

**OPTIMIZING SHADE MANAGEMENT AND FERTILIZER APPLICATION TO ENHANCE VEGETATIVE GROWTH OF LIBERICA COFFEE**

Paramyta Nila Permanasari\*<sup>1</sup>, Syifa Mursetiawati<sup>1</sup>, Akbar Saitama<sup>1</sup>, Fitria Yuliasmara<sup>2</sup>

<sup>1</sup>Department of Agronomy, Faculty of Agriculture, Universitas Brawijaya, Indonesia.

<sup>2</sup>Indonesian Coffee and Cocoa Research Institute (ICCRI), Indonesia.

\*Corresponding Author

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**ABSTRACT**

Liberica coffee (*Coffea liberica*) has high potential for cultivation on marginal lands due to its tolerance to flooding, low pH, and high humidity. However, its productivity remains low because of limited agronomic innovations, particularly in shade management and fertilizer practices. This research is significant because unshaded cultivation can enhance photosynthesis but increases climate stress and photorespiration, whereas excessive shade reduces productivity. This study aimed to analyze the effects of *Leucaena leucocephala* shade density and NPK fertilizer dosage on vegetative growth of Liberica coffee and to determine the most efficient and sustainable combination. The research was conducted in Indonesian Coffee and Cocoa Research Institute (ICCRI), Jember (June-September 2024) using a nested design with two factors: shade density (no shade, 1:2, 1:1) and NPK dosage (400–700 g tree<sup>-1</sup>). Observed variables included leaf area, number of leaves, internode length, number of nodes, leaf greenness index, and stomatal density. Data were analyzed using ANOVA and LSD test at a 5% significance level. Thirty-six experimental plots were analyzed. NPK dosage had no significant effect on most variables, except stomatal density in the second and third months. Moderate shade (1:2 and 1:1) produced larger leaf areas (8637–8927 cm<sup>2</sup>), higher leaf numbers (243.4 leaves), and greener leaves compared to no-shade conditions. The unshaded treatment consistently showed the lowest growth across all parameters. Findings indicate that shade management plays a more critical role than fertilizer dosage in improving photosynthetic efficiency and maintaining water balance. Moderate shade (1:2 or 1:1) is recommended to achieve optimal vegetative growth, while fertilizer dosages can be reduced for efficiency (600 g without shade, 500 g under 1:2, 400 g under 1:1). Future research should explore dynamic shade management and organic nutrient integration.

**Keywords:** Liberica coffee, shade density, NPK fertilizer, photosynthesis, vegetative growth

## INTRODUCTION

Coffee is a strategic plantation commodity with high economic value and a strategic role in supporting the farmer's economy and national exports. In addition to Arabica and Robusta, Liberica coffee (*Coffea liberica*) is gaining attention as an alternative for development on marginal land. This coffee variety is known to be more tolerant of extreme environmental conditions, such as flooding, low soil pH, and high humidity, making it a potential solution for suboptimal land use. However, Liberica coffee productivity remains relatively low due to limited implementation of agronomic innovations, particularly related to shade management and fertilization.

Shade-free coffee cultivation systems are often implemented to encourage high productivity, as full light intensity can increase photosynthesis and accelerate vegetative and generative growth. However, it makes coffee plants more vulnerable to climate stress, resulting in unstable long-term production. High light intensity causes plants to experience photorespiration, so that plants lose some of their energy for growth (Mayoli & Afr, 2012). Conversely, the use of shade can improve microclimate quality, enhance soil fertility, and extend the productive life of the plants. The use of shade trees such as *Leucaena leucocephala* and *Calliandra calothyrsus* reduces light intensity by 58-72.5% and this condition increases the stem diameter and coffee fruit production (Lisnawati *et al.*, 2017). However, excessively high shade density can significantly reduce light intensity, resulting in decreased photosynthesis, limited vegetative growth, and reduced plant productivity.

On the other hand, NPK fertilizer plays a crucial role in supporting early vegetative growth and coffee canopy formation. Nitrogen is essential for leaf and chlorophyll formation, phosphorus supports root development and energy metabolism, while potassium plays a role in osmotic regulation and increases resistance to environmental stress. The effectiveness of NPK fertilizer is strongly influenced by light intensity. In moderate shade conditions, fertilizer dosage can be reduced without reducing growth. Therefore, research in interaction between shade plant density and NPK fertilizer dosage on Liberica coffee growth is crucial for formulating efficient and sustainable cultivation strategies.

## RESEARCH MATERIALS AND METHODS

The research was conducted from June to September 2024 at the Indonesian Coffee and Cocoa Research Institute (ICCRI), Wirolegi Central Experimental Garden, Wirolegi Village, Summersari District, Jember Regency, East Java, located in 75 meters above sea level, air temperature range 21.6-33.0 °C and average air humidity of 87%. The tools used include a thermohygrometer, lux meter, Soil Plant Analysis Development (SPAD), microscope, hand counter, and documentation tools. The materials used in the research were NPK fertilizer (16% nitrogen, 16% phosphorus, 16%

potassium), liberica coffee plants (aged >7 years), *Leucaena leucocephala* shade plants (aged >8 years).

