JEE Journal of Ecological Engineering

Journal of Ecological Engineering, 2025, 26(8), 202–218
https://doi.org/10.12911/22998993/203977
ISSN 2299–8993, License CC-BY 4.0

Received: 2025.03.27
Accepted: 2025.05.26
Published: 2025.06.10

Enhancing soil microclimate and cacao productivity with organic biomass and superior clones in hedgerow systems for climate resilience

Darmawan Risal[1,2], Risma Neswati[3*], Muh Jayadi[3], Ifayanti Ridwan[4], Kurniawan[1], Nirmala Juita[5], Muhammad Nur Alam[6]

[1] Department of Agriculture Science, Hasanuddin University, Jalan Perintis Kemerdekaan KM. 10, Makassar, Indonesia
[2] Department of Forestry, Universitas Indonesia Timur, Jalan Rappocini Raya No. 171-173, Makassar, Indonesia
[3] Department of Soil Science, Faculty of Agriculture, Hasanuddin University, Jalan Perintis Kemerdekaan KM. 10, Makassar, Indonesia
[4] Department of Agronomy, Faculty of Agriculture, Hasanuddin University, Jalan Perintis Kemerdekaan KM. 10, Makassar 90245, Indonesia
[5] Department of Life Environment Conservation Science, Ehime University, Darumacho 3-5-7 Tarumi, Japan
[6] Department of Chemistry, Hasanuddin University, Jalan Perintis Kemerdekaan KM. 10, Makassar 90245, Indonesia
* Corresponding author's e-mail: neswati76@gmail.com

ABSTRACT

Climate change threatens soil quality and cocoa productivity in the tropics. This study aims to evaluate the effectiveness of integrating organic biomass application with superior cacao clones in a hedgerow system to enhance soil microclimate resilience, fertility, and plant growth under climate stress in South Sulawesi. A split-plot experimental design was employed, featuring MCC 02 and SULAWESI 2 clones as primary factors, along with four biomass treatments (no biomass, coconut leaves, banana leaves, and litter) subplots. Measurements include soil microclimate, plant growth, and soil fertility indicators. Results indicated that the MCC 02 clone exhibited superior climate adaptation, showing a lower soil temperature (31.85 °C) and higher soil moisture levels, particularly in the morning (35.22%) and afternoon (33.11%). The banana leaf biomass treatment (B2) significantly reduced afternoon soil temperature by 1.44 °C, improved relative humidity, and reduced heat stress. Additionally, the MCC 02 clone achieved the highest hedgerow shade percentage in the morning (57.44%), which supported optimal photosynthesis. Growth analysis showed that MCC 02 had superior plant height (156.32 cm) and canopy width (157.53 cm) compared to the SULAWESI 2 clone. Combining the MCC 02 clone with the B2 biomass treatment enhanced soil fertility, nitrogen content (0.19%), and cation exchange capacity (20.7 cmol kg^{-1}). These results demonstrate that integrating the MCC 02 cacao clone with banana leaf biomass in a hedgerow system provides an effective and sustainable approach to improving soil resilience and supporting cacao productivity under climate stress conditions.

Keywords: soil microclimate, banana leaf biomass, cacao adaptation, soil fertility, hedgerow system.

INTRODUCTION

The cacao farming sector in Indonesia, a leading global producer, faces substantial challenges due to climate change (Rahmah et al., 2024). Rising global temperatures, extended droughts, and changed rainfall patterns significantly impact cacao productivity, especially in areas reliant on traditional farming methods. (Sasmita et al., 2023). South Sulawesi, a key area of national cacao production, has seen a marked decline in productivity, exacerbated by temperature fluctuations, plant aging, and growing pest and disease threats (Igawa, 2022). According to the International Cacao Organization (ICCO, 2023) national cacao production dropped from 270,000 tons in 2017 to 170,000 tons in 2021, highlighting the sector's growing vulnerability. This decline highlights the urgent need for effective adaptation strategies, especially for smallholder farmers, who frequently lack access to advanced technology.

Climate change is degrading soil quality and causing a 17 to 23% reduction in cacao yields (O et al., 2024). Drying soil conditions, along with damage to soil structure, decreased water availability, and deficiencies in essential nutrients like nitrogen and phosphorus, greatly diminish the ability of cacao plants to endure environmental stress (Alfonso et al., 2024). Extreme temperatures above 30 °C can increase evaporation from the soil and reduce moisture, worsening conditions for cacao plants that rely on stable moisture (Budiastuti et al., 2018). In addition, prolonged drought inhibits water absorption by plant roots, resulting in decreased photosynthesis and overall plant growth (Alban et al., 2024). This decrease in soil quality disrupts the physiological processes of cacao plants, significantly inhibiting essential functions such as photosynthesis and transpiration, which are necessary to overcome heat and drought stress (Mensah et al., 2024). Therefore, an innovative approach is needed that combines adaptation technology, selection of superior cacao clones, and biomass management strategies to increase resilience to climate change and maintain sustainable cacao production.

The hedgerow system utilizes local plants such as coconut, banana, *gliricidia*, and *setaria* grass arranged in rows of plants, functioning as providers of organic biomass and shade for cacao plants (Song et al., 2023). Shade plants in the hedgerow system play a vital role in regulating soil temperature and reducing the rate of evaporation, which is crucial in overcoming drought problems. Additionally, the biomass produced from pruning serves as organic mulch, enhancing soil structure and enriching nutrient content through decomposition. (Numbisi et al., 2021). Shade plants in the hedgerow system play a key role in regulating soil temperature and reducing the rate of evaporation. In addition, the biomass from pruning functions as organic mulch that improves soil structure and enriches soil nutrient content through decomposition (Asigbaase., 2019). By fostering more stable soil and environmental conditions, the hedgerow system can mitigate the negative impacts of high temperatures and drought while being easily adopted by smallholder cacao farmers significantly affected by climate change (Cataldo, 2021).

Using superior cacao clones resistant to environmental stress strengthens cacao's resilience to climate change (Lahive et al., 2021). Research shows that soil temperatures can inhibit soil water availability and worsen the activity of soil microorganisms, which in turn causes a decrease in cacao production of up to 37% (Sarjana et al., 2021). In facing this challenge, increasing soil moisture is crucial in optimizing nutrient absorption by plant roots, especially during the vegetative phase. In addition, the instability of the soil microclimate risks triggering pests and diseases, such as fruit rot and cacao fruit borers (McMahon et al., 2015). Although several studies, such as by Acheampong et al, 2019 and Li et al. (2020) have examined the role of biomass and superior cacao clones in coping with climate change separately, very few have examined the interaction of these two factors in the context of sustainable hedgerow farming systems. Most previous studies have focused more on the impact of biomass on soil fertility or the benefits of superior cacao clones in increasing stress tolerance.

This study aims to fill this information gap by analyzing the interaction between organic biomass and high-yield cacao clones in a hedgerow system, focusing on their effects on soil temperature, soil moisture, and cacao plant growth under climate stress. The results are expected to provide valuable insights for cacao farmers in the tropics facing climate change challenges. Additionally, this research will contribute to the broader goal of enhancing the sustainability and resilience of cacao farming systems through innovative and integrated ecological engineering approaches.

MATERIALS AND METHODS

Place and time of research

This study was conducted on a community farm located in Macinna Village, Pataro District, Herlang Sub-district, Bulukumba Regency, South Sulawesi, Indonesia, at coordinates 5°22'42.0" S and 120°22'24.4" E, from July to December 2023. This location has arid climate conditions with an average rainfall of 5.17 mm and a temperature of 31.02 °C during the research (BMKG, 2024).

The community garden adopts a hedgerow farming system, where the plant spacing includes coconut (10 m), banana (5 m), *Gliricidia*

(2 m), and *Setaria* grass (0.3 m) between rows of hedgerow plants. The cacao plants used in this study were approximately 40 months old and planted in rows spaced at 3 m intervals. The arrangement of hedgerow plants and cacao clones is illustrated in Figure 1. Figure 1a depicts the hedgerow rows, Figure 1b presents MCC 02 cacao clones, and Figure 1c features Sulawesi 2 cacao clones.

Research materials and tools

The biomass utilized in this study resulted from the dry pruning of leaves and twigs from hedgerow plants, as shown in Figure 2. The various types of biomass include coconut leaf biomass, depicted in Figure 2a, banana leaf biomass, illustrated in Figure 2b, and litter biomass, presented in Figure 2c.

The research tools used included measuring tapes, diameter tapes, machetes, soil temperature meters, stationery, observation sheets, and other supporting agricultural equipment. To measure the hedgerow shade percentage on cacao plants, a simple shadow grid measuring 100 cm² was used, following the method by Nasution (2022), as illustrated in Figure 3. The shadow grid tool is shown in Figure 3a, the measurement procedure in Figure 3b, and the shade percentage measurement under the cacao sub-canopy in Figure 3c.

