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Light Intensities Affect Canopy Architecture and Fruit Characteristics of Cayenne Pepper (*Capsicum frutescens* L.)

Intensitas Cahaya Mempengaruhi Arsitektur Kanopi dan Karakteristik Buah Cabai Rawit (*Capsicum frutescens* L.)

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ABSTRACT

Mechanical harvesting in cayenne pepper is developing, however, factors affecting canopy architecture and fruit characteristics are still lack. Study aimed to evaluate the effect of shade intensities on canopy architecture and fruit position in cayenne pepper to support developing smart harvesting tools. The experiment was conducted in Babakan Sawah Baru Experimental Farm, IPB from September 2021 to March 2022. The experiment used nested design with shade levels (no shade, 25%, 30%, 50%, 60%, 90%, and 100%) as the main plot and time of shading application (4, 6, 8, and 10 weeks after planting) as sub-plot. The canopy architecture and fruit position were affected by the shade level and its time application. Plant height increased and the canopy widened with increasing shade levels up to 50%. Thus, the shading level should be considered in the development of smart harvesting methodology.

Keywords: cabai rawit, climate change, labor, low light intensity, plant architecture

ABSTRAK

Pemanenan cabai rawit secara mekanis sedang berkembang, namun faktor-faktor yang mempengaruhi arsitektur kanopi dan karakteristik buah masih kurang. Penelitian bertujuan untuk mengevaluasi pengaruh intensitas naungan terhadap arsitektur kanopi dan posisi buah pada cabai rawit untuk mendukung pengembangan alat panen cerdas. Percobaan dilaksanakan di Kebun Percobaan Babakan Sawah Baru, IPB pada bulan September 2021 sampai Maret 2022. Percobaan menggunakan rancangan bertingkat dengan tingkat naungan (tanpa naungan, 25%, 30%, 50%, 60%, 90%, dan 100%) sebagai petak utama dan waktu pemberian naungan (4, 6, 8, dan 10 minggu setelah tanam) sebagai *sub-plot*. Arsitektur kanopi dan posisi buah dipengaruhi oleh tingkat naungan dan waktu penerapannya. Tinggi tanaman bertambah dan kanopi melebar seiring bertambahnya tingkat naungan hingga 50%. Oleh karena itu, tingkat naungan harus dipertimbangkan dalam pengembangan metodologi pemanenan cerdas.

Kata kunci: cabai rawit, perubahan iklim, tenaga kerja, intensitas cahaya rendah, arsitektur tanaman

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INTRODUCTION

Cayenne pepper (*Capsicum frutescens* L., Solanaceae) or *cabai rawit* is an important horticultural crop in many countries (Madala and Nutakki, 2020; Hilmiyah and Supriono, 2022). It is a taste enhancer, and as raw material in medicines and food industries (Andersen *et al*., 2017; Madala and Nutakki, 2020). In Indonesia, *cabai rawit* contributes to national inflation (Hilmiyah and Supriono, 2022).

Harvesting in cayenne pepper is mostly done manually, resulting in high production cost about 50-70% of the total cost (Hill *et al*., 2023). Hill *et al*. (2023) noted that the cost of harvesting depends on plant architecture, genetics, and environmental factors such as edaphic and climatic. In Indonesia, the cayenne pepper is grown in different climatic conditions and different season, e.g., dry and wet seasons also receives different light intensity causing different plant morphology (Kesumawati *et al*., 2020). Some farmers apply intercropping to maximize land and reduce risk against climate change (Rahman *et al*., 2021).

Mild shading applications in cayenne pepper increases yield and quality (Dewi *et al*., 2017; Lekala *et al*., 2019; Kesumawati *et al*., 2020; Hassanien *et al*., 2022; Siahaan *et al*., 2022; Alhidayah *et al*., 2024). However, the effect of light intensity on canopy architecture and fruit position are rarely evaluated in context to develop smart harvesting tools (Masood and Haghshenas-Jaryani, 2021). This study aimed to evaluate the effect of shade intensities on canopy architecture and fruit position in cayenne pepper to support developing smart harvesting tools.

MATERIALS AND METHODS

The research was conducted from September 2021 to March 2022, at Babakan Sawah Baru Experimental Farm, IPB University, Bogor (250 m above sea level). The highest rainfall was in November (69.5 mm day^{-1}) and the day without rainfall, occurred every month. Shading used a black paranet. Cayenne pepper used Bara variety.