The research design used was a nested pattern design with 2 factors, NPK fertilizer doses nested in the density of shade plants. The NPK fertilizer dosage rates consist of 400 g tree<sup>-1</sup> (this is the existing treatment in coffee plantation), 500 g tree<sup>-1</sup>, 600 g tree<sup>-1</sup> and 700 g tree<sup>-1</sup>, and shade density consists of no shade, 1:2 shade (1 shade plant: 2 coffee plants) and 1:1 shade (1 shade plant: 1 coffee plant). The treatment was repeated 3 times so that there were 36 experimental plots, each consist of 15 coffee plants.

## RESULTS AND DISCUSSION

### Abiotic Factor Data

Increasing shade density significantly affected light intensity, air temperature, and relative humidity in the study environment. The data in Table 1 show that the unshaded condition provided the highest light intensity, at 820 lux, representing 100% light exposure. Under these conditions, the air temperature reached 33.9°C with a relative humidity of 58%. When shade density of 1:2 was applied, light intensity decreased to 684 lux (83.4% of full light), air temperature dropped to 29.1°C, and air humidity increased to 71%. The decrease in light intensity was more pronounced in the 1:1 shade, where only 69.1% of light could penetrate (567 lux), air temperature dropped drastically to 25.7°C, and air humidity increased to 78%. These findings are in line with the basic principles of plant ecophysiology, which explain that shade reduces direct solar radiation, thereby lowering microclimate temperatures and increasing humidity due to reduced evaporation (Taiz et al., 2015).

**Table 1: Light Intensity, Temperature and Humidity at Shade Density Levels**

Shade Level	Light intensity (Lux)	Percent -age of light (%)	Air temperature (°C)	Air humidity (%)
Without Shade	820	100	33,9	58
1:2 Shade	684	83,4	29,1	71
1:1 Shade	567	69,1	25,7	78

### **Growth of Liberica Coffee Plants**

The results showed variations in vegetative growth of Liberica coffee at different levels of shade. Further tests indicated that 1:2 and 1:1 shade yielded similar values for leaf area, number of leaves, and internode length, while the number of nodes per plant showed no significant differences between treatments.

### **Leaf Area**

The results of the analysis of variance on the research data obtained showed no effect of several types of fertilizer doses on leaf area, but there were significant differences due to differences in shade levels on leaf area. Data obtained from shade levels and fertilizer doses on leaf area variables are presented in Table 2.

Based on Table 2, it is known that differences in fertilizer dosage did not affect the leaf area of coffee plants at each shade density. However, differences in shade density resulted in significantly different leaf areas. The first to third months showed no significant difference in leaf area between 1:1 and 1:2 shade, but a significant difference without shade.

In the first month, the effect of shade on the leaf area of coffee plants was clearly visible, where unshaded coffee plants showed the lowest average leaf area (3609 cm<sup>2</sup>), while 1:2 shade (5407 cm<sup>2</sup>) and 1:1 shade (6101 cm<sup>2</sup>) showed significant differences. A similar pattern was seen in the second month with an increase in leaf area in all treatments. Unshaded plants still showed the lowest value (4324 cm<sup>2</sup>), while 1:2 shade (6598 cm<sup>2</sup>) and 1:1 shade (7373 cm<sup>2</sup>) remained superior. In the third month, the positive trend continued with all shade treatments showing an increase in leaf area. 1:1 shade had an average leaf area of 8927 cm<sup>2</sup>, 1:2 shade had an average leaf area of 8637 cm<sup>2</sup> and unshaded had an average leaf area of 5734 cm<sup>2</sup>.

### **Number of Leaves**

Analysis of variance showed that the fertilizer dose had no effect on the number of leaves, while the level of shade provided a significant difference. Based on Table 3, the NPK fertilizer dosage had no significant effect on leaf area at various shade densities, while differences in shade significantly affected leaf number. In the first to second months, 1:2 and 1:1 shade were not significantly different but both were different with no shade, while in the third month, 1:2 shade showed a significant difference compared to both 1:1 shade and no shade.

In the first month of observation, a clear pattern emerged where shaded coffee plants (both 1:2 shade and 1:1 shade) exhibited a significantly higher number of leaves than unshaded plants. Plants with 1:2 shade achieved an average of 191,6 leaves, while those with 1:1 shade achieved 189,2, compared to 159,7 for unshaded plants. This difference was approximately 18,4% to 20% higher

for shaded plants. The same pattern continued in the second month, with an increase in leaf number across all treatments. Plants with 1:2 shade showed the most significant increase in leaves (reaching 209,8 leaves), followed by those with 1:1 shade (203,1 leaves) and those without shade (162,1 leaves). The difference between 1:2 shade and 1:1 shade was even more pronounced in this month, with a difference of 60%. In the third month, the effect of shade became even more pronounced, with a significant difference. Plants with 1:2 shade achieved the highest number of leaves (243,4), about 46,8% more than those without shade (165,8). The number of leaves in the 1:1 shade (208,1) was between that in the unshaded and 1:2 shaded areas.

