

## Determination of yield by plant leaf temperature and thermal imaging in banana (*Musa* spp. AAA) under different cover materials

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### Abstract

Global warming, particularly drought and climate change, negatively affects plant production. In crops like bananas, which have high water consumption, it is important to identify drought-resistant varieties. The objective of the study to investigate the effects of two different types of plastic cover material (CM), namely the traditional plastic cover (CM1) and produced with CO-EX technology cover material (CM2), on the yield, and certain quality parameters of two different banana cultivars ('Grand Nain' (BC1), 'Williams' (BC2)). In addition to the leaf temperature values were obtained by acquiring the thermal images for banana grown under different greenhouse cover materials. Beside the climatic data and thermal imaging, some physical characteristics and yield such as the number of hand, number of finger, finger weight, finger length and yield per ha were examined. The properties of plastic cover materials have significant effects on the average inside temperature and humidity values, and thus on related parameters in banana including number of fingers, finger weight, yield and leaf temperature. The produced with CO-EX technology cover material (CM2) exhibited higher temperature and relative humidity compared to the traditional plastic cover (CM1). The FLIR Tools analysis results of thermal images obtained for banana crops under different greenhouse cover materials, it is evident that warm colors dominate more in the CM2 greenhouse for both banana cultivars. The yield per ha was the highest in CM2BC2 (41.9 ton ha<sup>-1</sup>) and the lowest in CM1BC2 (37.8 ton ha<sup>-1</sup>). These findings indicate that optimizing greenhouse cover materials can enhance yield and resilience to abiotic stresses, thereby supporting sustainable banana production under changing climatic condition.

**Keywords:** banana; climate; greenhouse; sustainability; thermal image

### Introduction

Bananas rank as the fourth most important food crop in the world; following rice; wheat; and milk (Pareek, 2016). They are currently cultivated in over 135 countries; predominantly in tropical and subtropical regions (Drenth and Kema, 2021). This situation brings bananas to the forefront in terms of production and trade volume. There are over 1000 varieties of bananas globally. The Cavendish group is particularly significant

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in commercial terms; comprising over half of global banana production with an annual volume of approximately 50 million tons (FAO, 2022). The countries with the highest banana production worldwide are India, Brazil, China, Tanzania and Congo. According to 2020 reports, India ranked first with 26.3%, Brazil ranked second with 9.6% and Indonesia ranked third with 6.8% of the world banana producers (Polat, 2022). In 2021, World table of the banana production reached up to 125 million tons, 54.4% was produced in Asia, 25.3% in the Americas, 25.3% in Africa, 1.4% in Oceania and 0.5% in Europe (FAO, 2021a). Global banana production is projected by 1.5% per year, it will be reaching up to 135 million tons in 2028 (Cabanas *et al.*, 2021).

Banana is one of the most important agricultural commodities worldwide in terms of both export and import. It represents a vital food source and is widely consumed across many countries. Beyond its nutritional significance banana trade holds substantial socio-economic value, providing opportunities for national economic growth. Banana cultivation also serves as a major source of employment for millions of people, playing a critical role in the sustainability of the farming enterprises and smallholder livelihoods. Consumed either fresh or processed, bananas contribute significantly to global food supply and continue to attract strong consumer demand worldwide. With its considerable potential in both export and import markets, banana occupies a prominent position in international trade.

Climate change is one of the most important challenges of our time, creating serious risks for ecosystems, economies, and human health. Its effects on agriculture and food supply are especially critical because they directly affect human nutrition and global food security. Higher temperatures, changes in rainfall patterns, and more frequent extreme weather events disrupt traditional farming practices, reduce crop yields, and threaten the livelihoods of millions of farmers worldwide. These challenges highlight the urgent need for sustainable agricultural practices and adaptation strategies to ensure resilient food systems under changing climatic conditions (Manucharyan, 2021).

Bananas can be cultivated under controlled conditions to minimize the impact of adverse weather on plant growth. In this system, key environmental factors such as temperature, humidity, and light are carefully regulated to optimize growth and development. Compared with open-field cultivation, this approach offers several advantages, including higher yield, shorter vegetative growth periods, reduced water consumption, and improved fruit quality. Among the materials used for controlled cultivation, plastic coverings are the most widely adopted due to their effectiveness. These materials not only mitigate the effects of unfavorable climatic conditions but are also selected based on their light and heat transmission properties. Additional benefits of using plastic covers or nets include low cost, durability, and ease of installation (Robinson, 1996; Gübbük *et al.*, 2004).

Overall, the vast majority of the greenhouse area covered by plastic materials is dominated by the use of polyethylene (PE) plastic films (Briassoulis *et al.*, 1997). In particular; low-density polyethylene (LDPE) is the most widely used type due to its relatively good mechanical and optical properties and competitive market price (Dilara and Briassoulis, 2000). Additives and coating materials developed for greenhouse plastics are used to enhance durability and lifespan. Ultraviolet (UV) additives increase the resistance of greenhouse covers to sunlight; prolonging their lifespan. Long-wave infrared (IR) additives conserve heat; reduce plant stress, and save energy. Anti-fog (AF) additives minimize damage from water droplets formed by condensation. Ethylene vinyl acetate (EVA) additives increase film transparency. Anti-drip (AD) additives prevent dust accumulation while anti-virus (AV) and anti-bacterial (AB) additives prevent pests and diseases. Lastly; light diffusing (LD) additives reduce the impact of sunlight; preventing plant sunburn (Sethi and Sharma, 2008; Cabrera *et al.*, 2009). The plastic sector, like many other industries, is continuously evolving with advancing technology. In this context, not only have plastics containing different additives been developed for sustainability, but production technologies have also changed. Nowadays, plastics are produced in a layered structure known as CO-Extruded (CO-EX) plastic. Compared to traditional mono technology, CO-EX technology offers the advantage of providing a more homogeneous distribution of both the additives used and the film thickness. This study investigated the advantages of greenhouse plastic produced with CO-EX technology over mono

technology, specifically in terms of microclimate control and yield. It is believed that working with a new generation of plastic under subtropical conditions in a tropical plant like bananas increases the originality of the article.