The study used a nested block design with two factors. The first factor was seven shading levels (N0-without shading/control, N1-25%, N2-50%, N3-60%, N4-70%, N5-90%, and N6-100% shading) as main plot. The second factor was the time of shading application, i.e., P1 (shade was installed at the time 80% of plants bloom first flowering; 4 weeks after planting [WAP]), P2 (2 weeks after flowering; 6 WAP), P3 (8 WAP), and P4 (10 WAP). The experiment used three replicates, each replication consisted of 20 plants; five plants were selected randomly for measurements. Microclimate condition was recorded using an automatic data logger (Elitech GPS-6). Light intensity was measured using LICOR (Li-250A). Based on measurement, light intensity (n=4) under full, 25, 50, 60, 70, 80, 90, and ~100% of shading was 871.77, 571.40, 451.09, 181.14, 158.87, 23.80, and 3.63 µmol m^{-2} s^{-1}, respectively. Shading of ~100% was installed by using double layers of the black net of 90% blocked sunshine. Shading was installed at 2.5 m above soil, and all sides were covered by shading. Size of each shading was 5m x 3m.

The raised bed of 90 cm (width) and 20 cm (height) was covered using black plastic mulch. A 20 tons ha^{-1} of cow manure was applied at four weeks before planting. Initial fertilizer was broadcasted before installing plastic mulch, based on recommendations from Susila (2006) using 199 kg urea ha^{-1}, 311 kg SP-36 ha^{-1}, and 90 kg KCl ha^{-1}. At planting, one week after spreading plastic mulch, carbofuran (Furadan 3G®) was applied. Seedling aged 1.5 months after sowing was planted at distance 50 cm x 50 cm. Additional fertilizers were given at 2, 4, 6, and 8 WAP at a dose of 75 kg urea ha^{-1} and 34 kg KCl ha^{-1}. Urea, SP-36, and KCl contained 46% N, 36% P_2O_5, and 60% K_2O, respectively.

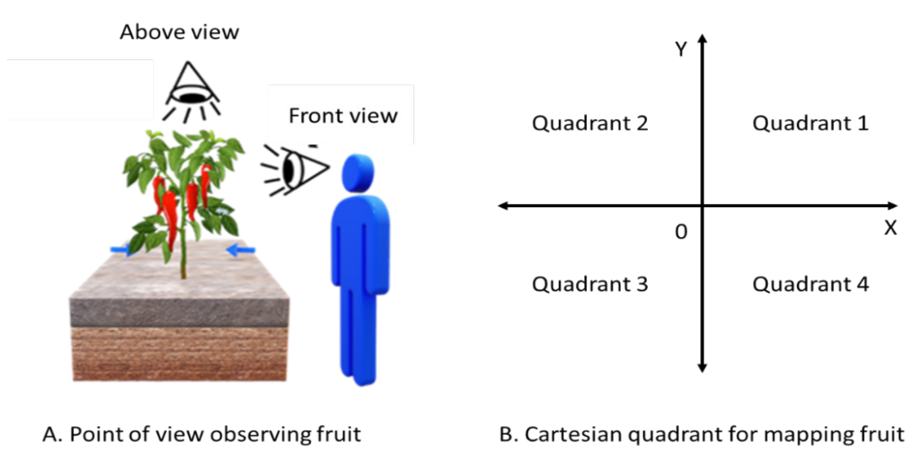

Figure 1. Point of view in measuring fruit position from the front and above of plant (A) and quadrant for mapping fruit position (B) by both front visions.

Watering was done every morning, in the absence of rainfall. Pesticide spraying was done based on the presence of pests and diseases. Weeding was done manually every two weeks. Fruit harvesting was done after became red.

Plant height was measured from the soil surface to the highest growing point. Stem diameter was measured at the middle main stem. The canopy diameter was determined as the widest point of the plant crown. The number of primary, secondary, and tertiary branches were counted. Fruit drop, young and red fruit, fruit size, and pedicel length were observed. All measurements were conducted at 11 WAP (maximum growth phase).

