Hedgerow Shading Reduces Heat Stress and Improves Cacao Physiology and Soil Fertility in Tropical Systems

Darmawan Risal

darmawanrisal09@gmail.com

Hasanuddin University: Universitas Hasanuddin

Risma Neswati

https://orcid.org/0000-0003-0358-389X

Muh Jayadi

Ifayanti Ridwan

Baharuddin Baharuddin

Sartika Laban

Novaty Eny Dungga

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Abstract

Aims

Elevated temperatures during the vegetative phase pose a significant threat to the physiological stability and growth of cacao (Theobroma cacao L.), particularly on limited land in tropical areas. This study examined the efficacy of vegetation-based hedgerow shading for enhancing cacao performance under extreme heat stress conditions.

Methods

Field experiments were conducted in South Sulawesi, Indonesia, using three levels of natural shade intensity (0–25%, 25–50%, and 50–75%), quantified via aerial imaging. The hedgerow system utilized native multipurpose species arranged in layered canopies to regulate microclimate and soil characteristics. Key physiological (chlorophyll concentration and light penetration) and edaphic parameters (nitrogen availability, carbon-to-nitrogen (C/N) ratio, and cation exchange capacity) were measured along with vegetative growth traits.

Results

The 50–75% shading treatment yielded the most favorable physiological and agronomic outcomes. This condition improved the chlorophyll concentration, light distribution, and nitrogen content, while reducing the C/N ratio and increasing cation exchange capacity. Vegetative cacao growth under this treatment showed significantly greater height (247.5 cm), stem diameter (7.8 cm), and canopy width (223.6 cm) than under the other shade levels.

Conclusions

This hedegrow system is an agroecological strategy that provides a sustainable approach for climate-resilient cacao cultivation in tropical regions vulnerable to extreme temperatures.

Introduction

Cacao (*Theobroma cacao L.*) is a tropical crop that is highly susceptible to the increasing temperatures associated with climate change (Ceccarelli et al., 2021). Global surface temperature rises of 0.95–1.2°C have induced thermal stress in cacao, particularly during its vegetative growth phase (Song et al., 2022). When thermal thresholds are surpassed, critical physiological functions are compromised, including diminished photosynthetic efficiency, chloroplast damage, and disrupted stomatal gas exchange, collectively leading to stunted growth and yield reduction (Lahive et al., 2019; Suárez et al., 2021). These physiological disruptions are a primary factor contributing to the decline in cacao yield. According to the

International Cocoa Organization (ICCO, 2025), Indonesia's cacao production has significantly decreased, from 170,000 tons in 2020/2021 to 160,000 tons in 2023/2024. This downward trend reflects the mounting climatic pressure on national cacao production systems, with the most severe impacts observed among smallholder farmers in vulnerable regions, such as South Sulawesi. In this region, farmers encounter significant challenges in adapting to extreme climatic conditions due to limited land ownership, minimal access to inputs, and ongoing soil degradation (Zhafran et al., 2022). These challenges are further exacerbated by prolonged droughts and intense solar radiation, which accelerate the depletion of soil organic matter and reduce the nutrient retention factors critical to sustaining cacao productivity. Consequently, there is an urgent need for adaptive solutions that are ecologically sound, locally applicable, and resource-efficient.

One such approach involves the integration of local vegetation-based hedgerow systems, an agroecological method incorporating structured rows of native shade species, such as coconut (*Cocos nucifera*), banana (*Musa* spp.), and Gliricidia (*Gliricidia sepium*), within cacao plantations (Hatt et al., 2024; Popescu et al., 2023). These species form multilayered canopies that buffer the microclimate, mitigate heat stress, and improve soil structure and fertility (Biffi et al., 2022; Risal et al., 2014). Beyond regulating temperature and solar radiation, the organic matter derived from these hedgerow species enhances nutrient cycling, particularly nitrogen, phosphorus, and potassium, which are essential for chlorophyll synthesis and stomatal regulation (Anokye et al., 2021). This integrative system supports physiological adaptation and sustainable productivity by leveraging local biodiversity and traditional agroecological knowledge (Dominati et al., 2016).

However, the efficacy of shade systems is significantly influenced by factors such as canopy cover percentage, shade tree species, density, and regional climate characteristics (Famuwagun et al., 2021; Kohl et al., 2024). Although some studies have indicated that cacao yields are higher under full sun conditions, these systems often necessitate intensive external inputs and may jeopardize long-term environmental sustainability, particularly on smallholder farms with limited land resources (Benjamin & Santos, 2021; Mensah et al., 2024; Niether et al., 2020). Conversely, the integration of cacao with shade has been demonstrated to enhance climate resilience through microclimate regulation and the preservation of ecosystem services, such as soil moisture conservation and biodiversity enhancement (Macías et al., 2024; Numbisi et al., 2021; Wainaina et al., 2021). Nonetheless, during periods of extreme heat, competition for water and nutrients between cacao and shade trees may adversely affect plant physiology, underscoring the importance of species selection and shade density management for optimizing hedgerow system performance in tropical climates (Isaac et al., 2024).

This study aims to assess the impact of varying shade intensity levels in a local vegetation-based hedgerow system on cacao physiology, soil fertility, and vegetative growth under elevated temperature stress in a tropical environment. The findings are anticipated to provide empirical evidence supporting the development of climate-resilient and sustainable cacao production systems that leverage local resources.

Materials and methods

Location and time of research

This study was conducted during the extended dry season, from July to December 2023, on smallholder cacao farms utilizing a hedgerow system in Bulukumba Regency, South Sulawesi, Indonesia. The research site was situated at coordinates 5°22’42.1"” S and 120°22'24.2”" E, at an elevation of 70 m above sea level. This location was selected because of its relatively high production intensity and the presence of significant climatic challenges, rendering it pertinent for assessing the adaptation of the hedgerow system employed by farmers in the region.

Climate data from the preceding five years indicated daily maximum temperatures ranging from 26°C to 28°C. However, during the study period, the average daily temperature increased to between 26°C and 30°C, and the level of solar radiation showed a relatively increasing pattern throughout the research period with an average value of 107.49 W/m², with the highest recorded temperatures occurring from September to November 2023 (Fig. 1). Daily temperature data were sourced from (CHIRPS, 2024), with a daily data frequency employed to capture the microclimate conditions at the research site.