Global plastic production has surged over the past 70 years; increasing nearly 230-fold from its 1950 levels; reaching 460 million tons in 2019 (Hannah and Roser, 2018). According to a report by the FAO; plastic usage in the agricultural sector is expected to rise by 50% by 2030 (Diaz, 2022). In Türkiye, greenhouse farming is implemented as a highly efficient production system. As of 2020, the total greenhouse area was recorded at 80516 hectares. Of this, 48257 ha comprised glass (8078 ha) and plastic (40180 ha) greenhouse areas, with the remaining area covered by low (21833 ha) and high (10426 ha) tunnels (TUIK, 2021).

Stress in plants affects various growth parameters, such as leaf water potential, stomatal conductance, chlorophyll content, and photosynthesis rate (Peñuelas *et al.*, 1993). However, data obtained from measuring these parameters are often point-based focusing on individual leaves and may not represent the entire plant. Conducting these *measurements* on many leaves requires considerable labor and can cause damage to the plants (Meyer *et al.*, 1985). Instead, using remote sensing techniques to identify stress factors quickly and with minimal labor; without harming the plants, has become a topic of research today (Çamoğlu and Genç, 2013). Plant canopy temperature has long been recognized as an indicator of plant stress. This parameter is used to identify water or salt stress in plants, as stress causes stomatal closure, reducing transpiration, and thereby increasing leaf temperature. The temperature of the plant leaf can be determined using a thermal camera (Ghazouani *et al.*, 2017). Thermographic cameras capture temperatures emitted by objects in the infrared (IR) spectrum (approximately 900-14000 nm) and create images based on this radiation (Çalışan and Türkoğlu, 2011; Yastıklı and Güler, 2013). Thermographic imaging has been extensively used in applications such as agriculture and industrial damage detection (Patil *et al.*, 2015; He *et al.*, 2018). Canopy temperatures can be measured quickly and accurately with thermal cameras, which have recently made the IR band visible and provided an easy-to-use opportunity (Kurunc *et al.*, 2023). Song *et al.* (2020) examined the surface temperatures of 28 tree varieties using high-resolution thermal cameras and found that the leaf temperature of the dominant tree cultivar, *Pometia tomentosa*, was the highest at 31.8 °C, which was 10.2 °C higher than that of the *Mezzettipsis creaghii* tree cultivar. Eroğlu *et al.* (2020) reported that thermal images could quickly and accurately determine water stress in pepper plants. Zhao *et al.* (2022) studied the thermographic profiles of frozen soil specimens (clay; sand; and gravel) under a uniaxial compression test and reported that cracks in different frozen soils could be identified through infrared topography. 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 fruits, and bruise detection in fruits and vegetables (Ishimwe *et al.*, 2014). However, limited research has focused on the effects of greenhouse cover materials using this technique (Tezcan *et al.*, 2025).

It is hypothesized that the properties of the greenhouse cover material (CM) are effective on the greenhouse microclimate, leaf temperature and banana yield. Layered plastics (three, five, seven layers) produced with CO-EX technology have become widespread in the plastics industry. CO-EX is a technology that allows the additive and film thickness to be applied more uniformly. This is important in terms of greenhouse microclimate, yield and sustainability. However, there is no study for the determination of greenhouse microclimate, leaf temperature and yield on banana crop by thermal imaging technique.

In this study, the effects of two types of plastic cover materials, the traditional plastic cover (CM1) and the CO-EX technology cover (CM2), on microclimate and yield were investigated in banana cultivation. Additionally, the impact of these greenhouse cover materials on leaf temperature was assessed using a thermal camera.

## Materials and Methods

### *Experimental site and plant material*

The experiment was conducted at Akdeniz University's Agricultural Research and Implementation Area in Antalya, Türkiye. This area is geographically situated at 36°53'15" north latitude and 30°38'53" east longitude, with an average altitude of 54 meters above sea level. The study was carried out under two polyethylene-covered greenhouses.

The plant material for the study included two banana varieties propagated through tissue culture: the 'Grand Nain' (BC1) and 'Williams' (BC2) varieties. Their specific characteristics are detailed below:

'Grand Nain' (BC1): This variety, also known as 'Grand Nain', is an alternative to the Dwarf 'Cavendish' for greenhouse cultivation. It has a medium height of 3-4 meters. In recent years, it has gained significant importance in international exports due to its superior yield and quality compared to the Dwarf 'Cavendish' (Güven, 2011).

'Williams' (BC2): Adaptable to various ecological conditions, the 'Williams' variety is known for its high yield. It is taller than the 'Grand Nain' with heights ranging from 6-8 meters. The fruits are large, sweet, and flavorful. This variety is also resistant to wind and cold, possesses a robust root system, and is resistant to nematodes and root rot (Güven, 2011).

### *Experimental greenhouses and cover materials*

The experiment was performed in two arched-roof greenhouses; each covering a floor area of 500 m<sup>2</sup>. The dimensions of each greenhouse are as follows: width of 16.0 meters; length of 31.0 meters; side wall height of 5.5 meters; and ridge height of 7.5 meters. The long axis of the greenhouses is oriented in the north-south direction. The greenhouse structures are made from galvanized steel and aluminum profiles. Natural ventilation is applied through openings located on the roof walls; constituting 25% of the total floor area.