Fruit height position was measured from the ground surface to the fruit (as Y axis). The distance of the fruit from the main stem horizontally (cm) was measured from the main stem with a negative symbol (-) for the fruit to the right of the stem and a positive symbol (+) for the fruit to the left of the stem (as X axis). The fruit position inside the canopy (cm) was measured from the outer canopy projection to the fruit (as the Z axis). Fruit position was observed from the front and the top side (Figure 1A).

Fruit position was also mapped using a Cartesian diagram (Figure 1B). From above vision, Quadrant III and IV were for fruits that located in between planting beds, while Quadrant I and II were for fruits that located in the middle of the planting bed. Here X-axis position was parallel to the length of the beds, while Y-axis crossed the bed. From front vision, Quadrant I and II were for fruits that located above dichotomous branching, while Quadrant III and IV were for those that located below the dichotomous branching.

Data were analyzed with ANOVA using the Statistical Analysis System (SAS) 9.0 and Statistical Tool for Agricultural Research (STAR) 2.0.1. For any significant effect of treatment on traits, a further test of DMRT α 5% was performed. Fruit distribution was visualized using the Google Collaboratory program to produce a three-dimensional graph.

RESULTS AND DISCUSSION

Fruit position

Chili pods spread in the canopy both above vision (horizontal) and front vision (vertical) (Table 1). In the above vision, most of the chilies are in Quadrants III and IV with a proportion of 63.25% or more, except for the shading level of 60% where the number is 31.87%. In the field, chilies in Quadrants III and IV are on the edge of the beds.

The fruit distribution by front vision showed >88.89% of the chilies were in quadrants I and II, thus most of the fruits were above the dichotomous branching. In quadrant III there were no chilies except in the control treatment and 50% shade, while the fruit in quadrant IV came from plants with 70% shade (Table 1). The minimal distribution of chilies in Quadrant IV indicates that the bending of the chili canopy is relatively small, especially for the varieties used. The bending capacity of the chili canopy is influenced by genetics (Virga *et al*., 2021). In this study, the high proportion of chilies in quadrants I and II indicated that the effect of shading on the position of chilies was relatively smaller than expected (Table 1). The reason for the smaller distribution of chilies in quadrants I and II of the plants that received 50% shade could not be explained yet. It is possible that the bending of the chili canopy is slightly affected by the intensity of shading, but this assumption requires further research.

Table 1. Fruit number of cayenne pepper in each quadrant by above and front visions at 11 weeks after planting

Shading level (%)	Fruit number						Fruit distribution (%)				
	Q.I	Q.II	Q.III	Q.IV	0,0[z]	Total	Q.I	Q.II	Q.III	Q.IV	0.0[z]
Above vision											
0	18	0	42	87	10	157	11.46	0	26.75	55.41	6.37
25	12	28	52	22	3	117	10.26	23.93	44.44	18.80	2.56
50	5	8	35	6	0	54	9.26	14.81	64.81	11.11	0
60	45	15	11	18	2	91	49.45	16.48	12.09	19.78	2.20
70	6	10	29	27	3	75	8.00	13.33	38.67	36.00	4.00
Front vision											
0	105	39	3	0	10	157	66.88	24.84	1.91	0	6.37
25	34	80	0	0	3	117	29.06	68.38	0	0	2.56
50	11	37	6	0	0	54	20.37	68.52	11.11	0	0
60	63	26	0	0	2	91	69.23	28.57	0	0	2.20
70	29	39	0	4	3	75	38.67	52.00	0	5.33	4.00