Figure 1. Rows of hedgerow plants and cacao clones at the research location. rows of plants forming the hedgerow system (a), rows of MCC 02 cacao clones (b), rows of SULAWESI 2 cacao clones (c)

Figure 2. Hedgerow biomass from pruning. coconut leaf biomass (a), banana leaf biomass (b), litter biomass (c)

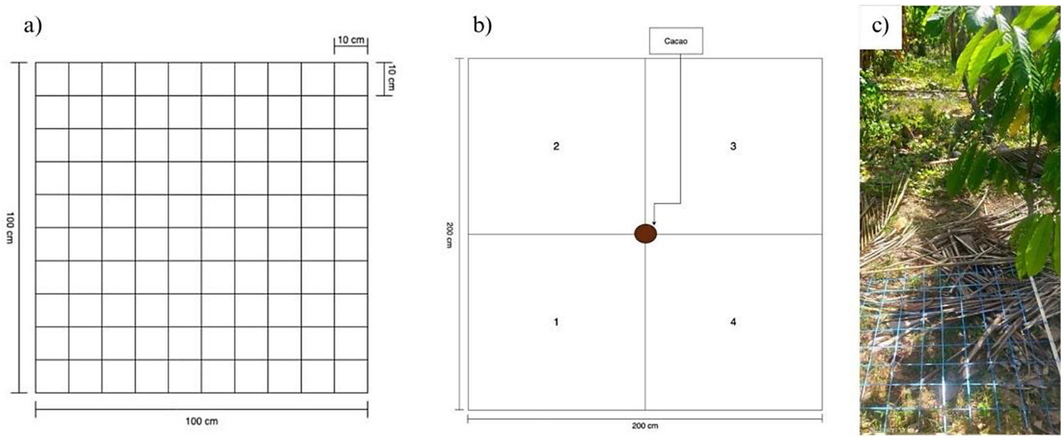

Figure 3. Equipment and procedures for measuring the percentage of shade using a shadow grid. measuring tool (a), measurement steps (b), shade percentage measurement under the cacao sub-canopy (c)

Research design

This study employed a split-plot experimental design featuring two cacao clones as the main plot factor and four biomass treatments as the subplot factor (Figure 4). The cacao clones included MCC 02 (K1) and Sulawesi 2 (K2). The biomass treatments included a control (B0) with no biomass application (Figure 4a), B1 with 5 kg of coconut leaf biomass (Figure 4b), B2 with 5 kg of banana leaf biomass (Figure 4c), and B3 with 5 kg of litter biomass (Figure 4d). All biomass materials were uniformly applied to a 2.25 m² area (1.5 × 1.5 m) surrounding each cacao plant, extending from the stem base to the edge of the canopy, to ensure consistent coverage. Each treatment was replicated three times, totaling twenty-four experimental units from eight combinations of two cacao clones and four biomass types.

Observation parameters and data analysis

Measurements of soil temperature, soil moisture, and shade percentage were conducted 14 days after treatment, which were then repeated every week for three consecutive weeks. Measurements were carried out in the sub-canopy area of the cacao plant, with a distance of 70 cm from the main tree and a depth of 10 cm from the ground surface. The process of measuring the percentage of shade used a shadow grid with the tools and methods shown in Figure 3, which recorded data three times, namely morning (09.00–10.00 am), afternoon (1.00–2.00 pm), and evening (4.00–5.00 pm). For four months after treatment, observations were made of plant growth, which included plant height, lower stem circumference (15 cm from the ground surface), and canopy width on two sides of the direction (east-west and north-south). In addition, soil samples were taken at four points around the sub-canopy of the cacao plant in each treatment at a depth of 1–10 cm. Soil samples were mixed homogeneously, cleaned from roots and stones, and about 500 g were taken for analysis in the laboratory with parameters included soil pH (measured in H_2O), soil organic carbon (SOC) using the Walkley–Black method, total nitrogen (N) using the Kjeldahl method, available phosphorus (P) using the Bray method, exchangeable potassium (K) using ammonium acetate extraction, and cation exchange capacity (CEC) determined by ammonium acetate (NH_4OAc) saturation.

The data obtained were analyzed using analysis of variance (ANOVA). If the results showed a significant difference, the honest significant difference (HSD) test was continued at a significance level of α = 0.05. The interaction between cacao clones and biomass treatments was analyzed to determine the effect of the combination of the two factors on the observed variables.

RESULTS AND DISCUSSION

Soil temperature

The analysis results in Figure 5 show a significant difference in soil temperature between the MCC 02 and Sulawesi 2 clones, with MCC 02 maintaining a lower soil temperature in the morning (29.39 °C) compared to Sulawesi 2 (30.89 °C),

Figure 4. Biomass treatments in research plots. control treatment or without biomass (a), coconut leaf biomass treatment (b), banana leaf biomass treatment (c), litter biomass treatment (d)

with a difference reaching 1.5 °C ($p < 0.05$). The HSD test revealed that the B3 biomass treatment significantly reduced soil temperature compared to the B0 treatment. This temperature difference indicates that the Sulawesi 2 clone, which has a more vertical and sparse canopy growth, is more susceptible to heating due to direct solar radiation. In contrast, the MCC 02 clone, which has a denser canopy, can reduce direct heating of the soil surface by increasing light absorption efficiency, as explained by (Jaimez et al., 2022), which shows that a denser canopy can reduce soil temperature in extreme summers. These differences have an impact on the photosynthesis and transpiration processes, where MCC 02 has a higher potential in regulating micro-temperatures around the root zone and soil surface, reducing direct solar radiation and reducing thermal stress in plants, which is also supported by the findings by (De Almeida et al., 2019), which showed that plants with dense canopies more effectively regulate soil temperature and increase plant growth.

The soil temperature during the day was recorded to reach its peak (31.85 °C) in the MCC 02 cacao clone, lower than the Sulawesi 2 clone (32.19 °C), which was caused by increased direct solar radiation on plants and the soil surface. This impacted the cacao plant biomass treatment, where treatments B1, B2, and B3 significantly decreased soil temperature compared to B0, which was not treated. In particular, the B3 treatment on the MCC 02 clone resulted in a decrease in soil temperature of 0.67 °C lower than B0 during the day, which reflects the thermal insulation effect of organic biomass, playing a role in reducing direct solar radiation to the soil surface and increasing soil moisture retention. This finding is consistent with the research by Rofner et al. (2022), which showed that organic mulch, such as litter and banana leaves, effectively reduces soil temperature fluctuations. Such temperature reduction helps minimize excessive water evaporation and moisture deficits, critical challenges for cacao plants under hot weather conditions. Optimal soil temperatures for root activity and microbial function range from 25 to 30 °C, while prolonged exposure to temperatures above 32 °C can inhibit root respiration and enzymatic processes (Yoroba et al., 2019). These results underscore the effectiveness of banana leaf biomass in maintaining favorable thermal conditions that support cacao growth and resilience in tropical climates (Figure 5).

The soil temperature in the afternoon gradually decreased, with temperatures recorded at 30.39 °C for the MCC 02 cacao clone and 30.69 °C for the Sulawesi 2 clone, indicating a significant decrease in temperature compared to the temperature during the day. This decrease in temperature was influenced by changes in the sun's position and optimal shade from the hedge, which reduced the intensity of direct sunlight on the soil and cacao plants. These results align with the findings by (Famuwagun et al., 2018), which stated that lower soil temperatures can increase soil moisture and support the survival of cacao plants, especially in the flowering process and production of

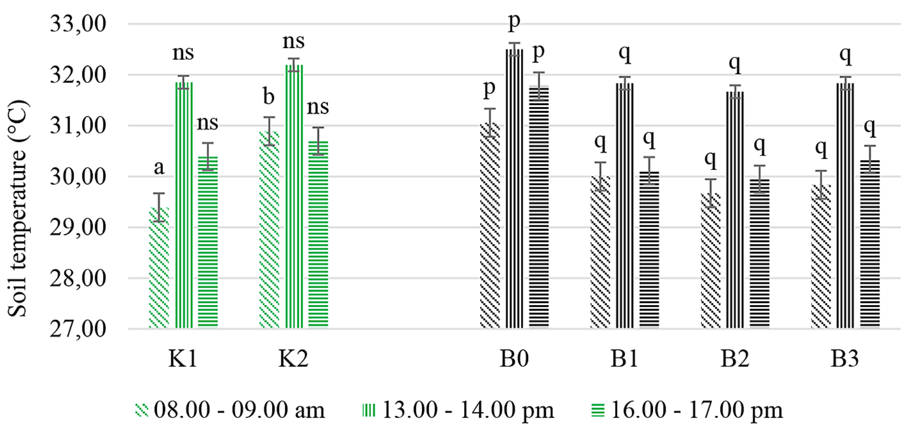

Figure 5. Soil temperature affected by cacao clone and biomass treatments. The same letters (a, b), and (p, q) in each observation time are not significantly different based on the HSD test at the significance level $\alpha = 0.05$ and (ns) not significant. The coefficient of diversity values at the observation time of 08.00–09.00 am are K = 0.34 and B = 0.89, observations at 13.00–14.00 pm are K = 0.34, and B = 0.89, and observations at 16.00–17.00 pm K = 0.38, and B = 1.07

new shoots. Biomass treatments B1, B2, and B3 showed a more significant decrease in soil temperature compared to treatment B0, indicating the effectiveness of organic biomass in maintaining more stable soil temperatures and reducing thermal stress. Previous research by (Mohamed et al., 2022) This finding was also supported by the use of banana leaf biomass (B2), which effectively reduced soil temperature by 1.44 °C in the afternoon. This shows biomass's role in increasing micro-humidity and reducing temperature through evaporative cooling. These results indicate that organic biomass can be an effective soil protector, essential for the sustainability of cacao plant growth under extreme temperature conditions.