**Table 2: Leaf Area at Several Shading Densities and NPK Fertilizer Doses**

Shade	Fertilizer dosage	Leaf area (cm <sup>2</sup> plant <sup>-1</sup> ) in each month		
		1	2	3
Without Shade	400 g	4097	6843	6931
	500 g	3539	3254	5987
	600 g	3376	3444	4528
	700 g	3423	3755	5490
1:2 Shade	400 g	6079	7361	9555
	500 g	5276	6548	8044
	600 g	5193	5587	8077
	700 g	5080	6895	8872
1:1 Shade	400 g	6280	6948	8367
	500 g	5107	7588	9025
	600 g	6397	7396	8532
	700 g	6618	7559	9786
LSD 5%		ns	ns	Ns
Without Shade		3609 a	4324 a	5734 a
1:2 Shade		5407 b	6598 b	8637 b
1:1 Shade		6101 b	7373 b	8927 b
LSD 5%		903,0	1702	1850
KK		17,59	27,39	23,38

Description: Numbers followed by the same letter in the same column do not show a significant difference based on the BNJ test at the 5% level, ns = not significant.

**Table 3: Number of Leaves at Several Shading Densities and NPK Fertilizer Doses**

Shade	Fertilizer dosage	Number of leaves (blades) in each month		
		1	2	3
Without Shade	400 g	154,9	156,8	160,9
	500 g	169,1	174,3	176,8
	600 g	165,6	167,1	170,8
	700 g	149,3	150,1	154,7
1:2 Shade	400 g	203,9	156,8	237,2
	500 g	191,2	174,3	274,7
	600 g	199,0	167,1	260,3
	700 g	172,3	150,1	201,3
1:1 Shade	400 g	200,7	156,8	227,5
	500 g	200,4	174,3	206,0
	600 g	176,9	167,1	204,1
	700 g	178,9	150,1	194,7
LSD 5%		ns	ns	Ns
Without Shade		159,7 a	162,1 a	165,8 a
1:2 Shade		191,6 b	209,8 b	243,4 c
1:1 Shade		189,2 b	203,1 b	208,1 b
LSD 5%		29,37	40,70	32,18
KK		15,99	20,84	15,35

Description: Numbers followed by the same letter in the same column do not show a significant difference based on the BNJ test at the 5% level, ns = not significant.

### Length of Main Stem Internodes

The results showed no significant effect of various fertilizer doses and shade levels on internode length, but there were significant differences due to different shade levels on internode length. Based on Table 4, it is known that the difference in NPK fertilizer dosage did not have a significant effect on the length of the main stem of the coffee plant at each shade density. However, the difference in shade density resulted in significantly different internode lengths. In the first month, it showed that the length of the main stem internodes showed a significant value based on the shade density. Plants without shade had the lowest average internode length (5,049 cm), while 1:1 shade produced the highest internode length (6,181 cm). Further test results showed that 1:1 shade was significantly different from no shade, but 1:2 shade (5,747 cm) was not significantly different from the other two treatments.

In the second month, the response pattern to shade became clearer. 1:2 shade and 1:1 shade were not significantly different, but significantly different from unshaded plants. Unshaded plants still had the lowest internode length (5,215 cm), while 1:1 shade (6,592 cm) and 1:2 shade (5,979 cm) showed significant increases. In the third month, 1:2 shade and 1:1 shade were not significantly different, but significantly different from unshaded plants.

### **Number of Nodes in Main Stem**

The results of the analysis of variance on the research data obtained showed that there was no significant influence of several fertilizer doses and shade density on the number of nodes. Based on Table 5, it is known that the difference in NPK fertilizer dosage in each shade density condition did not have a significant effect on the number of coffee plant nodes, both in the first month and the third month of observation.

### **Physiological Characteristics of Liberica Coffee Plants**

In the physiological characteristics of Liberica coffee plants, the results showed no significant effect of fertilizer dosage on Liberica coffee plants, but shade density had a significant effect on the leaf greenness index. Conversely, the results of the analysis of variance showed a significant effect of fertilizer dosage and shade density on the stomatal density of Liberica coffee plants.