Note: [z]0,0 means fruit position at the point of the dichotomous branch; n=3

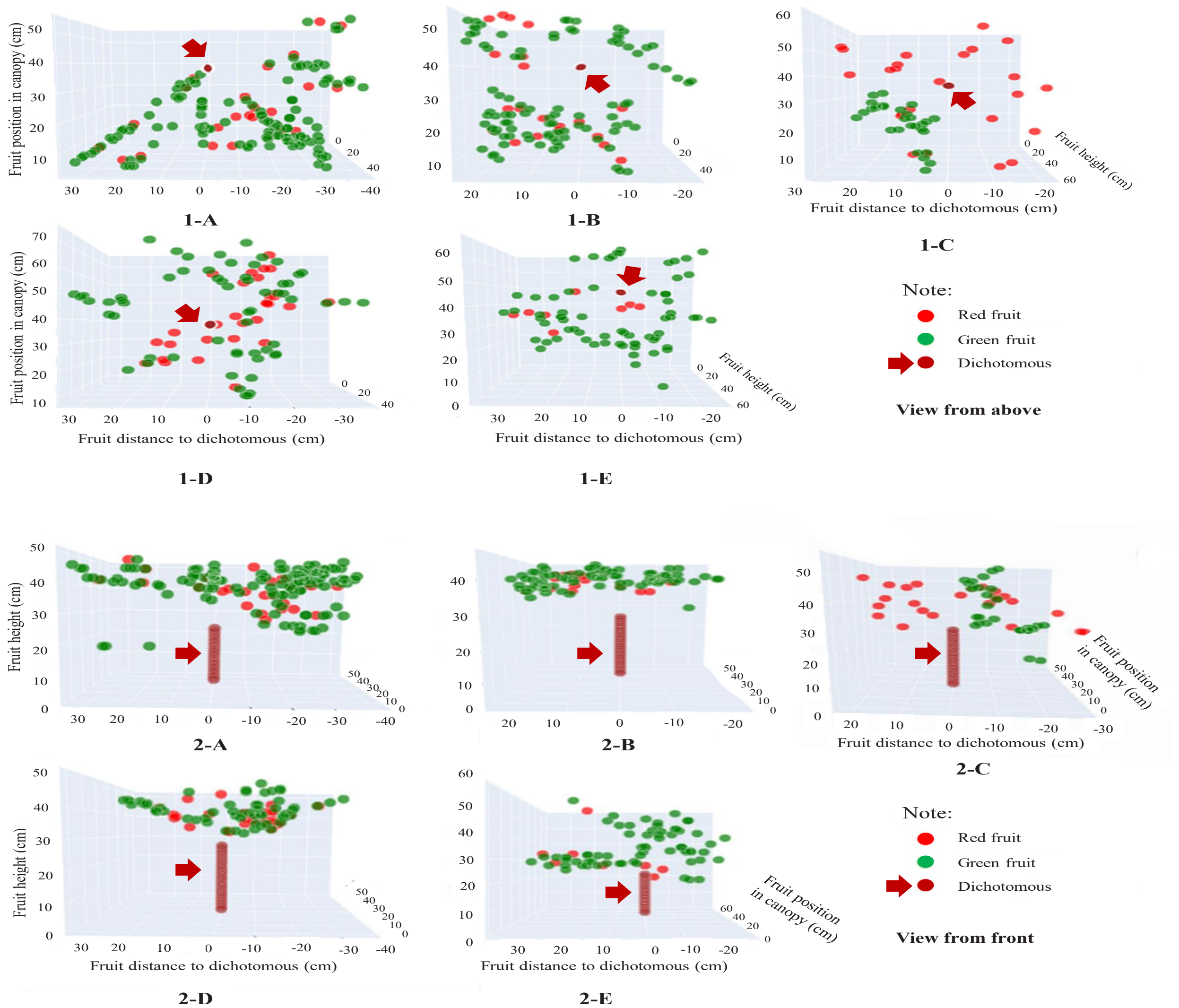

Figure 2. Fruit cayenne pepper position at 12 weeks after planting from above (above the line, 1A to 1E) and front vision (below the line, 2A to 2E). A-control plant, B-shading 25%, C-shading 50%, D-shading 60% and E-shading 70%. Plants from shading >70% did not survive

Table 2. Plant height and main stem diameter of cayenne pepper on different shading levels and its application time at 11 weeks after planting

Shading level	Plant height (cm)				Main stem diameter (mm)			
	P1	P2	P3	P4	P1	P2	P3	P4
0	60.20 ab	51.13 b	55.93 a	60.33 a	12.26 a	11.71 a	11.99 a	12.54 a
25	60.80 ab	53.20 b	58.33 a	60.52 a	9.90 b	8.97 b	10.73 ab	10.84 a
50	51.13 b	57.53 ab	60.00 a	60.27 a	7.85 b	8.41 b	8.99 bc	10.39 a
60	66.40 a	46.93 b	52.27 a	52.67 a	8.98 b	7.27 b	7.77 c	10.79 a
70	62.53 ab	66.33 a	60.00 a	54.53 a	7.98 b	8.31 b	10.37 ab	10.66 a
90	27.17 c	50.53 b	54.93 a	55.60 a	4.48 c	7.03 b	7.53 c	8.09 b
100	-	-	51.67 a	59.00 a	-	-	7.55 c	12.09 a

Note: Values in a column followed by similar alphabet are no significant by DMRT test α 5%; [z]Dead; P1-shading from 4 WAP, P2-shading from 6 WAP, P3-shading from 8 WAP, P4-shading from 10 WAP.

