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Growth Diversity, Total Phenol, and Flavonoid of Various Cayenne Pepper (*Capsicum frutescens*) Genotypes Under Shading Stress

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Abstract

The study of adaptation mechanisms in cayenne pepper under shade stress is crucial for further exploration. Cayenne pepper is one of the primary commodities that play an essential role in the agricultural industry. This research focuses on the adaptation of morphological, physiological, and secondary metabolite characteristics of cayenne pepper under shading treatments, while also examining the role of microclimate on these characteristics. The study was conducted from August 2023 to February 2024 at the Leuwikopo experimental field of Bogor Agricultural University, using five genotypes of cayenne pepper cultivated under two shading treatments: 0% and 50% shading, achieved using shade netting. The results showed that among the five genotypes tested, shade-loving genotypes, such as "Bonita," and shade-tolerant genotypes, like "Ori 212," displayed a greater morphological response in terms of plant height and canopy width under 50% shade compared to the other genotypes. In terms of yield traits, shade-tolerant genotypes, such as "Ori 212", exhibited the highest fruit weight per plant under a 50% shading treatment compared to the other genotypes. Regarding physiological responses, specifically pigment content, no significant effect of shading treatment was observed. However, in terms of secondary metabolite content, all genotypes responded by increasing total phenol and flavonoid levels when grown in unshaded conditions or under full light intensity. This study provides insights into the adaptive responses of various cayenne pepper genotypes to microclimatic conditions in their growing environment.

Keywords: light intensity, microclimate, shade stress, yield performance

Introduction

Cayenne pepper is a shrubby species renowned for the heat of its fruit, a characteristic attributed to its high capsaicinoid content (Amaechi et al., 2021). This plant contains various essential nutrients and vitamins, including calories, protein, fat, carbohydrates, calcium, and vitamins A, B1, and C, making it one of the high-value horticultural commodities (Amaechi et al., 2021). As a member of the Solanaceae family, cayenne pepper is not only economically valuable but also offers significant nutritional benefits with its distinctive combination of color and flavor (Mweta and Nnungu, 2023). It is often cultivated commercially due to its high demand in both domestic and international markets (Siahaan et al., 2022).

Cayenne pepper has great potential for cultivation under shade or canopy systems, as studies have shown that certain levels of shading can enhance its growth and productivity (Febrianto et al., 2024). Some studies report that the yield of fresh green chili increases significantly under 35% shading intensity, although a notable decline in yield occurs when shading intensity reaches 75% (Gustiar et al., 2023). Other research has focused on developing shade-tolerant plant genotypes for various crops, such as tomatoes and rice. For example, Sulistyowati et al. (2016) reported that shade-tolerant tomato genotypes can grow optimally under 50% shading intensity, resulting in a productivity increase of up to 30%. Similarly, rice adapted to low light stress under 70% shading intensity demonstrated comparable or even higher productivity than in optimal conditions (Ma et al., 2023).

Siahaan et al. (2023) examined 20 cayenne pepper genotypes and observed variations in their responses to shading. Some genotypes were shade-loving, some were tolerant, and others were sensitive to shading. According to Samanta and Hazra (2019),

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low light stress in shaded environments can reduce light intensity by more than 50,000 lux, potentially decreasing cayenne pepper productivity. Shade-loving genotypes typically exhibit better adaptation mechanisms, enabling them to maintain high yields under low light intensity. Previous research on tomato plants also indicated that 50% shading significantly influenced the number of fruits produced (Ulinnuha et al., 2022). Additionally, Ritonga et al. (2019) noted that using 50% shade nets increased plant height, fruit count, and fruit weight per plant.

According to Arta et al. (2024) and Siahaan et al. (2023), managing light intensity with appropriate shading can serve as a strategy to enhance the productivity and adaptability of cayenne pepper plants. Beyond productivity, another critical aspect affected by shading conditions is the morphological and physiological growth of the plants, as well as the accumulation of secondary metabolites such as phenols and flavonoids. Plant pigments, including chlorophyll, carotenoids, and anthocyanins, play a crucial role in photosynthesis and plant adaptation responses to low light intensity (Yue et al., 2021). Meanwhile, secondary metabolites such as phenols and flavonoids are vital compounds in the plant's defence mechanisms against environmental stresses, including low light stress caused by shading (Al-Khayri et al., 2023).

This study specifically examines the morphophysiological growth changes of various cayenne pepper (*Capsicum frutescens*) genotypes under shading conditions and analyzes the accumulation of secondary metabolites, including phenols and flavonoids, in these genotypes. Additionally, observations were made regarding the impact of microclimate on the growth and development of the tested genotypes. Therefore, this research aims to provide a deeper understanding of the adaptive mechanisms of cayenne pepper to shaded conditions, as well as the contribution of pigment compounds and secondary metabolites in supporting the growth and resilience of cayenne pepper plants in shaded environments.