To evaluate the impact of different cover materials (CM) produced with CO-EX technology on the growth and yield of banana plants; each greenhouse was covered with a different material:

Cover Material 1 (CM1): The outer layer is a 200 µm thick (36 months) UV + IR + LD + EVA added polyethylene (PE); and the inner layer is a 140 µm thick (24 months) UV+AB (Anti-Bacterial) + EVA added PE. This cover material is produced using mono (single layer) technology.

Cover Material 2 (CM2): The outer layer is a 200 µm thick (36 months) UV + IR + LD + EVA added PE; and the inner layer is a 110 µm thick (12 months) UV + IR + LD added PE. This material is produced with CO-EX (three layer) technology.

The infrared (IR) effectiveness of the covering materials was measured as 91.4% for CM1 and 96.5% for CM2; according to Turkish Standards Institution (TSE, 1998).

### *Climate parameters*

To assess the effects of the greenhouse cover materials on the environmental microclimate, three temperature and humidity sensors were used. These sensors are capable of measuring temperatures between -10 °C and +50 °C and relative humidity from 0% to 100%. Two sensors were placed inside the greenhouses; and one was positioned outside in a meteorological instrument shield. All sensors were placed at 1.5 meters above the ground and centrally located within the greenhouses (Barroso *et al.*, 1999).

The temperature and relative humidity measurements were performed during 24 h on open sky days. During the experimental period, accurate data were collected from sensors on five clear sunny days of each month (Geoola *et al.*, 2004; Emekli *et al.*, 2016).

*Thermal imaging*

Thermal images were acquired using the FLIR E53 model thermal camera, which operates within the 7.5-14.0  $\mu\text{m}$  spectral range. The thermal camera used is capable of detecting temperatures between 20 °C and 650 °C and taking pictures with a total of more than 43200 pixels with a size of 240x180 pixels. Before the thermal imaging, the distance, emissivity, temperature and humidity values were registered to the camera. The thermal radiation emissivity of most plant surfaces between 10.5-12.5  $\mu\text{m}$  wavelengths ranges from 0.97 to 0.99 (Hatfield, 1990; Chen, 2015). Therefore, the emissivity value was taken as 0.98 during the imaging. Thermal imaging was made both on the plant and on the spike at clear sky conditions between 11:00-14:00. To determine the background temperature in thermal imaging, measurements were made at a distance of 1 m from the plant with aluminium foil. The emissivity value was taken as 1.0 in aluminium foil measurements (Jones *et al.*, 2002). FLIR Tools software was used for the analysis of the thermal images. The thermal images were analyzed using FLIR Tools software, which facilitated detailed examination and processing of the thermal data. Thermal imaging was performed at six specific intervals after seedling establishment: on the 70<sup>th</sup>, 103<sup>rd</sup>, 154<sup>th</sup>, 189<sup>th</sup>, 220<sup>th</sup>, and 250<sup>th</sup> days after sowing (DAS). For each replication, the leaf temperature of randomly selected plants was measured from three different directions. Each direction was measured three times to ensure accuracy. The average of these measurements was then calculated to determine the overall leaf temperature for each plant.

*Cultural practices; measurements and analyses*

Banana seedlings were planted in pre-prepared areas inside the greenhouse with a spacing of 1.80 m between plants in a row and 2.50 m between rows on April 22, 2022. Before planting, the land was plowed with a tractor; and approximately 8 kg of farm manure per meter was applied. The irrigation and fertilization of the banana seedlings were carried out using a sub-sprinkler irrigation system (with a manifold pipe of 63 mm; lateral pipes of 20 mm; and 6 bar pressure-resistant; 7 mm diameter spaghetti tubes of 1 meter, 75 cm sprinkler stakes and a flow rate of 120 L h<sup>-1</sup>). Additionally; to lower the air temperature inside the greenhouse and increase relative humidity during the summer months; a misting system (Netafim coolnet 4x5.5 L h<sup>-1</sup> (22 L)) was used. Fertilization was done following the recommendations by Gübbük *et al.* (2010). During the vegetative growth stage, nitrogen-based fertilizers were applied. During the flowering stage, phosphorus-based fertilizers were used; and after the formation of the bunches, potassium-based fertilizers were administered. Water and fertilizer applications were uniformly carried out in all greenhouses during the experimental period with a sub-sprinkler irrigation system. Weed control was performed manually as needed. Pruning of leaves was done after the formation of the bunches, where dry, broken, and damaged leaves were pruned. During the growth process of the plants, red spider mite infestations were encountered and treated with pesticides.

In the experiment, several post-harvest, physical characteristics were considered, including the number of hands, the number of fingers, finger weight (g), finger length (cm), and yield per hectare. The number of hands and fingers was determined by counting all the hands and fingers on a bunch. Finger weight was measured immediately after harvest by individually weighing each finger on a precision scale. Finger length was measured from the dorsal side of the fingers using a tape measure from the tip of the fruit to the base of the stem. For yield determination, the harvested bunches were weighed on a scale to determine their weight. Yield (ton ha<sup>-1</sup>) was calculated by multiplying the average bunch weight by the number of plants per hectare (200 plants).