In three dimensions, the distribution of chilies varies in each shade and depends on the viewing angle (Figure 2). The distribution can be seen from the color distribution of young fruit (green) and ready-to-harvest fruit (red). The horizontal distribution of the fruit shows that the higher the shade treatment, the more the grouping of the distribution of red fruit and green fruit is seen. In the control treatment (Figure 2.1A), the distribution of red fruit was relatively even compared to the 50% and 60% shade which were more clustered (Figures 2.1C and 2.1D).

There is a change in fruit position grouping based on the color in certain areas due to shading (Figure 2). This grouping may be related to alternate photosynthate allocations. Alternate photosynthate allocation is observed in fruit trees (Akmal *et al*., 2023), but it requires further research in cayenne pepper.

Figure 2.2C shows old fruit on the left side while green fruit is on the right. This incident is thought to be because the red fruit is a strong sink (Zakaria *et al*., 2020) causing it suppresses the presence of young fruit. It is still a question of why the 60% shade treatment (Figure 2.2D) does not show clustering pattern as strong as the plants at 50% shade. Figure 2.2A and Figure 2.2B show red fruits are concentrated in the middle of the canopy, while in Figure 2.2D there are some red fruits clustered in green fruit. The position of red fruits in the middle is a consequence of the chili plant which has an indeterminate growth pattern (Tang *et al*., 2023).

Figures 2.2A to E shows that increasing the intensity of shade on chili plants causes more fruit close to dichotomous branches, especially shading > 25%. But the plants given the unshaded control also had some green fruits close to dichotomous (Figure 2.2A).

Canopy architecture

Plants with different shade treatments and the time of application had differences in plant height and main stem diameter (Table 2). Plants grown at > 60% shade had a larger canopy compared to control plants and 25% shade. The finding inline with Siahaan *et al*. (2022). According to Kesumawati *et al*. (2020), plants in low sunlight have higher auxin levels which encourage additional stem height.

Interestingly, shading only significantly affected plant height when applied at 4 WAP and 6 WAP, whereas application at 8 and 10 WAP did not affect the height (Table 2). This indicates that shading for 1-3 weeks has no significant effect on plant height. The inconsistency effect of shade on height of chili plants was also conveyed by Kesumawati *et al*. (2020). According to Chen *et al*. (2022) giving far-red light increased stem length and *Capsicum annuum* plants had more upright branches. In eggplant, Nguyen *et al*. (2022) stated that in shaded plants will be bushier.

Plants had smaller stem diameters with increasing shade levels in all treatments at the time of shading (Table 2). Plants in full light have the largest stem diameter. Plants from the treatment of 90% shading showed the smallest diameter compared to other treatments when shading was given at P1 (4 WAP) and P4 (10 WAP). Chili stems were getting smaller the longer the duration of the shade, indicating lower stem vigor. According to Kang *et al*. (2021) the sturdier stem, the more it supports harvest mechanization. Unfortunately, the strength of plant stems was not observed in this study.

Canopy diameter and dichotomous height were significantly affected by shade treatment (Table 3). Wu *et al*. (2017) stated that shading increased auxin and gibberellin, and decreased the cytokinin contents in leaves of soybean. In this study, an increase in the level of shade to some extent tended to increase the diameter of the canopy, depending on the time of application. Canopy diameter tended to increase relative to control plants at the timing of shading P1, P2, P3, and P4 at shade levels of 60%, 70%, 70%, and 100%, respectively. Enlarging the canopy favor to manually pick chili and possibly mechanized harvesting as well. According to Zhang *et al*. (2020), manual harvest efficiency increases with better visibility, whereas according to Mishra *et al*. (2023), mechanized harvesting of cotton is difficult with the larger canopy size.