Materials and Methods

Genetic Materials and Field Conditions

The genetic material used in this study consists of five cayenne pepper genotypes resulting from crossbreeding conducted at the Plant Breeding Laboratory, Department of Agronomy and Horticulture, IPB University (Table 1). The field research was carried out from August 2023 to February 2024 at the Leuwikopo Experimental Farm, IPB University.

This study employed a nested plot design with two treatment factors. The first factor was the shading treatment with two levels (0% and 50% shading), while the second factor was the five cayenne pepper genotypes (F7.32190-5-2-2-1-4B, "Bonita", "Pulai Putih", "Ori 212", and F10-321290-252). The experiment comprised 10 treatment combinations, each replicated three times, resulting in a total of 30 experimental units. The cayenne pepper plants were cultivated under two distinct treatments per plots: one with 50% shading and the other without shading, using a total land area of 250 m². The entire experiment was conducted in an open field.

Procedures

The study began with the sowing of cayenne pepper seeds using seed trays filled with a mixture of loose soil and manure in a 1:1 ratio (w/w). Two seeds were placed in each hole of the tray. During the nursery phase, regular maintenance was conducted, including watering and applying AB Mix fertilizer (2 $mg.L^{-1}$ of water) when the seedlings were two weeks old. Shade structures were prepared by installing black shade nets with densities of 0% (N0) and 50% (N1) on all sides of the frames. The shade structures were 1.8 meters high above the ground and were installed two weeks before transplanting. The frames were constructed from bamboo and oriented east to west to maximize sunlight exposure. Field planting was carried out on raised beds measuring 25 m × 1.2 m, with a 1 meter spacing between beds and a height of 30 cm. Manure at a rate of 60 $tons.ha^{-1}$ and agricultural lime at 2 tons per hectare were applied to the beds two weeks prior to transplanting. Silver-black

Table 1. List of cayenne pepper genotypes

No	Genotype	Species	Owner agency	Shading preference
G1	F7.32190-5-2-2-1-4B	*C. frutescens*	Breeding Laboratory, IPB University	Shade-loving
G2	"Bonita"	*C. frutescens*	Breeding Laboratory, IPB University	Shade-loving
G3	"Pulai Putih"	*C. frutescens*	Breeding Laboratory, IPB University	Shade-tolerant
G4	"Ori 212"	*C. frutescens*	CV. Aura Seed Indonesia	Shade-tolerant
G5	F10-321290-252	*C. frutescens*	Breeding Laboratory, IPB University	Shade-sensitive

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plastic mulch was used to minimize weed interference and reduce pest and disease attacks. Transplanting of seedlings from the seed trays was performed when the plants were 30 days old, having 4–5 leaves. Only uniform, healthy seedlings, free from pests and diseases, and with fresh green leaves, were selected. Seedlings were planted in pre-prepared holes, one seedling per hole, at a depth of 3–5 cm and a spacing of 50 cm × 50 cm. During transplanting, Furadan was applied to the seedlings.

Crop maintenance from transplanting to harvest included watering, staking, pruning, fertilization, weeding, pest and disease control, and harvesting. Watering was conducted in the morning and evening, except during the rainy season when it was unnecessary. Staking was done a week after transplanting to support the plants, ensuring they grew upright and were protected against strong winds and rain. The stakes were 150 cm long. Pruning involved the removal of lateral shoots, conducted once a week from 7 to 30 days after planting, to enhance vegetative growth. Follow-up fertilization with NPK Mutiara (16-16-16) was applied weekly (10 $g.L^{-1}$ of water), with 250 ml per plant. Weeding was performed monthly, while pesticide spraying was conducted if pests posed a significant threat to plant growth and yield. Insecticide application was carried out biweekly using Abamectin-based insecticides (2 $g.L^{-1}$). If pest infestations affected plant growth, spraying was increased to once every three days until recovery. Plants were considered recovered when no visible pest damage was observed on new leaves and plant growth resumed normally, indicated by the emergence of healthy new shoots and leaves. Disease control involves the application of fungicides. Regular maintenance was essential to prevent the development of pests and diseases. Common pests and diseases in cayenne pepper cultivation include thrips (*Thrips parvisipinus*), *aphids, anthracnose*, and Fusarium wilt (Desita et al., 2015). Regular and scheduled plant care ensured optimal growth and yield while minimizing pest and disease outbreaks.

