Original scientific paper
DOI: /10.5513/JCEA01/27.3.4792
Journal of Central European Agriculture, 2026, 27(3), p.659-666

# Plastic film mulch color affects leaf gas exchange, plant growth, and fruit yield of papaya (*Carica papaya* L.) in the southeast United States

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Received: March 27, 2025; accepted: May 10, 2026

## ABSTRACT

Papaya is a widely grown tropical fruit. In the subtropical US, therefore, relatively little work has been done on its production. The purpose of this one-year study was to ascertain how the color of plastic mulch affected papaya plant growth and fruit yield. Using a randomized complete block design with four replications, greenhouse-grown papaya seedlings were moved into the field. Raised beds equipped with drip irrigation and covered with black and silver plastic film-mulches were used to establish the plants. Papaya plants on silver mulch had lower root-zone temperatures and higher leaf net photosynthesis than those on black mulch. Silver-mulched plants were taller and had thicker trunks than black-mulched plants. The total number of fruit and fruit yield per plant were 49 and 34 kg, respectively, with silver mulch, and decreased to 26 and 16 kg, respectively, with black mulch. Thus, silver mulch increased fruit number and yield by 86% and 116%, respectively, compared to the black mulch. In conclusion, silver mulch was associated with enhanced photosynthesis and increased papaya plant growth and fruit yield compared to black mulch.

**Keywords:** plasticulture, heat stress, root zone temperature, soil temperature, photosynthesis

## INTRODUCTION

Originally from Mexico and Central America, the papaya (*Carica papaya* L.) is a fast-growing herbaceous plant that was domesticated in this region (Fuentes and Santamaría, 2014). Papaya plants vary in size, with wild papayas reaching 10 m in height and living up to 20 years (Ruiz et al., 2023). Papaya is among the five major tropical crops worldwide. Annual world production is 13.8 Mt, with the primary producers being India (5.34 Mt), the Dominican Republic (1.28 Mt), Mexico (1.14 Mt), Brazil (1.11 Mt), and Indonesia (1.09 Mt). Mexico is the largest papaya exporter, with 192,658 t destined primarily for the US (FAO, 2022). Papaya is a nutritious fruit rich in vitamins (A, C, thiamin, riboflavin, folate, and niacin), minerals (Ca, K, and Fe), and fiber and low in calories (Annegowda and Bhat, 2016; Kabir and Hossain, 2024; Lim et al., 2007). Ripe papaya possesses digestive, carminative, diuretic, anthelminthic, antiprotozoal, and anticancer properties (Alara et al., 2020). In addition, papaya leaf extracts increase platelet counts in dengue fever (Haward et al., 2024).

Because plastic mulches alter root-zone temperature (RZT), boost plant growth and fruit yields, and decrease soil nitrogen leaching, weed growth, and soil evaporation, they are widely used in vegetable production (Amare and Desta, 2021; Díaz-Pérez and Batal, 2002; Lamont, 1993). By altering the temperature of the root zone, mulch color has been shown to affect tomato and bell pepper plant growth and fruit yield (Amare and Desta, 2021; Díaz-Pérez and Batal, 2002). Mulches have been utilized with mixed results in fruit trees (Zhang et al., 2021). Several factors—crop, climatic conditions, and season—determine mulch selection. Plastic mulches alter the crop microenvironment by altering the energy balance, thereby affecting plant growth and fruit yield (Lamont, 2005). Black mulch is inexpensive and warms

the soil more than white-on-black mulch (Amare and Desta, 2021). The silver-on-black reflective mulch reflects much more incident radiation, resulting in lower RZTs during midday than the black mulch (Díaz-Pérez and Batal, 2002). However, at night, RZTs under the silver-on-black mulch are higher than those under white-on-black and black mulches. Fruit tree crops have shown increased earliness in response to soil warming provided by the plastic mulches (Bavougian and Read, 2018).

Plastic mulches inhibit weed growth in papaya and other fruit trees in Florida (Balerdi, 1976). In India, papaya plants with silver mulch yielded more than those with organic mulch or without mulch (Prajapati et al., 2017). Papaya plants with silver mulch also increased plant height, stem diameter, and fruit yield, resulting in the maximum net income and benefit-cost ratio compared to black mulch or no mulch (Sakariya et al., 2018). In Brazil, plastic mulch increased water efficiency in papaya plants compared with soil without mulching (Coelho et al., 2022). In the USA, however, research on papaya cultivation under mulching systems remains limited, particularly regarding the comparative effects of different mulch colors on plant growth, root-zone microclimate, and fruit productivity under the subtropical conditions of the southeastern region. Although mulching has been widely studied in other horticultural crops, its role in papaya production in this region is less understood, creating a significant knowledge gap in crop management recommendations. Therefore, this study aimed to evaluate the effects of plastic mulch color on papaya plant growth and fruit yield in the southeastern USA.

