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Cocoa Root Morphology, Leaf Nutritional Status, and Bean Characteristics under Different Shade Tree Species

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Abstract

Cocoa is known to require shade during its growth phase. This research is a structured comparative field study to evaluate the effect of different shade tree species on cocoa root morphology, leaf nutritional status, and certain bean characteristics (100-bean dry weight and protein content). The study was conducted on cocoa plants under three species of shade plants and one control without shade, such as *Albizia chinensis* (sengon), *Cocos nucifera* (coconut), *Cassia spectabilis* (ramayana), and without shade. In the research field conditions, the planting ratio is that every 1 shade tree shades 1 cocoa plant sample being evaluated. The parameters observed included total root length at various soil depths, cocoa leaf nutrient content (N, P, K, Ca, Mg, B), dry weight of 100 beans, and protein content of cocoa beans. The results showed that shade tree species significantly influenced the total length of cocoa roots at certain soil depths (0–10 cm and 20–30 cm), and significantly influenced the dry weight of 100 beans and protein content. The *C. spectabilis* shade tree produced the highest dry weight of 100 beans and the highest protein content under the conditions of this study compared to *A. chinensis* and *C. nucifera*. Cocoa grown under *C. spectabilis* exhibited favorable bean and leaf nutrient characteristics under the conditions of this study. However, a full evaluation of causality requires further research using a multi-site design.

Keywords: agroforestry, cocoa, root morphology, shade trees, seed characteristics

Introduction

The cocoa plant, scientifically known as *Theobroma cacao* L., is an important plantation commodity in Indonesia. Rahmadona et al. (2023) reported that cocoa is included in the category of major export commodities in international trade, contributing relatively large foreign exchange to the country. International and national market demand can be met if cocoa plantation productivity is high and stable throughout the year. Overall, cocoa productivity depends on the growing environment, including the presence of shade plants. According to Kouassi et al. (2024), cocoa naturally grows under the canopy of tropical rainforests, so its root system and vegetative growth are greatly influenced by the presence of shade.

Shade plants function to stabilize the microclimate in cocoa plantations, increase soil fertility, and influence the growth and development of cocoa roots. The presence of different shade plant species affects nutrient availability, soil moisture, microtemperature, and lighting (Jaimes-Suarez et al., 2022). In agricultural ecology, shade trees can improve resource utilization efficiency, increase microbial activity in the rhizosphere, and reduce nutrient competition (Schmidt et al., 2022). This planting concept implements an agroforestry pattern that provides significant benefits in maintaining soil biodiversity and carbon stocks (Edelstein et al.,

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2025). Furthermore, Hernández-Nunez et al. (2024) stated that different shade plant species have diverse phenological, morphological, and physiological characteristics, the combination of which can influence agroecological functions through facilitation or competition effects. Morphologically, the presence of shade plants influences cocoa root architecture (Saleh et al., 2022). Arévalo-Gardini et al. (2021) added that the vegetative growth and rooting response of cocoa is influenced by canopy shade density. Research by Trebissou et al. (2021) showed that inter-tree competition can occur in cocoa plantations if shade tree selection triggers competition for growing space, such as reduced root length density in certain shaded areas due to overlapping roots (Saleh et al., 2022). However, Hernández-Nunez et al. (2020) concluded that proper shade tree management can ensure optimal cocoa growth.

In terms of production characteristics, planting cocoa under the shade of certain trees can influence yield and bean characteristics by creating a balanced microclimate. Hernández-Nunez et al. (2024) observed that good cocoa bean production was achieved under the shade of Fabaceae family members. A similar finding was also expressed by Schmidt et al. (2022) who stated that the presence of shade trees around cocoa trees is related to the dynamics of N, P, and pH in the cocoa rhizosphere. Based on this literature, evaluating root performance, leaf nutrition, and cocoa bean characteristics under the shade of different species is highly relevant. Therefore, this comparative field study aimed to evaluate root morphology at various soil depths, leaf nutrient status, and specific cocoa bean characteristics (100-bean dry weight and protein content) under the shade of different shade tree species.

Materials and Methods

Location and Time of Research

This comparative field research was conducted on a cocoa plantation owned by PT Pagilaran Unit Segayung Utara, Tulis District, Batang Regency, Central Java, Indonesia in September 2020–January 2021. Analysis of leaf nutrition and bean characteristics was conducted at the Processing Engineering Laboratory, Faculty of Agricultural Technology, Gadjah Mada University.

Research Design, Experimental Units, and Replication Structure

This research was structured as an observational comparative field study evaluating four different shade plots or stands, including cocoa without shade as a control, cocoa shaded by *Albizia chinensis* (sengon), cocoa with shade *Cocos nucifera* (coconut), and cocoa with shade *Cassia spectabilis* (ramayana). The research area has soil characteristics with a pH of around 5 and an environmental temperature ranging from 30–32 °C. Cocoa plants are planted with a spacing of 3 m × 3 m (population density of 1,111 trees/ha), while shade trees are planted with a spacing of 10 m × 12 m (around 83 shade trees/ha) which provides an average canopy shade percentage of around 30%. In the research field, planting and selection of sample trees were carried out with the condition that each shade tree shaded one sample cocoa plant being evaluated. In each shade treatment, 5 sample cocoa plants from the RCC 71 clone were selected with homogeneous criteria (15 years old, healthy, and uniform trunk circumference), resulting in a total of 20 sample plants. These sample cocoa plants served as subsamples/nested observation units within each shade stand plot. Since each shade species was evaluated in a single stand block at the site, this study focused on agronomic comparisons between shade stands with the assumption of homogeneity of local edaphic conditions.