Microclimate Recording

Microclimate observations were conducted using the Elitech RC-4HC Data Logger to record temperature and humidity data at two locations: unshaded (0%) and shaded (50%) areas. The Elitech RC-4HC device was placed beneath the shade net and above the cayenne pepper plants. Light intensity measurements were taken manually using a Digital Lux Meter LX1010B by positioning the device beneath the shade net above the plants and outside the net for measurements and observations in unshaded areas. The Elitech RC-4HC Data Logger and Digital Lux Meter LX1010B were moved weekly for each replication to ensure more accurate data collection. Microclimate data were recorded at three times of the day: morning (7:30 AM), midday (12:30 PM), and afternoon (4:30 PM), every 14 days, starting two weeks after planting.

Morphological, Physiological and Yield Measurements

Morphological traits, such as plant height, stem diameter, root length, canopy width, fresh canopy weight, fresh root weight, dry canopy weight, and dry root weight were measured and recorded 12 weeks after planting. For physiological traits, leaf pigments were analyzed, including chlorophyll a, chlorophyll b, total chlorophyll, anthocyanins, and carotenoids. Chlorophyll content (units) was measured on fully developed leaves at 9 weeks after planting, with three replications. Leaf pigment content was assessed following the procedure outlined by Sims and Gamon (2002). Yield-related traits were evaluated by measuring fruit weight per plant, which was determined by weighing all ripe fruits at harvest.

Secondary Metabolite Content Measurements

Secondary metabolite content measurement includes total phenolic content (TPC) and total flavonoid content (TFC) in the leaves. The TPC and TFC were determined based on sampled leaves. All mature leaves from a single plant, excluding petioles, were dried in an oven at 40°C for 72 hours. The dried samples were ground into powder using a food blender (Philips, Netherlands). One gram of powdered leaf sample was macerated in 70% ethanol at a ratio of 1:20 (one gram of leaf powder in 20 mL of ethanol) and shaken for 72 hours. The solution was then filtered and transferred into 50 mL glass vials. The filtrate was incubated in a refrigerator for 48 hours before being used for TPC and TFC analysis. Biological replicates were derived from three different plants.

The determination of total phenolic content (TPC) was performed using a gallic acid standard curve (Lawag et al., 2023). A prepared extract with a volume of 20 µL was added to a microplate. Subsequently, 100 µL of 10% Folin-Ciocalteu reagent (diluted in distilled water) was added to the microplate. After a 5-minute incubation, 80 µL of 7.5% Na_2CO_3 solution (w/v in distilled water) was added. The mixture was incubated in the dark for 120 minutes. Absorbance was measured at a wavelength of 750 nm using an ELISA reader. The total phenolic content was expressed as milligrams of gallic acid equivalent (GAE) per gram of dry weight (DW) (Sahid et al., 2022).

The determination of total flavonoid content (TFC) in

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the leaf extract followed the procedure described by Sahid et al. (2022). A volume of 10 μL of the extract was added to a flat-bottom microplate and mixed with 60 μL of methanol containing 10 μL of 10% $AlCl_3$ solution (in methanol), 10 μL of 1 M CH_3COOK solution (in methanol), and 110 μL of distilled water. The mixture was then incubated in a dark chamber for 30 minutes. The total flavonoid content in the sample was determined based on absorbance at a wavelength of 415 nm using a microplate reader spectrophotometer (Thermo Scientific Multiskan FC). The absorbance values were compared against a quercetin standard curve with various concentrations and expressed as mg QE (quercetin equivalent) per gram of dry weight.

Data Analysis

Data was analyzed using analysis of variance (ANOVA). Significant differences between treatments were separated with honestly significant difference (HSD) test at the 5% significance level, using PKBT Stat 3.1 (http://pbtstat.com/pkbt-stat/).

Results and Discussion

Microclimate

The results of the observations on microclimate, including temperature, humidity, and light intensity during the study, are shown in Figure 1. Overall, the daytime temperature at noon under 50% shading ranged from 29.2°C to 33.8°C, with an average of 32.24°C. Temperature and humidity data were recorded daily throughout the experimental period. Humidity under 50% shading ranged from 64.3% to 86.9%, with an average of 74.12%. The temperature under 50% shading was lower compared to the unshaded condition, while the humidity under 50% shading was higher than that in the unshaded condition. The average temperature under the unshaded condition was 32.9°C, with an average humidity of 69.17%. In addition to temperature and humidity, this study also measured the effect of light intensity under 50% shading and no shading (0%). Light intensity measurements were conducted using a lux meter. Under 50% shading, the average daytime light intensity was 40,541 lux, while in the unshaded condition, it reached 78,258 lux.