Experimental design and treatments

This study utilized a Randomized Complete Block Design with a single treatment factor, specifically the shading cover percentage of the hedgerow system, categorized into three distinct levels (Fig. 2): low shading percentage plot (0–25%) (Fig. 2c), moderate shading percentage plot (25–50%) (Fig. 2d), and high shading percentage plot (50–75%) (Fig. 2e). These categories were determined through spatial analysis of aerial imagery captured via drone between 12:00 PM and 01:00 PM to minimize horizontal shadow bias (Brahmantara, 2017). The aerial imagery was analyzed using ART-GIS software to conduct digital delineation and canopy cover classification, resulting in 35 plots (Fig. 2a). A 10 m × 10 m plot was selected for observation to ensure efficiency and represent the heterogeneity of the canopy across the research area (Fig. 2b). Three plots were randomly selected from each shading category as replicates, yielding nine experimental plots. Each plot contained an average of six cacao plants, totaling 54 cacao plants observed as the sample. Shading levels were controlled and verified through leaf and stem pruning in July 2023, ensuring no biomass was left within the plot area to maintain consistent environmental conditions. The established shading range was based on literature indicating that the physiological performance and productivity of cacao are optimal at approximately 50% shading (Arévalo-G et al., 2021; Rajab et al., 2016).

Tools, parameters, and analysis methods

In this study, we identified three principal parameter categories: plant physiology, vegetative growth, and soil fertility. These parameters were measured at the end of the study period. Physiological parameters, including leaf chlorophyll content, were assessed in November 2023, which was measured using a Chlorophyll Content Meter (CCM-200, Opti-Sciences Inc., USA) in four orientations of the plant (east, west, north, and south) to account for variations in light intensity. The device provides non-destructive estimates of relative chlorophyll content expressed as Chlorophyll Content Index (CCI) units. Stomatal analysis was conducted using the impression method with a clear nail polish applied to the abaxial surface of mature leaves (specifically, the third leaf from the tip). These impressions were examined using a light microscope (Olympus CX23) at 400× magnification to ascertain the number and density of the stomata per mm^2. Light distribution on the cacao canopy was quantified based on the absorption, reflection, transmission, and solar canopy openness percentage (Scop) using a portable spectrophotometer (Apogee PS-100) between 09:00 AM and 10:00 AM under clear sky conditions. The data were subsequently analyzed to determine the light capture efficiency of the canopy.

Vegetative growth parameters were measured in December 2023, including plant height from the soil surface to the highest point using a wooden ruler, stem diameter at a height of 15 cm from the soil surface was measured using a digital caliper, and canopy width was measured in two directions (north-south and east-west) and averaged. Soil fertility parameters were obtained by taking soil samples from four points within the treatment plot (at the intersection of the cacao canopy and banana plants) at a depth of 1–10 cm, which were then combined. The samples were filtered to remove roots and stones and packaged in 500 g portions for analysis in an accredited laboratory. Soil chemical analysis included soil pH (with a 1:2.5 ratio in H_2O), organic carbon (C-organic) using (Walkley-Black method), total nitrogen (N) using (Kjeldahl method), carbon-to-nitrogen (C/N ratio), and available phosphorus (P) using (Bray I method). Base cations, including calcium (Ca), magnesium (Mg), potassium (K), and sodium (Na), were extracted using NH_4OAc at pH 7.0, whereas cation exchange capacity (CEC) and base saturation (BS) were analyzed using the Soil Survey Staff method.

Statistical analysis

The observational data were analyzed using Analysis of Variance (ANOVA). If significant differences were found between treatments, post-hoc testing was performed using the Honest Significant Difference (HSD) method at a significance level of $\alpha = 0.05$, to identify specific differences between treatment groups. The results of the analysis are presented as means, with letter indicators showing significant differences at the same level.

Results

Physiological responses of cacao to hedgerow shading

Light distribution in the cacao canopy under varying shade percentages

The analysis result of light distribution (Fig. 4) showed that light absorption was the highest under 0–25% shading (11.2%), followed by 25–50% shading (9.3%), and lowest under 50–75% shading (8.3%) (HSD test, $\alpha = 0.05$). This pattern indicates that cacao leaves under low shading received a higher proportion of incident light, aligning with the light-demanding characteristics of cacao as an understory species up to moderate intensity (Zhen & van Iersel, 2017). Reflectance was greatest at 50–75% shading

(22.9%) and 0–25% shading (22.8%) and lowest at 25–50% shading (21.0%), suggesting a bimodal reflectance response to extreme light and dense shade conditions (An et al., 2022). Transmission increased with shading intensity, with the highest transmission at 50–75% shading (27.2%), followed by 25–50% (23.9%), and 0–25% shading (16.9%), indicating greater light penetration under denser shade. Light Scop also increases with shading intensity, with the highest value at 50–75% shading (25.0%), followed by 25–50% (22.5%) and 0–25% shading (19.9%) (Zhi et al., 2023). Higher shading levels enhance light diffusion through the canopy and improve light-capture efficiency at the leaf level.

Stomatal characteristics of cacao leaves under varying shade percentages

The shading intensity exerted a significant influence on the stomatal characteristics of cacao leaves (Fig. 5). The number of stomata per microscopic field declined with increasing shade, decreasing from 28.2 under 0–25% shading to 25.0 under 25–50% shading, reaching its lowest value under 50–75% shading (18.5), with all differences being statistically significant (HSD test, $\alpha = 0.05$). Similarly, stomatal density (stomata mm^2) decreased with increasing shading. The highest density was recorded under 0–25% shading (132.7 stomata mm^2), followed by 117.8 under 25–50%, and the lowest under 50–75% (87.2 stomata mm^2). These reductions were statistically significant, indicating that elevated shading levels inhibited stomatal development on the leaf surfaces (Wall et al., 2022). Conversely, the stomatal aperture area (mm^2) showed a decreasing trend with shade, declining from 0.00055 mm^2 at 0–25% to 0.00034 mm^2 at 25–50% and further to 0.00012 mm^2 under 50–75% shading. The differences were significant, suggesting that light availability regulates not only stomatal abundance but also their functional opening capacity (Ač et al., 2024).

Chlorophyll concentration in response to hedgerow shading

The statistical analysis results for the 0–25% shading percentage (Fig. 6) indicated that the chlorophyll a content was 130.4, chlorophyll b was 63.6, and total chlorophyll was 196.5, all of which were the lowest and significantly different (HSD $\alpha = 0.05$). At 25–50% shading, chlorophyll a content rose to 163.7, chlorophyll b to 72.6, and total chlorophyll to 240.7. Finally, at the 50–75% shading level, chlorophyll a, chlorophyll b, and total chlorophyll reached their highest values of 215.0, 88.8, and 310.2, respectively, which were significantly different from the other treatments (HSD $\alpha = 0.05$). The analysis revealed a clear inverse relationship between shade level and stomatal characteristics in cacao leaves. As shade levels increased from low (0–25%) to high (50–75%), there was a consistent decrease in stomatal number, density, and pore size (Li et al., 2024; Zhou et al., 2017). Cacao plants adapt their leaf structure in response to varying light conditions, potentially optimizing gas exchange and water-use efficiency under different shade regimes.

