Research Article

Synergistic Shade and Biochar Application for Improving Microclimate Conditions and Physiological Performance of 6-Month-Old Cocoa Trees

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Abstract | Cocoa productivity in smallholder plantations is often constrained by unfavorable microclimate conditions and declining soil fertility, which limit plant growth and physiological performance. Microclimate modification through shade management combined with soil improvement using biochar offers a promising strategy to enhance cocoa growth and resilience. This study evaluated the synergistic role of shading and rice husk biochar application in improving microclimate conditions and growth performance of unproductive cocoa plants. The experiment was conducted in a smallholder plantation in Sipatuo Village, South Sulawesi, using a split-plot design with three shade levels (45%, 65%, and 85%) as main plots and four biochar application rates (0, 10, 20 and 30 t ha^{-1} corresponding to 0, 0.062, 0.124, and 0.186 kg per tree) as subplots. Results showed that shading modified canopy light interception and radiation distribution, thereby influencing plant physiology and growth. Moderate shading (65%) significantly increased chlorophyll *a*, *b*, and total chlorophyll contents (314.69, 136.48, and 452.78 μmol m^{-2}), stem diameter (9.14 mm), leaf number (35.00), and Leaf Area Index (2.09). The highest transpiration rate (250.43 mg h^{-1} cm^{-2}) was also recorded under 65% shading, while excessive shading (85%) reduced transpiration. Biochar application improved soil chemical properties in a dose-dependent manner, increasing soil organic carbon (2.05–2.66%), cation exchange capacity (27.79 cmol(+)/kg), and available nitrogen, phosphorus, and exchangeable potassium. Biochar at 30 t ha^{-1} also enhanced vegetative growth, including stem diameter, branching, leaf number, total leaf area, and Leaf Area Index. Overall, moderate shading and biochar application effectively improved microclimate conditions, soil quality, and early cocoa growth performance.

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Introduction

Cocoa is one of the plantation commodities that plays a significant role in the national economy, particularly as a provider of employment, source of income, and foreign exchange for the country. Global cocoa consumption tends to increase every year, especially in developed countries. The largest cocoa consuming countries are still European countries, in the following order: Switzerland (8.8 kg/capita/year), Austria (8.1 kg/capita/year), Germany (7.9 kg/capita/year), the United Kingdom (7.6 kg/capita/year), and Sweden (6.6 kg/capita/year) (ICCO, 2020). In 2021, Indonesia ranked seventh among the world's largest cocoa producers after Ivory Coast, Ghana, Cameroon, Nigeria, Ecuador, and Brazil (ICCO, 2024).

Given the increasing demand for cocoa worldwide, it is important to develop a sustainable production system. To develop such a system, it is important to examine the benefits of agronomic practices in improving extreme growing conditions, particularly hydrothermal stress during the dry season, on the survival of cocoa plants in the field. Increased knowledge is needed to achieve optimal cocoa plant growth in the field. One aspect of Good Agricultural Practices (GAP) in the field is the use of agronomic practices such as shade percentage management. Mensah *et al.* (2022) stated that cocoa cultivation under shade can increase photosynthetic efficiency at high temperatures by reducing solar radiation, leaf temperature, soil temperature, and water stress. Niether *et al.* (2020) stated that shade maintains microclimate stability by lowering average temperatures and regulating extreme temperatures, thereby reducing the negative effects of climate change on cocoa plants.

Another current problem is that global warming is causing climate change, such as long dry seasons associated with the El Nino Southern Oscillation (ENSO), and seasonal shifts are also predicted. The decrease in rainfall due to seasonal climate variability has resulted in a decrease in the amount of water available for plants, while at the same time, the water requirements of plants tend to continue to increase (Afifah and Prijono, 2022).

On the other hand, cocoa is very sensitive to climate change, ranging from sun exposure, rainfall, water availability, soil conditions, and especially temperature due to its effect on evapotranspiration. To mitigate climate change, it is necessary to improve cocoa plant maintenance by applying organic materials and soil conditioners, such as biochar. Ren *et al.* (2024) stated that biochar contains various aromatic carbohydrate fractions and phenolic compounds that are structurally complex, such as polysaccharides, phenolics, and lignin. These compounds can act as natural adhesives that bind soil particles into stable aggregates. Septiana *et al.* (2021) stated that soil aggregates affect the soil's ability to provide pore space for storing water, air, and nutrients. Less stable aggregates and low organic matter cause the soil to crumble easily, which can reduce the number of soil pores that affect water availability for plants and bulk density.

The raw materials for making biochar are very easy to obtain, as they come from agricultural waste (Sukmawati *et al*., 2023) such as rice husks. Rahim *et al.* (2023) state that returning agricultural waste as a source of carbon to the soil means reducing carbon in the air. The production of biochar from rice husk charcoal has actually been practiced by farmers for a long time as a form of local wisdom, but it has now begun to be abandoned due to a lack of knowledge about the benefits of biochar. Kusman *et al.* (2024) state that chemically, negatively charged biochar has a large cation exchange capacity, so it can retain and absorb important nutrients such as K^+, Ca^{2+}, Mg^{2+}, and NH_4^+ so that they are not easily lost due to washing by rainwater and remain available to plants for a longer period of time. Iswahyudi *et al.* (2018) reported that applying 20 tons/ha of rice husk biochar is the optimal dose for enhancing the growth of cocoa seedlings. This study aims to investigate and analyze the synergistic shade and biochar application for improving microclimate conditions and physiological performance of 6-month-old cocoa trees.