According to Siahaan et al. (2023), in their study of 20 chili genotypes, they found that one genotype was sensitive to shading, five genotypes were tolerant, five genotypes were moderate, and nine genotypes thrived under shaded conditions. The study revealed that at temperatures between 28-34°C, with an average humidity of 54%-68%, and an average light intensity below 23,000 Lux, these conditions were generally suboptimal for chili plant growth. The optimal light intensity for chili plant growth was reported to be between 35,000 and 50,000 lux (Samanta and Hazra, 2019). Under shaded conditions, the microclimate changed significantly. Light intensity decreased as the shading level increased, thereby reducing the amount of Photosynthetically Active Radiation (PAR), which could potentially hinder plant growth (Wang et al., 2022). However, at certain levels, shading can have a positive impact on plant growth and increase productivity (Febrianto et al., 2024). A 50% shading with the highest light intensity of 50,812 lux, temperature of 32.33°C, and humidity of 60.46% increased chili yield per plant by 36% in the shading-preferred genotype. In contrast, other genotypes showed a relative yield reduction of 44% in the sensitive genotype, 33% in the moderate genotype, and 4% in the tolerant genotype under 50% shading (Siahaan et al., 2023).

Morphological-Physiological Growth and Yield Characteristics

The cayenne pepper genotypes (F7.32190-5-2-2-1-4B, “Bonita”, “Pulai Putih”, “Ori 2012”, F10-321290-252) showed different growth and yield responses to two shading conditions, namely no shading (N0) and 50% shading (N1) (Table 2). The genotypes that prefer shading (F7.32190-5-2-2-1-4B and “Bonita”) and are tolerant to shading (“Pulai Putih” and “Ori 212”) generally exhibited better growth under shading. In contrast, the genotype sensitive to shading (F10-321290-252) showed a significant decline in performance under these conditions.

The interaction between shading and chili genotype had a significant effect on plant height. The results of the ANOVA test showed that 50% shading increased plant height compared to the control for all genotype groups. The genotypes that prefer shade (“Bonita”) and those that are tolerant to shade (“Ori 212”) exhibited the highest average plant heights under 50% shading, at 118.11 cm and 118.27 cm, respectively, followed by the shade-sensitive genotype (“F10-321290-252”) with an average height of 102.81 cm. Under non-shaded conditions, “Bonita” also recorded the tallest growth at 110.20 cm, followed by “Ori 212” at 94.53 cm, and F10-321290-252 at 87.42 cm. The difference in plant height was caused by the shading proportion, which influences the cell elongation process. Luo et al. (2023) explained that the accumulation of auxin on the side of the stem, where light capture is low, causes faster elongation, resulting in etiolation under shading. Taiz and Zeigerb (2010) noted that plants under shade undergo etiolation as a response to

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capture more light, resulting in increased plant height. This is further supported by Handriawan et al. (2016), who stated that the canopy of plants exposed to direct sunlight inhibits auxin activity, slowing their growth, while plants under shade experience no inhibition of auxin activity. This condition leads to taller growth in plants that are shaded compared to those exposed to direct sunlight. According to Kabir et al. (2022), the height of chili plants correlates positively with their production, as taller plants will have more branches, resulting in higher fruit yields.

Under low-light conditions, plants undergo morphological changes to maximize light utilization. Kim et al. (2022) found that shade-tolerant paprika plants have longer stem internodes, larger leaves, and thinner leaves compared to plants adapted to high-light conditions. In this study, similar morphological traits were observed, particularly in shade-tolerant genotypes such as "Pulai Putih" and "Ori 212". These genotypes exhibited increased plant height, broader leaf area, and wider canopies under 50% shading, which are consistent with typical