Soil fertility at various percentages of hedgerow shading

Hedgerow shading had a significant influence on various soil fertility parameters (Fig. 7). The soil pH was highest under 25–50% shading (6.18), followed by 0–25% (6.03), and lowest under 50–75% shading (5.75), with significant differences observed between treatments (HSD test, $\alpha = 0.05$). The C/N ratio exhibited a declining trend with increasing shade, decreasing from 10.00 under 0–25% shading to 7.67 at 50–75% shading. The total nitrogen (N) content showed a slight increase under heavier shading, with the highest value recorded at 50–75% (0.29%) and the lowest at 0–25% (0.21%). Similarly, phosphorus (P) content decreased significantly with increasing shade intensity, from 13.38 ppm (0–25%) to 11.72 ppm (50–75%). Exchangeable magnesium (Mg) remained stable across treatments (1.16 cmol kg^{-1}), with no significant difference between 0–25% and 50–75% shading, although a slight decline was noted at 25–50% (1.07 cmol kg^{-1}). In contrast, exchangeable potassium (K) declined significantly with increasing shade, from 0.32 cmol kg^{-1} under low shade to 0.19 cmol kg^{-1} under 50–75% shading. The exchangeable sodium (Na) remained statistically unchanged across all shading levels. The cation exchange capacity (CEC) was highest under low shade (28.00 cmol kg^{-1}), decreased sharply at 25–50% (18.00 cmol kg^{-1}), and partially recovered at 50–75% (22.00 cmol kg^{-1}). Base saturation (BS) followed a similar trend, decreasing from 18.07% (0–25%) to 19.73% (50–75%), with the lowest value at 25–50% (19.32%).

Vegetative growth responses of cacao to varying levels of hedgerow shading

The results (Fig. 8) indicate that increasing levels of shade significantly influenced the vegetative growth parameters of cacao, including plant height, canopy width, and stem diameter, with statistically significant differences observed among the treatments (HSD test, $\alpha = 0.05$). The maximum plant height (247.5 cm) was recorded under 50–75% shade, which significantly surpassed the values observed under 25–50% and 0–25% shade. This suggests an adaptive etiolation response characterized by stem elongation under conditions of low light availability. Canopy width also increased significantly, reaching 223.6 cm at the highest shading level, indicating a lateral growth strategy to optimize light capture through an enhanced leaf surface area under diffuse light conditions (Visscher et al., 2024). Similarly, stem diameter consistently increased with shading intensity, from 4.5 cm (0–25%) to 5.6 cm (25–50%) and 7.8 cm (50–75%), reflecting a greater accumulation of structural biomass and improved vascular support for water and nutrient transport (Raza et al., 2019). Collectively, these findings suggest that 50–75% shading provides a favorable microenvironment that promotes both vertical and lateral vegetative development of cacao in a hedgerow planting system.

Discussion

Cacao adaptation to light availability under hedgerow shading

The decrease in light absorption at 50–75% shading aligns with the usual adaptation response of cacao, which thrives as an understory plant in tropical regions.This adaptation reflects cocoa's need for moderate light intensity (~ 200–600 μmol m^{-2} s^{-1}) or approximately 50% shade to optimize photosynthetic efficiency without the risk of photoinhibition (Arévalo-G et al., 2021; Leiva-Rojas et al., 2024). These results corroborate previous findings that cacao exhibits low light compensation and moderate photosynthetic saturation points (Baligar et al., 2021), emphasizing the critical nature of the light balance for this crop. The bimodal reflectance pattern observed, with high reflectance under both

0–25% and 50–75% shading, suggests complex light-adaptive mechanisms in cacao. The increased reflectance under dense shade (50–75%) likely indicates structural adaptations that allow deeper light penetration to maintain photosynthetic activity (Jiménez-Pérez et al., 2019). This adaptation is crucial for sustaining productivity under varying light conditions, which is a characteristic feature of agroforestry systems.

The progressive increase in light transmission with increasing shade intensity, peaking at 50–75% shading (27.2%), reveals the ability of the cacao canopy to optimize light utilization under reduced direct light conditions. This finding aligns with that of (Feng et al., 2023), who reported that increased light penetration under dense canopies creates a microclimate that enhances diffuse light and regulates temperature, thereby mitigating heat stress. Improved light capture under these conditions reflects the capacity of the hedgerow system to optimize photosynthetic performance (Asante et al., 2021) and create stable light gradients (Arévalo-G et al., 2021; Olesen et al., 2007). Interestingly, the increase in specific canopy optical properties (Scop) with shading, reaching its highest value at 50–75% shading (25.0%), further supports the notion of efficient light use in cacao canopies under moderate to high shade conditions. This trend aligns with the findings of (Zhi et al., 2023), who suggested that cacao plants can adapt their canopy structure to maximize light capture and utilization efficiency under reduced light availability.

Collectively, these findings highlight the critical role of appropriate shade management in cacao agroforestry systems. These results indicate that a shade level of 50–75% may offer an optimal balance for cacao, facilitating efficient light utilization while promoting robust vegetative growth. However, it is important to acknowledge that excessive shade can potentially reduce chloroplast density and leaf thickness, thereby limiting photosynthetic capacity under very low-light conditions (Mortimer et al., 2018). Consequently, careful consideration of local environmental factors and cacao genotypes is essential when designing and managing cacao agroforestry systems to achieve a delicate balance between light optimization and overall plant performance.

Stomatal regulation and transpiration control in shaded cacao

The observed increase in stomatal number and density under low shade intensity (0–25%) represents an adaptive response of cacao to elevated irradiance. Enhanced incident light on the leaf surface augments light absorption while reducing transmission, leading to higher leaf temperatures and increased evaporative demand (Jaimez et al., 2018). Consequently, wider stomatal aperture areas were formed to facilitate transpirational cooling and CO_2 uptake (Driesen et al., 2020a). Although this promotes gas exchange, it also increases the potential for water loss, necessitating a physiological trade-off between carbon assimilation and water-use efficiency, particularly under arid or wind-exposed conditions (McAusland et al., 2016). In contrast, under moderate shading (25–50%), stomatal traits, such as number, density, and pore area, were reduced, indicating a decline in evaporative demand driven by more favorable microclimatic conditions. These changes are consistent with enhanced light transmission and improved internal light distribution in the hedgerow canopy, which mitigates extreme leaf heating

(Campany et al., 2016). Moderate irradiance may stabilize stomatal conductance and reduce transpiration, allowing sustained photosynthetic function with improved water-use efficiency (Espinosa et al., 2020; Niether et al., 2018). Such conditions are particularly beneficial in humid tropical environments, where excessive transpiration is not necessary for cooling.

