et al., 1998; Geoola et al., 2004; Kittas et al., 2006). During the experimental period, accurate data were collected from quantum sensors on five clear sunny days of each month. PAR radiation transmittance percentages of greenhouse CMs were determined for the specified days, and the average value was accepted as the monthly transmittance value (Cemek and Demir, 2005; Emekli et al., 2016). The temperature and relative humidity data were measured for 24 h on selected open sky days for PAR measurements. All these measurements were collected every 10 min using a data logger system (model DL2e; Delta-T Devices Ltd., Cambridge, UK).

In the experiment, vegetative growth parameters, including plant height (cm), stem diameter (mm), number of leaves (per plant), and yield (kg per plant); and fruit quality parameters, including average fruit weight (g), length (mm), diameter (mm), fruit juice pH, total soluble solids (TSS, %), fruit flesh firmness (N/cm^2), and fruit skin color were measured. The TSS was determined in the extract obtained from 10 randomly selected fruits using a digital refractometer (model HI 96801, Hanna Instruments, Woonsocket, RI, USA) (Kurubas et al., 2019). Fruit juice pH values were also measured with a pH meter in the same extracts. The fruit skin color was determined on a total of five fruits, from three different points in the equatorial region of each fruit, using a Minolta CR-400 (Konica Minolta Inc., Tokyo, Japan) colorimeter, which provided CIE L*, h°, and C* values) (McGuire, 1992). Fruit flesh firmness was measured using a hand penetrometer with a 3 mm tip, on a total of five fruits from three different points in the equatorial region of each fruit (Sönmez et al., 2019).

Table 2. The radiation transmittance of plastic films used in the experiment.

Wavelength (nm)	Covering material		
	CM1	CM2	CM3
(UV-B) 280–315 nm	0.05%	0.11%	2.9%
(UV-A) 315–400 nm	22.8%	32.4%	6.4%
220–400 nm	10.9%	15.7%	4.8%
300–600 nm	59.7%	58.9%	50.6%
(PAR) 400–700 nm	80.9%	75.7%	74.9%

Chlorophyll fluorescence parameters such as maximum photochemical efficiency of photosystem II (PSII; F_v/F_m), relative variable chlorophyll (Chl) fluorescence at 2 ms (V_j), and relative variable Chl fluorescence at 30 ms (V_i) were measured using a portable FluorPen FP 100 fluorometer (Photon Systems Instruments Inc., Drásov, Czech Republic) on the same leaves. Chlorophyll fluorescence was measured at 30 (initial season), 60 (midseason), and 90 (late season) DAS in 12 plants between 11:00 AM and 02:00 PM.

2.4. Thermal imaging

In the study, leaf temperature in tomato plants were measured at 43, 56, 71, and 113 DAS using thermal imaging techniques. Thermal images were acquired using a FLIR E53 model thermal camera (FLIR Systems Inc., Wilsonville, OR, USA) in the wavelength range of 7.5–14 μm. The temperature detection range of the thermal camera used in the study was 20 °C to 650 °C. It is capable of capturing thermal images with a resolution of 240 × 180 pixels, totaling more than 43,200 pixels. Emissivity, distance, humidity, and temperature values were input into the camera prior to thermal imaging. It has been reported that at wavelengths between 10.5 μm and 12.5 μm, the thermal radiation emissivity of most plant surfaces ranges from 0.97 to 0.99 (Hatfield, 1990; Chen, 2015). Therefore, the emissivity value during thermal imaging was taken as an average value of 0.98. As usual, thermal imaging of the plants was performed between 11:00 AM and 02:00 PM under clear sky conditions. The background temperature during thermal imaging was determined using aluminum foil placed 75 cm away from the plant, and the emissivity value was set to 1.0 for these measurements (Jones et al., 2002). Thermal image analysis was performed using FLIR Tools software (FLIR Systems Inc., Wilsonville, OR, USA). The mean of three repeated measurements on randomly selected plants from each replication was calculated, and this value was used in the image analysis.