## MATERIALS AND METHODS

### *Growing conditions*

Papaya cv. Maradol was used for this study. 'Maradol' papaya fruit has red flesh and weighs 1.5 to 2.0 kg. It is prevalent in Cuba and Mexico (Alonso et al., 2008). Papaya seeds were sown (one seed per cell) in 200-cell black trays (Proptek Blackmore, Belleville, MI, USA) containing peat moss substrate (Pro-Mix PGX, 70% peat moss; Quakertown, PA, USA) on 15 Sept. 2008. When papaya seedlings were about 6 cm tall (27 Oct. 2008), they were transplanted from the trays to 4-L black pots (Hummert International, Earth City, MO, USA) containing the same peat moss substrate (one seedling per pot). The papaya seedlings were kept in a greenhouse [Univ. of Georgia (UGA), Tifton Campus] until transplanted to the field.

The field trial was carried out in sandy loam soil [pH 6.5; field capacity 0.13 $cm^3/cm^3$; permanent wilting point 0.06 $cm^3/cm^3$ at the UGA Tifton Campus Horticulture Farm in Tifton, Georgia (31.4797° N, 83.5213° W, and 109 m altitude). One drip tape (Ro-Drip; Roberts Irrigation Products, Inc., San Marcos, CA; emitter spacing of 20.3 cm and emitter flow of 8.3 mL/min) was buried 5 cm deep in each of the raised beds, which were 10 cm high and 90 cm wide. Plastic mulch (Pliant, Chesterbrook, PA, USA) was placed over the beds. Prior to applying the plastic mulch, 10-10-10 granular fertilizer (Super Rainbow fertilizer, Americus, GA, USA) was applied to the soil to supply nitrogen (N), phosphorus (P), and potassium (K) at rates of 50.0, 21.8, and 41.5 kg/ha, respectively. Following their transplantation to the field, papaya trees received weekly applications of 10 kg/ha of N and K via drip tape for the first two months. From then on, weekly applications of 15.7 kg/ha of N and K via the drip tape until their final harvest.

Papaya plants were transplanted from the pots to the field on 1 April 2009, once the risk of frost was minimal. Plants were established in a single row per bed, with a 2.4 m separation between plants and 3.6 m between rows (1,110 plants/ha). Plants received water equivalent to the reference evapotranspiration (ETo) (seasonal range 4 to 6 mm per day). Immediately after transplanting to the field, each papaya plant received about 500 mL of starter fertilizer solution (555 ppm N, 821 ppm P; 0 ppm K) applied to the base of each plant.

### *Experimental design*

Four replications and two plastic mulch treatments—black and silver-on-black—were included in the randomized complete block design. There were three plants in the plot.

***Rainfall, air temperature, and root zone temperatures***

A neighboring University of Georgia weather station (http://www.georgiaweather.net/) provided the field air temperature and rainfall data. Throughout the season, temperature sensors (four per treatment; placed at mid-day directly between two adjacent plants) were linked to a datalogger (WatchDog 1000 Series, Spectrum Technologies, Inc., Aurora, IL, USA) to measure root zone temperature (RZT) (10 cm deep) regularly.

***Volumetric soil water content (SWC)***

Three SWC measurements per plot were conducted weekly using the portable TDR sensor (CS-620, Campbell Sci., Logan, UT, USA). Readings were taken along the row of plants within the "dripping" area of the plant canopy.

***Chlorophyll concentration Index***

The chlorophyll concentration index (CCI) was determined weekly on two healthy, fully developed leaves per plant (three plants per plot) with a chlorophyll meter (SPAD-502, Minolta Co, Ltd., Ramsey, NJ, USA).

***Trunk diameter and plant height***

Trunk diameter was measured eight times [97, 107, 112, 126, 133, 141, 181, and 252 days after planting (DAP)] at a point 5 cm above the soil surface on each plant during the season in three plants per plot. Height was measured (from the base to the apex) on three plants per plot four times over the season (174, 181, 192, and 252 DAP).

***Leaf gas exchange***

A gas exchange system (LI-6400, LI-COR, Inc., Lincoln, NE, USA) was used to measure leaf net photosynthesis, internal $CO_2$, transpiration, stomatal conductance, leaf and air temperatures, and leaf vapor pressure deficit (VPD). With a $CO_2$ mixer and a $CO_2$ tank, the system was configured to have a $CO_2$ concentration of 400 µmol/mol. The ratio of leaf net photosynthesis to transpiration rate was used to compute the leaf photosynthetic water-use efficiency. Measurements were conducted on 8 September (153 DAP).

