

Article

Epiphytes Distribution and Yield of Cocoa Trees Under Shade and Full Sun Conditions

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Abstract

Cocoa agroforestry is widely promoted for biodiversity conservation and sustainable production; however, uncertainties remain regarding the distribution of epiphytes and cocoa yield under different shade regimes. This study evaluated the effects of shade on epiphyte distribution and cocoa productivity at two community sites located approximately 6 km apart. One site consisted of cocoa cultivated under indigenous and introduced shade trees, while the other site used a 40% shade net. Annual rainfall at the sites was 1364.70 mm and 1178.44 mm, respectively, with average monthly temperatures ranging from 28 to 35 °C. During the main dry season, light intensity under direct sunlight exceeded 13.00 Klux and was approximately three times greater than in shaded plots. Lichens were the dominant epiphytes across all shade systems, with 40–70 colonies per 225 m² plot. Only one vascular epiphyte species was recorded, occurring exclusively on cocoa trees under the shade net. Correlation coefficients between light availability and epiphyte abundance ranged from 0.08 to 0.62, indicating that light influenced epiphyte distribution and diversity. Cocoa pod production under indigenous shade trees and full sunlight was comparable (127–177 pods per plot), whereas production under the shade net was approximately twice that recorded in unshaded plots. Although flower cushion abundance varied among treatments, pods from shaded plots generally contained more beans. The highest incidence of diseased and wilted pods occurred under shade trees. Overall, the findings suggest that heavy tree shade may limit epiphyte development through reduced light availability, while uniform artificial shading may enhance cocoa yield.

Keywords: fungi; lichens; light distribution; mosses; pod production; *Theobroma cacao*



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1. Introduction

Cocoa (*Theobroma cacao* L.) is recognized globally due to its economic benefits [1]. Many livelihoods depend directly or indirectly on cocoa, apart from its numerous nutritional benefits [2]. In addition, cocoa has other economic benefits in cosmetics, soap preparations, and oil production companies [3]. It generates substantial revenues for producing countries

and consequently contributes a significant share to the gross domestic product (GDP) of those countries. Due to the industrial demand, cocoa production is a lucrative business, providing employment to many people along the value chain and thereby contributing to poverty reduction and household income [4]. More so, cocoa contributes to social development as the revenues from it are invested into government projects such as schools, roads and hospitals [5]. In many rural communities, cocoa farming supports local development and improves living standards [6]. The importance of cocoa, as an essential resource to support economies, industries and human well-being, makes it one of the most valuable agricultural products in the world.

Cocoa production is sensitive to biotic and abiotic factors [7]. Cocoa plants thrive well in tropical regions (roughly 20 degrees north and south of the equator) in the world, but their productivity depends on the prevailing environmental conditions and their interactions with other organisms [8,9]. For example, though pollination is mostly by midges (*Forcipomyia squamipennis*), some insect pests such as cocoa pod borers (*Conopomorpha cramerella*) and capsids (*Sahlbergella singularis* and *Distantiella theobroma*) damage pods, stems and leaves, which in turn affect yield [10]. Weeds compete with the cocoa plants for resources (light, water and soil nutrients) while diseases such as black pod and swollen shoot are major threats to cocoa production [11]. In addition, cocoa requires evenly distributed rainfall throughout the year with annual averages between 1500 and 2000 mm and a warm monthly temperature around 21 to 32 °C [9]. High temperature and low rainfall affect the photosynthetic machinery and reduce growth and yield [12,13]. Successful cocoa farming depends on managing environmental conditions and controlling the pests and diseases [14].

Adequate shade is often recommended to cushion cocoa plants against unfavorable abiotic conditions [15]. However, the impact of shade on cocoa production is being reviewed in light of climate change scenarios and the sustainability of the cocoa industry. Cocoa, in its natural habitat in the Amazon, evolved as an understory or sub-canopy tree species [16] and can maximize photosynthesis in low-light conditions [12,17]. However, the shade demands of adult cocoa have been debatable. While shade is reported to be beneficial [15,18], it is also considered a limiting factor in light interception and cocoa yield [19,20]. Almeida and Valle [21] noted that heavy shade is one of the greatest growth-limiting factors and that vigorous growth and higher yields are only possible without shade. This was followed by Gateau [22], who reported a higher mean yield of cocoa under full sun than under a heavily shaded farm.

On the other hand, Mensah et al. [12] contributed to the debate by using a uniform shade from a 40% artificial shade net and identified a higher yield in the shade than in the no-shade. Moreover, results from fertilizer–shade trials documented several deadly effects of shade removal over a long period [15,23]. In the no-shade, the productive lifespan of the cocoa did not extend beyond 10 years, the point at which yields started to decline [24]. The most deleterious effect is pest and disease damage under no-shade conditions compared with shade [25]. Faster weed growth and higher nutritional demands from the cocoa tree have also been observed under no-shade conditions [26]. Eliminating shade may increase yield in the short term; however, an unshaded cocoa system may not be economically justified given the negative effects of shade removal and the increased demand for farm inputs to maintain productivity [15]. Additionally, shade in cocoa plantations provides ecological and economic benefits, especially in low-input agriculture, where sustainability rather than a step-up in productivity is of major interest [14,27].

Aside from the shade and the no-shade debates, epiphytes associated with cocoa are regarded as pests in tree crop farms in the moist tropics [28], while other researchers have different views [29]. Mabbett [30] discovered that dense mycelium of lichen ramifying

on the surfaces of cocoa can negatively reduce photosynthesis. Epiphytic layers formed on the surface of the cocoa leaf would block the stomata, resulting in a reduced gas exchange, while some climbing epiphytes, such as *Microgramma owariensis* and *Calypstrochilum emarginatum*, reduce the irradiance level of cocoa plants [31]. Additionally, mosses and lichens can indirectly create a condition that may promote the growth of disease-causing organisms apart from causing the death and the scratching of the epidermis of cocoa trunks and branches [31–33]. For example, mosses and lichens can create a moist, humid condition on the bark of cocoa trees or serve as a microbial home to facilitate the growth of fungi and other pathogens [32]. Not all other researchers have noted that epiphytes can obstruct flower emergence and should be removed from the cocoa trees [33]. As a result, manual removal and chemical usage have been recommended to wipe out epiphytes from cocoa trees [34–36].

In another school of thought, epiphytes are considered an important component of biodiversity in natural forest environments. Epiphytes are noted to have no negative effects on cocoa yield and serve as a possible host for other beneficial organisms [37]. Gradstein and Sporn [38] stated that epiphytic species abundance was lower, and individual species were below the canopy on cocoa tree trunks (at a height of less than 2 m above ground), as they identified bryophytes and lichens as the most abundant epiphytic species associated with cocoa trees in Ecuador. Non-vascular epiphytic species (mostly bryophytes and lichens) do not pose challenges to cocoa yield, and removing them is unnecessary and time-consuming. The labor of farmers can be reduced, and the rich flora outside natural forests can be supported through biodiversity enhancement when the epiphytes are maintained [35].