Laboratory Observation and Analysis Methods

Leaf Nutrition Analysis

Leaf samples were taken from fully mature leaves in the middle canopy of the sample tree

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using the leaf sampling unit (LSU) method. Leaf chemical analysis was performed specifically according to standard laboratory procedures, where nitrogen (N) levels were analyzed using the Kjeldahl digestion and distillation/titration method. Phosphorus (P) content was extracted through mixed acid wet digestion (HNO_3–$HClO_4$) and measured using a UV-Vis spectrophotometer with the molybdate blue / vanadate-molybdate method. Meanwhile, the levels of potassium (K), calcium (Ca), and magnesium (Mg) were determined from the wet digestion extract solution using Atomic Absorption Spectrophotometry (AAS), and the boron (B) content was determined spectrophotometrically using the Azometin-H staining method.

Root Morphological Characters

Root samples were taken using a cylindrical root auger at four cardinal points, 60 cm from the base of the cocoa stem. Soil and root samples were taken at three soil depths: 0–10 cm, 10–20 cm, and 20–30 cm. Root samples were separated from soil particles by gently washing them over a graduated sieve. Total root length was then measured using a root length scanner/ analyzer.

Characteristics of Cocoa Beans

The cocoa bean characteristics evaluated included the dry weight of 100 beans and the protein content of the beans. The dry weight of 100 beans was determined by weighing 100 fermented and dried cocoa beans (moisture content ~7%) using a precision analytical balance (g). Meanwhile, the protein content (%) was analyzed based on the determination of the total nitrogen content of the beans using the Kjeldahl method, which was then multiplied by a specific protein conversion factor.

Data analysis

Data were analyzed using analysis of variance (ANOVA) with a nested design using SAS software version 9.4 at a significance level of α = 0.05. Root length data were first transformed using sqrt (x + 0.5). Significant differences between treatments were further tested using Duncan's multiple range test (DMRT) at a 95% confidence level.

Results and Discussion

Root Morphology

The results of observations showed that the shade tree species had a significant effect on the total root length of cocoa at soil depths of 0–10 cm and 20–30 cm, whereas at a depth of 10–20 cm there was no significant difference (Table 1).

In the upper layer (0–10 cm), the treatment without shade (1.89 cm) and under *C. nucifera* (1.94 cm) produced significantly higher root lengths than under *A. chinensis* shade (1.47 cm),

Table 1

Total Root Length in the Cocoa-Shade Tree Combination Pattern

Treatment	Total root length (cm)		
	0–10*	10–20*	20–30*
Albizia chinensis	1.47 b	1.28 a	0.85 b
Cassia spectabilis	1.62 ab	1.26 a	0.91 ab
Cocos nucifera	1.94 a	1.20 a	0.88 ab
Without shade	1.89 a	1.38 a	1.08 a
CV (%)	14.97	12.96	12.76

Note. Values followed by the same letter in one column indicate no significant difference according to the DMRT test at α = 5%. *Data are transformed in the form of √(x+0.5).

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while under *C. spectabilis* (1.62 cm) there was no significant difference with other treatments. At a depth of 20–30 cm, the treatment without shade showed the highest root length (1.08 cm), significantly different from *A. chinensis* shade (0.85 cm).

The high root length of cocoa in the unshaded treatment, particularly in the upper and lower layers, likely represents a physiological response and root adaptation to open environmental conditions. Cocoa plants are classified as C_3 photosynthetic plants that are susceptible to high radiation stress and high soil evaporation when unshaded. Under these conditions, plants are encouraged to elongate their roots to expand the reach of water absorption in the soil profile (Mensah et al., 2023). Conversely, in the cocoa treatment *A. chinensis* the lower root length values for cocoa are likely related to competition for root space in the immediate vicinity, given that in the field, each shade tree was in close proximity to one of the sample cocoa trees. Saleh et al. (2022) also reported that overlapping roots of shade trees with cocoa plants can limit cocoa root density in certain soil horizons.

Leaf Nutrient Absorption

The nutrient content of cocoa leaves reflects the status of nutrient availability and uptake in the rhizosphere (Table 2). Cocoa leaves under the shade of legumes *A. chinensis* (2.858%) and *C. spectabilis* (2.796%) had significantly higher leaf N content compared to those shaded by coconut *C. nucifera* (2.426%) and the unshaded control (2.526%).