*Statistical Analysis*

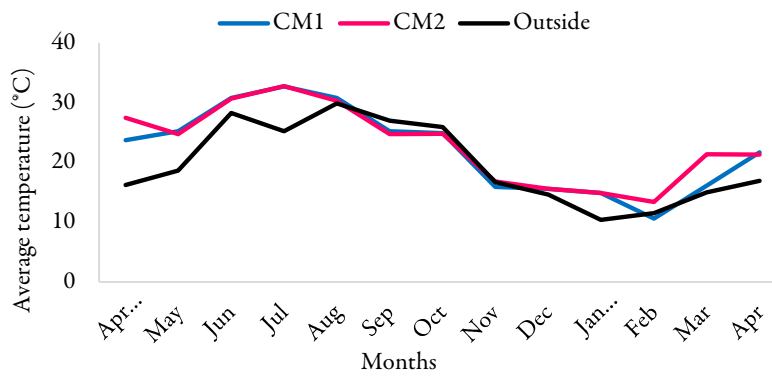
The experimental design was a randomized block design with four replications, each consisting of four plants. For fruit-related criteria, three replications were used with ten fruits per replication. Statistical analyses of some fruit quality parameters (the number of hands and fingers, finger weight and finger length) and yield were performed using SAS (Version 9.0). The leaf temperature data were subjected to analysis of variance

(ANOVA) using SPSS 13.0 (SPSS Inc., Chicago, Illinois). Means were separated using LSD multiple range test at 0.05 levels.

## Results and Discussion

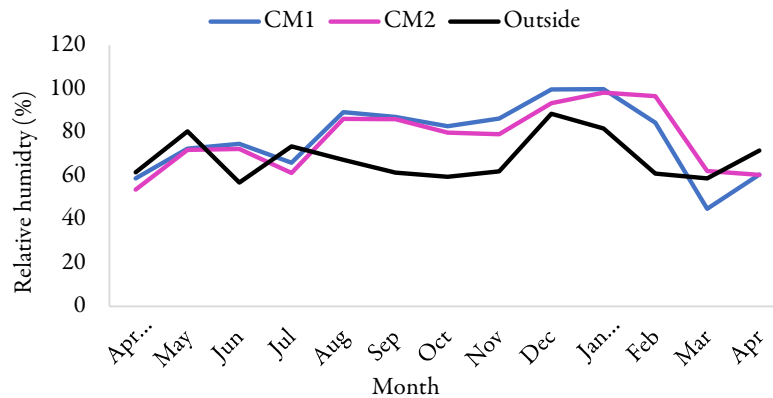
### *Climate parameters*

During the experimental period; the average temperature values under CM1 ranged from 10.6 °C to 32.7 °C while under CM2 they ranged from 13.4 °C to 32.8 °C. Outdoor temperatures varied between 10.4 °C and 29.9 °C. Within the experimental greenhouses; the lowest temperatures were recorded in February 2023 whereas the highest temperatures occurred in July 2022. Generally, the highest indoor temperatures were observed under CM2, while the lowest indoor temperatures throughout the experimental period were recorded under CM1 (Figure 1).



**Figure 1.** Monthly average inside and outside temperatures in greenhouses covered with different covering materials

The monthly average relative humidity inside the greenhouses was generally higher than the ambient relative humidity. The average relative humidity values for CM1 ranged between 44.8% and 99.9%; whereas for CM2 they ranged between 53.6% and 98.2%. Outdoor relative humidity values varied between 58.9% and 88.5% (Figure 2). There was no significant difference observed between the plastic cover materials in terms of relative humidity values. The highest average relative humidity values were observed in December in the CM1 greenhouse; in January in the CM2 greenhouse; and in December outside.



**Figure 2.** Monthly average inside and outside relative humidity in greenhouses covered with different covering materials

When considering temperature and relative humidity values, it has been observed that both parameters vary according to the greenhouse cover materials. According to research findings, CM2 was found to be more advantageous in terms of temperature and humidity compared to CM1. Relative humidity values were recorded higher in both plastic cover types compared to the outdoor environment. Furthermore, considering the relative humidity data, humidity values under the cover were recorded higher especially during spring and winter months compared to the outdoor environment. The determination of humidity values, which are important for banana cultivation as higher under the cover than in the outdoor environment positively affects yield and quality. Cemek *et al.* (2006) determined daytime air temperatures of 29.1 °C, 29.8 °C, 30.6 °C, and 27.8 °C in UV PE, UV + IR PE, double layer PE, and single PE greenhouses; respectively. They noted that relative humidity was highest in double layer PE and lowest in single PE houses. Papadopoulos and Hao (1997) reported that relative humidity was highest in double layer PE, intermediate in acrylic, and lowest in glass houses. Altinkaya and Gübbük (2020) recorded higher humidity under netting similar to our findings compared to exposed conditions.

#### *Plant leaf temperature*

Six measurements at the 70<sup>th</sup>, 103<sup>rd</sup>, 154<sup>th</sup>, 189<sup>th</sup>, 220<sup>th</sup> and 250<sup>th</sup> days after sowing plant leaf temperature values obtained from thermal camera measurements for the selected banana cultivars under two different greenhouse cover materials are given in Table 1.