The relationship among shade, epiphytes, and cocoa productivity remains poorly understood. Although cocoa agroforestry systems are widely promoted for both production and biodiversity conservation, limited research has examined how different shade regimes influence epiphyte abundance, distribution, and diversity, and how these changes affect cocoa yield. Most existing studies focus on either cocoa productivity or biodiversity independently, with few investigating the interactions between epiphyte communities and cocoa performance. Consequently, the effects of shade-induced changes in epiphyte distribution on cocoa production remain unclear. While shade trees and epiphytes may influence cocoa growth and fruiting, their removal could diminish important ecological functions that support plantation sustainability. It is therefore important to determine whether shade and epiphytes can be managed to enhance both biodiversity conservation and cocoa production. This study assessed the effects of different shade levels on epiphyte distribution and cocoa yield.

2. Materials and Methods

2.1. Study Area

The research was conducted at the Sefwi Wiawso Municipality of the Western North Region of Ghana (Figure 1) in the 2020/2021 production season. Sefwi Wiawso Municipality (6°4'0" N and 6°32'0" N and 2°44'0" W and 2°20'0" W) is within the rainforest climatic zone with temperatures between 25 and 30 degrees Celsius generally over the year and an adequate rainfall pattern between 1524 mm and 1780 mm per year [39]. Two rainy seasons, the major (May–July) and the minor (September–October), determine the “main crop (major harvesting period)” and “light crop (minor harvesting period)” cocoa seasons in the municipality. Humidity is relatively high, about 95% at night, falling to 70% during the day [40].

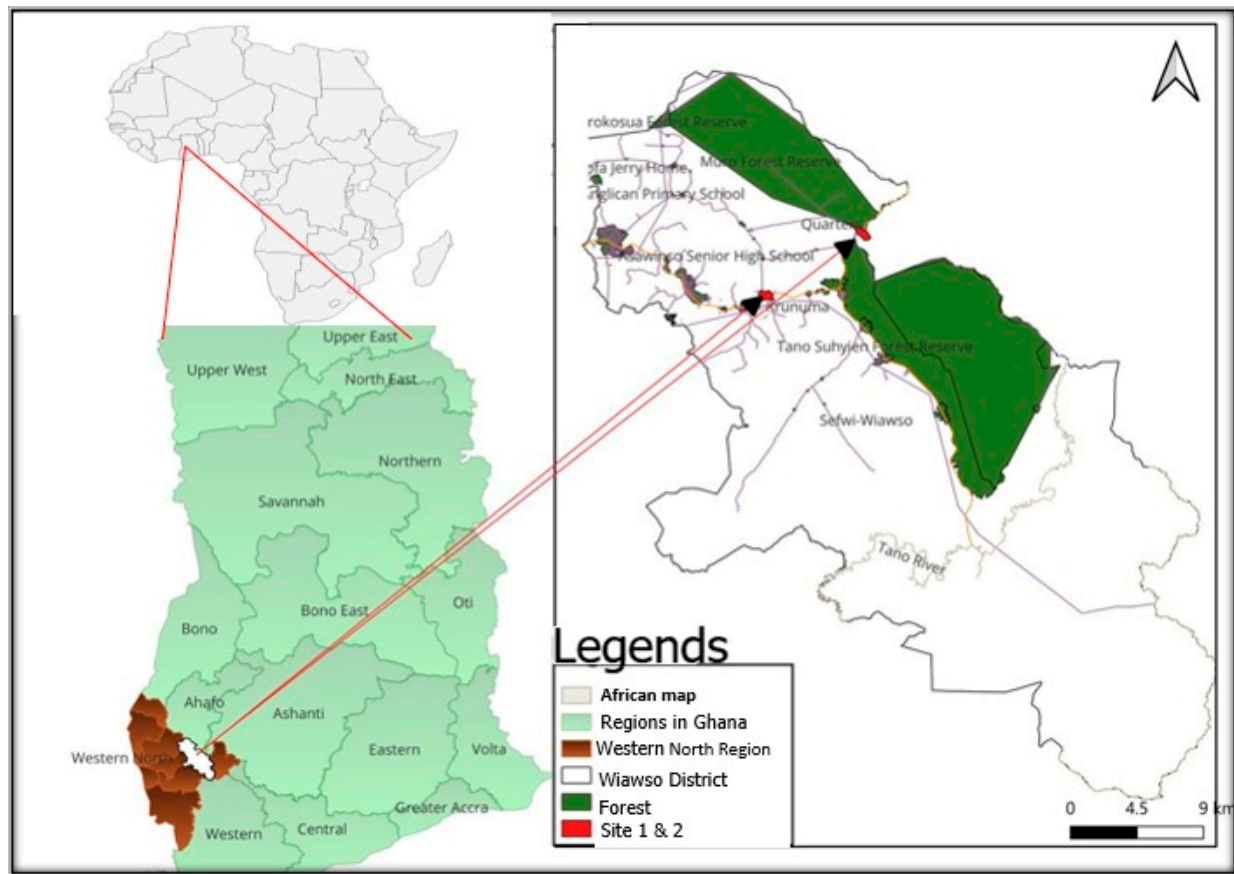


Figure 1. Ghana and the Western North Region maps showing the Sefwi Wiawso District containing forest reserves, towns, rivers, and the research sites. Modified from Osei-Wusu et al. [41].

2.2. Sampling Site and Study Design

Two farming communities within the municipality, approximately 6 km apart, were selected for the study—the Boako farming community (study site 1) and the Kunuma farming community (study site 2). The common cultivars of cocoa plants in the two farming communities were a mixed of PA7, C42, C85, and PA150 as cocoa seedlings were supplied from the same source (Boako Seedling Production Unit of Ghana Cocoa Board). In the two farming communities, four plots, each measuring half an acre, were demarcated. For example, in study site 1, the two farms selected included a cocoa farm with indigenous/human-introduced trees (shade trees) and a cocoa farm under direct sunlight/full sun (without shade trees). The study site 1 farm was managed by the Seed Production Unit of the Ghana Cocoa Board (COCOBOD). The farm in study site 2 was owned by a private farmer. Three knitted black shade net canopies measuring 7.1 m in height, 12 m in width, and 50 m in length were mounted over the cocoa trees (Shade net) in study site 2 in June 2018 for a project on climate change and cocoa production. The net provided 40% shade to the cocoa plants. Buffer zones of 6 m apart were created between the three canopies erected. Another plot on the same farm of about half an acre under direct sunlight (without a shade net) was also selected.