***Papaya pests and diseases***

Plants were visually evaluated for the incidence of diseases and insects every week. The presence of pests and diseases during the season was minimal.

***Fruit yield***

Plants were harvested on 11 Nov. (225 DAP), 3 Dec. (247 DAP), and 17 Dec. 2009 (261 DAP). Fruit from individual plants was harvested at the "turning" stage and graded as marketable (free from insect and mechanical damage and decay) and unmarketable. Due to freezing temperatures, the experiment was terminated in December, though many fruits had not reached the ripening stage.

***Data analysis***

SAS's GLIMMIX technique (version 9.4, SAS Inst. Inc., Cary, NC, USA) was used to analyze the data. Replication was a random effect, whereas plastic mulch color was a fixed effect. Treatment means were separated using the Tukey-Kramer test at the 0.05 significance level.

## RESULTS

***Air and root zone temperature***

Seasonal (1 Apr. to 17 Dec.) average minimal, mean, and maximal air temperatures were 17.0 °C, 22.1 °C, and 27.1 °C, respectively. Cumulative rainfall was 1120 mm. The daily mean root zone temperature (RZT) during the season was higher under black than under silver mulch (Figure 1). The daily mean RZT was about 20 °C at planting time (1 Apr.) in the field. The highest daily mean RZT for black mulch (30.5 °C) and silver mulch (28.6 °C) occurred between 80 DAP (20 June) and 130 DAP (10 Aug.). At the end of the season, the daily mean RZT was about 9.7 °C (silver mulch) and 9.9 °C (black mulch). The ANOVA showed that the mean seasonal root zone temperature was higher under black (mean 24.03 °C) than silver mulch (22.74 °C). Mean RZT under both black (RZT

= 5.97 + 0.828 x Tair; $R^2$ = 0.937; $P$ < 0.0001) and silver (RZT = 6.20 + 0.758 x Tair; $R^2$ = 0.948; $P$ < 0.0001) mulches was related with mean air temperature.

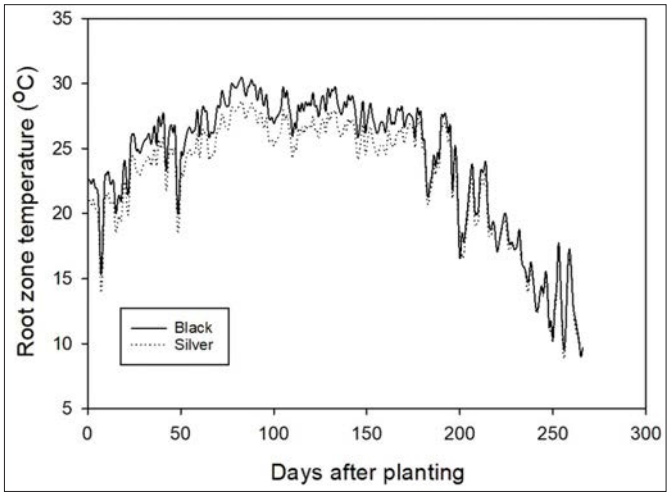



**Figure 1.** Daily mean root zone temperatures (10 cm deep) during the season in 'Maradol' papaya plants grown on black or silver plastic mulch (trees were planted in the field on April 1)

### *Soil water content and chlorophyll concentration index*

The volumetric soil water content (SWC) and leaf chlorophyll concentration index (CCI) did not vary due to the mulch's color (Table 1). SWC, numerically, was higher on black (9.45%) than on silver mulch (8.82%) during the growing season. The CCI of silver mulch was higher (51.63) than that of the black mulch (50.63) (Table 1).

**Table 1.** Soil water content and leaf chlorophyll index as influenced by the color of plastic mulch in papaya 'Maradol'

| Mulch | Soil water content (%) | Chlorophyll concentration index (CCI) |
|---|---|---|
| Black | 9.45 | 50.63 |
| Silver | 8.82 | 51.63 |
| *P* | 0.33 | 0.60 |

### *Plant height and trunk diameter*

Plant height and trunk diameter varied due to the mulch's color (Table 2). Papaya plants were taller on silver (mean seasonal height 1.67 m) than on black (1.35 m) mulch. Similarly, papaya grown with the silver mulch had a higher average trunk diameter (mean seasonal 8.28 cm) than the black mulch (6.02 cm).