The high leaf N content in cacao grown under *A. chinensis* and *C. spectabilis* is likely due to the family of these two shade trees (Leguminosae/Fabaceae). According to the literature, legume trees are generally associated with N_2–fixing bacteria and produce litter biomass with a low C/N ratio that decomposes easily (Wisnubroto et al., 2021; Zega & Lase, 2025). Although the rates of biological N fixation and litter decomposition were not directly measured in this study, the input of N-rich organic matter from legume shade trees is strongly suspected to increase the availability of N, which is then absorbed by the cocoa plants growing beneath them. For phosphorus (P), cocoa leaves under *C. spectabilis* (0.490%) and without shade (0.498%) had equivalent and higher concentrations compared to *C. nucifera* (0.408%) and *A. chinensis* (0.208%). The low P levels under *A. chinensis* shade are likely related to local rhizosphere interaction factors or the influence of the local microclimate on root absorption activity.

The highest leaf potassium (K) content was recorded in the cocoa–*A. chinensis* (1.744%) and *C. spectabilis* (1.590%) combinations, while the unshaded control yielded the lowest value (0.994%). Unshaded conditions with excessive direct radiation intensity have the

Table 2

Content of the Nutrients N, P, K, Ca, Mg, and B in Cocoa Leaves in the Cocoa-Shade Tree Combination Pattern

Treatment	Nutrient content (%)					
	N	P	K	Ca	Mg	B
Albizia chinensis	2.858 a	0.208 c	1.744 a	0.720 a	0.586 a	0.013 b
Cassia spectabilis	2.796 a	0.490 a	1.590 b	0.538 c	0.414 d	0.017 a
Cocos nucifera	2.426 c	0.408 b	1.096 c	0.718 a	0.546 b	0.016 a
Without Shade	2.526 b	0.498 a	0.994 d	0.610 b	0.504 c	0.013 b
CV (%)	4.912	15.034	5.153	7.01	8.628	16.642

Note. Values followed by the same letter in the same column indicate no significant difference based on the DMRT test at α = 5%. *Data are transformed in the form of √(x+0.5).

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potential to induce physiological stress that affects potassium translocation (Xu et al., 2020). Calcium (Ca) content showed that *A. chinensis* (0.720%) and *C. nucifera* (0.718%) treatments were higher than *C. spectabilis* (0.538%). This is likely influenced by antagonism in cation uptake due to the high N nutrient uptake in the shade of *C. spectabilis* (Avianto, 2025). For magnesium (Mg), cocoa under the shade of *A. chinensis* showed the highest value (0.586%), while the highest leaf boron (B) content was found in the shade of *C. spectabilis* (0.017%) and *C. nucifera* (0.016%). The supply of litter from decomposed shade leaves is thought to play a role in the release of micronutrients such as boron to the topsoil (Babu et al., 2021).

Characteristics of Cocoa Beans

The characteristics of the cocoa beans evaluated showed significant differences between shade tree species (Table 3). Cocoa plants under the shade of *C. spectabilis* produced the highest dry weight of 100 beans, namely 44.42 g, which was significantly higher than those under the shade of *A. chinensis* (37.98 g), *C. nucifera* (39.59 g), and without shade (36.83 g). In terms of seed protein content, the combination of cocoa and *C. spectabilis* also showed the highest value of 14.33%, significantly different from *C. nucifera* (13.76%), but not statistically significantly different from *A. chinensis* (14.11%). The high seed weight and protein content of cocoa under *C. spectabilis* are in line with the high accumulation of N in the leaves (Table 2), considering that N is a basic element in seed protein (Fathi, 2022). Although canopy light transmission was not measured quantitatively in this experiment, the individual shade conditions of *C. spectabilis* on the sample cocoa plants are thought to provide a combination of microclimate and nutrients that support better bean filling and protein accumulation under these research conditions.

It should be noted as a limitation of this study that because each shade treatment was represented within a single study block/site, the influence of shade tree species may interact with local soil microsite variability. Therefore, further research with broader multi-site replications and direct measurements of soil nutrient fluxes and canopy light penetration is highly recommended to strengthen causal conclusions (Somarriba et al., 2024).

Table 3

Quality of Cocoa Beans in the Cocoa-Shade Tree Combination Pattern

Shade Type	Dry weight of 100 seeds (g)	Protein (%)
Albizia chinensis	37.98 bc	14.11 ab
Cassia spectabilis	44.42 a	14.33 a
Cocos nucifera	39.59 b	13.76 c
Without Shade	36.83 c	13.97 bc
CV (%)	8.44	2.15

Note. Values followed by the same letter in the same column indicate no significant difference based on the DMRT test at a 5% confidence level.

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Conclusions

Based on the results of this comparative field evaluation, it can be concluded that shade tree species significantly influence the total root length of cocoa at soil depths of 0–10 cm and 20–30 cm, where unshaded conditions trigger the development of longer roots as an adaptive response to open environmental stress. Furthermore, under these study conditions, cocoa plants shaded by *Cassia spectabilis* showed higher values for certain bean characteristics (100-bean dry weight and protein content) and were able to maintain good leaf N and P nutritional status compared to both *Cocos nucifera* shaded and unshaded controls. However, given the comparative nature of this study as a single-plot-per-shaded block study, further experimental research with independent replications at the landscape level and direct measurements of biological dynamics and microclimate are needed before these agronomic recommendations can be broadly generalized.

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