Multistage (split-plot and simple random technique) sampling methods were used in this study, with four different treatments: site one (shade tree; without shade tree) and site two (shade net; without shade net). In each of the four farms/treatments, a study plot measuring 15 m × 15 m (225 m²) was demarcated and replicated three times. Each plot consisted of twenty-five (25) cocoa trees planted in five in row and five columns in a rectangular pattern. The planting distance of 3 m between two cocoa plants was

uniform between and within rows. Each site had six experimental plots, where three plots were demarcated in the shade (with shade trees or with shade nets, depending on the site), and the other three plots were demarcated in the full sun (without shade trees or without shade nets, depending on the site). In total, one hundred and fifty cocoa trees were selected at each experimental site/community. Six cocoa trees within the inner rows of the twenty-five cocoa trees per sub-plot were sampled using simple random techniques for data collection. The outer sixteen cocoa trees forming the border rows of each sub-plot were not involved in the trials due to edge effects. Flowering, fruit growth, and development, and epiphytic colonies data were collected from cocoa tree trunks between 2 cm above ground level and a height of 1.5 m, where the epiphytes were clearly visible and could be readily counted within the selected zones. For the farms with trees as shade, the demarcated plots had at least two to three trees per replicate plot. The major trees include *Terminalia superba* and *Terminalia ivorensis* of about 19 m average height and 1.5 m trunk diameter. Sampled cocoa trees were tagged for easy identification.

2.3. Study Sites Conditions

Rainfall, temperature, and relative humidity data were obtained from the Seed Production Department (SPD) at Sefwi Boako Cocoa Station from a Stevenson Screen and a digital weather station (Onset Computer Corporation, Bourne, MA, USA) at Kunuma Community. Temperature, rainfall, and relative humidity were measured daily over one year.

Light intensity under the cocoa canopies in the four treatments was measured in the last week of every month between February 2020 and October 2020. Measurements were done between 9.00 am and 12.00 noon using a Light Meter (Extech Instruments, LT300, Nashua, NH) for a two-day interval at the two experimental sites, mostly during the normal daily weather conditions. Light energy required for efficient photosynthetic activities of a cocoa plant occurs mostly during this period [21]. We understand that the lux meter may be influenced by human visual sensitivity, which may not directly represent photosynthetically available radiation. Measurements were conducted at five spots on each plot—the four corners and the center of the plot. The light meter was held close to the leaves, with the sensor directed towards the rays of the sun that penetrated through the leaves. The light intensities recorded from the five spots were used to calculate the mean light value per plot.

2.4. Abundance and Distribution of Epiphytes Associated with Cocoa

The abundance and distribution of epiphytic colonies commonly associated with cocoa were counted in June (heavy rains), July (light rains), and August (semi-dry) as successive weather conditions in the year occur during the selected months. The purposive selection of the wet months was to ensure enough moisture for the growth and development of the epiphytes. Six cocoa trees that were selected from each plot for yield (flower and fruit) determination were equally used to assess the epiphytes associated with the cocoa trees. The epiphytic colonies (at 2 cm above ground up to 1.5 m height), except for vascular epiphytes (mostly at the crowns), were counted and recorded. Individual colonies were marked and numbered to avoid interference and double-counting. The epiphytes were classified into fungi, algae, lichens, mosses, and vascular epiphytes based on visual assessment assisted by previous studies [28,35,42–44] and two epiphytes identification mobile apps (*iNaturalist* and *FungID*).

2.5. Flowers, Fruit Formation, and Development of Cocoa

Data collection on flowers and fruits started from June 2020 to January 2021, covering the major cocoa harvesting periods (October, November, and December). The number of flower cushions and the number of flowers per cushion were counted at two-week intervals

from 7.30 am to 11.30 am (a suitable period for flower opening and pollination activities). Successful flowers that form pods were equally counted and monitored until ripening and harvesting. Pods were grouped into green pods, diseased or dead pods, and ripe pods. Diseased and dead pods were counted and detached from the plant to avoid obstruction in the next count.

2.6. Statistical Analysis

The number of epiphytes per plot, flower production, and pod production were analyzed using repeated measures in the nonlinear mixed effect model (nlme). For each response variable (Y), shade type (S), time (T) and their interactions (ST) were used as the fixed effects. Plots or replicates (pl) were included as random effect to account for the variations among the plots and the non-independence of repeated observations collected from the same plot over time. The number of trees for data collection was nested into plots for the analysis.

$$Y_{ij} \text{ (repeated measurements)} = \alpha(S) + \beta(T) + Y(ST) + A(pl)_i + \varepsilon_{ij}$$

where Y is the response observed in plot (i) at time (j), $\alpha(S) + \beta(T) + Y(ST)$ —the non-linear function describing the relationship between the response and the fixed effects, $A(pl)_i$ is the random effect associated with plot (i), and ε_{ij} is the residual error term. The repeated observations within plots were modeled using the first-order autoregressive structure to account for temporal correlation among measurements. Alternative covariance structures were evaluated using Akaike's information criterion, and the first-order autoregressive structure provided the best fit to the data.

We checked data normality through quantile–quantile and histogram distribution plots. Log transformation of the number of pods and flower numbers was performed. Significant differences were tested with the backward reduction method and means were separated with multiple comparisons using the Tukey Honest Significant Difference test (Tukey HSD) at 0.05 probability. Pearson correlation between light intensity and epiphytes distribution was analyzed using the 'ggpubr' package [45] in the R statistical software version 4.4.0 [46] to provide an exploratory assessment of the overall association between light intensity and epiphytes abundance across treatments, plots and months.

3. Results

3.1. Environmental Conditions at the Study Sites

The total annual rainfall recorded was 1364.70 mm at Boako SPD Cocoa Station (Site 1) and 1178.44 mm at Kunuma community (Site 2) (Figure 2). Heavy rains occurred in June and October (between 137 mm and 359 mm). Low levels of rain were experienced in July (58.70 mm), with no rain in February and August 2020. Temperatures at the research sites were higher (between 28 °C and 35 °C), which occurred mostly during the dry season (February and March), but low temperatures occurred between June and August (24 °C), with a yearly average of around 28 °C. The average relative humidity for the year was 85.27% at Boako SPD and 82.44% at Kunuma community.

Light intensities in the farms under direct sunlight during the main dry season (February and March) were three times ($>13.00 \pm 0.42$ Klux) higher than those in the shaded farms (shade-tree and shade-net) (4.00 ± 0.31 Klux). The light intensity in the farm under the shade net (2.36 ± 0.67 Klux) was lower than that under the shade tree (4.17 ± 1.15 Klux) during the dry season. In the wet months, especially from June to October, heavy rainfall with low light intensities occurred, especially in the shaded farms. Average light intensities under the shade tree farm were lower (0.82 ± 0.08 – 1.33 ± 0.05 Klux) compared to the shade

net farms (3.59 ± 0.48 – 2.33 ± 0.15 Klux), while it was lower in the cocoa without shade trees (between 2.43 ± 0.42 – 4.72 ± 0.11 Klux) compared to the dry months.