**Table 2.** Plant height and stem diameter as influenced by plastic mulch color in papaya 'Maradol' [z]

| Mulch | Plant height (m) | Trunk diameter (cm) |
|---|---|---|
| Black | 1.35[b] | 6.02[b] |
| Silver | 1.67[a] | 8.28[a] |
| *P* | 0.004 | 0.023 |

[z] The Tukey-Kramer test indicates that values in a column that is followed by a different letter are substantially different at $P$ < 0.05.

Over the growing season, papaya trunks were thicker on silver than on black (Figure 2). Trunk diameter was highly correlated with plant height ($R$ = 0.941; $P$ < 0.0001) (data not shown).

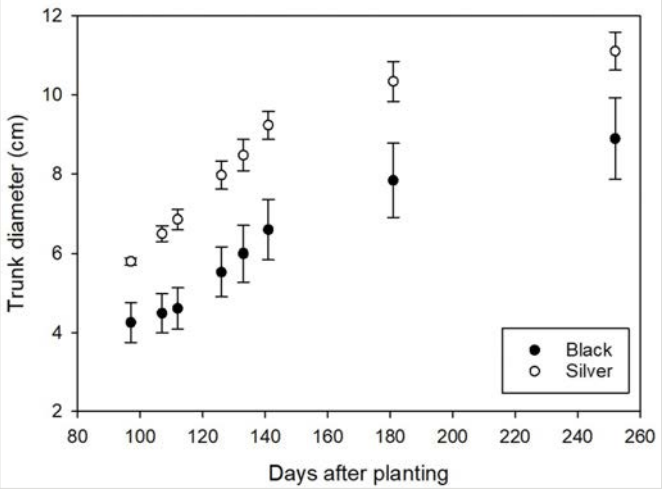



**Figure 2.** Effect of plastic mulch color on the trunk diameter of 'Maradol' papaya plants. Each point represents the mean (± SE) of 12 measurements

### *Leaf gas exchange*

Leaf net photosynthesis and stomatal conductance (barely nonsignificant) were higher in plants on silver mulch than in black mulch (Table 3). Internal $CO_2$ concentration, transpiration, leaf vapor pressure deficit (VPD), air temperature, leaf temperature, and photosynthetic water use efficiency did not differ due to mulch colors. However, numerically, silver mulch resulted in higher internal $CO_2$ concentration (230.67 µmol/m per second), transpiration (8.73 mmol/m$^2$ per second, air temperature (37.03 °C), and photosynthetic water use efficiency (2.23 µmol/m$^2$ per second) than black mulch. On the other hand, black mulch had higher leaf VPD (3.88 kPa) and leaf temperature (37.4 °C) than the silver mulch (Table 3).

### *Fruit yield*

The fruit number per plant was higher on silver mulch compared to black mulch (Table 4). Total fruit yields were also higher on silver mulch than on black mulch. Silver mulch yielded marketable fruits more than twice (2.19 times) that of black mulch. Fruit weight did not vary due to plastic mulch color, indicating that plant yield differences were attributed to differences in fruit number per plant. Nonmarketable yields did not differ between the mulch colors. Fruits were almost free from insect or disease damage (ca. 97% were marketable) (data not shown).

**Table 3.** Leaf gas exchange as influenced by the color of plastic mulch in papaya 'Maradol' [z]

| Mulch | Net photosynthesis (µmol/m² per second) | Stomatal conductance (mol/m² per second) | Internal $CO_2$ (µmol/m² per second) | Transpiration (mmol/m² per second) | Leaf VPD (kPa) | Air temperature (°C) | Leaf temperature (°C) | Photosynthetic water use efficiency (µmol/m² per second) |
|---|---|---|---|---|---|---|---|---|
| Black | 16.6[b] | 0.220 | 221.58 | 7.32 | 3.88 | 36.96 | 37.4 | 2.19 |
| Silver | 20.0[a] | 0.300 | 230.67 | 8.73 | 3.49 | 37.03 | 36.7 | 2.23 |
| *P* | 0.039 | 0.054 | 0.273 | 0.209 | 0.569 | 0.709 | 0.326 | 0.431 |

[z] The Tukey-Kramer test indicates that values in a column that is followed by a different letter are substantially different at $P < 0.05$