Long-term soil temperature fluctuations can affect the physical and chemical processes of the soil and the activity of microorganisms that play a role in the decomposition of organic matter and the release of nitrogen and phosphorus, which are very important for plant growth (Daunoras, 2024). Higher soil temperatures during the day can accelerate the decomposition of organic matter and increase the risk of nitrogen loss through evaporation (Luo, 2025). This aligns with our findings, showing that mitigation strategies using organic biomass, such as banana leaf mulch, litter, and coconut leaves, can reduce the negative impacts of sharp temperature fluctuations. More effective biomass treatments, such as banana leaves, can maintain more stable soil temperatures, increase water use efficiency, and reduce water needs during the dry season. Research by (Fan, 2024) also supports these findings, showing that better soil temperature stability supports more stable enzyme activity and plant cellular metabolism, which can ultimately improve cacao plant growth. Thus, the use of organic biomass as a strategy to mitigate extreme soil temperatures plays a vital role in increasing the sustainability of cacao plant growth in increasingly uncertain climate conditions.

Soil moisture

The analysis results in Figure 6 show a significant difference in soil moisture between the MCC 02 and Sulawesi 2 cacao clones at most observation times, with the HSD test showing a significant difference ($p < 0.05$). In the morning, soil moisture in the MCC 02 clone (35.22%) was significantly higher than in the SULAWESI 2 clone (30.11%), indicating that MCC 02 is more effective in maintaining soil moisture at lower temperatures. In the afternoon, although there was a difference, soil moisture between the two clones did not show a significant difference (ns), indicating that the decrease in sunlight intensity in the afternoon caused more minor soil temperature fluctuations, and the influence of the plant canopy became more homogeneous in both clones. The significant difference in soil moisture in the morning indicates that the MCC 02 clone has a more adaptive rooting mechanism, allowing

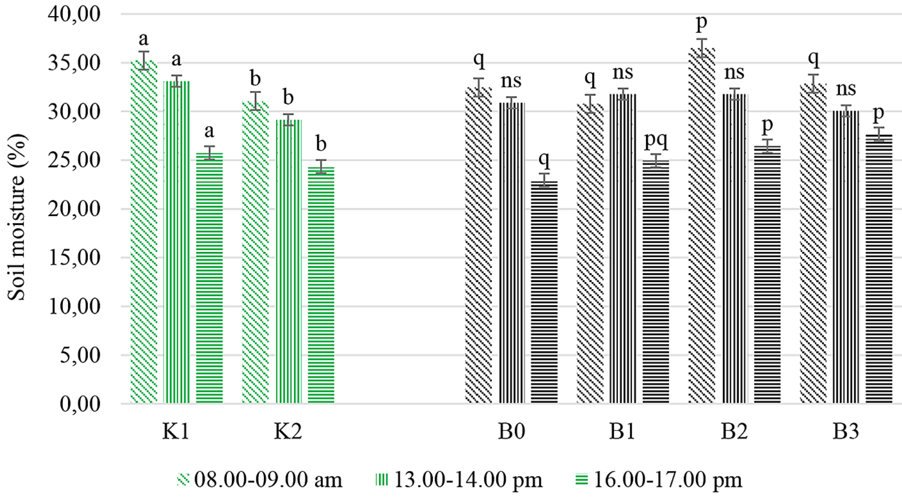

Figure 6. Soil moisture affected by cacao clone and biomass treatments. The same letters (a, b), and (p, q) in each observation time are not significantly different based on the HSD test at the significance level α = 0.05 and (ns) not significant. The coefficient of diversity values at the observation time of 08.00–09.00 am are (K) = 2.18 and (B) = 3.09, observations at 13.00–14.00 pm are (K) = 1.48 and (B) = 7.52, and observations at 16.00–17.00 pm (K) = 0.71 and (B) = 2.25

for better water absorption and retention, especially under drought conditions (Zasari, 2020). In addition, the MCC 02 clone showed efficient nutrient absorption, such as nitrogen, which supports better soil moisture (Ruseani et al., 2022). Physiologically, this clone is also better at adapting to drought stress by increasing the production of abscisic acid (ABA) and proline, compounds that play a role in osmotic regulation and maintaining water balance in plant tissues during the dry season. The decrease in soil temperature in the afternoon reduces soil moisture fluctuations, which explains why the differences between the two clones were insignificant at that time.

The analysis showed that the B2 biomass treatment, which used banana leaves, had the most significant effect on soil moisture, with the highest soil moisture recorded in the morning (36.50%) and afternoon (31.78%) compared to other treatments. The ability of banana leaves to maintain soil moisture can be explained by the leaf structure, which has a large surface area that helps reduce direct sunlight exposure to the soil (Rodrigues et al., 2023). This finding is consistent with previous studies showing that banana leaf mulch maintains soil moisture for longer. The B1 (coconut leaf) and B3 (litter) biomass treatments also positively impacted soil moisture, although not as optimal as B2. Coconut leaves, which have a stiffer and more elongated texture, tend to cover the soil unevenly, increasing soil temperature and moisture variability. Meanwhile, litter has good water absorption capacity, but its rapid decomposition can reduce the stability of soil moisture in the long term. This variation in performance is important considering that optimal soil moisture for cacao root function typically ranges between 30% and 40%, as noted in international cacao cultivation guidelines (Santos et al., 2023). This difference in biomass effectiveness indicates that organic matter's physical and chemical characteristics, such as leaf surface area and decomposition rate, play an essential role in determining water retention capacity and its effect on soil microclimate.

The interaction between cacao clones and biomass significantly affected soil moisture in the morning and afternoon, with the combination of MCC 02 clones and B2 biomass treatment showing the best results. This finding aligns with research by (Rofner et al., 2022), which showed that using organic biomass, such as banana leaves, can reduce soil temperature fluctuations and maintain soil moisture, especially in hot and dry environmental conditions. In the afternoon, although there was an interaction effect, the difference in soil moisture between biomass treatments became insignificant. This indicates that during this period, environmental factors such as decreased soil temperature and reduced solar radiation are more dominant, according to the findings put forward by (Feng et al., 2023). In addition, air humidity, which tends to be higher in the afternoon, especially after the air temperature decreases, can reduce the difference in soil moisture between biomass treatments. Increased air humidity causes the evaporation process from the soil to be slower, which in turn reduces the role of biomass treatment in regulating soil moisture at that time.

Shade percentage

Based on the analysis graph (Figure 7), the study results showed a significant difference in the percentage of shade received by the MCC 02 and Sulawesi 2 cacao clones during most observation times. The HSD test showed a significant difference ($p < 0.05$) in several observation periods, indicating time's effect on the shade distribution received by the two clones. During morning observations, the MCC 02 clone received 57.44% shade, higher than the Sulawesi 2 clone, which only received 45.77% shade. This difference supports the findings of (Arévalo-G et al., 2021), which stated that photosynthesis in cacao plants can occur optimally at light levels of around 400 $\mu mol\ m^{-2}\ s^{-1}$, which is achieved at around (50%) shade. The shade that plants receive in the morning supports efficient photosynthesis, with transpiration increasing due to optimal water availability after soil cools at night (Mathur et al., 2018). This shows the importance of shade in supporting plants' physiological balance, especially in facilitating photosynthesis and regulating soil moisture.