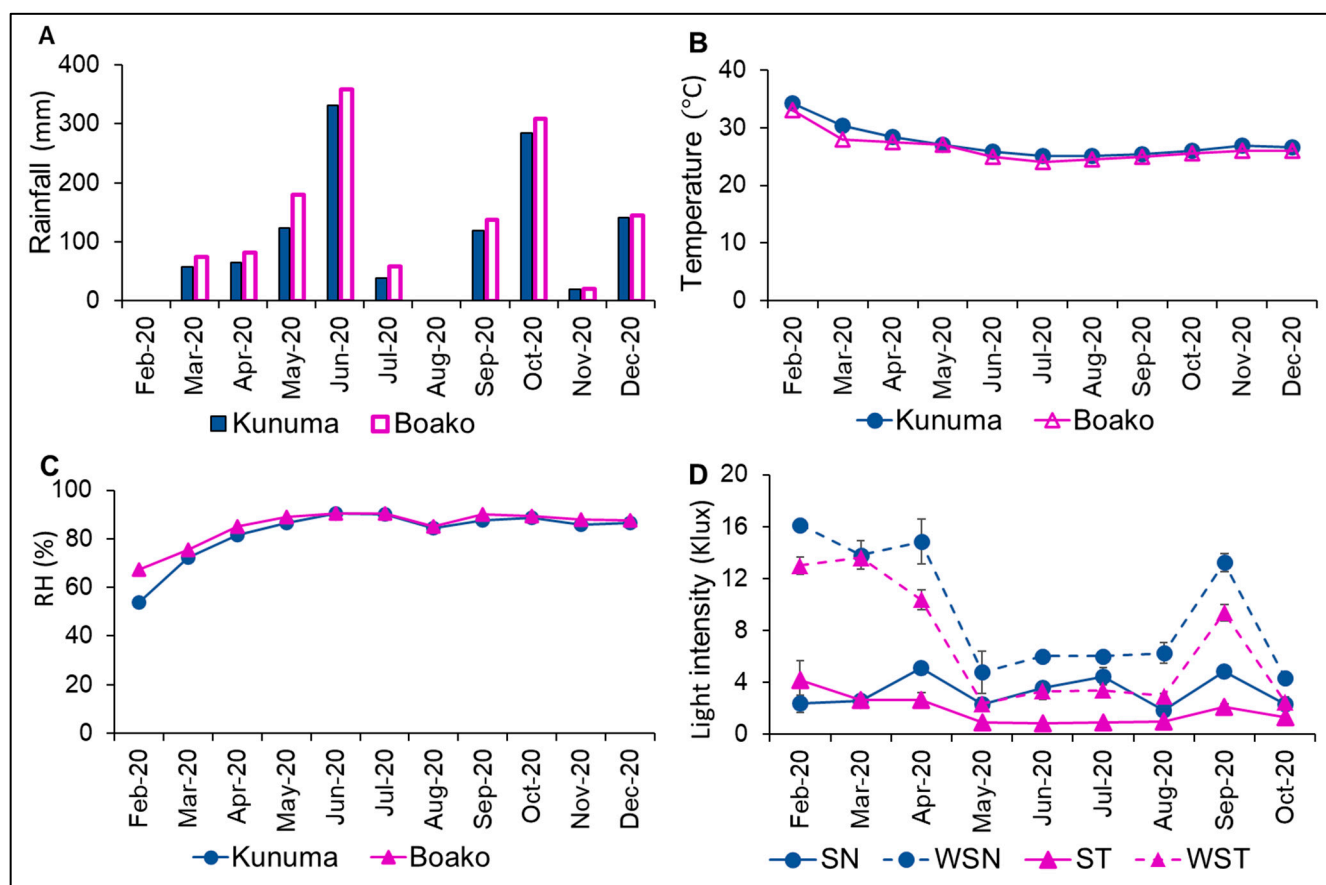


Figure 2. Environmental conditions at the experimental site between February and December 2020. (A–C): rainfall, temperature, and relative humidity at Boako and Kunuma. (D): variations in light intensity in cocoa under shade trees (ST), without shade trees (WST), shade net (SN), and without shade nets (WSN).

3.2. Abundance and Distribution of Epiphytic Species Associated with Cocoa Trees

The white patches (fungi) appeared to be associated with all cocoa trees, both shaded and non-shaded (Table 1; Figure 3). Algae appeared in the ‘pocket’ of patches on cocoa trees and occurred in all the farms, especially in the shade-tree farms. Lichens were the prominent epiphytic species identified in all the farms. Mosses and ferns (vascular epiphytes) rarely occurred on cocoa under shade tree farms.

Table 1. Epiphytic species identified on cocoa trees at the study plots based on visual assessment.

Types of Epiphytes	Assumed Family	Plot Found
Fungi	Verrucariaceae	ST, WST, SN, WSN
Algae	Trebouxiaceae, Trentepohliaceae	ST, WST, SN, WSN
Lichen	Lecanoraceae, Parmeliaceae	ST, WST, SN, WSN
Mosses	Brachytheciaceae, Polypodiaceae	WST, SN, WSN
Ferns (Pteridophyte)	Polypodiaceae	SN

Note. ST = Shade-tree, WST = Without shade tree, SN = Shade net, WSN = Without shade net. Complex lichens (Lecanoraceae, Parmeliaceae) were the commonest epiphytic species associated with cocoa trees in the without-shade tree and shade net farms. Mosses (Brachytheciaceae) occurred largely on cocoa trees in the without-shade tree farms. Only one vascular epiphyte (Polypodiaceae) was found under the shade net plot. The identification of the epiphyte types and families in the study sites was based on visual assessment, and it may need further confirmation.