Table 3. Canopy diameter and dichotomous branching height of cayenne pepper on different shading levels and its application time at 11 weeks after planting

Shading level	Canopy diameter (cm)				Dichotomous height (cm)			
	P1	P2	P3	P4	P1	P2	P3	P4
0	63.73 ab	56.07 ab	61.73 ab	64.47 ab	28.00 a	23.27 a	25.13 ab	28.53 a
25	61.85 ab	63.20 a	65.27 a	67.63 a	28.80 a	26.73 a	24.53 ab	28.98 a
50	55.20 b	57.63 ab	60.27 ab	62.47 ab	23.33 ab	27.40 a	26.73 ab	26.53 ab
60	70.10 a	58.90 ab	53.93 abc	62.60 ab	26.40 a	26.67 a	25.13 ab	24.87 ab
70	58.63 ab	66.50 a	64.83 a	54.10 ab	24.47 ab	22.93 a	19.33 b	20.53 b
90	20.42 c	45.70 b	48.87 bc	51.40 b	18.33 b	28.20 a	26.33 ab	25.33 ab
100	-	-	41.67 c	68.40 a	-	-	27.33 a	29.87 a

Note: Values in a column followed by different alphabet are significantly different using DMRT test α 5%; [z]Dead plant; P1-shading from 4 WAP, P2-shading from 6 WAP, P3-shading from 8 WAP, P4-shading from 10 WAP.

Table 4. Length and number of primary branches of cayenne pepper on different shading levels and its application time at 11 weeks after planting

Shading level	Primary branch length (cm)				Number of primary branches			
	P1	P2	P3	P4	P1	P2	P3	P4
0	16.13 ab	16.80 ab	15.33 a	20.47 a	10.40 a	8.60 a	6.80 a-c	9.00 a
25	15.20 ab	13.73 b	19.07 a	12.15 c	8.40 a-c	6.53 a	8.87 a	4.88 c
50	16.80 ab	16.27 ab	17.00 a	18.53 a-c	8.20 bc	7.20 a	8.33 ab	8.93 a
60	19.80 ab	14.07 b	12.70 a	14.87 a-c	6.93 c	7.00 a	4.33 d	6.20 bc
70	21.00 a	22.53 a	17.80 a	17.80 a-c	9.27 ab	7.40 a	7.47 a-c	7.20 ab
90	13.50 b	12.93 b	12.53 a	13.07 bc	2.50 d	6.73 a	6.53 bc	5.93 ab
100	-	-	17.17 a	19.07 ab	-	-	5.67 cd	8.47 a

Note: Values in a column followed by different alphabet are significantly different using DMRT test α 5%; [z]Dead plant; P1-shading from 4 WAP, P2-shading from 6 WAP, P3-shading from 8 WAP, P4-shading from 10 WAP.

Table 5. Number of secondary and tertiary branches of cayenne pepper on different shading levels and time of shading application at 11 weeks after planting

Shading level	Number of secondary branches				Number of tertiary branches			
	P1	P2	P3	P4	P1	P2	P3	P4
0	20.67 a	16.07 a	20.40 a	16.80 a	32.40 a	21.80 a	24.40 ab	27.20 a-c
25	16.27 ab	12.67 a	18.47 ab	8.97 b	24.00 b	23.27 a	30.53 a	17.70 d
50	15.60 ab	13.87 a	16.40 a-c	17.20 a	26.33 ab	24.47 a	30.27 a	29.07 ab
60	13.87 b	13.20 a	8.67 d	11.87 ab	26.53 ab	22.67 a	15.87 c	22.07 b-d
70	17.73 ab	14.27 a	13.87 b-d	14.40 ab	28.93 ab	23.47 a	23.07 a-c	23.20 a-d
90	5.33 c	11.60 a	12.20 cd	11.40 ab	9.00 c	20.40 a	19.00 bc	19.60 cd
100	-	-	11.33 cd	17.07 a	-	-	19.33 bc	30.40 a

Note: Values in a column followed by different alphabet are significantly different using DMRT test α 5%; [z]Dead plant; P1-shading from 4 WAP, P2-shading from 6 WAP, P3-shading from 8 WAP, P4-shading from 10 WAP.

In general, the height of dichotomous branching is relatively the same in the shading treatment up to 60%, irrespective of the time of shading (Table 3). At higher shades, dichotomous branching height showed variation. The inconsistent response of plants to > 60% shade for the high dichotomous variable probably occurred due to the inconsistency of photo-assimilate allocation at low light intensity. Trewavas (2002) stated that low light stress causes signal transduction disorder. Another possibility is that plant height is generally controlled by many genes and its expression is influenced by many factors (Dwivedi *et al*., 2015; Engstrom and Pfleger, 2017).