At high shade levels (50–75%), stomatal number, density, and aperture area declined further, suggesting morphological adaptation to persistent low-light conditions. Reduced irradiance results in a lower vapor pressure deficit and a more stable leaf energy balance, thereby diminishing the need for large stomatal openings (Somarriba et al., 2024). The concurrent increases in Scop and light transmission under high shade conditions support this observation, indicating enhanced canopy-level light diffusion and reduced heterogeneity in photon distribution (Famuwagun et al., 2021). These conditions may favor a more conservative stomatal strategy, in which fewer stomata operate more efficiently to sustain photosynthesis with minimal water expenditure (Dow et al., 2017). Collectively, these results suggest that stomatal development and function in cacao are tightly regulated by the light environment, with canopy-level shading modulating microclimatic conditions to favor either gas exchange or water conservation, depending on irradiance intensity (Driesen et al., 2020b; Han et al., 2021). The hedgerow system, by influencing both light quantity and distribution, appears to promote a balanced stomatal strategy that enhances physiological resilience and water use optimization across varying shade levels in cacao agroforestry systems..

Chlorophyll response to hedgerow shading in cacao

Shading-induced alterations in chlorophyll accumulation in cacao leaves represent a series of physiological adaptations aimed at optimizing photosynthesis and minimizing stress. Under low shading conditions (0–25%), there was a significant reduction in chlorophyll a, b, and total chlorophyll content, indicating photoinhibitory stress, likely due to excessive light exposure. High irradiance under open canopy conditions can damage the photosystem apparatus, particularly PSII, leading to the degradation of chlorophyll pigments and a reduction in photosynthetic capacity (Qiao et al., 2021; Zhao et al., 2022). This stress response was accompanied by increased stomatal density and wider stomatal aperture in the same treatment (Fig. 5), potentially enhancing CO_2 uptake but at the cost of increased transpirational water loss (Matkowski & Daszkowska-Golec, 2023). However, such stomatal responses may be insufficient to compensate for limited chlorophyll content, resulting in an imbalance between carbon acquisition and energy absorption (Patil et al., 2020).

In contrast, moderate shading (25–50%) significantly increased all chlorophyll components, suggesting a more favorable microclimate for pigment synthesis. Under reduced light stress, cacao plants are likely to experience improved photosynthetic conditions without triggering oxidative damage (Umesh et al., 2023). The concurrent moderate reductions in stomatal number and pore area suggest an optimization strategy for maintaining gas exchange while enhancing water-use efficiency, which is a key adaptation in humid tropical environments (Srivastava et al., 2024). The highest chlorophyll levels were observed at 50–75% shading, indicating enhanced chloroplast development under low-light conditions. This trend is consistent with shade-acclimated leaves, which typically have increased chlorophyll b content to improve light-harvesting efficiency under limited photosynthetically active radiation (PAR) (Yu et al., 2022). However, the significantly reduced stomatal traits in this treatment (Fig. 5) may limit CO_2 diffusion, potentially constraining photosynthesis under extremely low irradiance conditions. These findings support the role of hedgerow-based shading in mediating cacao physiology, where moderate shade (25–50%) appears to provide the most balanced conditions for pigment accumulation, photosynthetic function, and water conservation. These conditions enhance both leaf-level adaptation and agroecosystem sustainability (Mortimer et al., 2018). Future research should investigate the long-term influence of intermediate shade levels on cacao yield and fruit quality and explore the interactive effects of temperature, soil moisture, and genotype-specific responses.

Soil fertility dynamics influenced by hedgerow shade percentage

Effects of shading on soil pH, cation exchange capacity (CEC), and base saturation (BS)

The moderate shading treatment (25–50%) yielded the most favorable soil chemical conditions, as evidenced by the highest pH (Fig. 7a) and relatively balanced cation exchange capacity (CEC) and base saturation (BS) (Fig. 7h). These findings suggest that intermediate canopy cover can buffer extreme microclimatic fluctuations, such as temperature and moisture, thereby maintaining stable decomposition rates and moderating organic acid accumulation (Wang & Kuzyakov, 2024). Conversely, the lowest pH and BS values observed under 50–75% shading indicate leaching of base cations due to excess moisture and slower organic matter turnover, despite an increase in CEC. This phenomenon suggests a decoupling between the cation retention capacity and base saturation under dense shade, likely due to the enhanced acidity of litter-derived organic acids (Russell et al., 2017; Sierra & Motisi, 2012).

Shading effects on nitrogen availability and C/N ratio

The decrease in the C/N ratio with increased shading, concurrent with rising total N content (Fig. 7c), suggests intensified mineralization processes driven by favorable microclimatic conditions for microbial activity (Sauvadet et al., 2020). However, under high shading, this could also predispose the soil to nitrogen loss via denitrification or volatilization if aeration is limited, particularly under extreme climatic conditions (Kaba et al., 2018). Although the low C/N ratio under 50–75% shading reflects active microbial processing, the moderate shading treatment maintained a sufficiently low ratio for efficient mineralization and sufficient N availability without pushing the system toward potential nutrient inefficiency or gaseous losses. This supports the conclusion that 25–50% shade represents a more balanced trade-off between N mineralization and retention (Nahdia et al., 2020).

Macronutrient (P, K, Mg, Na) responses to shade percentage

Regimes phosphorus (P) availability exhibited a non-linear response to shading (Fig. 7d), with the highest levels under low shade (0–25%), likely due to better mineralization and less fixation. The decline under 25–50% shading, despite favorable CEC and pH, suggests stronger P fixation by Al^{3+} and Fe^{3+} at acidic pH levels (Bouray et al., 2021). Under high shade, a slight recovery in P may be due to slow release from undecomposed litter; however, this form is not immediately bioavailable. These findings underscore the complexity of P dynamics, which are highly sensitive to microclimatic interactions rather than to shading intensity alone (Ragot et al., 2016). Potassium (K) exhibited a consistent decline with increasing shade (Fig. 7f), attributed not only to leaching, but also to strong adsorption to colloids at lower pH and increased uptake by shaded plants (Sidhu et al., 2024). Conversely, magnesium (Mg) remained relatively stable (Fig. 7e), confirming its low mobility and strong retention in clay-rich tropical soils (Zhu et al., 2020). Slight Mg fluctuation at 25–50% shading may result from enhanced uptake due to optimal root conditions or from contributions by base-rich litter from hedgerow species like Gliricidia and Musa spp. (Andoh-Mensah et al., 2023; Senbayram et al., 2015). Sodium (Na) showed no response (Fig. 7g), reinforcing its minimal role in cacao nutrition and its weak retention under tropical conditions (Rojas et al., 2022).