Materials and Methods

Study site

This research was conducted at a smallholder cocoa plantation in Sipatuo Village, Patampanua Subdistrict, within Pinrang Regency (3°19'13"–4°10'30" S; 119°26'30"–119°47'20" E). The area has a tropical monsoon climate (Am) with distinct wet and dry seasons, temperatures ranging from 18.8 °C to 37.9 °C, and annual rainfall ranging from 671 to 4,650.2 mm, with a mean annual rainfall of 3,182.9 mm during 2019–2023. The study area lies at 13–86 m above sea level and is dominated by alluvial, regosol, and podsolic soils, characterized by slightly acidic to strongly acidic pH and generally low to moderate fertility, typical of cocoa-growing environments in South Sulawesi.

Research methodology

This study employed a split-plot design, with shading as the main plot factor (45%, 65%, and 85%) and rice husk biochar as the subplot factor (0, 10, 20, and 30 t ha^{-1}), comprising 12 treatment combinations replicated three times, with each experimental unit consisting of three plants, for a total of 108 plants.

Plant materials

Six-month-old cocoa seedlings of MCC-02 clone, obtained from local farmers, were used in this study, representing nursery-grown plants at the field-ready stage. At this age, the seedlings had reached adequate morphological and physiological development for transplanting, with an average height of approximately ±50 cm.

Shade establishment

Paranets made of polyethylene materials with 45%, 65%, and 85% light reduction were used to establish shading. The paranets were installed over a 1.5 m-high bamboo frame to ensure uniform light reduction across the experimental area.

Rice husk biochar preparation

Rice husk wastes, as the main ingredient for biochar, were obtained from local farmers. The rice husk biochar production process is carried out using a tightly closed furnace to reduce oxygen availability during combustion at a temperature of 300-500 °C maintained by using a thermogun for 3-4 hours. After the material turns completely black, the fire under the furnace is extinguished and left to cool until the biochar temperature decreases. Next, the biochar is removed from the furnace and dried.

Bacterial preparation (Azotobacter sp.)

Before use, the rice husk biochar was enriched with a microbial fertilizer containing *Azotobacter* sp. at a density of 10^8 CFU/mL following methods by Ady *et al.* (2026). The enrichment was carried out by spraying *Azotobacter* sp. onto the biochar with a volume of 100 mL per 10 kg of biochar and mixing it evenly. The microbial-enriched biochar then left for incubation for 7 days before applied according to the treatment dosage. Based on biochar sample results from the Soil Chemistry and Physics Laboratory, Department of Soil Science, Hasanuddin University, analysis of the biochar used in this study showed a pH of 8.29, C-Organic content of 18.97%, nitrogen (N) content of 0.68%, phosphorus (P) content of 0.08%, potassium (K) content of 0.12%, C/N of 28, and cation exchange capacity (CEC) of 38.51 cmol(+)/kg.

Planting media

The planting medium consisted of topsoil and chicken manure mixed at a 2:1 ratio and placed in 18 L polyethylene planter bags (15 cm in diameter and 30 cm in height). Six-month-old cocoa plants were transplanted into the bags at a density of one plant per bag. A basal fertilizer of 889 kg ha^{-1} NPK (16:16:16) was applied based on the recommended rate, equivalent to 5.46 g per bag.

For the biochar treatment, rice husk biochar was applied at rates of 0, 10, 20, and 30 t ha^{-1}, corresponding to 0, 0.062, 0.124, and 0.186 kg per tree, respectively. All experimental units were then arranged under a shade structure with a spacing of 50 cm between planter bags. Analysis on soil sample before trials conducted at the Soil Chemistry and Physics Laboratory, Department of Soil Science, Hasanuddin University, showed a pH of 6.69, nitrogen (N) content of 0.19%, phosphorus (P) content of 10.68%, potassium (K) content of 0.28%, C-Organic of 2.05%, and C/N of 11%.

Crop establishment and maintenance

Crop maintenance consisted of daily watering and manual weeding. Irrigation was applied once per day, except during rainfall events. Weeding was conducted as necessary by manually removing weeds around the cocoa plants.

Parameter observed

Parameters observed in this study were changes in microclimatic conditions including leaves' light absorption, reflection, and transmission measured using a C1-710/*720 Miniature Leaf Spectrometer*, and light interception measured with a luxmeter.

Plant physiological parameters measured were leaf chlorophyll content, Leaf Mass Area (LMA), Leaf Area Index (LAI), and leaf transpiration. The leaf chlorophyll content consisted of chlorophyll a, b, and total were measured using a CCM-200 plus on the fifth and seventh leaves from the tip. The LMA was calculated using the formula by Poorter and Villar (1997) as shown in Equation 1, while LAI was calculated using the formula by Suwarsono *et al.* (2011) in Equation 2.

$$\text{LMA} = (\text{Dry leaf weight}) / (\text{Leaf area})$$
$$\text{LAI} = (\text{Leaf area})/(\text{Planter bag surface area})$$

Leaf transpiration rate was observed using cobalt chloride paper method. Transpiration rate measurements were taken on the second, third, and fourth leaves that had fully opened on the outer canopy. The paper was placed under a 2 x 2 cm thick transparent plastic sheet on the underside of the leaf, clipped with a paper clip, and then the time required for the cobalt chloride paper to change color from blue to pink was recorded. The transpiration rate was calculated using Equation 3.

$$\text{Transpiration rate} = 1/L \times 60/T \times cf$$

Where:
T: Time required for the color change of the cobalt chloride paper (minutes).
L: Area of cobalt chloride paper (cm^2)
cf: Calibration factor, which is the weight increase in mg of 1 cm^2 of cobalt chloride paper that undergoes a color change (0.38 mg/cm^2) (Bailey *et al*., 1952).

In addition, growth parameters were also measured including increases in plant height, stem base diameter, number of branches, and number of leaves.