During the day, the percentage of shade received by the MCC 02 cacao clone decreased to (54.43%), while the Sulawesi 2 clone received (43.47%) shade, along with the shift in the sun angle, which reduced the capacity of the hedge to filter direct solar radiation. This decrease causes plants that do not get enough protection to be more susceptible to air stress, which triggers stomatal closure as an adaptation mechanism to reduce air loss. However, stomatal closure also limits CO_2 diffusion, which reduces the rate of photosynthesis and carbon assimilation,

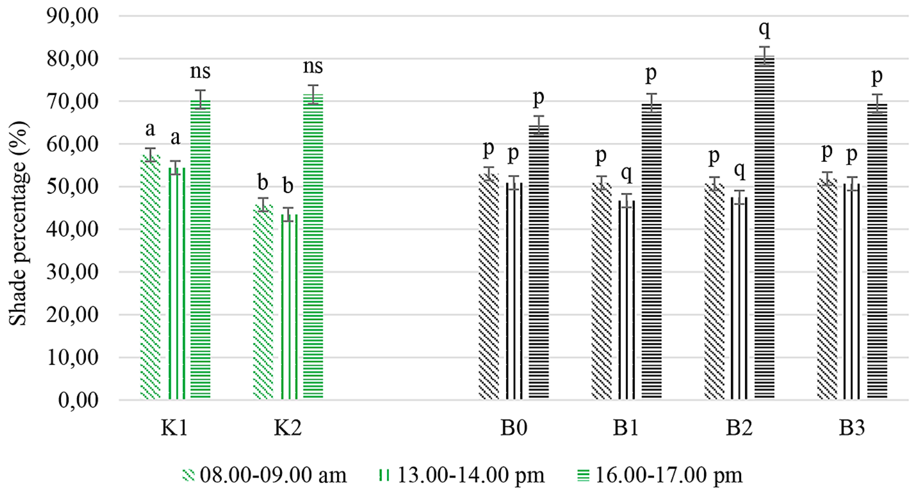

Figure 7. Percentage of hedgerow shade at three observation time intervals. The same letters (a, b) and (p, q) in each observation time are not significantly different based on the HSD test at the α = 0.05 level, and (ns) is not significant. The coefficient of diversity values at observation time 8.00–9.00 am are (K) = 5.55 (K) and (B) = 9.81, observation 13.00–14.00 pm are (K) = 15.12 and (B) = 9.35, and observation 16.00–17.00 pm are (K) = 6.47 and (B) = 13.08

potentially reducing plant biomass productivity (Gan et al., 2024)**.** In addition, exposure to direct solar radiation increases leaf and soil temperatures, accelerates evaporation, and reduces soil moisture, increasing plant thermal stress. Research by (Araújo et al., 2019) states that thermal stress can affect gas exchange and plant hydraulic conductivity, essential for growth and productivity. Therefore, proper shade management, such as hedges, reduces thermal and atmospheric stress and improves cacao plants' physiological performance and productivity.

In the afternoon, shade increased again, reaching 70.40% in the MCC 02 cacao clone and 71.58% in the Sulawesi 2 cacao clone. Although the soil temperature decreased again, the recovery effect on soil temperature and soil moisture was not as high as in the morning. At this time, shade helps improve plant physiological conditions by slowing down evaporation and decreasing soil temperature, which can reduce hydric stress and increase photosynthesis and respiration efficiency. Increased shade in the afternoon offers an opportunity for cacao plants to recover energy lost during the day, reduce water shortages, and maintain more stable physiological conditions at night (Mensah et al., 2024). The hedgerow system, integrated with organic materials such as banana leaves, provides additional benefits in maintaining soil moisture and reducing evaporation rates, which are very important for cacao plants exposed to direct sunlight. This study also revealed the importance of using organic biomass to increase water use efficiency and reduce heat stress. Cacao plants with B2 treatment in the afternoon showed the highest shade of 80.58%, significantly reducing soil temperature and soil moisture loss. These results align with the findings by (Lewis et al., 2021) which shows that organic matter can increase water availability and optimize plant resistance to drought.

Plant height growth

The result analysis (Figure 8) revealed that the cacao clone factor had a statistically significant effect on plant height ($p < 0.05$). The MCC 02 clone reached an average height of 156.32 cm, significantly higher than Sulawesi 2, which reached 129.17 cm. The HSD test confirmed a significant difference between the two clones, indicating that MCC 02 had more significant vegetative growth potential. This finding aligns with previous research by (Cho, 2022), which demonstrated that MCC 02 has higher photosynthetic efficiency and more effective nutrient and water absorption, contributing to enhanced plant growth under field conditions. In contrast, the biomass treatment factor did not significantly affect plant height at all biomass types (B0, B1, B2, B3). However, a descriptive trend was observed, where applying coconut leaf biomass (B1) tended to support better plant height than

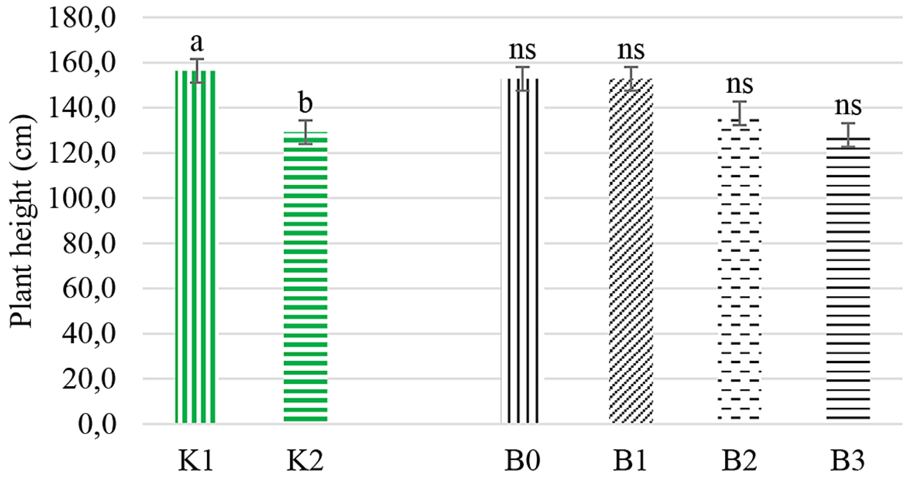

Figure 8. Growth of cacao plant height. The same letters (a, b) in each observation time are not significantly different based on the HSD test at the α = 0.05 level, and (ns) is insignificant. The coefficient of diversity (K) value is 9.89

other treatments. Although this effect was not statistically significant, the result suggests a potential benefit of B1 in improving soil conditions that indirectly affect plant growth.

The tendency of higher plant height in B1-treated plots may be attributed to improved soil microclimate conditions. According to (Rajão et al., 2023), coconut leaf biomass enhances water retention and reduces evaporation, supporting stable soil moisture levels under the canopy. While not evident statistically, this microclimatic improvement likely contributed to better plant water availability, particularly under the MCC 02 clone, which exhibited a more vigorous growth response. Furthermore, applying coconut leaves may contribute to higher organic carbon content (Silva et al., 2024), essential for improving soil structure and nutrient-holding capacity.

Additionally, a previous study by (Gopal et al., 2020) have shown that coconut biomass increases microbial activity and enzymatic functions (e.g., catalase, urease, sucrase), which are critical in nutrient cycling. These biological processes may enhance the availability of key nutrients such as nitrogen and phosphorus, even if not directly reflected in height measurements in this short-term study (Lu et al., 2024). Overall, the observed trend highlights the potential of combining MCC 02 with coconut biomass (B1) to promote more favorable soil-plant interactions, although further studies are needed to confirm long-term effects. This may indicate that MCC 02 clones respond more positively to improved soil conditions created by coconut biomass than Sulawesi 2, highlighting the importance of matching clone types with site-specific organic inputs.

Plant canopy growth

The analysis results in Figure 9 indicate that cacao clone type significantly affected plant canopy width, while biomass treatments and their interaction did not yield significant effects. The MCC 02 clone developed more expansive canopies (157.53 cm) than the Sulawesi 2 clone (89.76 cm), with a statistically significant difference ($p < 0.05$). This suggests that MCC 02 possesses stronger vegetative vigor and canopy expansion potential, aligning with its superior physiological adaptation to higher temperatures and limited water availability (Bolívar et al., 2022). A more expansive canopy likely reflects more efficient resource capture and stress tolerance, contributing to more effective light interception and microclimate modification under field conditions.

Although the applied biomass treatments did not significantly influence canopy width, B1 (coconut leaf biomass) and B3 (litter) tended to moderate microclimatic stress by reducing surface temperature and increasing soil moisture. However, during periods of high thermal load, these benefits were insufficient to stimulate significant canopy expansion. This finding supports previous results by (Fischer et al., 2021), who emphasized that genetic traits often play a more dominant role than environmental modifications in determining canopy development. Thus, the lack of significant biomass treatment effects

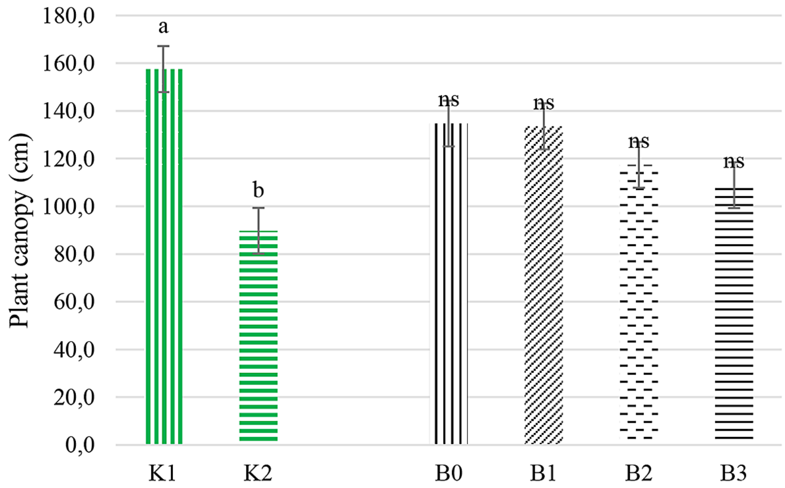

Figure 9. Growth of cacao plant canopy. The same letters (a, b) in each observation time are not significantly different based on the HSD test at the α = 0.05 level, and (ns) is not significant. The coefficient of diversity (K) value is 5.38

suggests that short-term microclimate regulation may benefit root zone conditions but has limited influence on above-ground growth, like canopy width, especially under extreme climate stress. Despite the statistical insignificance, biomass covers still contribute to improving soil conditions through enhanced moisture retention and reduced radiation exposure, which may indirectly support physiological processes. Studies have shown that combining superior genotypes with organic amendments improves overall plant performance by enhancing root development, nutrient cycling, and stress-buffering (Hebbar et al., 2020). The observed trends suggest that MCC 02 may better utilize these soil benefits due to its inherent efficiency in resource use. Therefore, a long-term integrated approach combining adaptive clones and targeted organic biomass application may provide more consistent improvements in canopy development under variable environmental conditions.