### **Leaf Greenness Index**

The results of the analysis of variance on the research data obtained showed no effect of several types of fertilizer doses on the leaf greenness index, but there was a significant difference due to differences in shade density on the leaf greenness index. Based on Table 6, it is clear that differences in fertilizer dosage for each shade condition did not significantly affect the leaf greenness index of coffee plants. However, differences in shade density resulted in significantly different leaf greenness indices. The first to third months showed no significant difference between the 1:2 and 1:1 shade treatments, but no shade treatments did. In the first month of observation, the leaf greenness index showed significant variation between shade treatments. Plants without shade had the lowest value (61,49), while those with 1:2 shade (67,62) and 1:1 shade (73,24) showed significantly different values. A similar pattern was observed in the second month. Plants without shade continued to show the lowest value (65,75), while those with 1:2 shade increased to 72,06 and 1:1 shade reached 74,19.

### **Stomata Density**

Based on the analysis of Table 7, it is known that the treatment of different fertilizer doses has a significant effect on the stomatal density of coffee plants in the second and third months. In the first month, the fertilizer dose treatment at each shade density did not have a significant effect. In

the second month, the treatment without shade with a fertilizer dose of 600 g tree<sup>-1</sup>, 700 g tree<sup>-1</sup> had the highest stomatal density value and was significantly different compared to the fertilizer dose of 500 g tree<sup>-1</sup>, but not significantly different from the fertilizer dose of 400 g tree<sup>-1</sup>. In the 1:2 shade with a fertilizer dose of 700 g tree<sup>-1</sup> produced the highest stomatal density value compared to 400 g tree<sup>-1</sup>, 500 g tree<sup>-1</sup> and 600 g tree<sup>-1</sup>. In the 1:1 shade with a fertilizer dose of 400 g tree<sup>-1</sup>, the stomatal density results were the highest and were significantly different compared to the fertilizer dose of 500 g tree<sup>-1</sup>, but not significantly different from the fertilizer dose of 600 g tree<sup>-1</sup> and 700 g tree<sup>-1</sup>.

In the third month, the treatment without shade with a fertilizer dose of 600 g tree<sup>-1</sup> and 700 g tree<sup>-1</sup> had the highest stomatal density value and was significantly different compared to the fertilizer dose of 400 g tree<sup>-1</sup> and 500 g tree<sup>-1</sup>. In the 1:2 shade with a fertilizer dose of 700 g tree<sup>-1</sup> produced the highest stomatal density value and was significantly different compared to the fertilizer dose of 400 g tree<sup>-1</sup>, but not significantly different from the fertilizer dose of 500 g tree<sup>-1</sup> and 600 g tree<sup>-1</sup>. In the 1:1 shade with a fertilizer dose of 400 g tree<sup>-1</sup> produced the highest stomatal density value and was significantly different compared to the fertilizer dose of 500 g tree<sup>-1</sup>, but not significantly different from the fertilizer dose of 600 g tree<sup>-1</sup> and 700 g tree<sup>-1</sup>. In each treatment, the shade density had an effect on stomatal density both in the first month and the third month. In the first and second months, the unshaded and 1:2 shaded treatments had the highest density values and were significantly different compared to 1:1 shaded treatments. In the third month, the unshaded treatment had the highest stomatal density values and were significantly different compared to 1:1 shaded treatments and 1:2 shaded treatments.

**Table 4: Length of Main Stem Internode at Several Shading Densities and NPK Fertilizer Doses**

Shade	Fertilizer dosage	Length of main stem internode (cm) in each month		
		1	2	3
Without Shade	400 g	5,135	5,281	5,326
	500 g	5,293	5,367	5,768
	600 g	5,038	5,260	6,286
	700 g	4,728	4,950	5,165
1:2 Shade	400 g	5,899	6,218	6,951
	500 g	5,239	5,344	5,955
	600 g	6,491	6,640	6,779
	700 g	5,358	5,712	5,911
1:1 Shade	400 g	6,077	6,789	6,850

	500 g	6,389	6,992	7,125
	600 g	6,311	6,407	6,699
	700 g	5,946	6,180	6,742
LSD 5%		ns	ns	ns
Without Shade		5,049 a	5,215 a	5,636 a
1:2 Shade		5,747 ab	5,979 b	6,399 b
1:1 Shade		6,181 b	6,592 b	6,854 b
LSD 5%		1,061	0,752	0,671
	KK	18,40	12,45	10,46

Description: Numbers followed by the same letter in the same column do not show a significant difference based on the BNJ test at the 5% level, ns = not significant.

**Table 5: Number of Nodes in Main Stem at Several Shading Densities and NPK Fertilizer Doses**

Shade	Fertilizer dosage	Number of nodes (nodes) in each month		
		1	2	3
Without Shade	400 g	15,33	18,00	21,00
	500 g	19,33	22,44	23,67
	600 g	14,78	19,44	21,33
	700 g	17,33	22,11	21,67
1:2 Shade	400 g	18,11	19,89	19,94
	500 g	15,83	18,91	19,20
	600 g	16,17	20,78	21,28
	700 g	16,00	19,22	21,00
1:1 Shade	400 g	19,72	22,50	24,89
	500 g	19,61	21,50	21,83
	600 g	18,61	19,33	19,50
	700 g	18,28	20,33	21,22
LSD 5%		ns	ns	ns
Without Shade		16,53	19,70	20,36
1:2 Shade		16,69	20,50	21,86
1:1 Shade		19,06	20,92	21,92
LSD 5%		ns	ns	ns

Description: Numbers followed by the same letter in the same column do not show a significant difference based on the BNJ test at the 5% level, ns = not significant.