Structural vegetative responses of cacao to hedgerow shading

The significant increase in cacao plant height under 50–75% shading (247.5 cm) exemplifies a typical shade-adaptive response through stem elongation (etiolation), facilitating enhanced light acquisition under low-light conditions (Baligar et al., 2021). This phenomenon is corroborated by the elevated Scop and light transmission values under dense shading, which augments diffuse light penetration within the canopy (Fig. 4), thereby promoting vertical growth. Conversely, minimal shading (0–25%) results in excessive irradiance, increased reflectance, and diminished Scop, leading to photoinhibition and heat stress that constrain height expansion (Leiva-Rojas et al., 2024). The physiological traits further elucidated these morphological outcomes. Reduced stomatal aperture and density under high shade conditions decrease transpiration, conserve water, and allow energy to be redirected towards structural growth (Driesen et al., 2020a). Concurrently, increased chlorophyll levels enhance the photosynthetic efficiency under reduced irradiance, thereby fostering biomass accumulation (Tham-Agyekum et al., 2023). These conditions were complemented by increased nitrogen availability (0.29%) and a lower C/N ratio (7.67), indicative of active organic matter mineralization and enhanced protein synthesis for meristematic growth (Dos Santos et al., 2024). Although base saturation declined, increased cation exchange capacity (CEC) under high shading conditions improved nutrient retention and supported root function.

Canopy width also increased significantly under 50–75% shade (223.6 cm), indicating lateral growth plasticity in response to optimized vertical and horizontal light gradients. Enhanced Scop and uniform light distribution across canopy layers promote leaf expansion and improve light-capture efficiency (Adamiec et al., 2024; Emmel et al., 2020). The north–south row orientation of hedgerow planting further supports symmetrical canopy development by ensuring balanced light exposure throughout the day (V et al., 2024). Soil contributions, including improved Mg and N availability and stable CEC, sustain cell division, and nutrient transport (Shi et al., 2024; Zuo et al., 2023). Stem diameter also responded positively, increasing from 4.5 cm to 7.8 cm with shading. This growth reflects enhanced cambial activity and carbon allocation to supportive tissues, aligning with increased photosynthetic output and efficient source–sink dynamics (Drexler et al., 2021). Elevated CEC and nitrogen availability, along with a lower C/N ratio, further facilitate nutrient delivery to stem tissues (Baligar et al., 2021). Adequate Mg supports structural protein synthesis (Oliveira et al., 2024), whereas balanced lateral lighting from the row orientation promotes uniform radial stem growth and maintains mechanical integrity (Dupraz et al., 2018). Collectively, these findings confirm that 50–75% shading in hedgerow systems fosters a favorable microenvironment for vegetative development through the synergistic interaction of physiological plasticity, soil fertility, and spatial light dynamics, offering a viable ecological strategy to sustain cacao growth under increasing environmental stress.

Conclusion

The present study elucidates that shading levels of 50–75% within a hedgerow system establish the most conducive conditions for cacao growth under tropical heat stress. At this shading intensity, physiological responses, such as increased chlorophyll content, enhanced Scop, and improved light transmission, indicate greater photosynthetic efficiency and adaptive light utilization under reduced irradiance. Simultaneously, soil fertility dynamics revealed higher nitrogen availability, a lower C/N ratio, and improved cation exchange capacity, which supported sustained nutrient uptake and vegetative development, despite a moderate reduction in base saturation. Structural growth traits, including plant height, canopy width, and stem diameter, were optimized under these conditions, suggesting an optimal balance between source and sink relationships and structural biomass allocation. These integrated responses imply that moderate to high shade levels not only mitigate extreme climatic conditions but also enhance physiological plasticity and soil resource efficiency. Collectively, our findings advocate the implementation of hedgerow-based shading as a sustainable agroecological strategy for improving cacao performance in increasingly variable tropical environments.

Declarations

Supplementary Information

No supplementary material is associated with this article. All the relevant data are presented in the main manuscript.

Conflict of interest

The authors declare that they have no conflict of interest.

Author contributions

DR conceived the study, designed the experiments, and performed fieldwork. RN supervised the research, analyzed the data, and wrote the manuscript. MJ and B contributed to data interpretation and physiological assessments. IR, SL, and NED conducted the soil and nutrient analyses. All authors have revised and approved the final manuscript.

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Figures

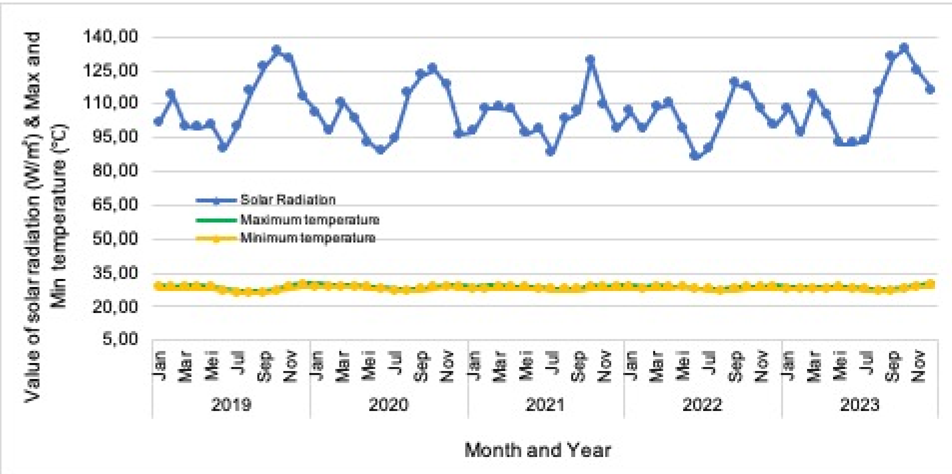

Figure 1

Trends in monthly solar radiation (W/m²), maximum daily temperature (°C), and minimum daily temperature (°C) at the experimental site in South Sulawesi from 2019 to 2023.