Shading treatments tended to increase the length of primary branches but their number tended to decrease (Table 4). The longest primary branches were owned by plants with 70% shade treatment at P1 and P2 shading. P3 and P4 treatments did not affect the size of the primary branches.

Control plants had the highest number of primary branches (Table 4). Except for P2, an increase in shading up to 60% markedly decreased the number of primary branches. An increase in shade > 60%, the plant responds erratically so that it shows varying values. It should be noted that in general the side shoots of the main stem of the chili plant are removed during treatment by retaining 2-3 primary branches which are in the dichotomous. However, in this study, the branches below dichotomous were unremoved which might affect the plant performance.

The number of secondary and tertiary branches decreased with increasing shade levels (Table 5). Control plants had the highest number of secondary and tertiary branches, especially at P1. Table 5 shows that there were variations in the number of primary and secondary branches from the control treatment in the treatment group at the time of shading (P). In this study, variations in control treatment could be due to variations in environmental factors, especially water availability, considering that the research was conducted during the dry season and irrigation was given manually. Various water levels affect the growth and yield of cayenne pepper according to Sinaga *et al*. (2020).

Table 6. Pedicle length, fruit length, and fruit diameter of cayenne pepper on different shading levels and its application time of harvested fruits at 11 weeks after planting

Shading level	Pedicle length (cm)				Fruit length (cm)				Fruit diameter (mm)			
	P1	P2	P3	P4	P1	P2	P3	P4	P1	P2	P3	P4
0	2.82 b	2.77 a	2.53 ab	2.74 ab	3.34 a	3.13 b	3.45 a	3.52 a	8.07 b	7.41 c	7.73 a	7.58 ab
25	2.57 b	2.68 a	2.68 a	2.50 bc	3.31 a	3.46 a	3.38 ab	3.19 b	7.76 b	7.69 bc	7.64 a	7.41 ab
50	2.72 b	2.64 a	2.68 a	2.78 a	3.28 a	3.14 b	3.13 b	3.18 b	8.20 b	7.61 bc	7.82 a	7.75 ab
60	2.70 b	2.55 ab	2.46 ab	2.62 ab	3.16 a	3.21 b	3.14 b	3.24 b	8.82 a	7.45 c	7.50 a	7.79 ab
70	3.07 a	2.68 a	2.39 b	2.67 ab	3.28 a	3.47 a	3.23 ab	3.49 a	7.85 b	8.31 a	7.56 a	7.94 a
90	2.50 a	2.34 b	2.68 a	2.35 c	3.32 a	3.28 ab	3.12 b	3.17 b	7.79 b	8.04 ab	7.60 a	7.33 b
100	-	-	2.42 b	2.54 a-c	-	-	3.12 b	3.19 b	-	-	7.50 a	7.39 ab

Note: Values in a column followed by a different alphabet are significantly different based on DMRT test α 5%; P1-shading from 4 WAP, P2-shading from 6 WAP, P3-shading from 8 WAP, P4-shading from 10 WAP.

According to Dewi *et al*. (2017), application of 40% shading increases the number of leaves of cayenne pepper. Unfortunately, in present study, the number of leaves was not observed, so the findings by Dewi *et al*. (2017) could not be confirmed.

Fruits characteristics

The highest amount of green fruit drop was in full sunshine and tended to decrease with increasing shade, and it significantly decreased at 50% shade relative to the control. The high fruit loss in full sunshine conditions is different from the findings of Joshi *et al*. (2019) who stated that the young fruit of bell pepper (paprika) was lower in full light conditions. Total green fruit decreased with the increasing shading treatment (data not shown). In the shade of 90% or more, the number of fruits was around 17-20% compared to the control and 25% shade. On the other hand, the time of shading had no significant effect on the amount of green that fell. A decrease in the number and size of fruit on Solanaceae due to shading has been reported (Ulinnuha *et al*., 2019; Kesumawati *et al*., 2020). According to Chen *et al*. (2022), far-red treatment reduced fruit set in *C. annuum*.