Data analysis
The data were analyzed using analysis of variance (ANOVA) based on a split-plot arrangement within a randomized block design (RBD). When significant effects were detected, mean comparisons were performed using Fisher's Least Significant Difference (LSD) test at $\alpha = 0.05$. Statistical analyses were conducted using STAR (Statistical Tool for Agricultural Research) software and Microsoft Excel.

Results and Discussion

A summary of the analysis of variance (ANOVA) is presented in Table 1, showing the significance of the main effects (shading and biochar) and their interaction. The analysis of variance (ANOVA) revealed that the interaction between shading and biochar application was not significant for all observed variables, indicating that the effects of shading and biochar acted independently.

Neither shading nor biochar application showed significant effects ($p>0.05$) on the microclimatic conditions eg. leaves' light absorption, reflection, transmission, or overall light interception. In contrast, shading had a pronounced effect on chlorophyll content, significantly increasing chlorophyll a, chlorophyll b, and total chlorophyll ($p<0.05$). Additionally, shading significantly influenced ($p<0.05$) Leaf Area Index (LAI) and leaf transpiration, but had no significant

Table 1: *Analysis of variance (ANOVA) overview of the effects of biochar application and shading.*

Measured Response	Treatments			CV (%)
	Shading [S]	Biochar [B]	Interaction [SXB]	
Mircoclimatic Conditions				
Leaves' light absorption	ns	ns	ns	S = 18.90 and B = 13.24
Leaves' light reflection	ns	ns	ns	S = 10.18 and B = 12.23
Leaves' light transmission	ns	ns	ns	S = 10.09 and B = 5.60
Light interception	ns	ns	ns	S = 36.40 and B = 25.86
Physiological Parameters				
Chlorophyll a	**	ns	ns	S = 5.48 and B = 6.04
Chlorophyll b	**	ns	ns	S = 8.54 and B = 8.62
Chlorophyll total	**	ns	ns	S = 5.70 and B = 6.21
Leaf mass area (LMA)	ns	*	ns	S = 17.03 and B = 11.08
Leaf area index (LAI)	*	*	ns	S = 15.24 and B = 11.96
Leaf transpiration	*	ns	ns	S = 5.40 and B = 14.41
Growth Parameters				
Plant height	*	ns	ns	S = 8.21 and B = 13.32
Stem base diameter	*	*	ns	S = 9.56 and B = 9.87
Number of branches	**	**	ns	S = 13.34 and B = 18.85
Number of Leaves	**	**	ns	S = 6.52 and B = 7.17

** = significant effect (p<0.05), ** = highly significant effect (p<0.01), ns = non-significant (p>0.05).*

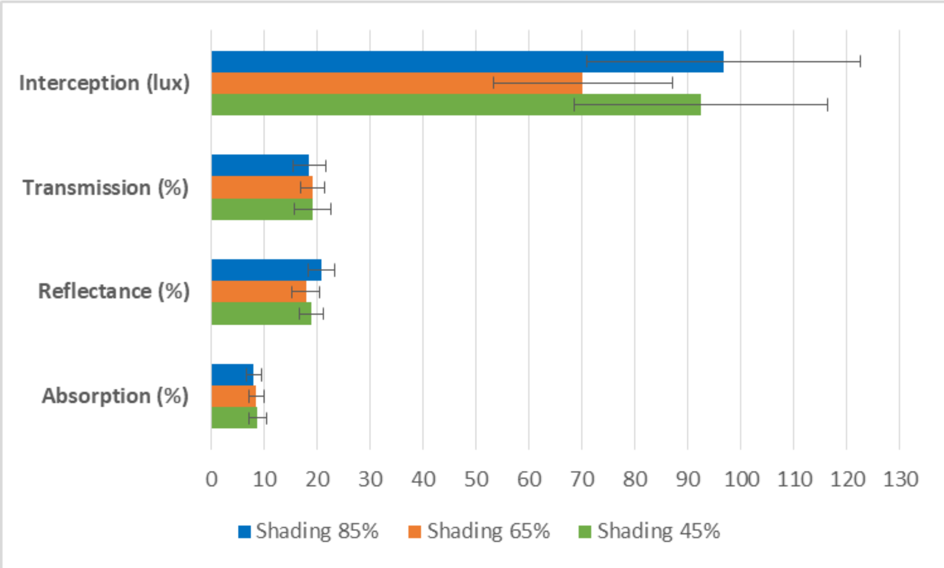

Figure 1: *Effects of shading levels (45%, 65%, and 85%) on light partitioning components. Values are presented as mean ± standard deviation.*

effect ($p>0.05$) on Leaf Mass Area (LMA). On the other hand, biochar application significantly affected ($p<0.05$) LMA and LAI, while its effects on chlorophyll content and leaf transpiration were not significant ($p>0.05$). In addition, several growth parameters were significantly affected by the main treatments. Shading significantly influenced ($p<0.05$) plant height, stem base diameter, number of branches, and number of leaves, with highly significant effects ($p<0.01$) observed for branching and leaf number. Biochar application significantly ($p<0.05$) affected stem base diameter, number of branches, and number of leaves, although its effect on plant height was not significant ($p>0.05$). Overall, these results indicate that shading played a more dominant role in influencing plant physiological responses, whereas biochar primarily contributed to improvements in structural growth traits. The absence of interaction effects suggests that the responses to biochar application were consistent across different shading conditions.

Radiation partitioning under different shading levels

Shading did not significantly modify the partitioning of incoming radiation at the plant canopy level of the 6-month-old cocoa. Nevertheless, light interception tended to increase under higher shading level, while the parameters of reflectance, transmission, and relative absorption showed little variation between treatments (Figure 1).