**Table 6: Leaf Greenness Index at Several Shading Densities and NPK Fertilizer Doses**

Shade	Fertilizer dosage	Leaf Greenness Index (units) in each month	
		1	2
Without Shade	400 g	62,32	65,79
	500 g	58,13	63,66
	600 g	66,56	71,30
	700 g	58,93	62,26
1:2 Shade	400 g	70,04	66,49
	500 g	67,10	71,29
	600 g	67,07	77,30
	700 g	66,28	73,18
1:1 Shade	400 g	71,51	74,91
	500 g	73,27	70,89
	600 g	73,91	75,14
	700 g	74,26	75,82
LSD 5%		ns	ns
Without Shade		61,49 a	65,75 a
1:2 Shade		67,62 b	72,06 b
1:1 Shade		73,24 b	74,19 b
LSD 5%		5,537	6,198
KK		7,317	8,021

Description: Numbers followed by the same letter in the same column do not show a significant difference based on the BNJ test at the 5% level, ns = not significant.

**Table 7: Stomatal Density at Several Shading Densities and NPK Fertilizer Doses**

Shade	Fertilizer dosage	Stomatal density ( $\Sigma$ stomata.mm <sup>-2</sup> ) in each month		
		1	2	3
Without Shade	400 g	393,0	422,3 ab	432,4 a
	500 g	360,3	375,3 a	459,3 a
	600 g	499,7	511,0 b	614,0 b
	700 g	583,3	598,3 b	609,7 b
LSD 5%		ns	99,31	108,5
1:2 Shade	400 g	382,7	423,2 a	446,7 a
	500 g	399,7	428,7 a	496,9 ab
	600 g	375,3	472,0 a	496,3 ab
	700 g	476,7	591,0 b	594,7 b
LSD 5%		ns	99,31	108,5
1:1 Shade	400 g	328,0	462,0 b	463,0 b
	500 g	302,0	325,3 a	333,4 a
	600 g	346,7	388,9 ab	405,0 ab
	700 g	308,7	366,7 ab	376,0 ab
LSD 5%		ns	99,31	108,5
Shade		459,1 b	476,8 b	528,9 c
e		408,6 b	478,7 b	508,6 b
e		321,3 a	385,7 a	394,3 a
LSDJ 5%		80,19	77,84	85,07
KK		19,85	17,09	17,49

Description: Numbers followed by the same letter in the same column do not show a significant difference based on the BNJ test at the 5% level, ns = not significant.

## DISCUSSION

### Leaf Area

The results of the study showed a diversity of vegetative growth responses of Liberica coffee at various levels of shade. Based on further tests, Liberica coffee plants in 1:1 and 1:2 shade had similar values in leaf area, number of leaves, and internode length, while the number of nodes per plant did not differ significantly across all treatments. These findings indicate that Liberica coffee is able to adapt to variations in light intensity at moderate levels of shade. Jaramillo-Botero *et al.* (2010) and Ricci *et al.* (2023) explained that shade conditions can significantly increase leaf area, which is also supported by Rokmah *et al.* (2023) that coffee leaves under shade tend to be larger in size as a form of adaptation to increase light absorption.

Related to fertilization, the nutrients in NPK play a crucial role in supporting plant adaptation to shaded conditions. Nitrogen functions in the formation of chlorophyll and enzyme proteins that increase photosynthetic efficiency in low-light conditions (Gardner *et al.*, 1991; Sholikhah *et al.*, 2015). Phosphorus plays a role in the transfer of energy (ATP) required for photosynthesis and cell division, while potassium regulates the opening and closing mechanisms of stomata so that plants

can maintain a balance between CO<sub>2</sub> absorption for photosynthesis and controlling water loss due to transpiration (Taiz *et al.*, 2015). Thus, the interaction between shade levels and NPK fertilization directly influences photosynthetic capacity, water use efficiency, and ultimately determines the effectiveness of vegetative growth of Liberica coffee.