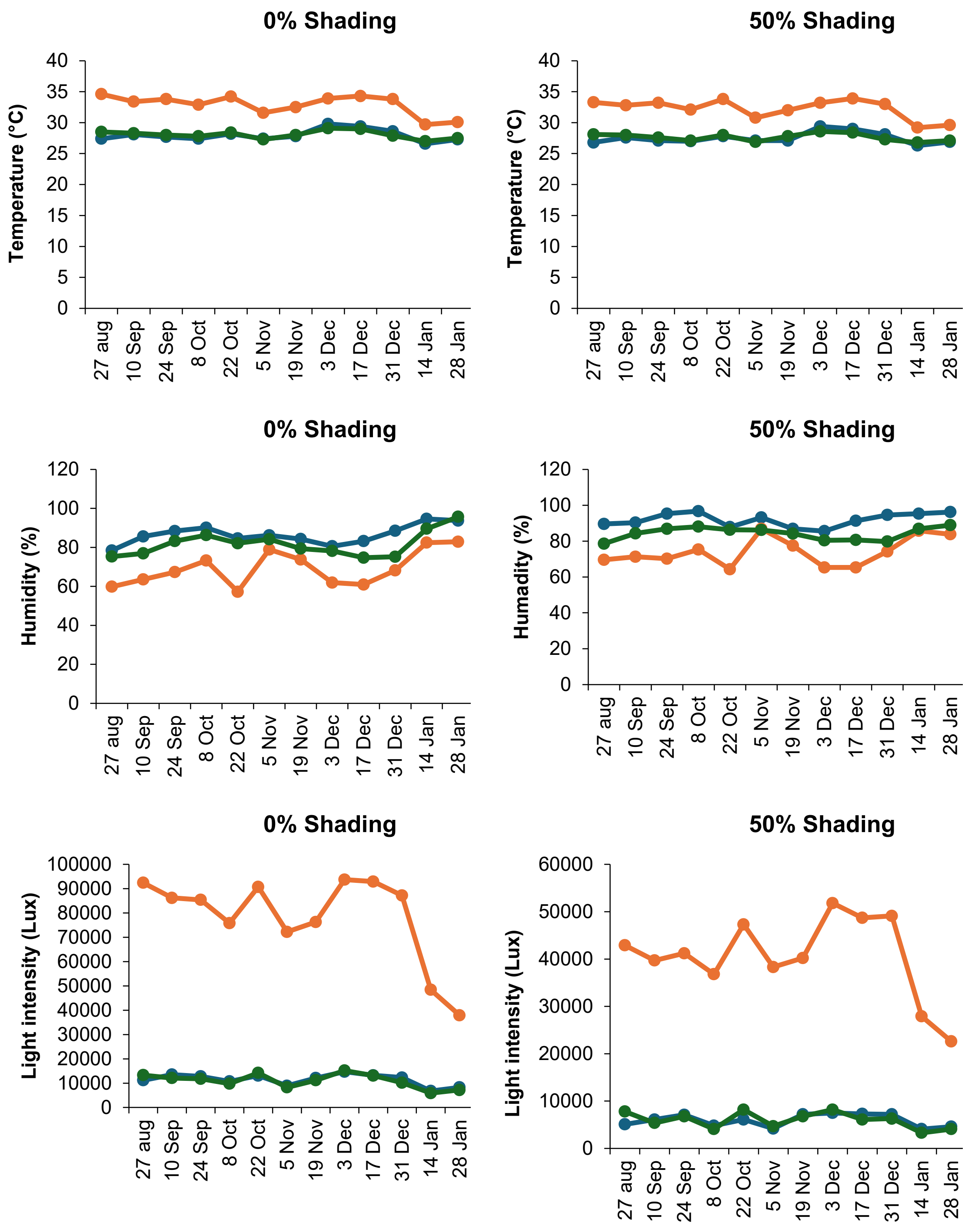

Figure 1. Microclimate (temperature, humidity, and light intensity) on the land during the study.

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shade adaptation responses. Under 50% shading, plant height was larger; however, it was generally not supported by strong stems when compared to plants in non-shaded conditions. Based on the comparison of plant height and stem diameter data, the shade-tolerant genotypes with the tallest plant height ("Pulai Putih" and "Ori 212") under 50% shading had larger stem diameters in non-shaded conditions, and these were significantly different from the shade-preferring genotype (F7.32190-5-2-2-1-4B). Under 50% shading, "Pulai Putih" had a height of 114.67 cm with a stem diameter of 13.72 mm, while "Ori 212" had a height of 118.27 cm with a stem diameter of 12.85 mm. This adaptive response is a strategy employed by shade-tolerant and shade-preferring genotypes to absorb more light under shaded conditions, thereby ensuring that the photosynthesis process remains optimal (Sulistyowati et al., 2019). Generally, shading treatments increase plant height, leaf number, and leaf area (Sulistyowati et al., 2019). The canopy width also showed significant differences, with "Ori 212" having the densest canopy, both under shading and non-shading conditions. In contrast, F10-321290-252 exhibited a decrease in canopy density under shading, indicating its limited ability to utilize lower light resources. This aligns with research by Ulinnuha and Syarifah (2022), who stated that chili plants can optimize their leaf surface area to absorb more light under shading conditions. Canopy width is closely related to the plant's mechanism for capturing and maximizing available light for photosynthesis. Providing 50% shading resulted in lower light intensity and a more uniform distribution compared to plants receiving full sunlight. Plants respond to low light by altering phytohormones that regulate phytochrome balance, particularly changes in ethylene, gibberellin, and auxin content, which leads to stem and petiole elongation (Tan and Qian, 2003; Susanto and Sundari, 2011).

Regarding phenolic and flavonoid content, higher concentrations in plants under shading may indicate enhanced antioxidant responses to light stress. Phenols and flavonoids function as protective compounds against oxidative stress, helping to stabilize cellular metabolism under suboptimal light conditions (Jadidi et al., 2023). Therefore, an increase in these compounds in shade-tolerant genotypes can be interpreted as an adaptive mechanism that maintains physiological function and protects photosynthetic tissues. Conversely, lower levels of these compounds in shade-sensitive genotypes may indicate limited biochemical adaptability to low-light environments.