2.5. Statistical analysis

One-way analysis of variance (ANOVA) was used to analyze the obtained data, except for chlorophyll fluorescence and thermal imaging data, using IBM SPSS Statistics software, version 20.0 (IBM Corp., Armonk, NY, USA). Since chlorophyll fluorescence and thermal imaging measurements were repeated at different times, the two-way interaction effects between DAS and CMs were analyzed using univariate regression in SPSS (version 13.0, SPSS Inc., Chicago, IL, USA). Unless stated otherwise, all statistical tests were performed at the 0.01 level of significance. The assumption of normality was checked with the Shapiro–Wilk test. Where appropriate, mean separations were performed using the Duncan test at a significance level of $p < 0.05$.

3. Results and discussion

3.1. Microclimate of greenhouses with different covering materials

Throughout the experiment, the outside PAR radiation (400–700 nm) values varied between 214.7 and 394.9 mol/m^2/s, whereas the values inside the greenhouses ranged from 140.6 to 272.8 mol/m^2/s under CM1, 115.4 to 226.3 mol/m^2/s under CM2, and 119.3 to 233.8 mol/m^2/s under CM3, respectively.

The average monthly PAR transmittance values are presented in Figure 1. Throughout the experimental period, the lowest PAR transmittance values under CMs were obtained in December and the highest in October. With a thickness of 160 μm, CM2 is thinner, but it has lower transmittance values than CM1 (180 μm) and CM3 (200 μm) (Figure 1). This is probably due to the properties of the additives used in CM2 (PLUS UV and IR additives). In fact, CM2 provides higher transmittance in the UV spectrum (220–400 nm) than CM1 and CM3, due to the characteristics of its PLUS UV additive. At the same time, the increased effectiveness of the IR additive used in CM2

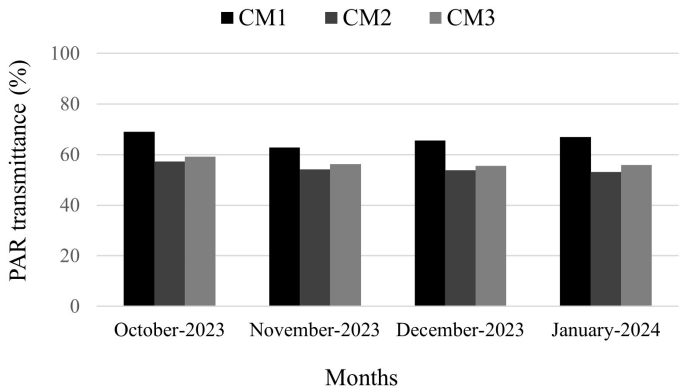


Figure 1. PAR transmittance of covering materials (CMs) throughout the experiment.

(91.9%) increases its haziness and, therefore, reduces PAR transmittance. The effectiveness rate of the IR additive in CM3 (90.0%) is lower than that of CM2, and this appears to have a positive effect on the PAR transmittance. These findings reveal that, especially in the autumn period with lower radiation intensity and scattered radiation effects, additives rather than the film thickness of greenhouse CMs have a significant effect on PAR transmittance.

Throughout the experimental period, the outside temperatures ranged from 5.4 to 32.0 °C, with an average value of 16.5 °C. The indoor air temperatures, on the other hand, ranged from 3.9 to 36.6 °C under CM1, 4.4 to 40.1 °C under CM2, and 4.5 to 39.0 °C under CM3 PE films. The average indoor air temperatures were calculated as 17.1, 17.4, and 18.0 °C under CM1, CM2, and CM3, respectively. Under CM1, CM2, and CM3, the minimum air temperatures were 1.5, 1.0, and 0.9 °C lower, and the maximum temperatures were 4.6, 8.1, and 7.0 °C higher than those of the outdoor air temperatures, respectively. The indoor air temperature of all greenhouse CMs was likely lower than the outdoor air temperature due to the influence of radiant cooling (Figure 2). Papadakis et al. (2000) reported that the most important physical properties of greenhouse CMs can be considered as transmittance in three wavebands: solar spectrum, PAR, and longwave. They stated that a good CM should have maximum transmittance in the PAR spectrum and minimum transmittance in the longwave band. von Elsner et al. (2000) and Baxevanou et al. (2018) claimed that the radiative transmittance of the greenhouse CM is affected by factors such as material thickness, pollution on the material, additives in the material, and moisture condensation on the material. Emekli et al. (2016) found that the PAR transmittance of a 175 μm UV + IR + EVA + antidrip (AD) PE CM was 66.2% in October. Similarly, Katsoulas et al. (2007) noted that the solar radiation transmittance of CMs with standard, AD additives, and AD + AF additives was 64.4%, 63.85%, and 59.19%, respectively. In our study, it can be seen that additives (UV-A and IR) are especially effective in the PAR transmittance of CMs. As a result, among the studied CMs, CM1 can be classified as the most suitable greenhouse CM thanks to its high PAR transmittance.