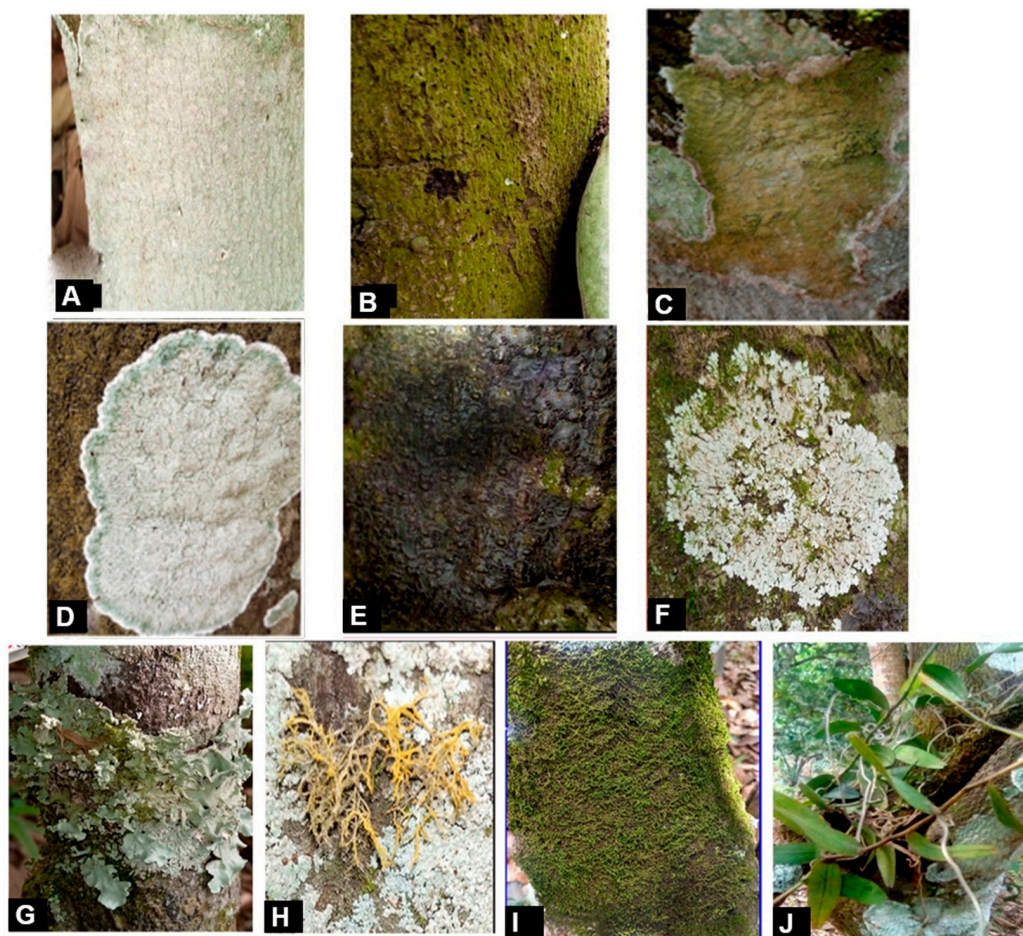


Figure 3. Type of epiphytes identified on the cocoa trees. (A): fungi, (B,C): algae., (D–H): lichen, (I): mosses, (J): ferns. The identification of the epiphyte types and families in the study sites is based on visual assessment, and it will need further confirmation.

Statistical differences existed in the abundance and distribution of fungi, algae, lichens, and mosses (Figure 4; $P_{(0.05)} = 0.001$), with no differences in vascular epiphytes for farms under shade (shade tree and shade net farms) and the farms under direct sunlight (without shade tree and without shade net farms). The farms under direct sunlight had the highest number of fungi colonies (14 ± 2.5 and 18 ± 2.08 colonies) on the cocoa trees. Shaded farms had the fewest fungi colonies on cocoa trees (6 ± 1.00 and 11 ± 1.15 colonies). A slight difference in the number of algal colonies in shaded and direct sunlight farms was identified. The lowest count of epiphytes (3 ± 1.53 colonies) occurred in August on cocoa under shade trees, and the highest (8 ± 1.00 colonies) was in June on cocoa without shade trees.

In general, lichens were the most common epiphytes associated with the cocoa trees. Lichens occurred largely in the cocoa farms without shade trees (54 ± 10.50 colonies). There was no clear difference in the number of lichen colonies in other farms (shade tree, shade net, and without shade net) (between 28 ± 3.21 and 44 ± 1.53 colonies). The farm under the shade net and the farm without the shade net had the highest number of mosses (between 7 ± 1.00 and 13 ± 3.21 colonies). Cocoa farms under shade trees had no moss, and fewer colonies occurred in farms without shade trees (2–3 colonies). Only one vascular epiphytic species was identified on the farm under the shade net.

The linear relationships between epiphyte distributions and light intensities were identified as significant for fungi, algae, and mosses, with R values between 55% and 62% (Figure 5A–D). However, the distribution of Lichen was not related to light intensities in the cocoa farm.