In terms of the fresh and dry weight of both the canopy and roots, the shade-tolerant genotypes ("Bonita", "Pulai Putih", "Ori 212") consistently showed high

Table 2. Morpho-physiological characteristics, growth, and yield of five cayenne pepper genotypes

Treatments	Plant height (cm)	Stem diameter (mm)	Canopy density (cm)	Root length (cm)	Fresh root weight (g)	Fresh canopy weight (g)	Dry root weight (g)	Dry canopy weight (g)	Fruit weight per plant (g)
No shading									
F7.32190-5-2-2-1- 4B	57.92^{d}	9.68^{b}	47.83^{b}	19.72	11.05	99.33^{c}	6.19	47.00^{d}	27.47^{de}
"Bonita"	110.20^{abc}	14.94^{a}	89.07^{ab}	27.83	24.44	346.78^{ab}	11.19	134.28^{abc}	85.21^{ab}
"Pulai Putih"	113.72^{ab}	13.58^{a}	92.45^{ab}	28.73	21.45	361.33^{ab}	12.28	148.69^{ab}	52.50^{bcd}
"Ori 212"	94.53^{abc}	14.78^{a}	101.73^{a}	29.29	23.86	455.27^{a}	11.75	174.97^{a}	64.10^{bc}
F10-321290-252	87.42^{bcd}	11.98^{ab}	58.17^{ab}	21.25	10.34	99.08^{c}	5.09	53.83^{cd}	19.85^{de}
50% shading									
F7.32190-5-2-2-1- 4B	81.12^{cd}	12.68^{ab}	88.43^{ab}	19.13	13.33	110.54^{c}	6.99	48.70^{d}	37.33^{cde}
"Bonita"	118.11^{a}	12.64^{ab}	78.44^{ab}	24.35	16.00	219.73^{bc}	7.54	68.90^{bcd}	83.83^{ab}
"Pulai Putih"	114.67^{ab}	13.72^{a}	92.14^{ab}	22.83	14.08	145.98^{c}	6.77	69.58^{bcd}	70.75^{b}
"Ori 212"	118.27^{a}	12.85^{ab}	105.03^{a}	24.33	20.02	404.35^{ab}	9.15	91.82^{bcd}	111.83^{a}
F10-321290-252	102.81^{abc}	12.25^{ab}	86.86^{ab}	20.11	9.36	107.43^{c}	4.94	46.97^{d}	9.47^{e}
Sig.	**	**	**	ns	ns	**	ns	**	**

Notes: Values followed by the same letter in the same column indicate results that are not significantly different according to the HSD test at the 5% level; **: significant at the 1% level; ns: not significant.

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results under shading, especially “Ori 212”, which had the highest fresh weight of the canopy, both under non-shaded and shaded conditions, at 455.27 g and 404.35 g, respectively. This indicates that shade-tolerant genotypes are capable of maintaining biomass production in low-light environments, a mechanism that enhances photosynthetic efficiency despite reduced light intensity. In contrast, the shade-sensitive genotype, such as F10-321290-252, exhibited a reduction in both fresh and dry weight of the canopy and roots under shading conditions.

According to Blomme et al. (2020), chili plants grown under shading can experience a biomass reduction of up to more than 90%, depending on plant density. This indicates that F10-321290-252 is less efficient in utilizing the limited light available for growth.

Genotypes F7.32190-5-2-2-1-4B and “Bonita” (shade-preferring) as well as “Ori 212” (shade-tolerant) showed higher fruit yields under shading, particularly “Ori 212”, which produced the highest fruit weight of 111.83 grams (Figure 2). When comparing the fruit weight per plant between shaded and non-shaded conditions, F7.32190-5-2-2-1-4B showed an increase of 35.90%, “Bonita” experienced a decrease of 1.62%, “Pulai Putih” showed an increase of 34.76%, “Ori 212” had a significant increase of 74.47%, and F10-321290-252 experienced a sharp decrease of 52.28%. Notably, F10-321290-252 consistently exhibited the lowest fruit weight across both conditions, indicating poor yield performance compared to the other genotypes, regardless of the shading treatment. Several studies on different chili genotypes have reported a reduction in the number of fruits and fruit weight per plant under shaded conditions, ranging from 24% to 50% (Putri et al., 2025). However, Díaz-Pérez (2013) reported a 30-47% increase in chili yields under shading. This suggests that the chili genotypes used by Díaz-Pérez (2013) were more tolerant to low light-intensity stress compared to the genotypes studied by Putri et al. (2025). The provision of 50% shading increased production per plant in shade-preferring genotypes by up to 36%. In contrast, other genotypes showed reduced production, with relative production decreases of 44%, 33%, and 4% for the sensitive, moderate, and tolerant genotypes, respectively, under 50% shading (Siahaan et al., 2023). This indicates that certain chili genotypes can adapt well to low-light environments and even produce more fruit.