Baytorun and Başçetinçelik (1993) reported that the wavelength of longwave rays in greenhouses varies between 3000–50,000 nm, and the maximum wavelength increases to 9000 nm in greenhouses without heating. They also reported that PE CMs without IR additives transmit rays of this wavelength, and therefore, radiant cooling occurs at night when the air is clear and calm. Cemek et al. (2006) found that under UV PE, UV + IR PE, double-layer PE, and single PE greenhouses, the daytime air temperatures were 29.1 °C, 29.8 °C, 30.6 °C, and 27.8 °C, and the nighttime air temperature was 23.9 °C, 24.8 °C, 25.7 °C, and 21.1 °C, respectively. Their study shows that the IR additive affects both the daytime and nighttime air temperatures. Similar results were obtained in our study. Although the minimum greenhouse temperatures under CM2 and CM3 were 1.0 and 0.9 °C lower than the outdoor environment, respectively, these values were higher than those under CM1. CM1 has the lowest IR efficiency rate (86.9%). Therefore, it can be concluded that the IR additive and its ratio have an important effect on the inside air temperature of the greenhouse. These results reveal that the thickness, as well as the IR efficiency rate of the CM, affects the average and minimum indoor temperature values. In fact, CM3 with a 200 μm thickness has the highest average greenhouse indoor temperature (18.0 °C).

3.2. Growth parameters and total yield

Statistical analysis results regarding some growth, yield, and quality parameters of tomato plants grown under greenhouse CMs with different characteristics are given in Table 3. The effects of different CMs on plant height ($p < 0.05$), yield ($p < 0.05$), fruit juice pH ($p < 0.05$), TSS ($p < 0.01$), fruit flesh firmness ($p < 0.01$), and fruit skin color ($p < 0.01$ for L^* and h^o, and $p < 0.05$ for C^*) in tomato were

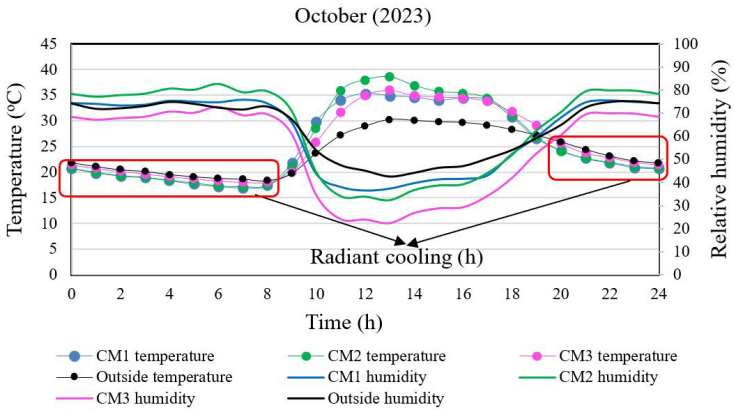


Figure 2. Changes in hourly average temperature and relative humidity under selected greenhouse covering materials (CMs) on a typical autumn day.

Table 3. Statistical analysis of growth and yield parameters of tomato plants under different greenhouse covering materials (CMs).