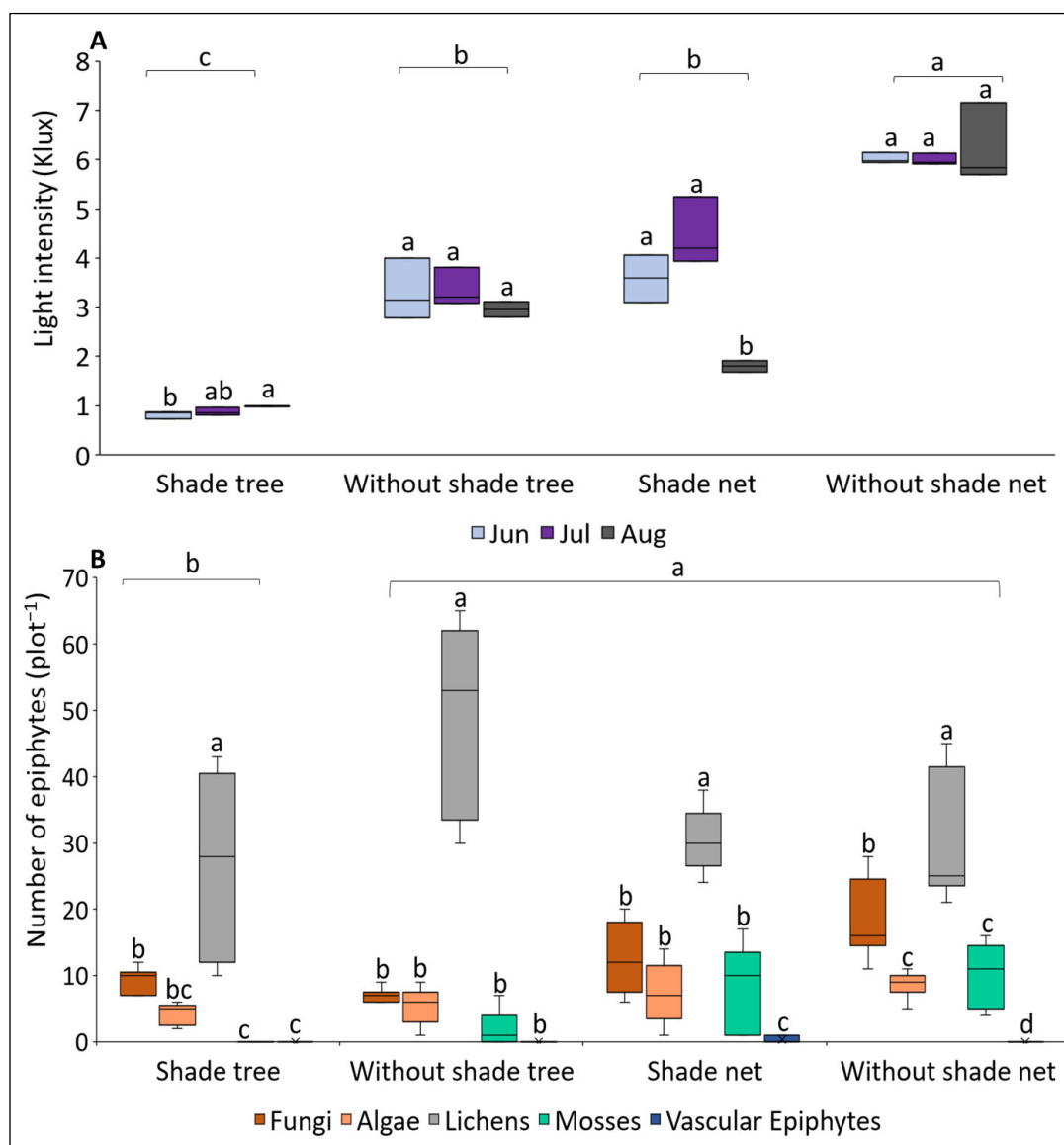


Figure 4. Light intensity under the four shade systems (A) and abundance of epiphytic species colonies (B) studied in June, July, and August 2020. Letters on the top lines represent significant differences among the plots, while the letters on the boxes represent significant differences among the epiphytes within a plot. Boxes with the same letters in a particular treatment (shade tree, without shade tree, shade net, and without shade net farms) are not statistically significant.

3.3. Effects of Shade on Cocoa Flower and Fruit Formation

The study indicated that the farm under direct sunlight (control to shade trees) at Boako Cocoa Station had the highest number of flower cushions (39 ± 3.95 flower cushions tree⁻¹), followed by the shade net farm (29 ± 5.19 flower cushions tree⁻¹) and shade tree farm (26 ± 4.36 flower cushions tree⁻¹) (Table 2). The least number of flower cushions was on the farm under direct sunlight (17 ± 3.12 flower cushions tree⁻¹).

For the number of flowers per cushion, the results indicated a statistical difference among the plots ($P_{(0.05)} = 0.001$). The cocoa trees under direct sunlight (without shade trees) had the highest number of flowers per cushion (27 ± 3.14 flowers) in the four plots studied, followed by shade net (22 ± 2.34 flowers). The lowest number of flowers per cushion was recorded in shade tree farms and farms under direct sunlight (without shade net) (17 ± 1.54 flowers and 16 ± 2.69 flowers) with no significant difference ($P_{(0.05)} = 0.98$).

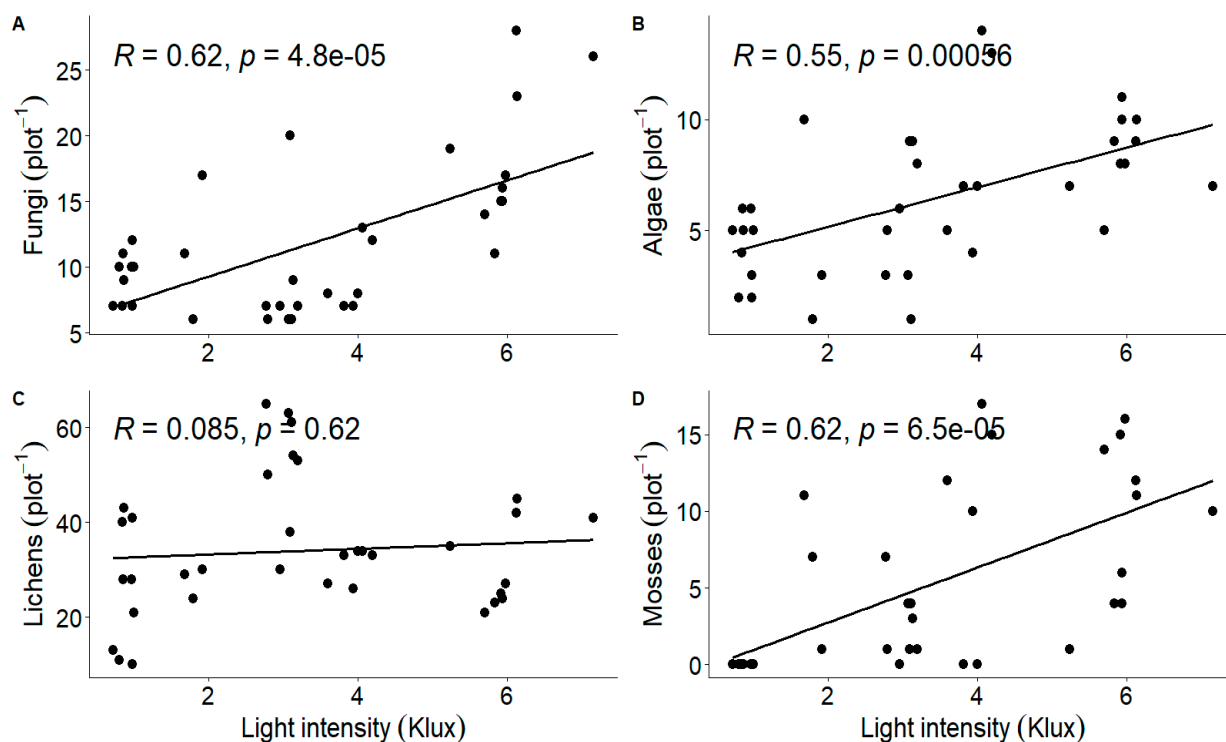


Figure 5. Correlation between epiphytes distribution and light intensities in the cocoa agroforestry farms on (A) Fungi, (B) Algae, (C) Lichens and (D) (Mosses). R = the correlation coefficient, and P = the significance value at a 0.05 probability level.

Table 2. The mean number of flower cushions, flowers per cushion, pod production, and pods' physical characteristics.