Plant stem circumference growth

The result analysis in Figure 10 shows that cacao clones significantly affected stem circumference growth ($p < 0.05$), while biomass treatments and their interactions did not. The MCC 02 cacao clone exhibited a larger average stem circumference (27.0 cm) compared to Sulawesi 2, highlighting the influence of genetic factors. The superior performance of MCC 02 may be related

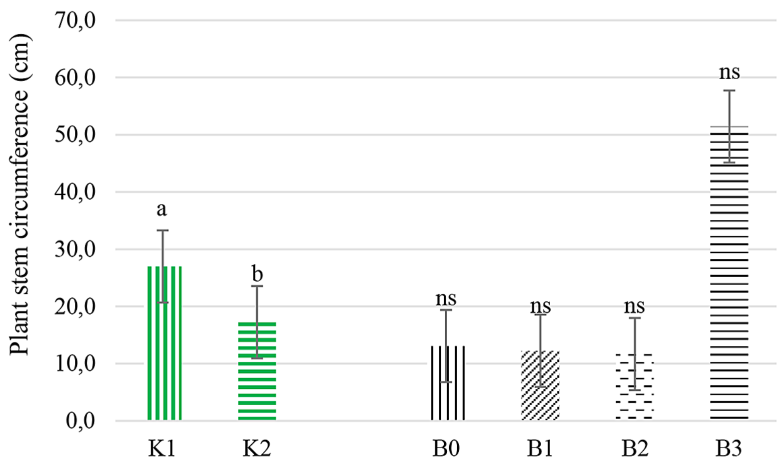

Figure 10. Growth of the circumference of the cacao plant stem. The same letters (a, b) in each observation time are not significantly different based on the HSD test at the α = 0.05 level, and (ns) is insignificant. The coefficient of diversity (K) value is 0.38

to its higher leaf area index (LAI), more excellent light interception, and efficient carbon assimilation. This advantage allows MCC 02 to maintain higher physiological activity even under suboptimal conditions. Research results from (Matthews et al., 2023) further support that genotype-environment interactions strongly influence clone response to environmental stress.

Figure 10 shows that although biomass treatments (B0-B3) did not significantly affect stem circumference, B2 (banana leaf biomass) showed a numerical increase, indicating a possible trend. This is consistent with the findings by (Bai et al., 2022), who reported that rapidly decomposing biomass can enhance nutrient cycling and improve soil fertility. While the short-term effect was not statistically evident, improved soil conditions, such as better nutrient availability and moisture retention, could contribute to stem thickening in more responsive clones. However, under the current study conditions, these benefits may not have been sufficient to produce measurable changes in stem circumference, especially when compared to the dominant influence of clone genetics.

The better stem development in MCC 02 may also be linked to its more expansive canopy, which improves internal light distribution and promotes more efficient metabolic activity. This facilitates increased cell expansion and lignification, contributing to thicker stem formation. A research result by (Sugiatno, 2022) notes that canopy structure plays a key role in regulating internal physiological processes. The lack of significant interaction between biomass and clone treatment supports findings by (Ofori et al., 2019), indicating that clone traits are more decisive under moderate to high stress. Therefore, while biomass treatments can potentially improve soil microclimate and fertility, their effect on stem circumference may only become apparent when combined with physiologically adapted genotypes to utilize these improvements over a more extended growth period.

Soil fertility

The results of the analysis of cacao clone and biomass treatments on soil fertility parameters, as shown in Table 1, indicate a significant effect on several variables, including pH, SOC, and K. However, the interaction between biomass treatments and cacao clones was not significant for N, phosphorus (P), and cation exchange capacity (CEC). The MCC 02 cacao clone showed better results on most soil fertility parameters than SULAWESI 2, emphasizing the importance of genetic characteristics in influencing soil quality and plant growth. Although the SULAWESI 2 clone exhibited a slightly higher soil pH (5.82) than MCC 02 (5.71), this did not directly correlate with improved field performance. The adaptability of MCC 02 to stressful conditions and its efficient nutrient uptake likely enabled it to thrive despite lower soil pH. Although the pH ranged from 5.58 to 5.95 across treatments, these values are within the optimal range of 5.5 to 6.5 for cacao cultivation, indicating suitable soil reaction for nutrient uptake. This supports the findings by (Dogbatse et al., 2020), who highlighted that superior clones can maintain growth across varied soil conditions due to physiological and genetic advantages. Furthermore, (Bhavishya et al., 2024) emphasized that plant growth is not solely determined by pH but by the complex interaction of metabolic efficiency, root dynamics, and environmental responsiveness.

SOC content varied significantly across treatments and cacao clones, with the Sulawesi 2 clone, particularly under the B2 biomass treatment, recording the highest SOC level (2.52%). In contrast, MCC 02 reached 1.78% in the same treatment. The rapid decomposition of banana leaf biomass in B2 likely enhanced SOC through increased microbial activity and carbon deposition, supporting findings by (Nugroho et al., (2023) that fast-decomposing organic inputs stimulate microbial respiration and improve soil organic matter in tropical systems. SOC values above 1.5% (as found in B1 and B2 treatments) are considered moderate to high in tropical agroecosystems (Morales et al., 2017), suggesting that applying banana and coconut biomass meets or exceeds critical thresholds for sustainable soil health. However, the superior growth of MCC 02 despite lower SOC levels highlights the dominant role of genotype-specific nutrient use efficiency. CEC, though not significantly influenced by clone and biomass interactions, showed numerical increases in treatments such as B1 (MCC 02) and B2 (Sulawesi 2), reflecting SOC's indirect contribution to nutrient retention. Since CEC changes are gradual and strongly tied to organic matter and clay content, their impact may be more evident in long-term applications (Kong et al., 2021). The trend suggests that repeated biomass input, especially from high-lignin and cellulose

Table 1. Results of the analysis of the interaction of biomass and cacao clones on soil fertility parameters

Parameter	Cacao clone (K)	Biomass (B)				Average	HSD α 0.05
		(B0)	(B1)	(B2)	(B3)		
pH	K1	5.76	5.64	5.58	5.85	5.71b	0.02
	K2	5.95	5.65	5.85	5.84	5.82a	
	Average	5.85p	5.65r	5.72q	5.85p		
	HSD α 0.05 = 0.05						
C-Organic/ SOC (%)	K1	$0.88\frac{s}{a}$	$1.97\frac{p}{a}$	$1.78\frac{q}{b}$	$1.48\frac{r}{b}$		0.06
	K2	$0.80\frac{s}{b}$	$1.80\frac{r}{b}$	$2.52\frac{p}{a}$	$2.37\frac{q}{a}$		
	HSD α 0.05 = 0.07						
N (%)	K1	$0.09\frac{r}{a}$	$0.24\frac{p}{a}$	$0.17\frac{q}{a}$	$0.26\frac{p}{a}$		0.07
	K2	0.15b	0.06b	0.30b	0.24b		
	HSD α 0.05 = 0.08						
P (ppm)	K1	$9.2\frac{q}{b}$	$13.8\frac{p}{a}$	$13.1\frac{p}{a}$	$13.0\frac{p}{a}$		0.12
	K2	$12.4\frac{r}{a}$	$13.2\frac{q}{a}$	$13.1\frac{q}{a}$	$13.6\frac{p}{a}$		
	HSD α 0.05. = 0.19						
K (cmol kg^{-1})	K1	$0.15\frac{r}{b}$	$0.18\frac{qr}{b}$	$0.21\frac{pq}{b}$	$0.25\frac{p}{b}$		0.03
	K2	0.19a	0.41a	0.25a	0.36a		
	HSD α 0.05 = 0.04						
CEC (cmol kg^{-1})	K1	$18.6\frac{q}{b}$	$20.6\frac{p}{a}$	$17.7\frac{r}{b}$	$20.2\frac{p}{a}$		0.52
	K2	$20.7\frac{p}{a}$	$19.3\frac{q}{b}$	$20.2\frac{p}{a}$	$19.6\frac{q}{b}$		
	HSD α 0.05 = 0.54						

Note: The numbers followed by the same letter in letters (a, b) and (p, q, r) are not significantly different in the HSD α 0.05 test.

sources like coconut leaves, could enhance CEC through stable humus formation. These findings emphasize that while organic biomass improves key soil fertility parameters, its effectiveness depends on the physiological response of each cacao clone, underscoring the need to integrate genetic adaptability with soil management practices for sustainable and climate-resilient cacao cultivation.