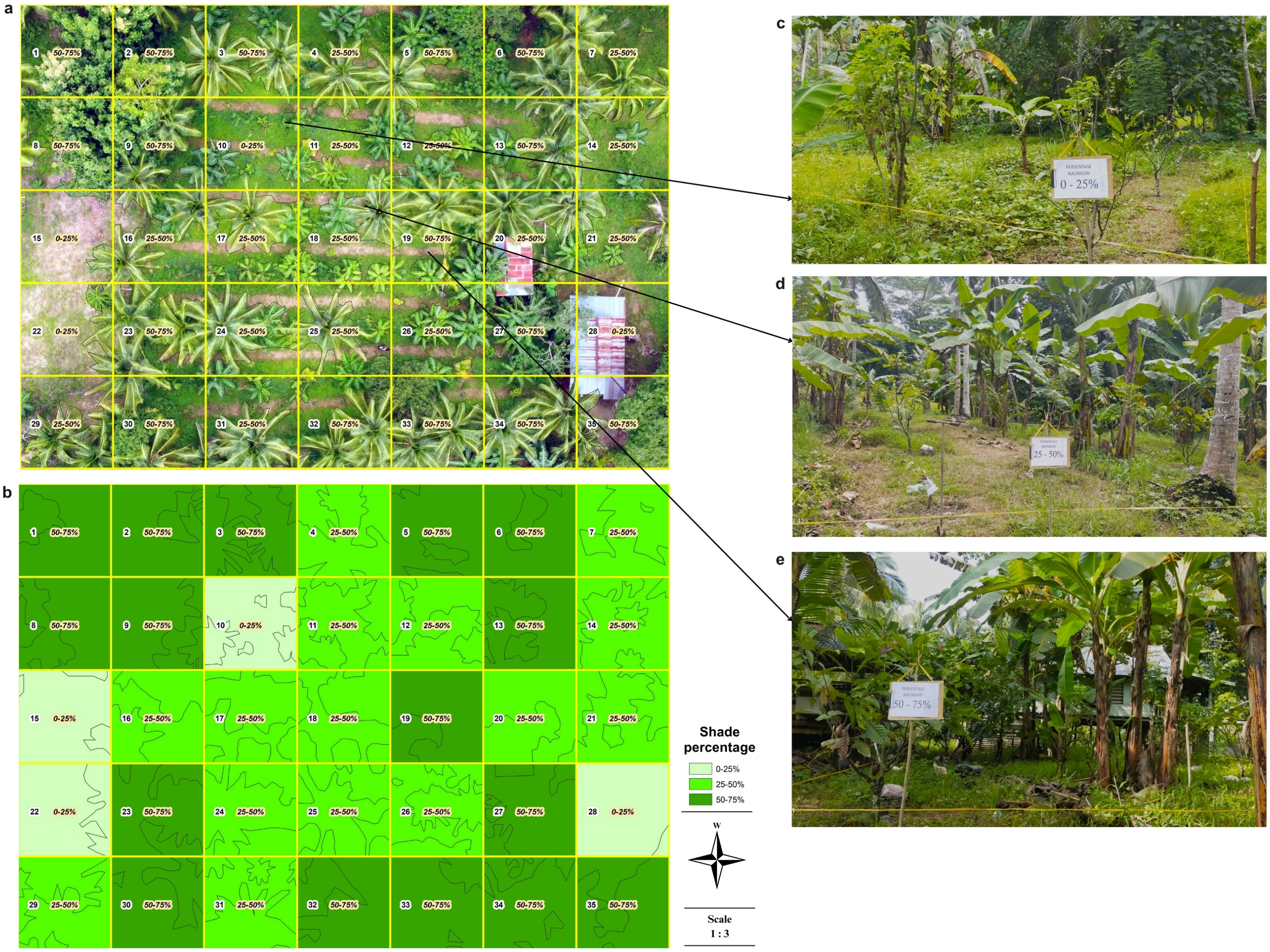

Figure 2

Classification of hedgerow shading based on spatial analysis of aerial imagery obtained via close-range drone surveys: (**a**) grid layout of experimental plots in the hedgerow system, (**b**) spatial classification of shade percentage within each grid plot, (**c**) representative plot with 0-25% shade, (**d**) representative plot with 25-50% shade, (**e**) representative plot with 50-75% shade.