Figure 1 shows changes in interception (lux), transmission (%), reflectance (%), and absorption (%). The changes in the radiation components show that shading did not substantially alter the optical behavior of the leaves or the overall radiation balance within the canopy system. Thus, under the conditions of this study, microclimate modification through shading had a limited effect on light distribution and did not significantly influence leaf-level radiation partitioning. Tasa *et al.* (2025) stated that shade creates a modified microclimate by reducing solar radiation, lowering air temperature, and maintaining higher relative humidity around the plant canopy. By reducing extreme environmental stress, shade can improve plant water use efficiency and enhance physiological processes. Durand *et al.* (2021) stated that when sunlight reaches leaves, photons can be reflected, transmitted, or absorbed by parts of the leaves. The optical properties of leaves vary depending on the species, side, anatomy, pigment concentration, surface features, stage of development, and water content.

Effect of shading and biochar on the plant physiology of cocoa

The analysis of variance indicated that shading significantly influenced most physiological parameters of cocoa plants, whereas biochar application showed more selective effects, and no significant interaction between the two factors was observed. The highly significant effect ($p<0.01$) of shading on chlorophyll content, including chlorophyll a, chlorophyll b, and total chlorophyll suggests that increased shading enhanced the photosynthetic pigment concentration, likely as an adaptive response to lower light availability. In addition, the recent study also shows that shading significantly ($p<0.05$) affected the LAI and leaf transpiration, indicating its important role in regulating canopy structure and plant water relations. The fact that shading did not significantly ($p>0.05$) influence the LMA, suggesting that leaf structural thickness remained relatively stable across shading levels. Although biochar application did not significantly ($p>0.05$) affect chlorophyll content or leaf transpiration, but it had a significant effect ($p<0.05$) on both LMA and LAI, indicating that biochar primarily influenced structural and canopy-related traits rather than directly affecting physiological processes associated with photosynthetic pigments.

Table 2: *Average Chlorophyll content of 6-month-old Cocoa under different levels of Shading.*

Shading Levels (%)	Chlorophyll a (μmol m^{-2})	Chlorophyll b (μmol m^{-2})	Chlorophyll total (μmol m^{-2})
45	286.34b	119.43b	410.89b
65	314.69a	136.48a	452.78a
85	264.26c	108.21b	378.98c
$LSD_{0.05}$	17.93	11.75	26.77

The numbers followed by the same letter in a column (a,b,c) for each parameter are not significantly different in the LSD test at a confidence level of 95%.

Table 2 shows that optimum chlorophyll a, b, and total content is shown in 65% shading level, while the lowest value of these parameters was found in the heaviest shading treatment of 85%. Karami *et al.* (2025) stated that Chlorophyll biosynthesis is influenced by external factors, such as light and temperature, as well as the activity of genes encoding the enzymes involved in this process. In chlorophyll biosynthesis, the enzyme protochlorophyllide oxidoreductase (POR) acts as a key reductase and is light-dependent in higher plants. Under dark conditions, inhibition of POR causes rapid accumulation of protochlorophyllide (Pchlide) and subsequently decreases ALA synthesis. This is due to a feedback regulatory mechanism between ALA and Pchlide synthesis.

Chl a and Chl b undergo conversion through the Chl cycle. Protein complexes such as PSI, PSII, and cytochrome b6f contain chlorophore a. Through the enzymatic conversion of 7-hidroksimetil klorofil a by CAO, chl b is synthesized from chl a. CAO activity is determined by the negative feedback that is mediated by Chl b. Additionally, hydroxymethyl chlorophyll a reductase (HCAR) and chlorophyll b reductase (CBR) catalyze a two-step mechanism that converts chlorophyll b to chlorophyll a (Karami *et al.*, 2025).

Application of rice husk biochar increased the LMA of the 6-month-old cocoa. This key functional trait, related to light adaptation strategy and resource-use efficiency, increased significantly with the rice husk biochar doses. Figure 2 shows the LMA response to the biochar dosages under the shading levels used. Overall, LMA increased with higher biochar application across all shading treatments, although the magnitude and pattern of response differed among shade intensities. Under 45% shading, LMA showed a strong positive linear relationship with biochar dose ($y = 4E{-}05x + 0.0051$; $R^2 = 0.97$; $r = 0.98$). This high coefficient of determination indicates that biochar application consistently enhanced leaf structural investment under moderate light availability. The linear trend suggests improved leaf

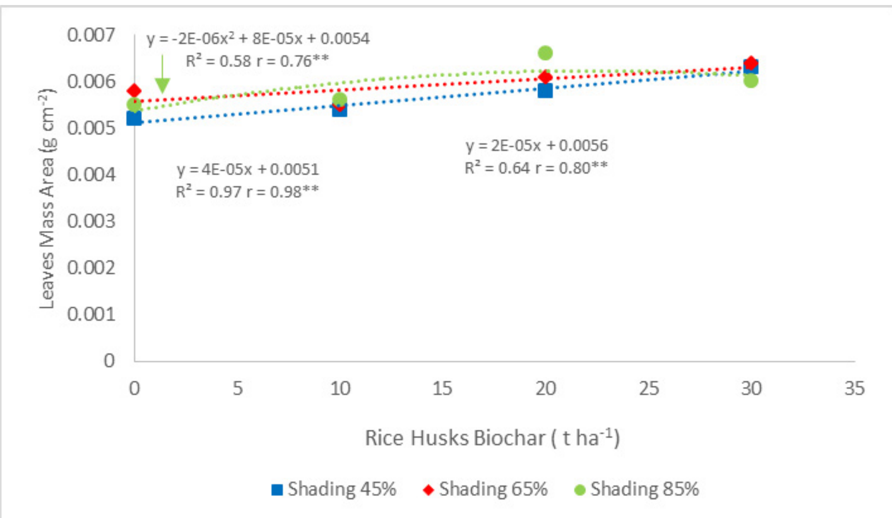

Figure 2: *Leaves mass area (g cm^{-2}) of 6-month-old cocoa under different levels of shading and rice husk biochar dosage*