Nitrogen content also showed variable results across treatments. Sulawesi 2 generally had slightly higher nitrogen percentages than MCC 02, particularly under B2, which reached 0.30%. This may be due to nitrogen-rich root exudates released by Sulawesi 2, which stimulate microbial activity and accelerate nitrogen mineralization in the rhizosphere. The highest nitrogen value of 0.30% under B2 treatment meets the general critical N level for cacao growth, which ranges between 0.2% and 0.3% in tropical conditions, that genotypes with active rhizosphere interactions tend to have greater nitrogen uptake efficiency (Kumar, 2017). These findings suggest that while organic inputs contribute to nutrient availability, the clone's ability to mobilize and absorb those nutrients is equally essential. A research result by (Paguntalan et al., 2023) supports that high-N availability is not always converted into biomass unless the genotype is responsive and metabolically active. Therefore, although Sulawesi 2 benefits from higher soil nitrogen in specific treatments, its overall growth remains limited compared to MCC 02.

Regarding P, the differences between clones and biomass treatments were generally not significant. However, there was a consistent trend of increased P levels in both clones under B1 and B2 biomass treatments, indicating the role of organic matter decomposition in enhancing P availability. Organic acids produced during decomposition can mobilize phosphorus by breaking down P-bound minerals. This aligns with findings from (Adiyah et al., 2023), who highlighted the potential of biomass in integrated systems to enhance P availability in weathered tropical soils. Despite this, the efficiency of P uptake again appears to be linked to genetic response, with MCC 02 showing better physiological development despite slightly lower soil P in some treatments.

K content increased significantly under B2 and B3 treatments, with Sulawesi 2 consistently showing higher K levels in each biomass treatment. The B2 treatment under Sulawesi 2 reached 0.41 cmol kg^{-1}, compared to 0.21 cmol kg^{-1} in MCC 02. The potassium values above 0.25 cmol kg^{-1} are aligned with cacao nutrient demand under water stress. Research result by (Anokye et al., 2021) emphasized that potassium is essential for physiological processes such as stomatal regulation, osmotic adjustment, and enzyme activation, which influence drought resistance and growth. Similarly, (Kaba et al., 2022) also reported that potassium supports plant resilience under water-limited conditions by enhancing root water uptake and maintaining turgor pressure. However, the higher K values in Sulawesi 2 did not lead to better vegetative growth, further emphasizing the genotype's dominant role in efficiently utilizing available nutrients.

Although biomass application improved several soil fertility parameters, the statistical analysis indicated that the interaction between biomass type and cacao clone did not significantly affect most soil chemical properties. This suggests that while biomass has a clear role in improving soil conditions, its effectiveness depends on the genotype's capacity to utilize those conditions efficiently. Research result (Tosto et al., 2024) emphasized that genotype effects often surpass agronomic inputs like mulch or compost, particularly under stress conditions. These findings underline the importance of selecting cacao clones based on aboveground vigor and belowground responsiveness to organic matter and soil nutrient dynamics. Optimizing soil fertility in sustainable cacao systems requires an integrated approach that combines genetic potential with organic resource management tailored to specific environmental contexts (Baligar et al., 2021). Thus, future research should explore the long-term interactions between organic biomass quality, soil chemistry, and clone-specific nutrient acquisition strategies.

CONCLUSIONS

This study concluded that the combination of MCC 02 cacao clone with banana leaf organic biomass improved soil microclimate resilience and plant growth under climate stress. Due to its denser canopy, the MCC 02 clone showed superior adaptation, maintaining lower soil temperature and higher moisture retention than the Sulawesi 2 cacao clone. Biomass treatments, especially B2, significantly reduced soil temperature fluctuations and improved soil fertility, with increased organic carbon and better nutrient availability. While biomass treatments did not significantly affect plant height or stem circumference, the MCC 02 clone showed better vegetative growth, which was associated with higher photosynthetic efficiency and improved nutrient uptake. These findings emphasize that genetic factors, particularly photosynthetic efficiency and drought tolerance, are vital for plant growth, while organic biomass enhances soil fertility and moisture retention. A limitation of this study is the narrow range of biomass types examined. Future studies should investigate more organic matter under diverse environmental conditions. Moreover, the short duration of the study indicates a need for long-term evaluations to gauge the effects of biomass on soil health and cacao productivity while also accounting for other environmental stress factors, such as drought or pests.

Acknowledgements

The authors express gratitude to the Center for Higher Education Funding and Assessment (PPAPT), the Education Fund Management Institute (LPDP), and the Indonesian Education Scholarship (BPI) for their support in publishing articles for doctoral students awarded scholarships under contract number 00912/J5.2.3./BPI.06/9/2022.

REFERENCES

1. Adiyah, F., Csorba, Á., Dawoe, E., Ocansey, C. M., Asamoah, E., Szegi, T., Fuchs, M., Michéli, E. (2023). Soil organic carbon changes under selected agroforestry cocoa systems in Ghana. *Geoderma Regional*, *35*, e00737. https://doi.org/10.1016/j.geodrs.2023.e00737
2. Alban, K. M. A., Cherif, M., Kouadio, K., Germain

Adolphe, M., Bamba, A., N'Datchoh Toure, E., Kouadio Okou, A., Brunelle, R., Rouseau, Y., Koné, D. (2024). Climate Variability and Outlook of Cocoa Production in Côte D'ivoire under Future Climate. In *Shifting Frontiers of Theobroma Cacao - Opportunities and Challenges for Production*. IntechOpen. https://doi.org/10.5772/intechopen.112643

3. Alfonso-Alfonso, L., Escobar-Pachajoa, L. D., Montealegre-Bustos, F., Carvalho, F. E., Carvajal-Rivera, A. S., & Rojas-Molina, J. (2024). Assessment of transitory crops in cocoa (Theobroma cacao L) agroforestry in Páez, Boyacá. *Revista de Ciencias Agrícolas*, *41*(1), e1225. https://doi.org/10.22267/rcia.20244101.225
4. Anokye, E., Lowor, S. T., Dogbatse, J. A., Padi, F. K. (2021). Potassium application positively modulates physiological responses of cocoa seedlings to drought stress. *Agronomy*, *11*(3), 563. https://doi.org/10.3390/agronomy11030563
5. Araújo, D. C. dos S., Montenegro, S. M. G. L., Montenegro, A. A. de A., Santos, D. P. dos, Rodrigues, R. A. S. (2019). Temporal stability of soil moisture in banana cropping area in the Brazilian semiarid region. *Revista Brasileira de Engenharia Agrícola e Ambiental*, *23*(11), 852–859. https://doi.org/10.1590/1807-1929/agriambi.v23n11p852-859
6. Arévalo-G, Enrique, Farfán, A., Barraza, F., Arévalo-Hernández, C. O., Zúñiga-Cernades, L. B., Alegre, J., Baligar, V. C. (2021). Growth, physiological, nutrient-uptake-efficiency and shade-tolerance responses of cacao genotypes under different shades. *Agronomy*, *11*(8), 1536. https://doi.org/10.3390/agronomy11081536
7. Asigbaase, M., Sjogersten, S., Lomax, B. H., Dawoe, E. (2019). Tree diversity and its ecological importance value in organic and conventional cocoa agroforests in Ghana. *PLOS ONE*, *14*(1), e0210557. https://doi.org/10.1371/journal.pone.0210557
8. Bai, S. H., Gallart, M., Singh, K., Hannet, G., Komolong, B., Yinil, D., Field, D. J., Muqaddas, B., Wallace, H. M. (2022). Leaf litter species affects decomposition rate and nutrient release in a cocoa plantation. *Agriculture, Ecosystems & Environment*, *324*, 107705. https://doi.org/10.1016/j.agee.2021.107705
9. Baligar, V. C., Elson, M. K., Almeida, A.-A. F., de Araujo, Q. R., Ahnert, D., He, Z. (2021). Carbon dioxide concentrations and light levels on growth and mineral nutrition of juvenile cacao genotypes. *American Journal of Plant Sciences*, *12*(05), 818–839. https://doi.org/10.4236/ajps.2021.125056
10. Bhavishya, Bhat, R., Apshara, S. E., Pushpa, T. N., Prasad, D. S., Nayana, H., Thube, S. H., Pandian, R. T. P., Ramesh, S. V. (2024). Genotypic variation in flowering, fruit set, and cherelle wilt, and their relationship with leaf nutrient status in cocoa (*Theobroma cacao* L.) grown in humid tropics of India. *Innovations in Agriculture*, *7*, 1–5. https://doi.org/10.3897/ia.2024.124253
11. BMKG. (2024). *Herlang Sub-district Weather Forecast*.
12. Budiastuti, S., Purnomo, D., Supriyono, Yunindanova, M. B., Mahardini, P. C. A., Utami, R. R. (2018). Land management strategy for cocoa cultivation at home gardens. *IOP Conference Series: Earth and Environmental Science*, *200*, 012005. https://doi.org/10.1088/1755-1315/200/1/012005
13. Cataldo, E., Fucile, M., Mattii, G. B. (2021). A review: Soil management, sustainable strategies and approaches to improve the quality of modern viticulture. *Agronomy*, *11*(11), 2359. https://doi.org/10.3390/agronomy11112359
14. Cho, A. R., Chung, S. W., Kim, Y. J. (2022). Shortening the vegetative growth stage of phalaenopsis queen beer 'mantefon' by controlling light with calcium ammonium nitrate levels under enriched CO_2. *Horticulturae*, *8*(2), 157. https://doi.org/10.3390/horticulturae8020157
15. Daunoras, J., Kačergius, A., Gudiukaitė, R. (2024). Role of soil microbiota enzymes in soil health and activity changes depending on climate change and the type of soil ecosystem. *Biology*, *13*(2), 85. https://doi.org/10.3390/biology13020085
16. De Almeida, J., Herrera, A., Tezara, W. (2019). Phenotypic plasticity to photon flux density of physiological, anatomical and growth traits in a modern Criollo cocoa clone. *Physiologia Plantarum*, *166*(3), 821–832. https://doi.org/10.1111/ppl.12840
17. Dogbatse, J. A., Arthur, A., Padi, F. K., Konlan, S., Quaye, A. K., Owusu-Ansah, F., Awudzi, G. K. (2020). Influence of acidic soils on growth and nutrient uptake of cocoa (*Theobroma Cacao* L.) Varieties. *Communications in Soil Science and Plant Analysis*, *51*(17), 2280–2296. https://doi.org/10.1080/00103624.2020.1822384
18. Famuwagun, I. B., Agele, S. O., Aiyelari, O. P. (2018). Shade effects on growth and development of cacao following two years of continuous dry season irrigation. *International Journal of Fruit Science*, *18*(2), 153–176. https://doi.org/10.1080/15538362.2017.1416326
19. Fan, K.-T., Xu, Y. (2024). *Elevated Temperature Effects on Protein Turnover Dynamics in Arabidopsis thaliana Seedlings Revealed by 15N-Stable Isotope Labeling and ProteinTurnover Algorithm*. https://doi.org/10.20944/preprints202405.0780.v1
20. Feng, W., Wang, T., Yang, F., Cen, R., Liao, H., Qu, Z. (2023). Effects of biochar on soil evaporation and moisture content and the associated mechanisms. *Environmental Sciences Europe*, *35*(1), 66. https://doi.org/10.1186/s12302-023-00776-7