### **Number of Leaves**

Results showed that there was no significant effect between the shade level treatment and fertilizer dose on the increase in the number of Liberica coffee leaves. It showed that the treatment of various shade levels significantly differed in producing the number of plant leaves when compared to coffee plants without shade, with the highest number of leaves found in 1:2 shaded coffee plants (243,4 leaves) in the 3rd month of observation. According to Hanggono and Astuti (2022), higher shade density results in thin and wide leaves, while full light results in small and thick leaves due to the presence of palisade cells. Research by Arisandi *et al.* (2015) suggests that treatments without shade produce the lowest number of leaves in coffee plants due to photorespiration and leaf loss. Coffee plants cultivated in high light intensity environments generally exhibit fewer leaves than those in shaded areas. This phenomenon can be attributed to increased light intensity, which leads to energy loss in plants through the process of photorespiration. Photorespiration is known to require substantial energy, resulting in a reduction in the energy available for plant growth (Mayoli and Gitau, 2012; Arisandi *et al.*, 2015).

### **Length of Internode in Main Stem**

Based on the length of the main stem internode of coffee plants grown under a 1:2 shade ratio and a 1:1 shade ratio, the results were similar, with the highest yield being 6,399 cm in the 1:2 shade ratio, while the highest yield was 6,854 cm in the 1:1 shade ratio. This difference is closely related to the quality of solar radiation, which influences plant morphogenetic traits, including stem internode elongation (internodes) and pigment formation (Hutasuhut, 2020). Under low light conditions, plants tend to elongate their stems as an adaptation to seek light (partial etiolation), resulting in changes in energy distribution that can impact photosynthetic efficiency (Sinaga *et al.*, 2020). Optimal shade not only affects stem morphology but also has implications for plant physiology. Excessive light intensity without shade can lead to increased transpiration due to more open stomata, resulting in greater plant water loss (Khusni *et al.*, 2018). Conversely, moderate shade lowers temperatures and maintains microhumidity, thereby suppressing excessive transpiration and allowing plants to maintain water balance. This is important because water is a key factor in photosynthesis and vegetative growth.

In relation to NPK fertilizer, nitrogen plays a crucial role in shaded conditions because it supports chlorophyll formation, which increases photosynthetic efficiency at low light intensities (Gardner *et al.*, 1991; Sholikhah *et al.*, 2015). Phosphorus is essential for the transfer of energy (ATP)

required for stem cell elongation, while potassium plays a role in stomatal regulation, maintaining a balance between photosynthesis and transpiration (Taiz *et al.*, 2015). Recent studies have also confirmed that the combination of shade management and NPK fertilization can increase light efficiency and nitrogen availability, thus supporting better vegetative growth and coffee productivity (Rahardjo *et al.*, 2022; Ricci *et al.*, 2023).

### **Number of Nodes in Main Stem**

The results of the study showed that the number of nodes in Liberica coffee did not differ significantly between shade levels. This phenomenon confirms that the morphological response of coffee plants to light intensity is specific, depending on environmental conditions, variety, and cultivation management (Beer *et al.*, 1988; Sobari *et al.*, 2012). As an annual plant with orthotropic stems and plagiotropic branching, the number of nodes on the main stem plays a crucial role in the formation of productive branches and the development of flowers and fruit (Wintgens, 2004).

Shading plays a crucial role in creating a more stable microclimate, including maintaining humidity, reducing extreme temperatures, and suppressing oxidative stress caused by excessive radiation. This has been shown to prolong the active photosynthesis period and reduce transpiration rates, allowing plants to more efficiently use water and energy for growth (Chiarawipa *et al.*, 2025). Physiologically, reduced light intensity due to shading will reduce the potential photosynthesis rate, making the need for essential nutrients such as nitrogen (N) even more crucial for supporting the formation of chlorophyll and photosynthetic enzymes (Taiz *et al.*, 2015; Rahardjo *et al.*, 2022).

Phosphorus (P) in NPK fertilizer supports energy transfer (ATP) which is essential for cell division and elongation in stem segments, while potassium (K) plays a role in regulating the opening and closing of stomata, thus balancing CO<sub>2</sub> absorption for photosynthesis with reducing water loss through transpiration (Fageria, 2010). The interaction between shade and NPK fertilization is key, because plants in shaded conditions can increase physiological efficiency when nutrient availability is sufficient. Recent studies confirm that the combination of agroforestry systems (shade) with proper nutrient management, including NPK, can increase photosynthetic capacity, maintain transpiration balance, and improve vegetative growth and coffee productivity (Ricci *et al.*, 2023; Chiarawipa *et al.*, 2025).

Thus, although the number of nodes is not directly affected by shade, the presence of shade indirectly modulates NPK fertilizer requirements through its effects on photosynthesis and transpiration. This makes integrating shade and fertilization management an important strategy for optimizing vegetative growth and productivity of Liberica coffee.

### **Leaf Greenness Index**

Leaf greenness index and stomatal density are very important physiological parameters. This shows that the application of various shades produces different results regarding physiological characteristics such as leaf greenness index and stomatal density and produces different results for fertilizer dose treatments such as stomatal density. Based on the results of the analysis of variance, it is known that the greenness index in coffee plants with different levels of shade shows significant differences every month in chlorophyll content values. The leaf greenness index value obtained results of 72,06 in the 2nd month in coffee plants with 1:2 shade, and obtained results of 74,19 in the 2nd month in coffee plants with 1:1 shade.