thickness or density as biochar rates increased, likely associated with enhanced nutrient availability and improved soil physical properties. Similarly, under 65% shading, LMA increased linearly (y = 2E-05x + 0.0056; R^2 = 0.64; r = 0.80), although the strength of the relationship was moderate compared with 45% shading. This indicates that while biochar still positively influenced leaf structural development, the response was less pronounced under reduced light conditions. In contrast, under 85% shading, the response followed a quadratic pattern (y = -2E-06x^2 + 8E-05x + 0.0054; R^2 = 0.58; r = 0.76). LMA increased at lower to moderate biochar rates but tended to plateau or slightly decline at the highest dose. This suggests a diminishing return effect under heavy shade, where limited photosynthetically active radiation may constrain carbon assimilation despite improved soil conditions.

Physiologically, the increase in LMA with biochar application indicates greater biomass allocation per unit leaf area, which may reflect enhanced leaf thickness or denser mesophyll structure. Under moderate shading (45%), the combined effect of sufficient light and improved soil conditions appears optimal for structural leaf development. However, under excessive shading (85%), light limitation likely becomes the dominant factor regulating leaf morphology, reducing the efficiency of biochar-induced improvements. Ghazouani *et al*. (2023) stated that biochar modifies the soil matrix, creating larger interstitial pore spaces. This increases aggregate stability and influences key hydrological properties such as hydraulic conductivity and water retention. Wang *et al*. (2022) stated that water availability can have a direct impact on leaf characteristics like LMA and photosynthetic rate at the leaf level. Charloq et al. (2024) stated that increasing leaf area can increase photosynthesis production, which contributes to plant dry weight. Increasing the dry weight of the plant canopy is a manifestation of the metabolism resulting from the successful photosynthesis process. In summary, rice husk biochar positively affected LMA across shading treatments, with the strongest and most consistent response observed under 45% shading. These findings suggest that biochar application is more effective in improving leaf structural traits under moderate rather than severe shade conditions.

Similarly, LAI of the young unproductive cocoa tree was significantly affected by shading and biochar treatments although statistically no significant interaction was found. The bivariate correlation analysis in Figure 3 shows that shade treatment and rice husk biochar provide a linear and quadratic responses and are significantly correlated with leaf LAI. The 45% shade treatment provides a linear response following the equation y = 0.0177x + 1.637 with a coefficient of determination R^2 = 0.93 and a correlation coefficient of r = 0.96. Similarly, under the 65% shade treatment, a linear response was exhibited following the equation y = 0.0162x + 1.842 with a coefficient of determination R^2 = 0.98 and a correlation coefficient of r = 0.97. On the other hand, the 85% shade treatment gave a quadratic response following the equation y = -0.0007x^2 + 0.0212x + 1.527 with a coefficient of determinationof R^2 = 0.85 and a correlation coefficient of r = of R^2 = 0.85 and a correlation coefficient of r =

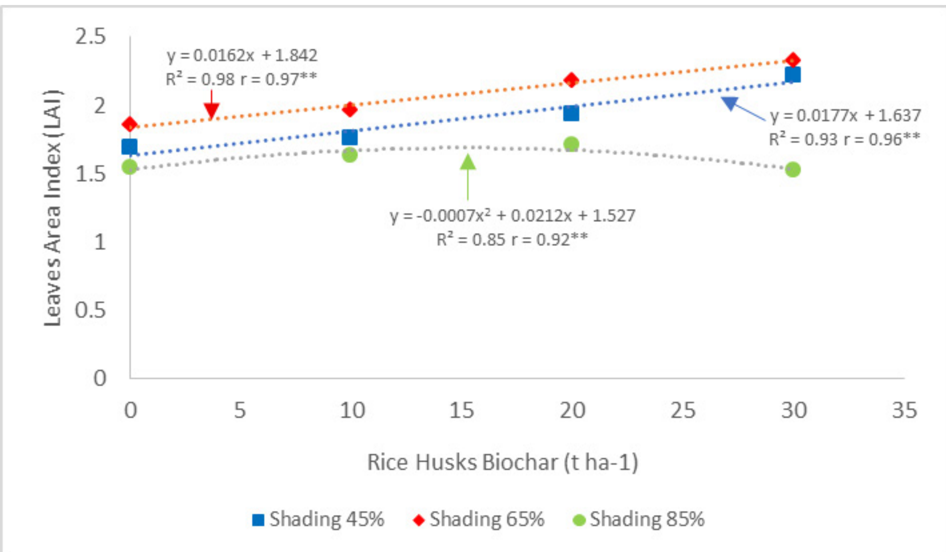

Figure 3: *Leaves area index (LAI) of 6-month-old cocoa under different levels of shading and rice husk biochar dosage.*

x65% shade indicate that canopy expansion remains proportionally regulated by improved soil conditions and carbon assimilation capacity. However, under 85% shade, the quadratic response suggests the presence of a physiological threshold, where excessive light limitation constrains carbon gain, leading to a decline in LAI beyond the optimum point. This reflects a shift from adaptive canopy expansion to carbon-limited growth regulation. Tang *et al.* (2022) stated that LAI reflects the number of plant leaves, changes in canopy structure, plant community vitality, and environmental influences. Lv *et al.* (2025) stated that a higher LAI usually indicates that plants have a larger leaf area, which can enhance photosynthesis and increase the plant's ability to absorb and store carbon. The leaf economic spectrum theory states that a larger leaf area can optimize carbon absorption from photosynthesis per unit of land area.