Parameter		Greenhouse covering material (CM)			p > F	Mean
		CM1	CM2	CM3		
Plant height (cm)		221.0 a	224.0 a	185.67 b	*	210.22
Steam diameter (mm)		16.72	14.14	14.65	ns	15.17
Number of leaves (per plant)		17	14	12	ns	14
Yield (kg per plant)		2.08 a	1.59 b	1.93 ab	*	1.87
Fruit weight (g)		185.3	174.7	183.9	ns	181.3
Fruit length (mm)		54.07	54.44	55.84	ns	54.78
Fruit diameter (mm)		71.05	69.60	71.03	ns	70.56
Fruit juice pH		1.22 b	1.32 a	1.27 ab	*	1.27
TSS (%)		3.73 a	3.27 b	3.83 a	**	3.61
Fruit flesh firmness (N/cm^2)		5.21 ab	4.96 b	5.48 a	**	5.21
Fruit skin color						
	L*	43.39 a	42.54 a	41.22 b	**	42.38
	C*	35.41 b	36.36 a	36.50 a	*	36.09
	h°	62.19 a	60.49 a	54.88 b	**	59.19

[#]: within rows, means followed by the same letter are not significantly different according to Duncan's multiple range test at the 0.05 significance level. *: significant at the 0.05 significance level. **: significant at the 0.01 significance level. ns: nonsignificant.

statistically significant. However, stem diameter (ranging from 14.14 to 16.72 mm), number of leaves (ranging from 12 to 17 per plant), fruit weight (ranging from 174.7 to 185.3 g), fruit length (ranging from 54.07 to 55.84 mm), and fruit diameter (ranging from 69.60 to 71.05 mm) of tomato did not show a significant difference among the greenhouse CMs (Table 3).

On 121 DAS, the highest plant heights were obtained under CM1 (221.0 cm) and CM2 (224.0 cm). The highest and lowest yields were obtained under CM1 (2.08 kg per plant) and CM2 (1.59 kg per plant), respectively, but the yield obtained under CM3 (1.93 kg per plant) did not differ significantly from either CM1 or CM2. The lowest water-soluble dry matter was determined under CM2 (3.27%), and the highest under CM1 (3.73%) and CM3 (3.83%).

Fruit juice pH value is taken into consideration as an important parameter for evaluating tomato quality (Tarı and Sapmaz, 2017). The highest and lowest fruit juice

pH values were obtained under CM2 (1.32) and CM1 (1.22), respectively, but the pH value obtained under CM3 (1.27) did not differ significantly from either CM1 or CM2. Fruit flesh firmness is another important quality parameter in tomatoes and is one of the most important factors affecting the storage life of the fruit (Özdemir and Özer, 2015; Tarı and Sapmaz, 2017). The lowest fruit flesh firmness was obtained under CM2 (4.96 N/cm^2), and the highest under CM3 (5.48 N/cm^2). L* value, one of the measured fruit skin color values, refers to brightness (Özdemir and Özer, 2015), which is an important fruit quality parameter in terms of market demand. According to the color measurement results, the highest brightness value was obtained under CM1 (43.39) and CM2 (42.54), and the lowest brightness value was obtained under CM3 (41.22). Cemek et al. (2006) investigated the effects of four different PE greenhouse CMs (UV + PE, IR + PE, double-layered PE, and single-layered PE) on the growth, yield, and energy needs of eggplants. They stated that crops under the double-layered PE greenhouses grew faster (more leaves and flowers) and the soil fertility was better than the other greenhouse CMs. Katsoulas et al. (2007) noted that crop growth and production were similar under standard, AD additive, and AF additive PE greenhouses. Petropoulos et al. (2019) studied the effects of three different PE greenhouse CMs (a conventional single three-layer PE, CM1; an inflated external three-layer PE, CM2; and seven-layer PE, CM3) on the growth, yield, harvesting dates, chemical composition, and antioxidant properties of tomato fruit. They noted that total yield showed significant differences among the CMs, with CM1 having the highest yield (24.3 kg/m^2), compared to CM3 and CM2 (20.9 and 22.9 kg/m^2, respectively) and mean fruit weight was not affected by CM. Their study is important in terms of showing the effect of the IR additive on yield. Saka et al. (2017) reported that the yield in organic tomato cultivation in the greenhouse varied between 5.3–13.9 kg/m^2, depending on plant density. Ünlü and Padem (2009) found that the TSS content of tomato fruits varied between 3.52%–4.18%. According to our results, with its thickness and UV-A transmittance rate and highest PAR transmittance values during the experimental period, CM1 had a positive effect on tomato yield.