Leaf Pigment and Secondary Metabolite Content

No significant differences in chlorophyll a and chlorophyll b were observed between shading treatments or among genotypes (Table 3). Photosynthetic pigments, such as chlorophyll a, chlorophyll b, the a/b ratio, anthocyanins, carotenoids, and total chlorophyll, can be used as indicators of plant tolerance to low light intensity (Bhanbhro et al., 2023). The response of shade-loving and shade-tolerant genotypes under shading conditions showed an increase in chlorophyll a and b, although not significant, with a greater tendency towards an increase in chlorophyll b than chlorophyll a. This is evident in “Bonita” and “Pulai Putih”, where chlorophyll a increased from 1.23 $mg.g^{-1}$ (“Bonita”) and 1.48 $mg.g^{-1}$ (“Pulai Putih”) to 1.77 $mg.g^{-1}$ (“Bonita”) and 1.59 $mg.g^{-1}$ (“Pulai Putih”). Similarly, chlorophyll b also increased in these two genotypes, from 0.44 $mg.g^{-1}$ (“Bonita”) and 0.55 $mg.g^{-1}$ (“Pulai Putih”) to 0.67 $mg.g^{-1}$ (“Bonita”) and 0.61 $mg.g^{-1}$ (“Pulai Putih”).

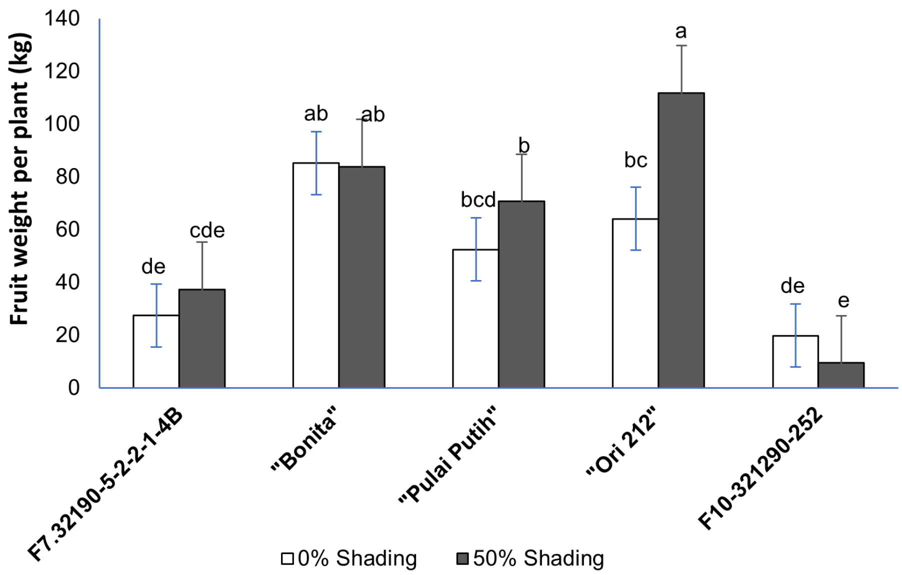

Figure 2. Fruit weight per plant of five cayenne pepper genotypes

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Table 3. Leaf pigment and secondary metabolite content in five cayenne pepper genotypes

Treatments	Chlorophyll a ($mg.g^{-1}$)	Chlorophyll b ($mg.g^{-1}$)	Anthocyanins ($\mu mol.g^{-1}$)	Carotenoids ($mg.g^{-1}$)	Phenols ($mg.g^{-1}$)	Flavonoids ($mg.g^{-1}$)
No shading						
F7.32190-5-2-2-1- 4B	1.30	0.48	0.68	0.46	2.50[ab]	0.98[abcd]
"Bonita"	1.23	0.44	0.67	0.48	2.49[ab]	1.21[a]
"Pulai Putih"	1.48	0.55	0.65	0.56	2.12[ab]	1.09[abc]
"Ori 212"	1.39	0.51	0.47	0.51	2.24[ab]	0.98[abcd]
F10-321290-252	1.34	0.50	0.73	0.52	2.62[a]	1.12[ab]
50% shading						
F7.32190-5-2-2-1- 4B	1.51	0.59	0.42	0.59	1.45[ab]	0.59[cd]
"Bonita"	1.77	0.67	0.46	0.63	1.83[ab]	0.67[bcd]
"Pulai Putih"	1.59	0.61	0.66	0.60	1.79[ab]	0.78[abcd]
"Ori 212"	1.32	0.49	0.41	0.48	1.97[ab]	0.53[d]
F10-321290-252	1.51	0.54	0.51	0.53	1.39[b]	0.59[cd]
Sig.	ns	ns	ns	ns	*	**

Notes: Values followed by the same letter in the same column indicate results that are not significantly different according to the HSD test at the 5% level; **: significant at the 1% level; ns: not significant.