The analysis results show a positive relationship between leaf chlorophyll content and LAI as shown in Figure 4. An increase in chlorophyll concentration is followed by an increase in LAI value, indicating that the photosynthetic capacity of leaves is closely related to canopy structure development. Tang *et al.* (2022) stated that LAI and above-ground biomass were found to be closely related to chlorophyll in leaves, as leaf growth requires chlorophyll to participate in photosynthesis. This factor is the fundamental reason for the growth of LAI and above-ground biomass.

Application of different shading levels also significantly affected the transpiration of the cocoa leaves, whose rate was varied with the intensity of light transmitted to the plant canopy. The highest transpiration rate was observed in 65% shading, while the lowest rate was shown by the 85% (Figure 5A). Figure 5B illustrates the response of leaf transpiration rate to increasing doses of rice husk biochar under the three shading levels. Overall, the response pattern differed depending on shading intensity, indicating a significant interaction between microclimate modification (shading) and soil amendment (biochar). Under 45% shading, transpiration exhibited a quadratic response (R^2 = 0.96), described by the equation: $y = 0.1293x^2 - 4.4013x + 259.87$. Transpiration initially decreased from 0 to 20 t ha^{-1} and slightly increased at 30 t ha^{-1}. This suggests that moderate biochar application reduced stomatal water loss, possibly through improved soil moisture retention and enhanced root-zone water availability, while excessive doses restored transpiration as vegetative growth and leaf area potentially increased. The high R^2 value indicates a strong model fit, suggesting that biochar dose was a major determinant of transpiration under moderate shading.

Under 65% shading, transpiration increased linearly with biochar dose (R^2 = 0.69): $y = 1.1642x + 232.96$. This positive trend suggests that under intermediate light limitation, biochar improved plant water status and possibly enhanced stomatal conductance. Increased transpiration under this shading level may reflect improved physiological activity rather than stress-induced water loss. The moderate R^2 value indicates that other environmental or physiological factors alsocontributed to variability. In contrast, under 85%

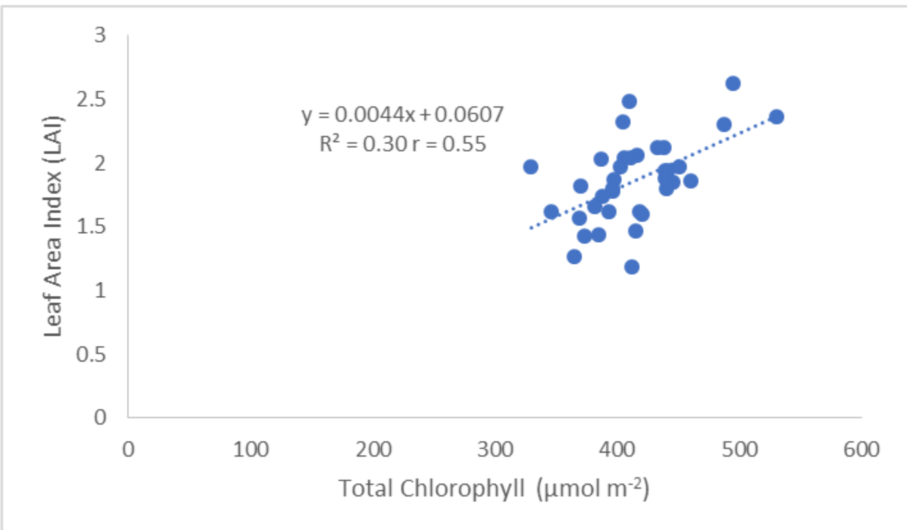

Figure 4: *Correlation between chlorophyll total and canopy development of 6-month-old cocoa indicated by leaf area index. data are means across all shading and biochar treatments, N=36.*