21. Fischer, K., Kreyling, J., Beaulieu, M., Beil, I., Bog, M., Bonte, D., Holm, S., Knoblauch, S., Koch, D., Muffler, L., Mouginot, P., Paulinich, M., Scheepens, J. F., Schiemann, R., Schmeddes, J., Schnittler, M., Uhl, G., van der Maaten-Theunissen, M., Weier, J. M., … Gienapp, P. (2021). Species-specific effects of thermal stress on the expression of genetic variation across a diverse group of plant and animal taxa under experimental conditions. *Heredity*, *126*(1), 23–37. https://doi.org/10.1038/s41437-020-0338-4
22. Gan, X., Sengottaiyan, P., Park, K. H., Assmann, S. M., Albert, R. (2024). A network-based modeling framework reveals the core signal transduction network underlying high carbon dioxide-induced stomatal closure in guard cells. *PLOS Biology*, *22*(5), e3002592. https://doi.org/10.1371/journal.pbio.3002592
23. Gopal, M., Gupta, A., Shahul Hameed, K., Sathyaseelan, N., Khadeejath Rajeela, T. H., Thomas, G. V. (2020). Biochars produced from coconut palm biomass residues can aid regenerative agriculture by improving soil properties and plant yield in humid tropics. *Biochar*, *2*(2), 211–226. https://doi.org/10.1007/s42773-020-00043-5
24. Hebbar, K. B., Apshara, E., Chandran, K. P., Prasad, P. V. V. (2020). Effect of elevated CO_2, high temperature, and water deficit on growth, photosynthesis, and whole plant water use efficiency of cocoa (*Theobroma cacao* L.). *International Journal of Biometeorology*, *64*(1), 47–57. https://doi.org/10.1007/s00484-019-01792-0
25. ICCO. (2023). *ICCO Quarterly Bulletin of Cocoa Statistics, 2023; Vol. XLIX, No.1, Cocoa year 2022/2023*.
26. Igawa, T. K., Toledo, P. M. de, Anjos, L. J. S. (2022). Climate change could reduce and spatially reconfigure cocoa cultivation in the Brazilian Amazon by 2050. *PLOS ONE*, *17*(1), e0262729. https://doi.org/10.1371/journal.pone.0262729
27. Jaimez, R., Loor, R., Arteaga, F., Márquez, V., Tezara, W. (2022). Differential response of photosynthetic activity, leaf nutrient content and yield to long-term drought in cacao clones. *Acta Agronómica*, *70*(3). https://doi.org/10.15446/acag.v70n3.92252
28. Kaba, J. S., Asare, A. Y., Andoh, H., Kwashie, G. K. S., Abunyewa, A. A. (2022). Toward sustainable cocoa (*Theobroma Cacao* L) production: The role of potassium fertilizer in cocoa seedlings drought recovery and survival. *International Journal of Fruit Science*, *22*(1), 618–627. https://doi.org/10.1080/15538362.2022.2092932
29. Kong, X., Li, D., Song, X., Zhang, G. (2021). Quantitative estimation of the changes in Soil CEC after the removal of organic matter and iron oxides. *Agricultural Sciences*, *12*(11), 1244–1254. https://doi.org/10.4236/as.2021.1211079
30. Kumar, Ray, D. P. (2017). Root-exudates in relation to microbial activity. *International Journal of Bioresource Science*, *4*(1), 17. https://doi.org/10.5958/2454-9541.2017.00005.6
31. Lahive, F., Handley, L. R., Hadley, P., Daymond, A. J. (2021). Climate change impacts on cacao: Genotypic variation in responses of mature cacao to elevated CO_2 and water deficit. *Agronomy*, *11*(5), 818. https://doi.org/10.3390/agronomy11050818
32. Lewis, V. R., Farrell, A. D., Umaharan, P., Lennon, A. M. (2021). Genetic variation in high light responses of Theobroma cacao L. accessions. *Heliyon*, *7*(6), e07404. https://doi.org/10.1016/j.heliyon.2021.e07404
33. Li, R., Li, Q., Zhang, J., Liu, Z., Pan, L., Huang, K., Zhang, L. (2020). Effects of organic mulch on soil moisture and nutrients in karst area of Southwest China. *Polish Journal of Environmental Studies*, *29*(6), 4161–4174. https://doi.org/10.15244/pjoes/119477
34. Lu, L., Tong, C., Liu, Y., Yang, W. (2024). Analysis of physicochemical properties, enzyme activity, microbial diversity in rhizosphere soil of coconut (*Cocos nucifera* L.) under organic and chemical fertilizers, irrigation conditions. *Agriculture*, *14*(11), 1937. https://doi.org/10.3390/agriculture14111937
35. Luo, Z., Ren, J., Fatichi, S. (2025). *Temperature regulates microbial carbon use efficiency effects on soil organic carbon storage*. https://doi.org/10.5194/egusphere-egu24-5211
36. Mathur, S., Jain, L., Jajoo, A. (2018). Photosynthetic efficiency in sun and shade plants. *Photosynthetica*, *56*(SPECIAL ISSUE), 354–365. https://doi.org/10.1007/s11099-018-0767-y
37. Matthews, A., Lima-Zaloumis, J., Debes II, R. V., Boyer, G., Trembath-Reichert, E. (2023). Heterotrophic growth dominates in the most extremotolerant extremophile cultures. *Astrobiology*, *23*(4), 446–459. https://doi.org/10.1089/ast.2022.0100
38. McMahon, P., Purung, H. bin, Lambert, S., Mulia, S., Nurlaila, Susilo, A. W., Sulistyowati, E., Sukamto, S., Israel, M., Saftar, A., Amir, A., Purwantara, A., Iswanto, A., Guest, D., Keane, P. (2015). Testing local cocoa selections in three provinces in Sulawesi: (i) Productivity and resistance to cocoa pod borer and Phytophthora pod rot (black pod). *Crop Protection*, *70*, 28–39. https://doi.org/10.1016/j.cropro.2015.01.001
39. Mensah, E. O., Vaast, P., Asare, R., Amoatey, C. A., Owusu, K., Asitoakor, B. K., Ræbild, A. (2024). Cocoa Under Heat and Drought Stress. In *Agroforestry as Climate Change Adaptation* 35–57. Springer International Publishing. https://doi.org/10.1007/978-3-031-45635-0_2
40. Mohamed, G. R., Mahmoud, R. K., Fahim, I. S., Shaban, M., Abd El-Salam, H. M., Mahmoud, H. M.