3.3. Chlorophyll fluorescence parameters in tomato plants

Chlorophyll fluorescence measurements taken on 30 (initial season), 60 (midseason), and 90 (late season) DAS are presented in Table 4. According to the two-way ANOVA analysis, none of the chlorophyll fluorescence parameters, including V_j, V_i, and F_v/F_m showed a significant interaction between DAS and CMs. However, all chlorophyll fluorescence measurement values averaged over CMs showed differences ($p < 0.01$) across DAS. Under the main factor DAS, the highest and lowest V_j values were obtained at 30 (0.73) and 60 DAS (0.43), respectively. The highest and lowest V_i values were measured at 90 (0.89) and 60 DAS (0.85), respectively, but the V_i value at 30 DAS (0.87) did not differ significantly from those at 90 and 60 DAS. Similarly, the highest F_v/F_m values at 60 (0.73) and 90 DAS (0.72) were significantly higher than those at 30 DAS (0.64) (Table 4).

V_j values averaged over the DAS, ranging from 0.54 to 0.56, were not significantly different among CMs. On the other hand, the differences ($p < 0.01$) among CMs were significant for V_i and F_v/F_m values averaged over the DAS. The highest and lowest V_i values were measured under CM2 (0.88) and CM3 (0.85), but the V_i under CM1 (0.86) did not differ from those under CM2 and CM3. Similarly, the highest F_v/F_m values were obtained under CM2 (0.71) and CM1 (0.70), whereas the lowest values were determined under CM3 (0.69) (Table 4).

Among CM treatments, none of the chlorophyll fluorescence parameters, except F_v/F_m values at 60 DAS, differed significantly. Similarly, none of the V_i values under any CM showed significant differences across DAS. On the other hand, among different DAS, V_j and F_v/F_m values under all CMs were significantly different at $p < 0.01$ or $p < 0.05$. Compared to the initial season, V_j values were lower, whereas F_v/F_m values were higher at midseason and late season (Table 4). Choi and Jeong (2019) claimed that the F_v/F_m value is defined as the maximum quantum efficiency of PSII photochemistry and is the most common indicator of chlorophyll fluorescence transient on leaves under stress conditions in general. Maxwell and Johnson (2000) stated that the F_v/F_m value in the range of 0.79 to 0.84 is optimal for many plant species. Liang et al. (2019) found that F_v/F_m gradually decreased with an increase in the degree of drought stress in tomatoes. Haque et al. (2017) found that F_v/F_m in the leaves of tomato plants grown under a constant temperature of 24 °C and under a variable temperature of 27/17 °C for 16 h and 8 h conditions were 0.81, 0.60, and 0.80, respectively. In our study, lower F_v/F_m values than the optimum values were obtained. On the other hand, V_j was significantly decreased under all CM treatments at midseason and late season. These results reveal that plant development periods, rather than CM characteristics, have a significant effect on F_v/F_m and V_j values.

3.4. Leaf temperature

Leaf temperature values obtained from thermal camera measurements at 43, 56, 71, and 113 DAS under three different greenhouse CMs are given in Table 5 and Figure 3. According to the two-way ANOVA analysis, there was no significant interaction between the main factors DAS and CM. However, leaf temperature values differed significantly under the main effects of DAS (averaged across CMs) and CM (averaged across DAS) ($p < 0.01$).

Table 4. Statistical analysis of chlorophyll fluorescence parameters in the leaves of tomato plants under different greenhouse covering materials (CMs) at 30, 60, and 90 DAS**.**

Parameter/DAS	Greenhouse covering material (CM)			p > *F*	Mean
	CM1	CM2	CM3		
V_j					
30 DAS	0.71 a[#]	0.75 a	0.72 a	ns	0.73 a
60 DAS	0.45 c	0.41 b	0.43 b	ns	0.43 c
90 DAS	0.52 b	0.50 b	0.48 b	ns	0.50 b
p > *F*	*	**	**		**
Mean	0.56	0.55	0.54	ns	
V_i					
30 DAS	0.85	0.89	0.86	ns	0.87 ab
60 DAS	0.85	0.86	0.83	ns	0.85 b
90 DAS	0.89	0.90	0.88	ns	0.89 a
p > *F*	ns	ns	ns		**
Mean	0.86 AB	0.88 A	0.85 B	**	
F_v/F_m					
30 DAS	0.64 b	0.65 c	0.62 b	ns	0.64 b
60 DAS	0.74 aA[‡]	0.75 aA	0.71 aB	*	0.73 a
90 DAS	0.72 a	0.72 b	0.72 a	ns	0.72 a
p > *F*	**	**	**		**
Mean	0.70 A	0.71 A	0.69 B	**	