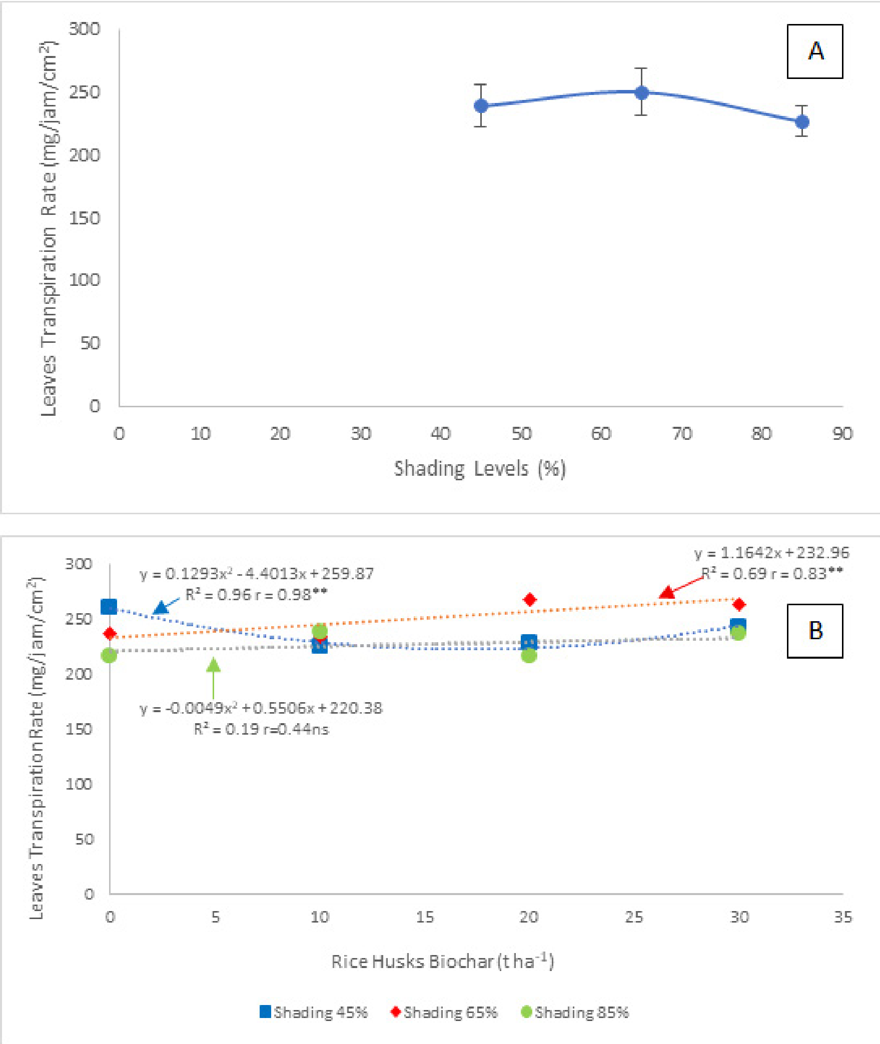

Figure 5: *Leaf Transpiration Rate of 6-month-old Cocoa under Different Levels of Shading (A) and Rice Husk Biochar Dosages (B). Values are presented as mean ± standard deviation.*

shading, the response was weak and statistically less robust ($R^2 = 0.19$): $y = -0.0049x^2 + 0.5506x + 220.38$. Transpiration remained relatively stable across biochar doses. Heavy shading likely limited radiation load and leaf temperature, thereby reducing evaporative demand. Under such low-light conditions, the contribution of biochar to transpiration regulation became minimal. The low coefficient of determination indicates that the biochar dose had little explanatory power under severe shade. Li *et al.* (2025) stated that transpiration is a dynamic physiological process influenced by real-time environmental conditions, the physiological state of the plant, and the inherited impacts of previous growth stages.

The transpiration process is influenced by various internal and external factors. Internal factors include leaf size, leaf thickness, wax layer thickness, number of leaf hairs, number of stomata, shape and location of stomata, as well as tissue age, tissue physiological state, and metabolic rate. External factors include light radiation, temperature, air humidity, wind and soil water content (Nuwa *et al.*, 2019). Stomata regulate transpiration, but the level of stomatal control is influenced or limited by external environmental conditions (Zhao *et al.*, 2025).

Effect of shading and biochar on the growth of cocoa

The analysis of variance showed that shading and biochar application significantly influenced several growth parameters of cocoa plants, while no significant interaction between the two factors was observed. The significant effect ($p<0.05$) of shading on plant height and stem base diameter, and a highly significant effect ($p<0.01$) on the number of branches and number of leaves indicating that shading plays a crucial role in promoting vegetative growth and canopy development in cocoa plants, which is a C3 plants. Insterestingly, the recent study shows that biochar application significantly ($p<0.05$) to highly significantly ($p<0.01$) affected stem base diameter, the number of branches, and number of leaves but no significantl effect ($p>0.05$) on plant height. These results suggest that biochar contributes more to structural growth and biomass allocation rather than vertical growth.

Table 3: *Effect of Shade Treatment and Rice Husk Biochar on the Growth of 6-month-old cocoa.*

Treatments	Plant height increase (cm)	Stem diameter increase (mm)	Number of Branches	Number of leaves (leaves)
Shading Levels (%)				
45	22.53b	8.60a	6.49a	33.71a
65	25.83a	9.14a	5.71a	35.00a
85	26.97a	7.64b	4.17b	25.04b
$LSD[S]_{0.05}$	2.34	0.92	0.82	2.31
Biochar (t ha^{-1})				
0	22.40	7.55b	4.50b	28.78b
10	25.83	8.64a	5.22b	30.06b
20	26.60	8.81a	5.50b	32.78a
30	25.61	8.85a	6.56a	33.39a
$LSD[B]_{0.05}$	ns	0.83	1.02	2.22

The numbers followed by the same letter in a column (a,b) for each parameter and treatment are not significantly different in the LSD test at a confidence level of 95%.

The results of the LSD test at the 0.05 significance level (Table 3) indicate that the 85% shading treatment resulted in the greatest mean increase in plant height (26.97 cm). This increase was not significantly different from that under 65% shading but was significantly higher than that under 45% shading. The 65% shading treatment produced the highest mean increase in stem diameter (9.14 mm), the greatest average number of branches (5.71), and the highest mean increase in leaf number (35.00 leaves). These values were not significantly different from those observed under 45% shading. However, shading treatments did not significantly affect total leaf area. The results of the LSD test at the 0.05 level for rice husk biochar application (Table 3) showed that the 30 t ha^{-1} treatment produced the greatest mean increase in stem diameter (8.85 mm), the highest number of branches (6.56), the largest increase in leaf number (33.39 leaves), and the highest total leaf area (409.13 cm^2). Nevertheless, biochar application had no significant effect on the mean increase in plant height.

Table 3 shows that the highest plant heights were found in the 65% and 85% shade treatments. This is thought to be influenced by the auxin hormone found in plants, which functions to assist in the cell division process. Zainal *et al.* (2022) stated that auxin works more actively when light intensity is low, so that plants grow taller but the stems are weak, the plants appear pale, the stems are not sturdy and the leaves are few due to etiolation. Meanwhile, when light intensity is high, the temperature becomes high, resulting in increased activity of soil microorganisms.