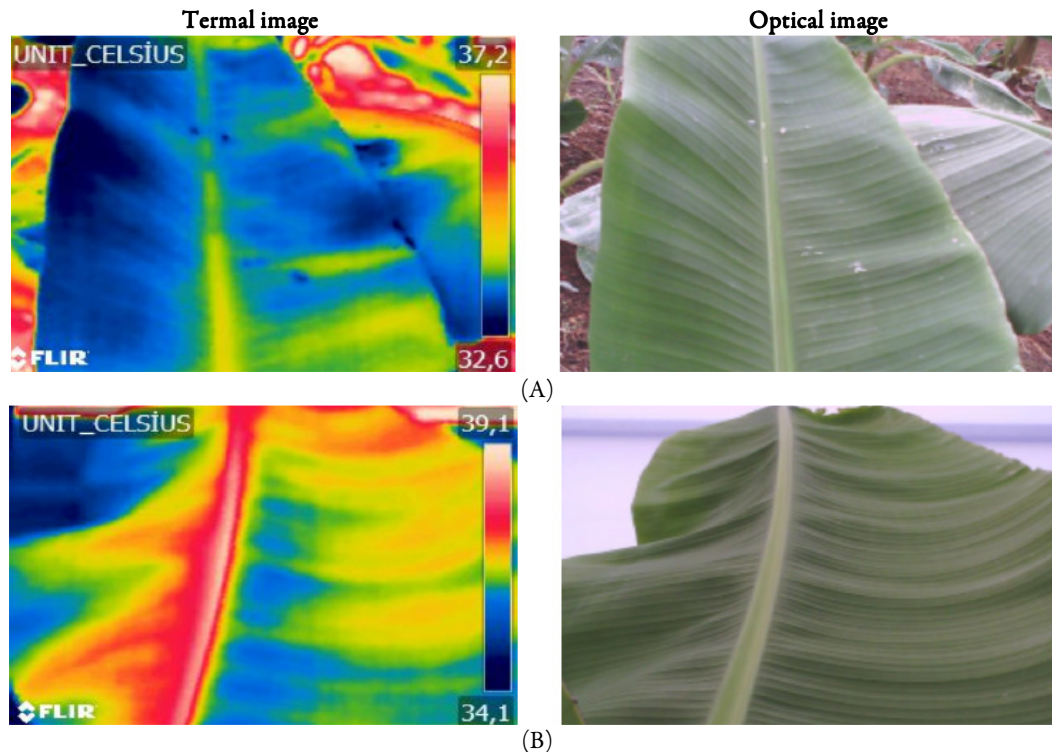
**Table 1.** Statistical analysis of leaf temperatures of banana cultivars (BC) under different greenhouse cover materials (CMs) at different days after sowing (DAS)

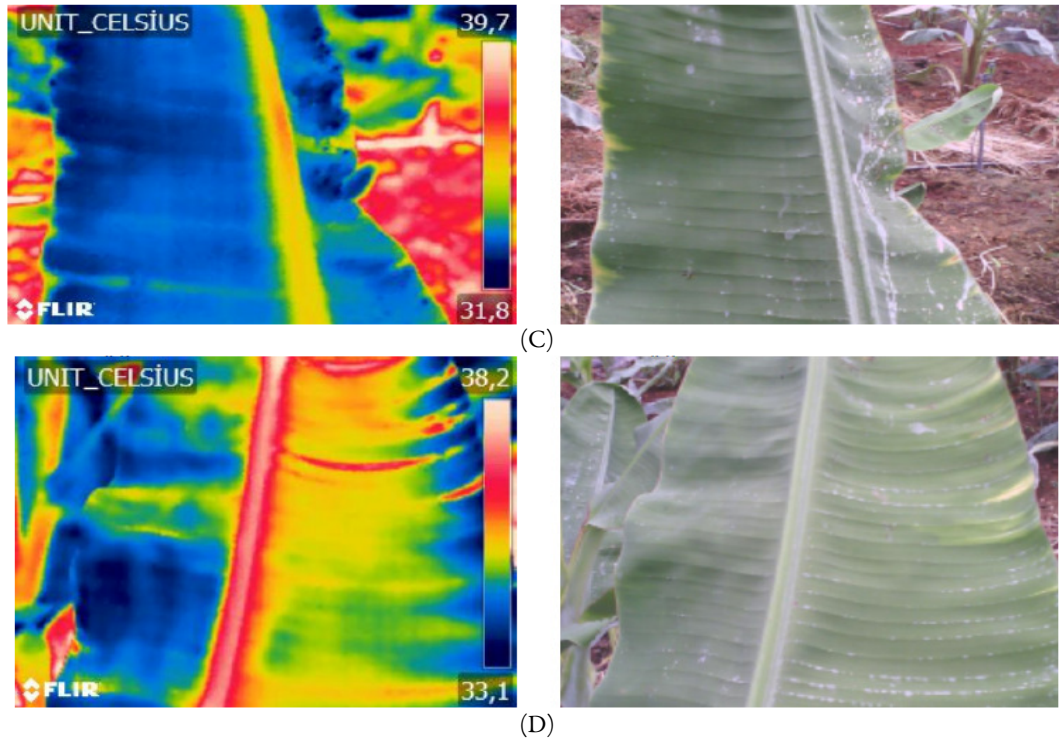
DAS	Banana cultivars (BC)	Cover material (CM)		<i>P</i> > <i>F</i>	<i>B/C Mean</i>
		CM1	CM2		
70 <sup>th</sup> DAS	BC1	31.31 <sup>†</sup>	33.29	***	32.30
	BC2	36.24	36.57	ns	36.41
	<i>P</i> > <i>F</i>	***	*	-	***
	<i>CM Mean</i>	33.78	34.93	*	-
103 <sup>rd</sup> DAS	BC1	32.85 <sup>#</sup> <i>d</i>	34.08 <i>c</i>	-	-
	BC2	36.54 <i>a</i>	35.59 <i>b</i>	-	-
154 <sup>th</sup> DAS	BC1	26.47	26.70	ns	26.58
	BC2	27.37	27.03	ns	27.20
	<i>P</i> > <i>F</i>	*	ns	-	*
	<i>CM Mean</i>	26.92	26.86	ns	-
189 <sup>th</sup> DAS	BC1	28.84	27.75	ns	28.30
	BC2	29.36	28.76	ns	29.06
	<i>P</i> > <i>F</i>	ns	ns	-	ns
	<i>CM Mean</i>	29.10	28.26	*	-
220 <sup>th</sup> DAS	BC1	25.77	25.10	ns	25.43
	BC2	26.74	26.01	*	26.37
	<i>P</i> > <i>F</i>	*	*	-	**
	<i>CM Mean</i>	26.25	25.55	**	-
250 <sup>th</sup> DAS	BC1	22.70 <sup>#</sup> <i>c</i>	22.44 <i>c</i>	-	-
	BC2	24.12 <i>a</i>	23.26 <i>b</i>	-	-