Treatment	Shade Tree	Without Shade Tree	Shade Net	Without Shade Net
Flowers				
Flower cushions (tree ⁻¹)	26 ± 4.36 ^b	39 ± 3.95 ^a	29 ± 5.19 ^b	17 ± 3.12 ^c
Flower (cushion ⁻¹ tree ⁻¹)	17 ± 1.54 ^c	27 ± 3.14 ^a	22 ± 2.34 ^b	16 ± 2.69 ^c
Pods production				
Green pods (plot ⁻¹)	127.28 ± 2.41 ^{ab}	177.28 ± 26.52 ^a	160.38 ± 16.41 ^{ab}	96.28 ± 14.66 ^b
Ripe pods (plot ⁻¹)	14.375 ± 6.76 ^c	34.375 ± 13.10 ^a	27.375 ± 10.17 ^{ab}	34.375 ± 13.10 ^a
Diseased green pods (plot ⁻¹)	24.5 ± 13.00 ^a	7.625 ± 3.59 ^b	9.75 ± 3.25 ^b	8.375 ± 2.57 ^b
Pods and beans' physical characteristics				
Pod length (cm pod ⁻¹)	15.57 ± 0.93 ^a	14.83 ± 1.70 ^a	15.68 ± 0.99 ^a	14.72 ± 1.50 ^a
Pod diameter (cm pod ⁻¹)	8.62 ± 0.90 ^a	8.49 ± 0.43 ^a	8.36 ± 0.33 ^a	7.30 ± 0.99 ^a
Pod weight (g pod ⁻¹)	438.71 ± 150.90 ^{ab}	461.86 ± 77.55 ^a	498.43 ± 89.16 ^a	355.80 ± 115.1 ^b
Bean number (pod ⁻¹)	41.00 ± 5.36 ^a	30.00 ± 4.61 ^c	39.00 ± 1.42 ^{ab}	36.00 ± 3.71 ^b
Fresh weight of beans (g pod ⁻¹)	116.06 ± 20.90 ^{ab}	92.54 ± 16.66 ^b	133.87 ± 22.40 ^a	84.17 ± 18.87 ^b
Fresh weight of 100 beans (g plot ⁻¹)	351.18 ± 18.51 ^a	319.81 ± 35.97 ^{ab}	335.46 ± 35.36 ^{ab}	261.69 ± 68.65 ^b
Dry weight of 100 beans (g plot ⁻¹)	131.52 ± 1.58 ^a	109.74 ± 6.31 ^b	116.91 ± 2.84 ^{ab}	97.37 ± 25.81 ^c

Means ± SD (in the same row) with different letters in superscripts differ significantly ($p < 0.05$).

Between June and September, the number of green pods per plot on cocoa plants under shade trees, without shade trees, and under shade net was similar, ranging from 127 to 177 per plot⁻¹ (Table 2). Green pods counted in the cocoa farm without a shade net were rather 96 per plot⁻¹. The number of green pods declined in all the plots in September and October as some pods became ripe and the majority turned out to be diseased. The

cocoa pods increased steadily in a shade tree farm but decreased gradually in a direct sunlight farm. The shade-net farm and the without-shade-net farm pods had a marginal increase in cocoa pods due to rains in late November and December.

Cocoa farms under direct sunlight (without shade trees) and under the shade net showed the highest ripe cocoa pods of 34 per plot⁻¹. Cocoa farms under shade trees had the lowest ripe pods of 14 pods per plot⁻¹. At the study site one (Boako Cocoa Station), the yields of green cocoa pods under direct sunlight (without shade trees) and the cocoa farm under shade trees were similar; however, at study site 2 (Kunuma community), the shade net farm yielded almost twice the yield of the farm without a shade net. The number of diseased and wilted pods in cocoa under shade trees was the highest, with 19.2% of the green pods counted. The number of diseased and wilted pods counted in cocoa under shade net and without shade net was 6.1% and 8.7%, respectively, of the total green pods. Farms under direct sunlight (without shade trees) had the least number of disease and wilted pods, with 4.3% of the green pods counted.

Pods' physical characteristics were similar across the different shade levels; however, pods from cocoa trees in the plots without shade net were lighter. Average bean number per pod ranged from 30 to 41, with a higher number counted in the shade plots. The other bean's physical characteristics were higher under the shade plots than in the plots without shade. Among the plots without shade, the study site two (without shade net) plots showed lower bean physical characteristics.

4. Discussion

The study of microclimates and shade types on the yield and epiphytes distribution in the two cocoa-growing communities has provided insight into the strategies needed to protect cocoa plants from climate scenarios while enhancing biodiversity conservation in cocoa-growing areas.

The microclimate of the experimental sites confirms the observations by Bari et al. [47] that annual rainfall has a significant negative trend in some regions. This provides evidence of a drying trend in parts of West Africa. There were negative trends in average temperature and humidity with reduced precipitation compared to the average climatic conditions suitable for cocoa [48]. The average temperature (27.55 °C) recorded was higher than the optimum temperature (2 °C) suitable for cocoa growth but within the optimum range for photosynthesis [13]. High temperatures hinder cocoa production and negatively affect flower and fruit development [21,49]; however, the recorded temperatures were close to normal for cocoa production in the research sites. Rainfall in the municipality declined by 23%, and there was a deviation in the pattern throughout the year when the research was conducted, compared with the optimum required by cocoa plants (between 1500 mm and 1700 mm). The limited rainfall might result in soil water deficits and reduced growth and yield of the cocoa trees, as proposed by Lahive et al. [50]. Relative humidity was low, with a reduction of 10%. These changes in microclimate may pose some level of threat to the cocoa production in the study sites [51,52].

Shade strongly influences epiphyte distribution and the yield of cocoa. In the cocoa agroforestry system, these effects are tightly linked as shade modifies the microclimate around the cocoa trees. Under shade, light availability, relative humidity and the bark conditions of the cocoa change [18]. The changing conditions either promote or hinder the growth of the epiphytes and the yield of cocoa. Higher humidity and lower temperature create a stable condition ideal for many epiphytes such as fungi, mosses and ferns [53,54]. However, dense shade can reduce light to affect the activities of light-demanding epiphytes [55]. Our observations did not show significant differences under shade and without shade in the two experimental sites in terms of the distribution of epiphytic fungi, mosses and ferns.

Factors could be due to the prevailing environmental conditions during the time of the epiphytes count or possibly due to the low association of epiphytic fungi, mosses and ferns with cocoa at the two experimental sites. Epiphytic counts of our work were conducted at the peak rainy season in Ghana, characterized by frequent rains, low temperature and high humidity. On the other hand, the number of lichens identified in the cocoa farms was higher than that of the other epiphytes, as also observed by Gladstein and Sporn [38], and they were comparatively higher under the full sun conditions. Earlier observations show that some species of lichens exhibit slower growth under shaded conditions than under full sun conditions [56]. Low light penetration brought about by the canopy cover of the cocoa crowns and the shade trees under the agroforestry configuration limits photosynthesis and reduces the energy available for growth and development. As most of these epiphytes are around the bark of the cocoa trees and are already shaded by the canopy cover of the crown of the cocoa, extra shade from shade trees and shade net might be disadvantageous to their photosynthetic activity and, hence, their higher number under the without shade treatments. The helotism (association) of algae and fungi, which later develop into lichens and other higher epiphytic forms, requires some amount of light to occur. The algae in the lichen produce carbohydrates, and the fungi take those carbohydrates to grow and reproduce [57]. This is evident in cocoa under shade trees, where algae and fungi do not form uniform and complicated lichens, though it is a common association in cocoa under direct sunlight. The identification and assessment of the epiphytes were based on visual observations during one cocoa production season. We encourage further research to confirm our results.