Cocoa plants grown under 45% and 65% shade successfully created conditions that supported gibberellin hormone function. Ultimately, this physiological process increased cambium division and overall xylem and phloem differentiation, leading to an increase in stem diameter. Better growth in vascular tissue (xylem and phloem) helps distribute nutrients and water more efficiently throughout the plant, allowing it to develop more branches and leaves, which aids overall plant growth. Putri *et al.* (2024) stated that gibberellin can help plants grow to their maximum height by promoting stem growth and increasing cell enlargement and multiplication.

Stem diameter will increase along with plant height. Each cell will develop as the number of cells increases, so stem cell proliferation will be faster.

Table 4: *Soil analysis results before and after biochar treatment.*

Soil sample	pH	C-Organic (%)	N (%)	C/N	P_2O_5 (%)	K (%)	Cation Exchange Capacity (cmol (+) kg^{-1})
Before trial	6.69	2.05	0.19	11	10.68	0.28	n.m.
After trial							
Biochar 10 t ha^{-1}	6.85	2.35	0.21	11	12.63	0.36	22.65
Biochar 20 t ha^{-1}	6.74	2.51	0.24	10	16.25	0.41	25.31
Biochar 30 t ha^{-1}	6.68	2.66	0.23	12	14.85	0.54	27.79

Soil Chemistry and Physics Laboratory, Department of Soil Science, Hasanuddin University, 2024. n.m.= not measured.

In plants, each plant hormone does not act independently. The interaction of hormone signals, including auxin, gibberellin, and cytokinin, is responsible for regulating stem height and diameter growth. These interactions regulate stem growth and elongation. Auxin is known to induce stem internodal elongation by regulating the production of active gibberellin. Gibberellins, on the other hand, can regulate auxin synthesis and transport to control stem internodal elongation. Cytokinins promote cell division and volume expansion, while auxin supports cambium activity and vascular tissue differentiation. Therefore, these three hormones regulate cell division, elongation, expansion, and differentiation, resulting in increased plant height and stem diameter (Jing *et al*., 2023).

The recent study shows that the application of rice husk biochar was able to increase the increase in stem diameter, number of branches, and number of leaves compared to without the application of rice husk biochar or control treatment. The improvement in plant growth observed under biochar application can be attributed to its role in enhancing soil fertility (Table 4). Rice husk biochar application improved soil chemical properties, including increased macro nutrient (N, P, and K). These changes create a more favorable root environment, allowing better nutrient availability for plant uptake. These improvements in soil conditions are reflected in the enhanced growth parameters, particularly in stem diameter, number of branches, and number of leaves. This suggests that biochar application supports biomass accumulation and canopy development by improving nutrient availability. Overall, the application of rice husk biochar at higher rates (30 t ha^{-1}) provides greater benefits to soil fertility, which in turn promotes better plant growth performance. This highlights the importance of biochar as a soil amendment for improving soil quality and sustaining plant productivity.

In addition, the porous structure of biochar also provides a suitable habitat for beneficial soil microorganisms, which further contributes to improved nutrient cycling and soil biological activity. It is suspected that rice husk biochar becomes a habitat for microorganisms that produce nitrogenase enzymes such as Azotobacter, which is very important for plant growth. This is supported by the opinion of Elfandari and Safitri (2022) that biochar has micropores that can be used as a habitat for microorganisms so that it can increase soil biological activity. The higher the activity of soil microorganisms, the more nutrients are available in the soil so that plants can absorb them properly.

Rice husk biochar is rich in carbon, which serves as a food source for soil microorganisms. Microorganisms that thrive in biochar can form a symbiotic relationship with plant roots, aiding nutrient uptake and increasing resistance to pathogen infection. Amalina *et al*. (2024) stated that higher microbiota diversity and a balance between beneficial and harmful microbes can reduce the chances of plant disease emergence. Beneficial microorganisms can compete with pathogens for resources and space and can produce antimicrobial compounds that protect plant roots from infection. Biochar application can reduce dependence on chemical pesticides, which in turn contributes to more sustainable and environmentally friendly agriculture.

Biochar also has the ability to clean up organic and inorganic pollutants in soil through complexation or adsorption. The stable aromatic organic carbon content in biochar does not degrade and, therefore, does not return to the atmosphere. This reduces CH_4 and N_2O emissions into the atmosphere, thereby contributing to mitigating the negative impacts of climate change (Enaime and Lübken, 2021).

Conclusions and Recommendations

Based on the results, shading and biochar application independently improved the physiological performance and growth of cocoa plants. No significant interaction was observed between shading and rice husk biochar, indicating that their effects acted independently. Among the shading levels, 65% shade resulted in the most favorable growth responses. Similarly, the highest biochar rate (30 t ha^{-1}) produced the best growth performance. Therefore, the combined use of 65% shading and rice husk biochar at 30 t ha^{-1} is recommended to enhance cocoa growth, as each factor contributes positively through independent effects. Further studies under field conditions, incorporating broader environmental variables and physiological parameters, are required to validate and extend these findings.

Novelty Statement

The originality of this research lies in its analysis of the integration of shade and rice husk biochar in supporting more efficient and sustainable cocoa plant growth, as well as reducing negative impacts on the environment, which has not been widely discussed in previous research related to cocoa plants.

Authors Contribution

Mutiara Nengsy Lengkang: Conceptualization, Methodology, Funding Acquisition, Investigation, Data Curation, and Writing Original draft
Nasaruddin Nasaruddin: Supervision, Methodology and Resources
Ifayanti Ridwan: Conceptualization, Methodology, Formal Analysis and Proofreading

Generative AI and AI-assisted technology statement
The authors declare that no generative AI and AI assisted technology was used in the creation of this manuscript.

Conflict of interest
The authors have declared no conflict of interest.

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