\*Notes: †: Each value is the mean of nine replications; \*: significant at the 0.05 probability level.; \*\*: significant at the 0.01 probability level.; \*\*\*: significant at the 0.000 probability level.; ns: statistically non-significant; #: Within each parameter (under all CMs and BCs) means followed by the same lowercase letter in italics are not significantly different according to LSD's multiple range test at 0.05 significance level

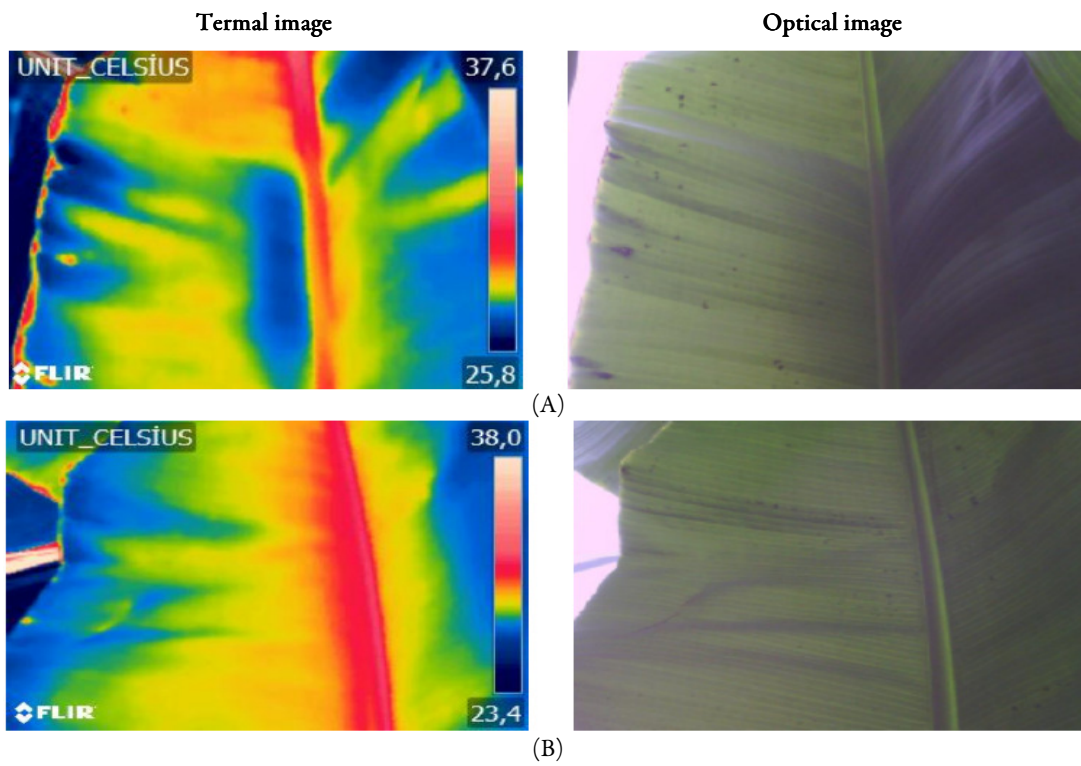
The first, third, fourth, and fifth plant leaf temperature values at the 70<sup>th</sup>, 154<sup>th</sup>, 189<sup>th</sup>, and 220<sup>th</sup> days after sowing (DAS) did not exhibit significant BC x CM interaction; but significant differences were observed for the first and fifth plant leaf temperature values under both BC and CM as the main factors. For the first thermal camera measurement conducted at the 70<sup>th</sup> DAS, the effects of both CM and BC on plant leaf temperature in banana plants were found to be statistically significant at 5% and 0.1% levels; respectively. Similarly, the fifth thermal camera measurement at the 220<sup>th</sup> DAS showed that the effects of both CM and BC as the main factors on plant leaf temperature in banana plants were statistically significant at 1%. The third thermal camera measurements at the 154<sup>th</sup> DAS revealed that the effect of BC as the main factor on banana plant leaf temperature was statistically significant ( $P < 0.05$ ); while CM as the main factor did not show significant differences in leaf temperatures averaged across BC. The fourth thermal camera measurements at the 189<sup>th</sup> DAS indicated that the effect of CM as the main factor on banana plant leaf temperature was statistically significant ( $P < 0.05$ ) whereas BC as the main factor did not show significant differences in leaf temperatures averaged across CM. However; plant leaf temperatures at the 103<sup>rd</sup> ( $P < 0.01$ ) and 250<sup>th</sup> ( $P < 0.01$ ) DAS exhibited significant BC x CM interaction (Table 1). With significant BC x CM interactions; the highest plant leaf temperatures at the 103<sup>rd</sup> and 250<sup>th</sup> DAS were recorded for BC2 under CM1 (36.54 °C and 24.12 °C). The lowest plant leaf temperatures were recorded for BC1CM1 (32.85 °C) at the 103<sup>rd</sup> DAS and for BC1CM1 (22.70 °C) and BC1CM2 (22.44 °C) at the 250<sup>th</sup> DAS (Table 1).