However, the percentage of fruit fall tended to be stable in the range of 0.79-1.57% in both control and shaded plants up to 70% (data not shown). Shading higher than 70%, increased the percentage of fruit fall. In tomatoes, Ito and Nakano (2015) stated that fruit fall occurs due to a decrease in auxin and an increase in ethylene in the pedicel. The ethylene concentration in the pedicel is affected by genotype, and plant age (Ulinnuha *et al*., 2019). Fruit fall also occurs due to increased FR (Chen *et al*., 2022).

Shading significantly affected the size of the pedicle and an increase in the level of shade tended to shorten the length of the pedicle, especially in P1 and P2 shading (Table 6). In P3 and P4 shading, the effect of shading on pedicle length did not have a regular pattern. Research on its relation to pedicel length in cayenne pepper and chili, in general, is still very limited. Chili fruit fall is positively correlated with fruit size, and negatively correlated with pedicle size (Setiamihardja and Knavei, 1990). Hill *et al*. (2023) stated that pedicel length was influenced by genotypes and their characteristics determined the success of mechanization in chilies.

Table 6 shows that shading does not affect fruit length, especially when shading was given at P1. The shade given to P2 and P4 showed a decreasing trend in fruit length with increasing shade intensity. The effect of shading on decreasing fruit size was in Solanaceae including chili (Yulianti *et al*., 2018; Ulinnuha *et al*., 2019; Siahaan *et al*., 2022). However, the decreasing trend was not statistically significant compared to the control. It should be noted that there are exceptions to the 70% shading which has a longer average fruit length, especially the shading given to P2 and P4.

Fruit diameter tended to be larger with the provision of shade, but depending on the time of application of shade (Table 6). Plants in 60% shade with P1 shading time had the largest diameter, while in P2 and P4 the largest fruit diameters were obtained in plants that were shaded 70%. At P3, the shading did not affect fruit diameter.

Research implication on smart harvesting

Models for smart chili harvesting are still under development (Lei *et al*., 2015; Nishanth *et al*., 2020; Masood and Haghshenas-Jaryani, 2021; Shin *et al*., 2021). According to Shin *et al*. (2021), a crucial step in chili mechanization is to separate fruits from the stems, and from the twigs. Setiamihardja and Knavei (1990) stated that the pedicle of cayenne pepper is firmly attached to the twig. According to Masood and Haghshenas-Jaryani (2021), the keys to a robotic harvester for chilies are the position of the chilies in 3D, affordability, and pedicle cutting.

Shading affected canopy geometry in present research. Many factors are known to affect plant geometry such as genotype (Swami *et al*., 2021; Siahaan *et al*., 2022; Alhidayah *et al*., 2024). In *Solanum nigrum*, canopy architecture is strongly influenced by nitrogen dosage and shade (Santosa *et al*., 2017; Yulianti *et al*., 2018). Thus, further research is needed using different chili varieties.

Second, shading makes the stem size smaller (Table 2); which might make it easier to cut the pedicle as hoped by Masood and Haghshenas-Jaryani (2021). Increasing the number of tertiary branches in shading up to 50% is very interesting from a mechanization perspective. According to Shin *et al*. (2021) separating chilies from the branches is relatively easier than separating them from the stems. It should be noted, however, that shading affects pedicle length, although in this study the pattern of relationship between pedicle length and degree of shading is not very clear.

Finally, shading changes the microclimate around the plants. The average temperature increased from 09:00 to 12:00 then decreased again at 15:00 in all shade treatments with the lowest temperature in shade 70% (28.13 °C) and the highest temperature in shade 60% (34.8 °C). Air relative humidity decreased at 09:00 to 12:00 and increased at 15:00. The highest humidity was found in the shade at 50% (91.95%) and the lowest in the shade at 100% (65.35%). According to Mahmood *et al*. (2018), shading reduces air circulation by 50-87% and increases relative humidity by 2-21%. In the context of Masood and Haghshenas-Jaryani (2021), changes in the microclimate are likely to affect sensor accuracy due to changes in light quality, temperature, and humidity.

CONCLUSION

Shade intensities affected the architecture of the chili canopy. The higher the shade intensity up to 50%, the larger the canopy of the chili plants and the taller the plants. The increase in height is supported by an increase in dichotomous height, while the widening of the crown is caused by an increase in the number of tertiary branches. On the other hand, the fruit pedicle shortened with increasing shading. Further research is needed on the effect of canopy architecture on the efficiency of harvesting chilies.

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