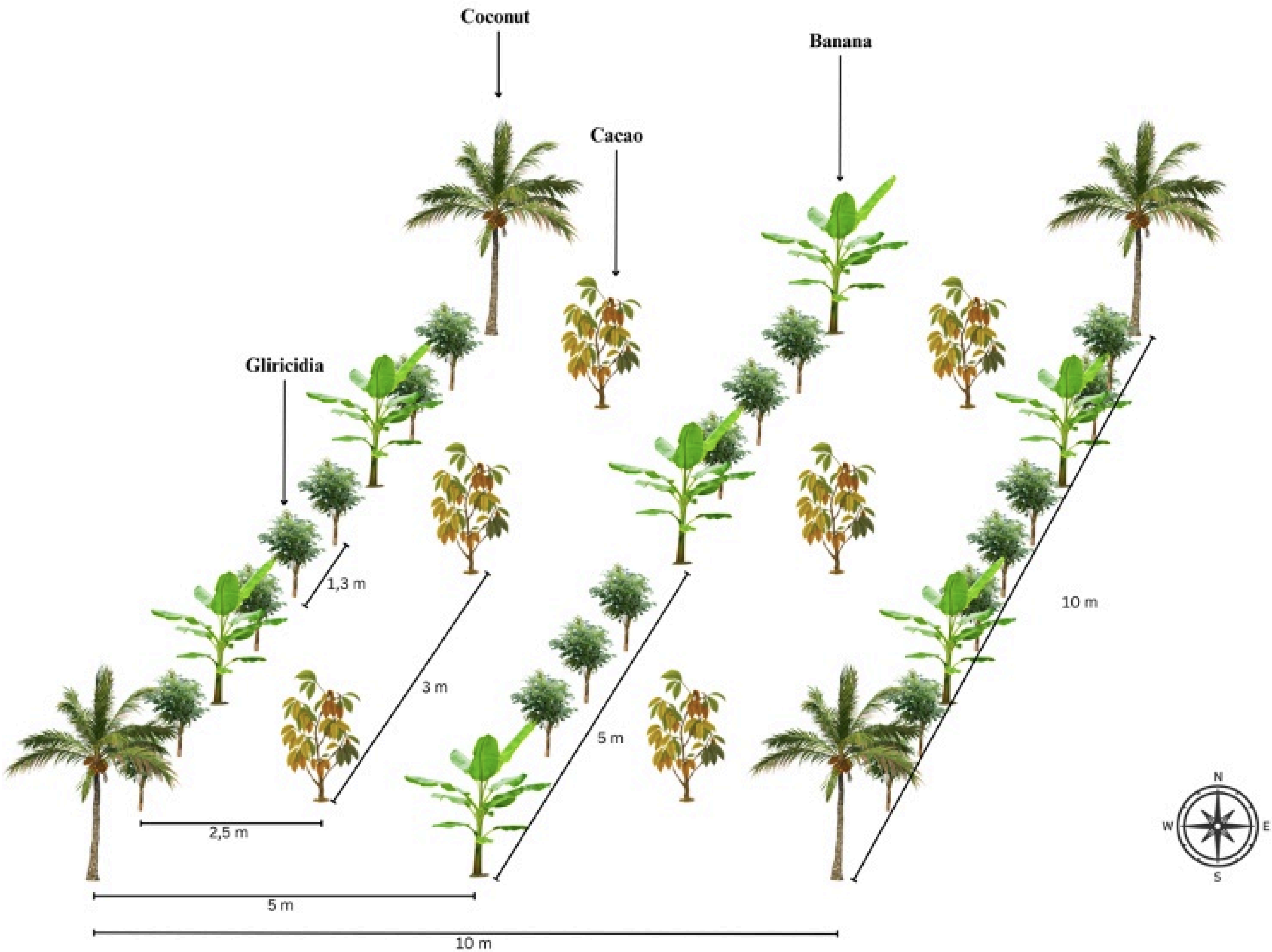

Figure 3

Schematic of spatial arrangement and interplant distances in the hedgerow system plot. The layout included Gliricidia, banana, coconut, and cacao plants, with distances measured between and within rows, as indicated. The north orientation was marked as a spatial reference.

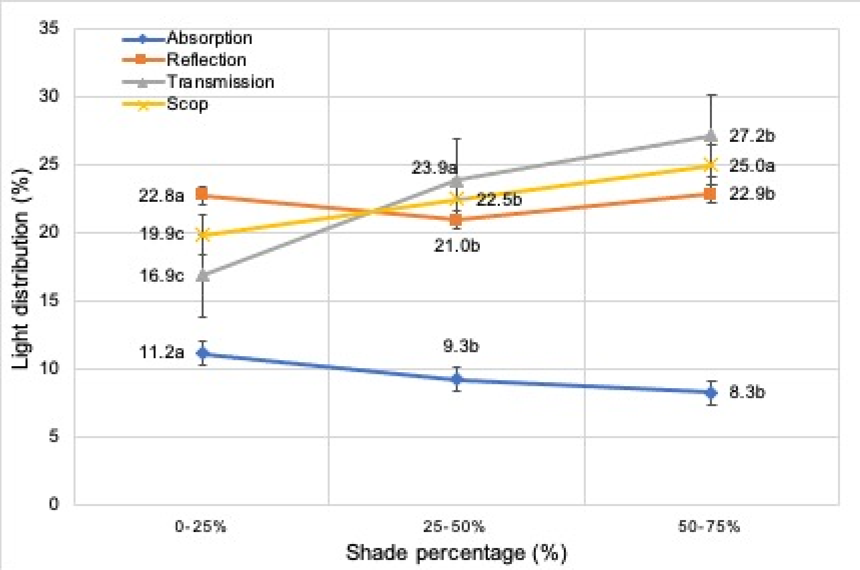

Figure 4

Light distribution in the cacao canopy under different shade levels. Different lowercase letters indicate significant differences according to the HSD test (α = 0.05). The HSD values for each light parameter are as follows: absorption, 1.1%; reflection, 1.5%; transmission, 0.8%; and Scop, 0.8%.

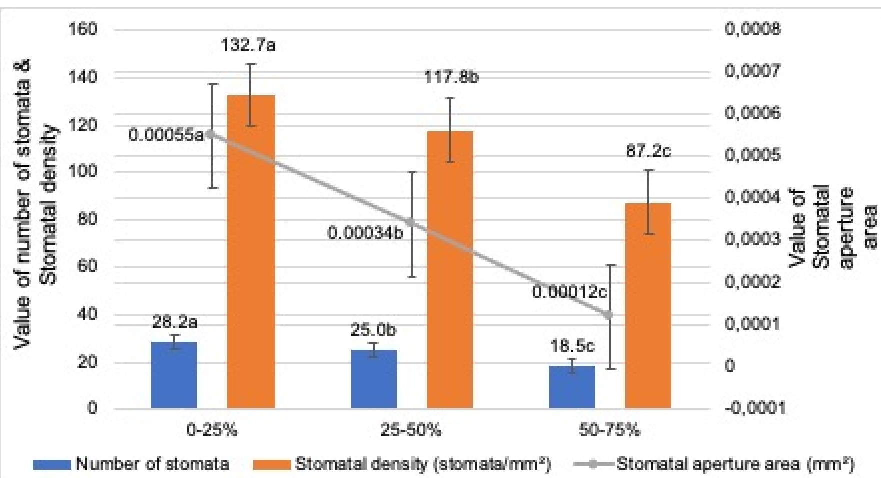

Figure 5

Stomatal responses of cacao leaves under different shade intensity levels. The shading treatments significantly influenced the number of stomata, stomatal density (stomata mm ²), and stomatal aperture area (mm²). Different lowercase letters indicate significant differences based on the HSD test (α = 0.05). The HSD values for each parameter were as follows: number of stomata = 2.38, stomatal density = 11.23 stomata mm; stomatal aperture area = 0.0000010 mm².

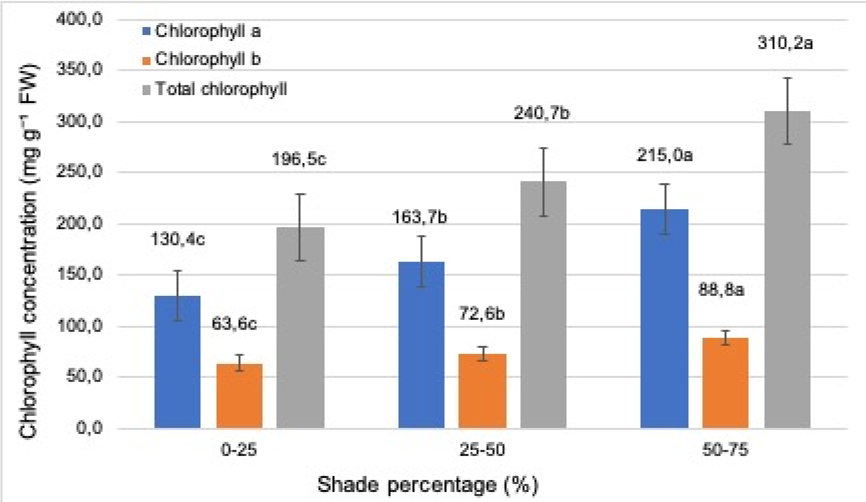

Figure 6

Chlorophyll concentrations (a, b, and total) in cacao leaves under different shading treatments. Values with different lowercase letters indicate significant differences according to the HSD test (α = 0.05). HSD values were: chlorophyll a = 23.89, chlorophyll b = 7.56, and total chlorophyll = 7.56.