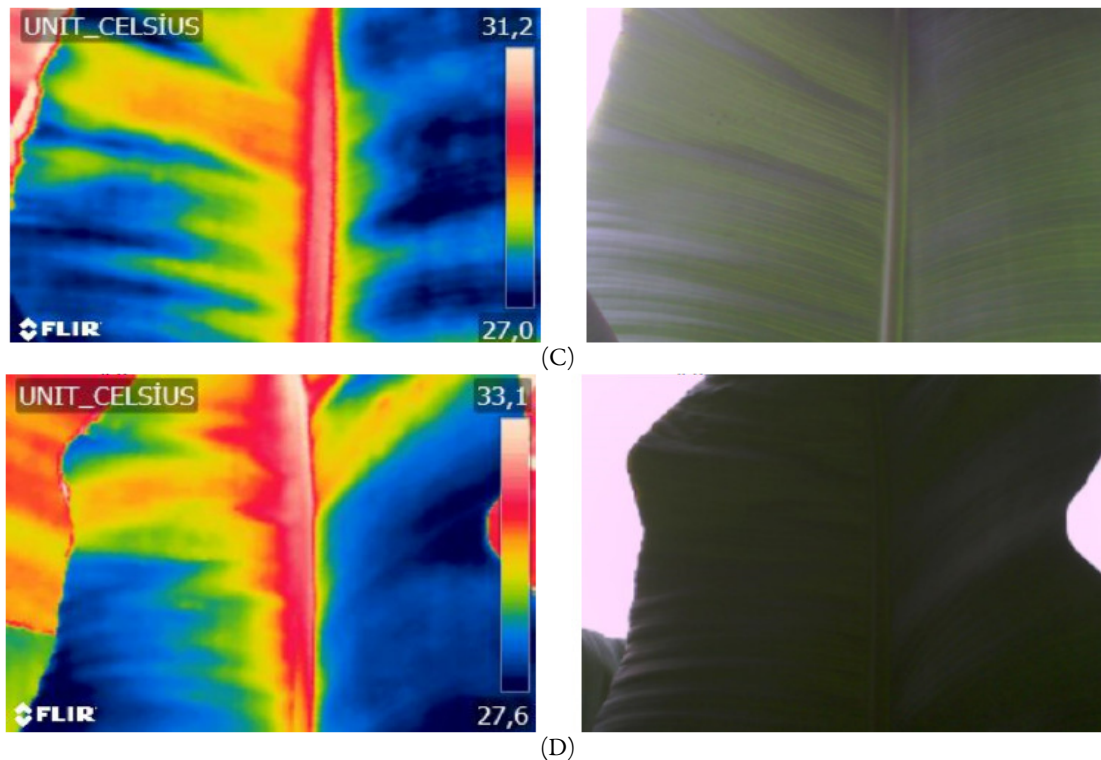
The FLIR Tools analysis results of thermal images obtained for banana crops under different greenhouse cover materials on August 3<sup>rd</sup> and October 28<sup>th</sup> are presented in Figure 3 and Figure 4, respectively. Upon examining the thermal images; it is evident that cold colors; especially blue tones; are more prevalent in the BC1 banana cultivar compared to BC2 in both types of cover materials. Notably; warm colors dominate more in the CM2 greenhouse for both banana cultivars in Figure 3 and Figure 4, respectively.





**Figure 3.** Thermal image analysis with FLIR Tools software for the banana cultivar; (A) BC1CM1; (B) BC2CM1; (C) BC1CM2 and (D) BC2CM2 at 103<sup>rd</sup> DAS





**Figure 4.** Thermal image analysis with FLIR Tools software for the banana cultivar; (A) BC1CM1; (B) BC2CM1; (C) BC1CM2 and (D) BC2CM2 at 189<sup>th</sup> DAS

In the six thermal camera measurements conducted, higher leaf temperature values were obtained for the BC2 banana cultivar compared to BC1 under both greenhouse cover materials. Statistically higher leaf temperature values were observed in BC2CM1 and BC2CM2 during the measurements on the 103<sup>rd</sup> and 250<sup>th</sup> days; where interaction effects were detected. Indeed; this situation is reflected in thermal images (Figure 3B, 3D, 4B, 4D).

Considering the impact of global climate change and the expected increase in temperature, which is predicted to adversely affect agricultural production (Ladrera and Cagasan, 2022; Suranny *et al.*, 2022; Saikanth *et al.*, 2023); the fact that higher leaf temperatures were observed in the ‘Williams’ cultivar without a decrease in yield indicates that this cultivar may be more tolerant to temperature stress.

Studies on other plants besides bananas have identified the effects of applied treatments using thermal cameras. Kurunc *et al.* (2023) reported that wheat plant leaf temperatures ranged from 17.5 to 34.2 °C while spike temperatures ranged from 26.6 to 36.3 °C during the experimental period. They observed the lowest plant leaf and spike temperature values under controlled conditions; whereas the highest values were recorded under severe water stress. They concluded that thermal cameras enable rapid and contactless data acquisition and have the potential to be used in detecting water stress in wheat crops. Fouda *et al.* (2023) investigated the use of infrared thermography (IR) to detect and continuously monitor lettuce plant stress under nitrogen and irrigation water shortages. They highlighted that the interaction between water regime and nitrogen fertilization levels affects lettuce temperature indices. As evident from the literature; plant leaf temperature serves as an important indicator of stress conditions.

#### *Physical parameters and yield*

The number of hands, fingers per hand, finger weight, finger length, and yield values determined according to two different varieties of cover types are given in Table 2.

**Table 2.** Statistical analysis of physical characteristics and yield parameters of banana cultivars (BCs) under different greenhouse cover materials (CMs)