Shade plants are a crucial component of agroforestry systems, particularly for plantation crops like coffee. The presence of shade plants directly impacts the light intensity received by the main plant, which in turn influences physiological processes, including chlorophyll production, as reflected in the leaf greenness index (GII) (Nugroho and Sumarni, 2021). The GII is a visual indicator that reflects leaf chlorophyll content. Chlorophyll plays a crucial role in photosynthesis, and its production is strongly influenced by environmental conditions, particularly light (Purwanto and Mulyai, 2018). The presence of shade plants can reduce the intensity of direct sunlight, resulting in cooler temperatures around the plant canopy and higher humidity. These conditions tend to support chlorophyll production, especially in plants that are intolerant of full sunlight.

The use of shade systems in coffee agroforestry also provides additional benefits in the form of biodiversity conservation and soil structure improvement. Based on research results on microclimate conditions, the 1:1 shade treatment (69,1% light intensity) was able to maintain moderate temperatures and stable relative humidity compared to no shade or 1:2 shade (83,4% light intensity). These results are in line with research by Muslimin *et al.* (2020) which stated that coffee plants with moderate shade (30% - 50%) were shown to increase the leaf greenness index compared to those without shade. This is because plants grown under moderate shade tend to have higher chlorophyll to maximize the absorption of limited light. According to Rizqon *et al.* (2023), it was also stated that the increase in leaf greenness index in plants under shade is closely related to plant adaptation to increase photosynthetic efficiency in low light conditions.

However, it's important to note that excessive shade levels (>70%) can reduce the leaf greenness index due to limited light, which can inhibit chlorophyll synthesis and overall plant growth (Setyowati *et al.*, 2019). Therefore, it's important to adjust the shade level to meet the physiological needs of coffee plants. Furthermore, leaf greenness index can be used non-destructively for direct plant health monitoring in modern cultivation practices.

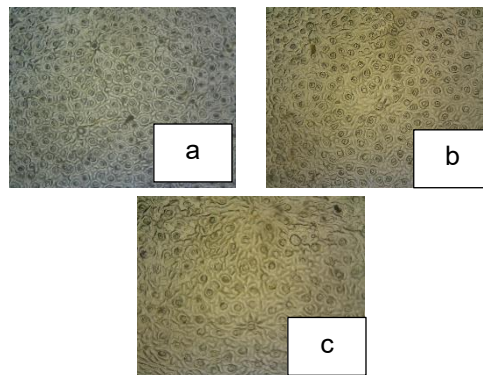
## **Stomata Density**

Differences in shade levels and NPK fertilizer doses applied can affect the stomatal density on Liberica coffee plant leaves. The results of this study indicate that coffee plants without shade have a higher stomata density value (528,9 stomata mm<sup>-2</sup>) compared to other treatments, while the 1:1 shade treatment has a lower stomata density value (321,3 stomata mm<sup>-2</sup>). This is in accordance with Rofiah's (2010) research that classifies stomata density into low density (<300 stomata mm<sup>-2</sup>), medium density (300-500 stomata mm<sup>-2</sup>) and high density (>500 stomata mm<sup>-2</sup>).

The density of coffee plant stomata decreases with decreasing light intensity. Stomata in unshaded plants are much denser than shaded plants (1:2 shade or 1:1 shade). This indicates that different levels of shade play a role in stomata formation. This is further clarified by the fact that leaf stomata density is influenced by temperature, humidity, and light intensity (Iriawati, 2009; Suherman and Asrul, 2016). The presence of light allows photosynthesis to occur, reducing CO<sub>2</sub> levels in the leaves and opening the stomata. Differences in light intensity received by leaves result in differences in leaf characteristics (Pompelli *et al.*, 2010; Suherman and Asrul, 2016). Differences in leaf stomata density can be seen in Figure 1.

Stomatal openings in each individual plant occur in the process of CO<sub>2</sub> absorption between coffee plants belonging to the C3 plant type and shade plants. Stomatal density will remain constant throughout the growth phase, but the size and characteristics of stomatal pores will be modified. Regulation of stomatal responses (especially the mechanism of stomatal opening and closing) to various stimuli is also modulated by physiological factors, including lower CO<sub>2</sub> concentrations in leaf tissue than in the surrounding atmosphere, which consequently results in a decrease in the effectiveness of CO<sub>2</sub> and acts as a barrier within the leaf blade (Zakaria, 2010).