Chlorophyll b is more efficient at capturing light under low-light conditions than chlorophyll a. Consequently, the response of shade-loving and shade-tolerant plants predominantly involves increasing chlorophyll b to efficiently harvest light, allowing photosynthesis to proceed normally under light-deficient conditions. This finding aligns with the study by Su et al. (2023) on shade-tolerant soybean Gongxuan, which showed increases in chlorophyll a, chlorophyll b, total chlorophyll (a+b), and a decrease in the chlorophyll ratio. The increase in chlorophyll content is associated with the high expression of the CAB (Chlorophyll a/b binding protein) gene, which is involved in forming the PSII (LHCII) light-harvesting protein complex. This gene encodes proteins that bind chlorophyll a and b, forming the light-harvesting complex within PSII (Zhang et al., 2025).

Shade-grown plants contain four to five times more chlorophyll a and b per unit volume of chloroplasts due to their higher levels of light-harvesting complexes. This is influenced by the binding of chlorophyll to pigment-binding proteins (CAB), forming the light-harvesting complex (LHC) in the thylakoids (Liu et al., 2020). Although the differences are not statistically significant, the data indicate that shade-loving and shade-tolerant genotypes (F7.32190-5-2-2-1-4B to F10-321290-252) exhibited increased chlorophyll a and b levels under shading. For instance, chlorophyll a increased from 1.30 $mg.g^{-1}$ (F7.32190-5-2-2-1-4B) and 1.34 $mg.g^{-1}$ (F10-321290-252) to 1.51 $mg.g^{-1}$ (F7.32190-5-2-2-1-4B) and 1.51 $mg.g^{-1}$ (F10-321290-252), while chlorophyll b increased from 0.48 $mg.g^{-1}$ (F7.32190-5-2-2-1-4B) and 0.50 $mg.g^{-1}$ (F10-321290-252) to 0.59 $mg.g^{-1}$ (F7.32190-5-2-2-1-4B) and 0.54 $mg.g^{-1}$ (F10-321290-252).

The increase in chlorophyll a and b in F7.32190-5-2-2-1-4B (G1) and F10-321290-252 (G5) under shading conditions is consistent with findings by Arta et al. (2024), which suggest that leaf pigment content can vary depending on environmental treatments such as shading and is also genotype-dependent. However, research by Hussain et al. (2020) emphasized that chlorophyll a and b levels often remain stable in genotypes well-adapted to shading conditions. Furthermore, Huang et al. (2021) reported that intercropping practices in tomatoes tend to enhance leaf pigment content (chlorophyll a, b, carotenoids) and other antioxidant enzyme activities. Photosynthetic pigments such as chlorophyll a, b, total chlorophyll, anthocyanins, and carotenoids can be considered indicators of a plant's tolerance to low light intensity (Siahaan et al., 2022).

The effect of light on plant growth is well known, and its intensity has a clear impact on plant growth and physiology (Paradiso and Proietti, 2022). However, more specifically, light intensity affects the accumulation of several secondary metabolites and nutrients. Higher light intensity is known to stimulate the synthesis of phenols and flavonoids, which protect living plants (Liu et al., 2020).

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Conclusions

This study demonstrated that 50% shading significantly influenced the microclimate, as well as the growth, yield, and secondary metabolite content of various cayenne pepper genotypes. Shade-loving genotypes (F7.32190-5-2-2-1-4B and "Bonita") and shade-tolerant genotypes ("Ori 212") exhibited strong adaptive responses to low light intensity. F7.32190-5-2-2-1-4B showed increased fruit yield under shading, while "Bonita" maintained stable yield and high flavonoid levels. "Ori 212" exhibited the best overall performance in terms of plant growth, fruit weight, and physiological adaptation, particularly under 50% shading, but also maintained high performance under full sunlight, making it the most promising genotype for both shaded and non-shaded environments. In contrast, the shade-sensitive genotype (F10-321290-252) showed a marked decline in growth, fruit yield, and total phenol and flavonoid content under shading, indicating limited adaptability to low-light stress. Overall, "Ori 212" and F7.32190-5-2-2-1-4B are recommended for cultivation in low-light or shaded production systems such as agroforestry or protected fields, due to their superior morphological performance, yield potential, and physiological resilience.

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