Parameter	Banana Cultivar (BC)	Greenhouse cover material (CM)		P > F	B/C Mean
		CM1	CM2		
Number of hand (piece)	BC1	9.00 <sup>†</sup>	8.62	ns	8.82
	BC2	8.52	8.99	ns	8.75
	<i>P &gt; F</i>	ns	ns	-	ns
	<i>CM Mean</i>	8.77	8.80	ns	
LSD <sub>05</sub> cultivar × cover material: ns; LSD <sub>05</sub> cultivar: ns; LSD <sub>05</sub> cover material: ns					
Number of fingers (piece)	BC1	145.16 <sup>#</sup> <i>b</i>	140.80 <i>d</i>	-	-
	BC2	142.29 <i>c</i>	160.87 <i>a</i>	-	-
LSD <sub>05</sub> cultivar × cover material: 1.272; LSD <sub>05</sub> cultivar: 0.899; LSD <sub>05</sub> cover material: 0.899					
Finger weight (g)	BC1	139.21 <sup>#</sup> <i>b</i>	135.85 <i>c</i>	-	-
	BC2	131.01 <i>d</i>	148.13 <i>a</i>	-	-
LSD <sub>05</sub> cultivar × cover material: 1.257; LSD <sub>05</sub> cultivar: 0.889; LSD <sub>05</sub> cover material: 0.889					
Finger length (cm)	BC1	20.32	20.80	ns	20.56
	BC2	20.79	21.15	ns	20.97
	<i>P &gt; F</i>	ns	ns	-	ns
	<i>CM Mean</i>	20.55	20.97	ns	-
Yield (ton ha <sup>-1</sup> )	BC1	40.2 <sup>#</sup> <i>ab</i>	39.5 <i>ab</i>	-	-
	BC2	37.8 <i>b</i>	41.9 <i>a</i>	-	-
LSD <sub>05</sub> cultivar × cover material: 0.251; LSD <sub>05</sub> cultivar: ns; LSD <sub>05</sub> cover material: ns					

\*Notes: †: Each value is the mean of four replications; #: Within each parameter (under all CMs and BCs) means followed by the same lowercase letter in italics are not significantly different according to LSD's multiple range test at 0.05 significance level; ns: non-significant

As seen in Table 2, except for the number of hands and finger length, interaction means are significant for all parameters. The number of hands ranged from 8.52 to 9.0 depending on the cover type and variety; while finger length varied between 20.32 and 21.15 cm. However, the highest number of fingers was found in CM2BC2 with 160.87 fingers; and the lowest in CM2BC1 with 140.80 fingers. Another parameter examined, finger weight was highest in CM2BC2 at 148.13 g and lowest in CM1BC2 at 131.01 g. The yield value, which had the most significant impact on hectare yield, was highest in CM2BC2 at 41.9 tons per hectare (t ha<sup>-1</sup>) and lowest in CM1BC2 at 37.8 t ha<sup>-1</sup>.

Yield and quality parameters in bananas vary according to cultivar, cover material, and ecological conditions. The higher yield in protected cultivation compared to open field has been supported by numerous studies in subtropical conditions (Eckstein *et al.*, 1998; Galán Saúco *et al.*, 1998; Mendez Hernandez, 1998; Gübbük *et al.*, 2004; Gübbük *et al.*, 2010; Altinkaya and Gübbük, 2020; Kumar *et al.*, 2023). Similarly, the effect of cultivar on yield and quality has been supported by various studies (Robinson *et al.*, 1993; Pınar *et al.*, 2021).

Among the parameters studied, bunch weight and finger count are directly influencing characteristics of yield. The effect of treatments on bunch count was found statistically insignificant with counts ranging from 8.52 to 9.00 across all treatments. When examining the effect on finger count, particularly CM2 was observed to have higher finger counts compared to CM1 as shown in Table 2. The effects on finger weight were found statistically significant based on interaction and plastic cover types, but insignificant based on cultivars. Finger length values were recorded above marketable fruit length in bananas; ranging from 20.32 cm to 21.15 cm. Pınar *et al.* (2021) evaluated yield and morphological characteristics of four banana cultivars under greenhouse conditions obtaining results lower than ours in terms of finger circumference and length. These differences are

believed to stem from differences in cover type and ecological factors. When examining the effect on yield per hectare, plastic cover type  $\times$  cultivar interaction was found statistically significant, while plastic cover type and cultivar alone were found insignificant (Table 2). Our findings indicate that the 'Williams' cultivar exhibited higher yield compared to 'Grand Nain'. Thus; besides ecological conditions and cultivar, the type of plastic cover material also influences yield and quality. However, there are limited studies comparing different cover materials. Studies on cultivation of some fruit species under different plastic cover types besides bananas have identified the effect of cover material. Akinaga and Hasbullah (2002) mentioned increased mango production with the use of plastic greenhouses in Okinawa. Galán Saúco and Rodríguez Pastor (2007) reported higher yield and fruit quality in papayas grown under greenhouse conditions compared to open field. In our study, it was determined that multi-layered plastic produced with CO-EX technology is more advantageous compared to mono technology.

### **Conclusion**

In this study, two different greenhouse cover materials, CM1 and CM2, were tested on 'Grand Nain' and 'Williams' banana cultivars. The results indicated that the CM2 cover provided better microclimate conditions, leading to higher yield and improved fruit quality compared to CM1. Between the tested cultivars, 'Williams' outperformed 'Grand Nain' and exhibited greater tolerance to heat stress, as confirmed by thermal imaging of leaf temperature. These findings emphasize that selecting suitable cultivars and advanced cover materials can enhance productivity, resilience to abiotic stresses, and support sustainable banana production in a changing climate. For future studies, it is recommended to investigate chlorophyll fluorescence parameters to better understand energy flow during photosynthesis, as well as to conduct economic evaluations, test additional cultivars, and assess irrigation strategies and water use efficiency under climate change scenarios.

### **Authors' Contributions**

Conceptualization: HG, NYT; Data curation: SK, NYT, HG; Formal analysis: HG, NYT, SK; Investigation: SK, HG, NYT; Methodology: HG, NYT; Supervision: HG; Validation: HG, NYT, SK; Visualization: NYT, HG, SK; Writing - original draft: SK, NYT, HG; Writing - review and editing: NYT, HG, SK.

All authors read and approved the final manuscript.

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### **Data availability of Data and Materials**

The data are available from the corresponding author upon reasonable request.

### **Conflict of Interests**

The authors declare that there are no conflicts of interest related to this article.

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