Shaded coffee plants will experience adaptation as a result of microclimate influences that will manifest as physiological adjustments. According to Murphy *et al.* (2014), it is stated that the transpiration process at each specific stomatal density is influenced by the difference in vapor pressure between the leaves and the surrounding atmosphere ( $VPD = \text{vapor pressure difference}$ ). The acclimatization process will change cell size rather than the overall cell number. Stomatal density is also influenced by the observed plasticity in cell size derived from cell number, which arises from the acclimatization process. Thus, different leaf and atmospheric pressures will affect cell number and leaf size. In addition to adaptive efforts at the cellular level, this also indicates the role of hormones such as abscisic acid (ABA) which increases when a plant experiences light or drought stress, which directly affects the opening and closing mechanisms of stomatal cells in regulating water balance (Wilkinson *et al.*, 2002).



**Figure 1: Stomatal density in Liberica coffee plants at different levels of shade: (a) Treatment without shade, (b), 1:2 shade treatment, (c) 1:1 shade treatment**

Based on Table 7, the fertilizer dose treatment shows that the application of  $600 \text{ g tan}^{-1}$  fertilizer to coffee plants cultivated without shade resulted in a higher stomatal density compared to other fertilizer doses. Meanwhile, for coffee plants in a 1:2 shade ratio with the application of a fertilizer dose of  $700 \text{ g tan}^{-1}$  resulted in an increased value, while for coffee plants in a 1:1 shade ratio, the optimal fertilizer dose was identified at  $400 \text{ g tan}^{-1}$  showing a higher value. In addition, the provision of nutrients and increasing the level of shade in coffee plants tend to result in a high stomatal density.

According to research by Padidi *et al.* (2024), it was stated that the fertilizer formulation applied with the addition of *Leucaena leucocephala* plants will tend to produce the highest average number of stomata with the highest density compared to other treatments caused by the very high nitrogen content contained in the fertilizer formulation. Nitrogen will increase the amount of chlorophyll in plant leaves so that there will be an increase in the rate of photosynthesis which results in an increase in the number of stomata and stomata density. According to Putri *et al.* (2017) it was stated that the increase in the number of stomata and chlorophyll content in plants results in an increase in the rate of photosynthesis so that it can stimulate plant growth.

The efficiency of N fertilizer application can also increase plant resistance to environmental stress, such as dry periods or extreme temperatures, because adaptive stomata and high chlorophyll levels are able to maintain optimal photosynthesis when resources are limited (Suryanto *et al.*, 2018). The K element functions in cell osmotic regulation and the opening and closing mechanism of stomata, thereby increasing the efficiency of water use and improving plant resistance to drought stress and extreme temperatures (Wibowo *et al.*, 2017). Thus, a balanced combination of N, P, and K fertilization can boost the physiological development of coffee plants so that they remain optimal in facing changing environmental conditions.

## CONCLUSION

The analysis encompassing both morphological parameters (leaf area, internode length, and number of leaves) and physiological parameters (stomatal density and chlorophyll content) provides a comprehensive understanding of *Coffea liberica*'s growth responses to environmental conditions. The reduction of fertilizer dosage under shaded coffee cultivation systems was still able to maintain growth performance, reinforcing the practical and ecological significance of this research. This study demonstrates that shade density plays a more decisive role than NPK fertilizer dosage in influencing the vegetative growth of Liberica coffee. Moderate shade levels (ratios of 1:2 or 1:1) consistently enhanced leaf area, leaf number, internode length, and leaf greenness index, whereas unshaded conditions resulted in the lowest growth performance. The NPK fertilizer dosage significantly affected only stomatal density during the second and third months of observation. These findings deepen the understanding of light–nutrient interactions in coffee-based agroforestry systems and support the integration of shade management with nutrient optimization for sustainable cultivation. In practice, farmers are encouraged to adopt moderate shade systems to sustain growth while reducing fertilizer inputs, thereby providing both economic and environmental benefits.

This research provides a scientific foundation for the implementation of adaptive shade management and fertilizer efficiency in Liberica coffee cultivation, with results that support enhanced vegetative growth alongside sustainable reductions in chemical inputs. The findings are consistent with the principles of tropical plant ecophysiology (DaMatta *et al.*, 2007) and the source–sink efficiency theory (Taiz & Zeiger, 2010), which emphasize that optimizing the balance between light and nutrient availability enhances photosynthetic efficiency and vegetative growth without compromising ecosystem sustainability. Moderate shade management combined with balanced fertilization represents a practical application of climate-smart agriculture, as described by Jose (2009), positioning coffee agroforestry as an environmentally friendly and climate-resilient production model.

Nevertheless, the study remains limited to a three-month period conducted at a single research site (Jember) and does not include the generative stages (flowering, yield, and bean quality), thereby lacking the capacity to reflect long-term impacts on productivity. Further research should strengthen the temporal and spatial dimensions by extending the study duration, involving multiple agro-ecological zones, and exploring relationships between vegetative improvement, economic productivity, and environmental sustainability. Future studies could also incorporate organic or micronutrient fertilizer treatments and dynamic shade levels to broaden the applicability of findings and improve generalization across diverse cultivation environments.

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