Epiphytes occurred predominantly on the farm under direct sunlight, where pod production was higher than in shade trees. This observation confirms the recommendations by Gladstein and Sporn [38] that epiphytes do not hinder the emergence of flowers and the yield of cocoa. Therefore, removal of epiphytes may not be necessary; however, farmers can resort to optimum and uniform shade (between 30 and 40% shade) in their cocoa farms to reduce other complications that can result from high epiphytic layers around cocoa trees, as proposed by Akrofi and Acheampong [31]. The identified epiphytes predominantly consisted of non-vascular epiphytes and may support biodiversity in cocoa agroforestry and other ecological roles [58]. However, thick epiphytic layers (vascular epiphytes) may ramify tree trunks and suppress the productivity of cocoa trees. This observation needs further research, as we provided general information on how light could affect epiphytes' distribution on cocoa farms across treatments and plots, though observations might not be fully independent. The light meter used may also not directly represent the photosynthetically available radiation. These primary measurements and analyses are to stimulate further and robust research on the presence of epiphytes and their activities under shade and full sun conditions of the cocoa tree.

The research outcome indicates that each cocoa plantation is unique and depends on the ecological factors prevailing in its locality. The shade canopy design and care (both shade tree and shade net) involved a range of factors (site conditions, selection, and maintenance) related to cocoa farm management, as proposed by Somarriba et al. [59]. The farms under the shade net and the one without the shade trees performed better concerning fruit and seed production than farms under shade trees and without the shade net. Although the farms without shade trees had reduced shade cover, tree vigor and higher yield could be attributed to a higher photosynthetic active radiation interception and a possible reduction in radiation load through the nearby forest reserve (Tano Suhien Forest Reserve), as seen on the map (Figure 1), which shares a border with the cocoa farms [15]. The absence of shade trees on the farm could also result in low competition for light, space, water, and minerals with the cocoa trees [60,61]. The wide differences

in terms of pod production between the two controls (the without-shade-tree and the without-shade-net farms) might be due to management. The without-shade-tree farm was managed by the Ghana Cocoa Board, an authority in charge of cocoa production in Ghana. They performed regular checks, including artificial pollination, regular disease assessment, fertilizer application and weed control. The other farm (the without-shade-net farm) was managed by a private farmer. Therefore, some of the checks (management) might not be as regular as the organized body (Ghana Cocoa Board).

The pod yield of cocoa under shade trees was low, as also seen with epiphyte distribution and light intensities. On the other hand, the beans' physical characteristics were better than those of the other treatments. This shows that the few pods produced under shade had better seed appearances than those from the other treatments. The observation has been confirmed by Kouassi et al. [62], who reported better commercial qualities of beans under shade than under full sun conditions. The researchers showed that acidity, protein content, and vitamin C levels of the beans were influenced by the shade. Farms without shade nets had the lowest pod count throughout the period, confirming the possible shading effects of the nearby forest for the no-shade farms in the first community. Shade could be a valuable resource for cocoa, considering the positive impact on physiological processes in cocoa [22,63]. Aside from the shade trees recommended in cocoa farms, the technology can also be considered in areas where cocoa plants do not perform well to serve as heat buffers, as observed in no-shade tree cocoa farms that possibly had some shading benefits from the nearby forest.

The emergence of flowers occurred quite early in farms under shade trees and no-shade trees at experimental site one (Boako Cocoa Station (SPD)) than in experimental site two (shade-net and direct sunlight farms at the Kunuma Community). The earlier flower formation might be due to locational differences, farm management activities or the prevailing below-canopy microclimates around the cocoa trees, which contribute to the activities of pollinators (the *Forcipomyia* midges) [64]. Flowers produced under direct sunlight farms appeared to be shorter and pinkish-red in color, suggesting the presence of anthocyanin [65] and structural adaptation to stresses; however, the rate of flower abscission in direct sunlight farms was found to be higher than that of the shade farms (shade trees and shade net). Moreover, the cocoa trees under a shade net produced more viable flowers than those without a shade net. This observation shows the adaptation of cocoa to optimum shade [66]. Flowering in cocoa depends primarily on plant water status and rainfall [67,68]. There were limited flowers during the dry season (February), which showed a lower yield during the lean season (April to June). Less than 5% of the flowers in each of the farms were converted to pods, as has been reported earlier [12,69,70]; however, higher pod yields were noted in farms with and without shade net at the latter part of the main harvest season compared to farms under shade trees and direct sunlight at study site one. Shade may have a slow positive effect on the yield of cocoa, but will ensure a prolonged lifespan of the trees [23,71].

5. Conclusions

Uniform shade (shade net) promoted a higher yield of the cocoa trees compared to the control farm under direct sunlight. On the contrary, the yield of cocoa under shade trees was lower than that of the no-shade-tree farms. Cocoa is considered a shade-tolerant species, but the shade trees should be pruned to ensure perfect sun-to-shade patterns to promote the photosynthetic efficiency of the plants, as the cost of shade net is very high. Notwithstanding, agroforestry and climate-smart cocoa should be encouraged under the current climate scenarios, as cocoa beans' physical qualities could be improved under

shade. More so, broader shade-management recommendations require further replicated studies to confirm our results.

Complexities of epiphytic species occur predominantly in cocoa farms under direct sunlight rather than in shade-tree farms. These species multiply only under favorable weather conditions with sufficient sunlight and moisture. Epiphytic association with cocoa is complex, and an extensive study is required to justify their interactions with cocoa and the effects on yield across treatments and locations.

Moderate shade may provide a balance between maintaining epiphytes communities and sustainable, profitable cocoa yields. By maintaining sufficient shade (such as shade trees), ecological conservation and cocoa productivity will be enhanced. Such conditions can maintain a suitable microclimatic condition, such as optimum temperature and relative humidity fluctuations, while also supporting sustainable and profitable cocoa production through adequate light availability for growth and fruit production. In a nutshell, a moderate shade could create favorable habitat conditions for biodiversity without excessively limiting the light required for cocoa production. Agricultural extension services should educate farmers on the ecological importance of epiphytes and cocoa production. We recommend regular monitoring of epiphyte communities to assess the long-term effects of shade on their activities and the yield of cocoa.

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Abbreviations

C	C series clones from the Cocoa Research Institute of Ghana (CRIG)
COCOBOD	Ghana Cocoa Board
PA	Peruvian Amazon—The inter-upper Amazon hybrid lines
SPD	Seed Production Division of COCOBOD
SN	Shade net
ST	Shade tree
WSN	Without-shade net
WST	Without-shade tree

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