**Table 4.** Papaya fruit yields as influenced by the color of the plastic mulch [z]

| Mulch | Marketable | | | Nonmarketable | | Total | | Fruit weight |
|---|---|---|---|---|---|---|---|---|
| | fruit/plant | kg/plant | % | fruit/plant | kg/plant | fruit/plant | kg/plant | g/fruit |
| Black (B) | 25.4[b] | 15.5[b] | 97.2 | 0.7 | 0.36 | 26.1[b] | 15.9[b] | 609 |
| Silver (S) | 47.8[a] | 33.9[a] | 98.4 | 0.8 | 0.47 | 48.6[a] | 34.4[a] | 715 |
| S: B | 1.88 | 2.19 | 1.01 | 1.14 | 1.31 | 1.86 | 2.16 | 1.17 |
| *P* | 0.006 | 0.039 | 0.258 | 0.824 | 0.773 | 0.005 | 0.038 | 0.255 |

[z] The Tukey-Kramer test indicates that values in a column that is followed by a different letter are substantially different at $P < 0.05$

## DISCUSSION

Mulching increases leaf area and productivity of crops (Fan et al., 2017; Hou et al., 2019). Black polyethylene film mulch conserves soil moisture and minimizes weed growth, thus increasing water and nutrient supply to the crop (Kasirajan and Ngouajio, 2012; Rodrigues et al., 2021). Plastic film mulching on medium-textured soil enhances papaya yield while improving water-use efficiency by maintaining adequate soil moisture. It can produce an optimal yield even at water supply levels of 75% of ETc (Coelho et al., 2022). In the present study, the mean RZT under black mulch was higher than that under silver mulch. The augmented RZT is due to the reduced light reflection of black mulch compared to silver mulch (Tarara, 2000). High RZT above the optimal RZT for the crop has been associated with reduced vegetative growth and yield (Cooper, 1973; Díaz-Pérez and Batal, 2002; Kaspar and Bland, 1992). The increased RZT under black mulch may explain the reduced papaya plant height, stem diameter, fruit number, and yield, suggesting that plants were exposed to RZTs above the optimal range for papaya. In India, papaya plant height, stem diameter, and fruit yield were also higher with silver mulch than with black mulch or in un-mulched soil (Sakariya et al., 2018); this study did not report the crop-growing temperature conditions.

Papaya is a C3 plant with an optimal growth temperature of 21-33 °C (Campostrini and Glenn, 2007). Leaves may have a photosynthetic rate of 25-30 µmol/m$^2$ per second. Papaya plants on black mulch showed lower leaf photosynthesis and stomatal conductance compared to plants on silver mulch. This reduction in leaf gas exchange decreased assimilate production, thereby contributing to the observed decline in papaya vegetative growth and fruit yield. Low-temperature stress in papaya reduces photosynthesis, stomatal conductance, and transpiration, leading to suppressed plant growth, with photosynthetic rate declining by 57.96% compared with the control (Pradhan et al., 2018). Since soil moisture and temperature strongly influence root length density and distribution, mulching plays an important role in modifying the root-zone environment (Ge et al., 2025). Mulching enhances soil moisture retention and alters soil temperature, resulting in greater root concentration within the upper 0–20 cm soil layer in tomatoes (Ge et al., 2025). Consequently, organic mulching can substantially influence crop microclimate, agronomic performance, and overall yield (Kader et al., 2017). For example, grass mulching significantly increased soil temperature and moisture retention (20.9%), leading to higher biomass production (17.9%), yield (11.2%), and water-use efficiency (13.6–20.5%) in greenhouse-grown tomatoes (Zhang et al., 2023). Similarly, plastic film mulch increased peach fruit yield by 25% through improving soil water content and net photosynthesis (Wang et al., 2015), while sun hemp mulching enhanced root and shoot growth in papaya by increasing photosynthesis and stomatal conductance (Vincent et al., 2017).

Environmental conditions may influence papaya leaf gas exchange and plant water relations (Campostrini and Glenn, 2007). Photorespiration or water-limiting conditions may reduce leaf photosynthesis by 30% (Jiménez et al., 2014). Possibly, the high RTZ under black mulch resulted in reduced plant water uptake, as suggested by the higher SWC under black mulch compared to silver mulch. The differences in leaf gas exchange between treatments were probably not associated with a leaf temperature effect since leaf temperature was similar between mulch treatments.

## CONCLUSIONS

Plastic mulch color affected papaya plant growth and fruit yield. Silver mulch was associated with enhanced papaya plant growth and fruit yield compared to black mulch. The increased root-zone temperatures under black mulch may have been above the optimal range for papaya. Most fruits failed to reach the ripening stage due to freezing temperatures in December, although the majority had already attained the marketable size. The freeze-free period in South Georgia, USA (April to November), was thus insufficient to allow the fruit to reach maturity. Therefore, one option for papaya production in South Georgia may be to grow green fruit.

However, as the experiment was conducted within a single growing season and included only two mulch treatments, the findings should be interpreted with caution and not broadly generalized; further multi-season validation is recommended.

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