[#]: within each column (across different DAS), means followed by the same lowercase letter are not significantly different according to Duncan's multiple range test at the 0.05 significance level. [‡]: within each row (among CMs), means followed by the same uppercase letter are not significantly different according to Duncan's multiple range test at the 0.05 significance level. *: significant at the 0.05 significance level. **: significant at the 0.01 significance level. ns: nonsignificant.

Under the main factor DAS, the highest plant temperature value (29.3 °C) was obtained at the 113th DAS, whereas the lowest values were measured at the 43rd (25.5 °C), 56th (24.6 °C), and 71st (25.3 °C) DAS. Similarly, under the main factor CM, the highest (27.5 °C) and lowest (24.8 °C) plant temperature values were obtained under CM2 and CM3, respectively (Table 5).

When the thermal images in Figure 3 are examined, it can be seen that, in general, warm colors (yellow to red) were dominant in all three greenhouses with different CMs. However, considering the data in Table 5, it is noteworthy that warm colors were more dominant in the CM2 greenhouse. As a matter of fact, in terms of greenhouse microclimate parameters, the greenhouse indoor temperature values in the CM2 greenhouse (4.4 to 40.1 °C) were relatively higher than those in other CMs. Depending on the indoor greenhouse temperature values, leaf temperature values were also high in CM2 on days 56 and 71. This situation was also reflected in the thermal images. Karaca (2020) determined that the average canopy temperature of tomato plants grown under a PE greenhouse was 23.4 °C. Nicacias (2009) measured the plant canopy temperature as 22.0 °C and 21.0 °C during flowering and fruit formation in two different tomato varieties under greenhouse conditions. They also claimed that the canopy temperature of tomato plants can increase by up to 7 °C on average under stress conditions.

Among the CM treatments, leaf temperatures at 56 ($p < 0.01$) and 71 ($p < 0.05$) DAS showed significant differences. In general, the highest leaf temperatures

Table 5. Statistical analysis of leaf temperatures of tomato plants under different greenhouse covering materials (CMs) at different DAS.

DAS	Greenhouse covering material (CM)			p > *F*	Mean
	CM1	CM2	CM3		
43 DAS	25.5 b[#]	26.5 b	24.6 b	ns	25.5 b
56 DAS	24.3 bB[‡]	26.5 bA	23.0 cC	**	24.6 b
71 DAS	25.3 bAB	26.3 bA	24.2 bcB	*	25.3 b
113 DAS	29.6 a	30.9 a	27.5 a	ns	29.3 a
p > *F*	*	**	**		**
Mean	26.2 B	27.5 A	24.8 C	**	

[#] Within each column (across different DAS), means followed by the same lowercase letter are not significantly different according to Duncan's multiple range test at the 0.05 significance level. [‡] Within each row (among CMs), means followed by the same uppercase letter are not significantly different according to Duncan's multiple range test at the 0.05 significance level. *: significant at the 0.05 significance level. **: significant at the 0.01 significance level. ns: nonsignificant.