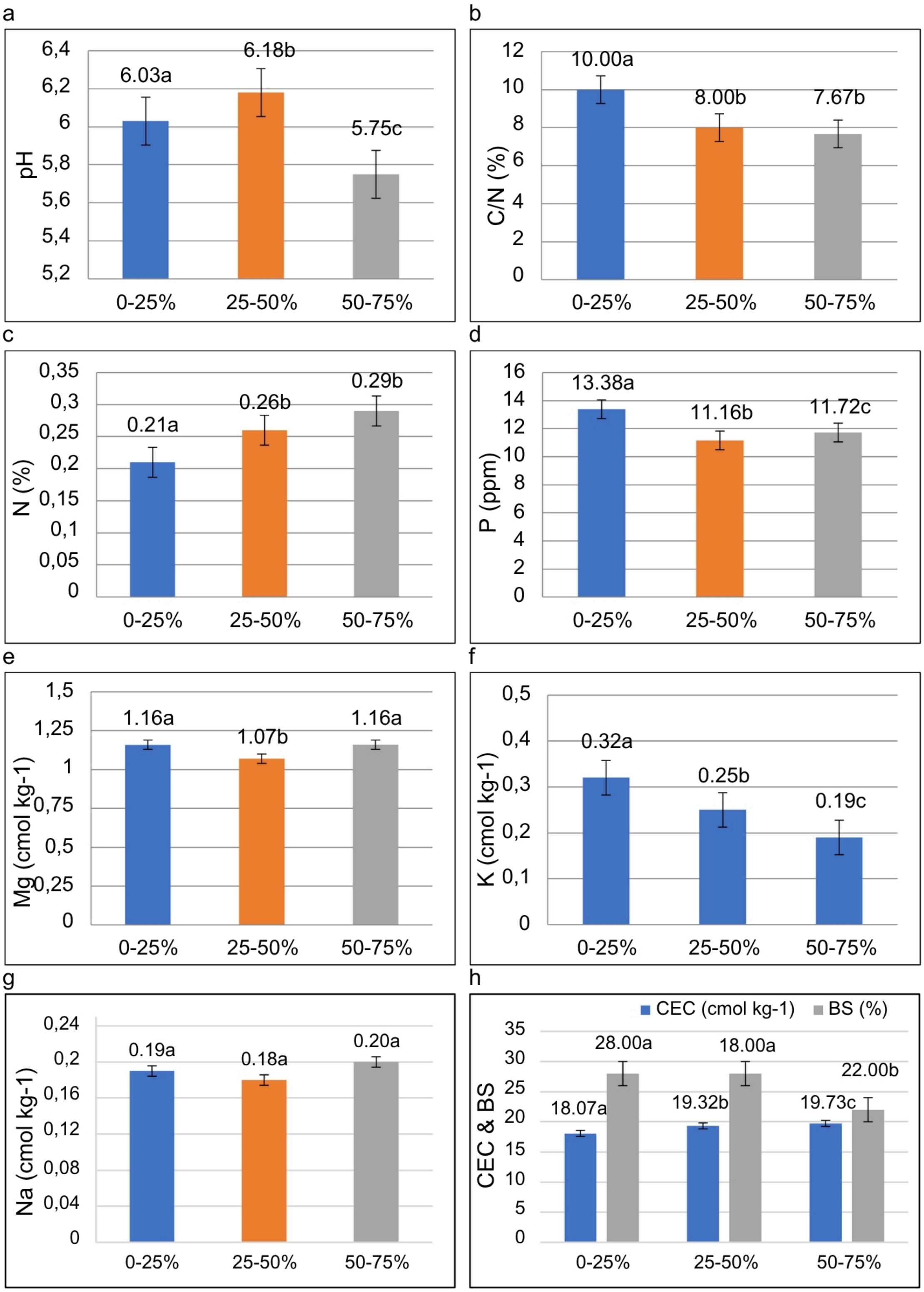

Figure 7

Soil fertility parameters under different hedgerow shade percentage: (a) soil pH, (b) C/N ratio, (c) total N (%), (d) available P (ppm), (e) exchangeable Mg (cmol kg^{-1}), (f) exchangeable K (cmol kg^{-1}), (g) exchangeable Na (cmol kg^{-1}), and (h) CEC (cmol kg^{-1}) and BS (%). Different letters indicate significant differences among treatments based on the HSD test at α = 0.05. HSD values: pH = 0.13; C/N = 0.69; N =

0.03%; P = 0.15 ppm; Mg = 0.03 cmol kg^{-1}; K = 0.03 cmol kg^{-1}; Na = 0.02 cmol kg^{-1}; CEC = 0.07 cmol kg^{-1}; BS = 2.27%.

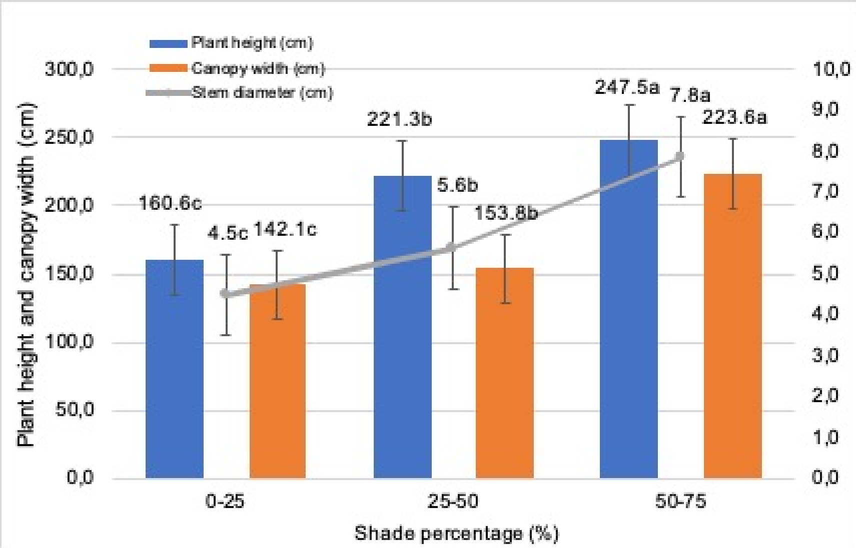

Figure 8

Growth responses of cacao to hedgerow shading intensity. Bars represent the mean values for plant height and canopy width, and the line indicates stem diameter. Different letters (a, b, c) indicate statistically significant differences between the HSD tests (α = 0.05). The HSD values for each parameter were: plant height = 21.59 cm, canopy width = 18.03 cm, and stem diameter = 0.66 cm.