(2022). Bio-composite thermal insulation materials based on banana leaves fibers and polystyrene: Physical and thermal performance. *Journal of Natural Fibers*, *19*(13), 4806–4821. https://doi.org/10.1080/15440478.2020.1870628

41. Nasution, D. P., Rusmayadi, G., Wahdah, R. (2022). *Acclimatization of Tiger Orchid (Grammatophyllum speciosum. Blume) Plantlets on Various Growing Media and Shade Levels*. *15*(6), 21–23. https://doi.org/10.9790/2380-1506012123
42. Nugroho, R. M. Y. A. P., Ustiatik, R., Prasetya, B., Kurniawan, S. (2023). Response of different coffee-based agroforestry management on microbial respiration and density. *Journal of Ecological Engineering*, *24*(9), 158–170. https://doi.org/10.12911/22998993/169179
43. Numbisi, F. N., Alemagi, D., Degrande, A., Van Coillie, F. (2021). Farm rejuvenation-induced changes in tree spatial pattern and live biomass species of cocoa agroforests in central cameroon: insights for tree conservation incentives in cocoa landscapes. *Sustainability*, *13*(15), 8483. https://doi.org/10.3390/su13158483
44. O, I., O, D. A., Oluyole, K., Famaye, A., Ipinmoroti, R. (2024). Impact of climate change on soil wetness and cocoa production in Ondo State, Nigeria: Implication for sustainable farming practices. *Asian Journal of Agricultural and Horticultural Research*, *11*(2), 89–99. https://doi.org/10.9734/ajahr/2024/v11i2316
45. Ofori, A., Arthur, A., Padi, F. K. (2019). Extending the cacao (*Theobroma cacao* L.) gene pool with underrepresented genotypes: growth and yield traits. *Tree Genetics & Genomes*, *15*(5), 75. https://doi.org/10.1007/s11295-019-1382-1
46. Paguntalan, D., Aggangan, N., Buot, I. J. (2023). The effect of AMF-cacao association on varying physicochemical, nutrient, and biological soil parameters in an agroforest system. *The Philippine Agricultural Scientist*, *106*(4), 400–413. https://doi.org/10.62550/JN125021
47. Rahmah, D. M., Januardi, Nurlilasari, P., Mardawati, E., Kastaman, R., Agus Kurniawan, K. I., Sofyana, N. T., Noguchi, R. (2024). Integrating life cycle assessment and multi criteria decision making analysis towards sustainable cocoa production system in Indonesia: An environmental, economic, and social impact perspective. *Heliyon*, *10*(19). https://doi.org/10.1016/j.heliyon.2024.e38630
48. Rajão, P. H. M., Berg, M. P., Cornelissen, J. H. C., Dias, A. T. C. (2023). The effects of leaf traits on litter rainfall interception with consequences for runoff and soil conservation. *Journal of Ecology*, *111*(12), 2662–2675. https://doi.org/10.1111/1365-2745.14203
49. Ríos-Bolívar, F. M., Garruña, R., Rivera-Hernández, B., Herrera, A., Tezara, W. (2022). Effect of high concentrations of CO_2 and high temperatures on the physiology of Mexican cocoa. *Plant Stress*, *6*, 100114. https://doi.org/10.1016/j.stress.2022.100114
50. Rodrigues, Renato Augusto, Mendes Pedroso de Lima, J. L., Assunção Montenegro, A. A., Brito Almeida, T. A., Lopes da Silva, J. R. (2023). Assessing soil temperature and moisture fluctuations under irrigated banana (*Musa spp*.) cultivation in response to coconut coir mulch cover. *DYNA*, *90*(226), 50–57. https://doi.org/10.15446/dyna.v90n226.105969
51. Rofner, F. N., Arce, P. M., Salazar, P. R. M., Vasquez, N. L., Rengifo. (2022). An organic management alternative that improves soil quality in cocoa plantations under agroforestry systems. *Scientia Agropecuaria*, *13*(4), 335–342. https://doi.org/10.17268/sci.agropecu.2022.030
52. Ruseani, N. S., Vanhove, W., Susilo, A. W., Van Damme, P. (2022). Cocoa clones reveal variation in plant biomass, root nitrogen uptake, and apparent nitrogen recovery at the seedling stage. *Journal of Soil Science and Plant Nutrition*, *22*(4), 4727–4738. https://doi.org/10.1007/s42729-022-00955-0
53. Salvador Morales, P., Sanchez Hernandez, R., Sánchez Gómez, D., López Noverola, U., Santiago, G. A., Valdés Velarde, E., Gallardo Lancho, J. F. (2017). Evolution of soil organic carbon during a chronosequence of transformation from cacao (*Theobroma cacao* l.) plantation to grassland. *Acta Agronómica*, *66*(4), 525–530. https://doi.org/10.15446/acag.v66n4.62543
54. Santos, I. C. dos, Silva, G. S., Silva, J. P. L., Souza, J. de S., Santos, M. S. dos, Souza Junior, J. O. de, Almeida, A.-A. F. de, Corrêa, R. X., Baligar, V. C., Zhang, D., Calle-Bellido, J., Jia, H., Ahnert, D. (2023). Screening of cacao clones for drought tolerance by assessing predawn leaf water potential, growth, and leaf gas exchange. *Plant Stress*, *10*, 100245. https://doi.org/10.1016/j.stress.2023.100245
55. Sarjana, P., Kasa, I. W., Gunam, I. B. W., Takama, T., Pratiwi, L., Putra, I. W. W. P. (2021). Effects of climate change on the vulnerability of cocoa production in Medewi, Bali Indonesia. *IOP Conference Series: Earth and Environmental Science*, *724*(1). https://doi.org/10.1088/1755-1315/724/1/012076
56. Sasmita, D. K., Wardiana, E., Saefudin, Pranowo, D., Aunillah, A., Kholilatul Izzah, N., Herman, M., Kholis Firdaus, N., Sobari, I., Sakiroh, Listyati, D. (2023). Challenges and opportunities for Indonesian cocoa development in the era of climate change. In *Shifting Frontiers of Theobroma cacao - Opportunities and Challenges for Production [Working Title]*. IntechOpen. https://doi.org/10.5772/intechopen.112238
57. Sauvadet, M., Dickinson, A. K., Somarriba, E., Phillips-Mora, W., Cerda, R. H., Martin, A. R., Isaac,

M. E. (2021). Genotype–environment interactions shape leaf functional traits of cacao in agroforests. *Agronomy for Sustainable Development*, *41*(2), 31. https://doi.org/10.1007/s13593-021-00690-3

58. Silva, I. E. B. da, Deon, M. D., Silva, D. J., Xavier, F. A. da S., Santos, A. P. G., Signor, D. (2024). Coconut residues increase light fraction of organic matter and water retention in semi-arid sandy soil under irrigated cultivation. *Revista Brasileira de Ciência Do Solo*, *48*. https://doi.org/10.36783/18069657rbcs20240042
59. Smith D, E., Gnahoua, G. M., Ohouo, L., Sinclair, F. L., Vaast, P. (2014). Farmers in Côte d'Ivoire value integrating tree diversity in cocoa for the provision of ecosystem services. *Agroforestry Systems*, *88*(6), 1047–1066. https://doi.org/10.1007/s10457-014-9679-4
60. Song, K., Qin, Q., Yang, Y., Sun, L., Sun, Y., Zheng, X., Lu, W., Xue, Y. (2023). Drip fertigation and plant hedgerows significantly reduce nitrogen and phosphorus losses and maintain high fruit yields in intensive orchards. *Journal of Integrative Agriculture*, *22*(2), 598–610. https://doi.org/10.1016/j.jia.2022.08.008
61. Sugiatno, S., Hansyah, A. F., Evizal, R., Ramadiana, S. (2022). The Effect of Drought on the Growth and Production of Seven Cocoa Clones. *Agrotropika*, *21*(1), 59. https://doi.org/10.23960/ja.v21i1.5830
62. Tosto, T. F., de Almeida, A.-A. F., Oliveira, B. R. M., Paiva, A. Q., de Carvalho Neto, C. H., Silva, R. J. S., Pirovani, C. P. (2024). Proteomic profiles in roots of young cacao plants grown in coastal plain compacted soil, with location and phosphorus limitation. *Scientia Horticulturae*, *332*, 113219. https://doi.org/10.1016/j.scienta.2024.113219
63. Yoroba, F., Kouassi, B. K., Diawara, A., Yapo, L. A. M., Kouadio, K., Tiemoko, D. T., Kouadio, Y. K., Koné, I. D., Assamoi, P. (2019). Evaluation of rainfall and temperature conditions for a perennial crop in tropical wetland: a case study of cocoa in Côte D'ivoire. *Advances in Meteorology*, *2019*, 1–10. https://doi.org/10.1155/2019/9405939
64. Zasari, M., Wachjar, A., Susilo, A. W., Sudarsono, S. (2020). Prope legitimate rootstocks determine the selection criteria for drought-tolerant cocoa. *Biodiversitas Journal of Biological Diversity*, *21*(9). https://doi.org/10.13057/biodiv/d210918