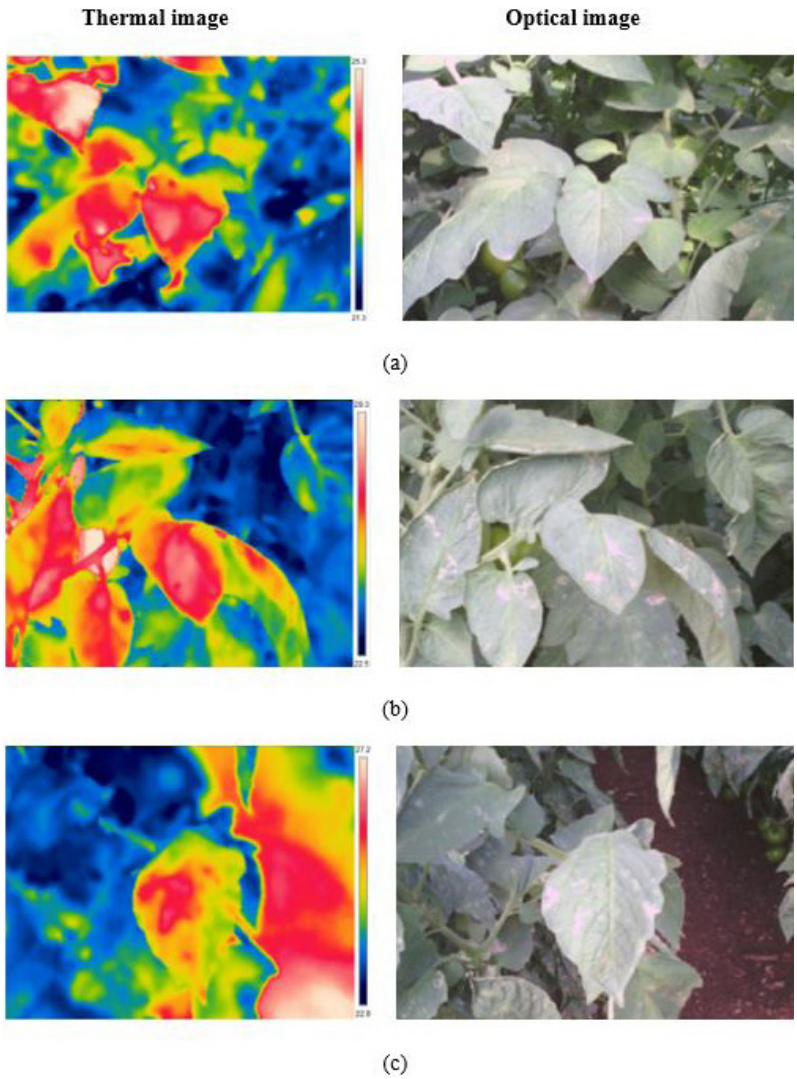


Figure 3. Thermal image analysis using FLIR Tools software for tomato plants under different plastic films (a: CM1, b: CM2, c: CM3) at the third measurement time.

at 56 and 71 DAS were observed under CM2, with a thickness of 160 μm, whereas the lowest leaf temperatures were recorded under CM3, with a thickness of 200 μm. Similarly, among different DAS, leaf temperatures under all CMs were significantly different ($p < 0.01$ or $p < 0.05$). As expected, the highest leaf temperatures were obtained at the last thermal camera measurement (Table 5). These results clearly reveal that the thickness of the greenhouse CM affects the leaf temperature. The solar radiation reaching CM3 travels approximately 1.25 times farther than in CM2. Research showed that radiation decreases as the film thickness increases. Tuchinda et al. (2006) reported that the radiation transmittance of materials for normal glass (3 mm), colored glass (3 mm), and double glass (6 mm) varies between 90%, 40%–62%, and 20%–57%, respectively. Mashonjowa et al. (2010) found that the total radiation transmittance for low-density PE CM with a 250 μm thickness varied between 55% and 74% in a 6-month period. Similarly, Emekli et al. (2016) reported that the total radiation transmittance of UV + EVA +IR + AF added PE CM with a 175 μm thickness varied between 83.6% and 56.7% in a 24-month period.

4. Conclusion

The results revealed that, with its thickness, UV-A transmittance rate, and highest PAR transmittance values during the experimental period, CM1 provided significant advantages in tomato cultivation under greenhouse conditions. With the highest PAR transmittance, CM1 showed the highest values in terms of efficiency. In the leaf temperature values obtained by thermal imaging, it was determined that the thickness of CMs affected the leaf temperature. It was determined that the leaf temperature decreased as the thickness of CM increased. The lowest leaf temperature values were obtained from CM3 with a 200 μm thickness. As chlorophyll fluorescence parameters, V_j and F_v/F_m values were affected by plant development periods rather than CM characteristics. In future studies, other chlorophyll fluorescence parameters can be investigated to reveal the energy flow during photosynthesis for tomato plants. Since this study reveals the significant effects of thickness, UV-A transmittance rate, and PAR transmittance of CM on plant growth and yield, determining the performance of any newly developed CM on plant growth and yield will be helpful.

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Conflicts of interest

The authors declare no conflict of interest.

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