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Soil Fertility and Cocoa Yield in Agroforestry Systems Dominated by *Terminalia superba, Terminalia ivorensis,* and *Ricinodendron heudelotii* in the Nawa Region, Côte d'Ivoire

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Abstract **Original Research Article**

Declining soil fertility is a major challenge in cocoa farming at both the international and national levels. In Côte d'Ivoire, the world's leading producer of cocoa beans, farmers have adopted various agroecological practices to address this issue, including agroforestry. The study was conducted to evaluate the effect of three tree species on soil fertility and cocoa pod yield in four agroforestry systems. The experimental design consisted of three circles with radii of 5, 10, and 15 meters placed around the tree where cocoa trees are in production. Additionally, a second experimental plot was established in a cocoa monoculture to serve as a control. The study revealed that certain soil chemical properties are improved under these tree species: pH (pH = 5.1 in the monoculture and 5.5 < pH < 6.5 under the three tree species), C (1.25%) under *Termiliana ivorensis* within a 10-meter radius, P (P=0.6%) under *Termiliana superba within a 15-meter radius, N (N>0.1%) and CEC (CEC>15 Cmol/kg) in the soils under the three* tree species within a 15-meter radius. Furthermore, pod yields were significantly higher within the three radii under the three species (45 to 85 pods), especially under *Ricinodendron heudelotii,* compared to (20 to 25 pods) in monoculture. The three tree species improve soil chemical fertility through litter. Introducing these species not only rehabilitates degraded land but also provides an alternative to the use of costly and often harmful chemical inputs. Thus, cocoa cultivation combined with these trees should be accompanied by appropriate cover crops to improve the bioavailability of nutrients.

Keywords: shade trees, chemical fertility, yield, cocoa, Ivory Coast.

INTRODUCTION

Theobroma cacao L. is a woody species reclassified within the Malvaceae family. It is native to the Amazon and was introduced to West Africa in the early 20th century, where its cultivation has flourished. Today, the main producers of cocoa beans are Côte d'Ivoire and Ghana (Lanaud, 1987; Kouakou *et al.,* 2013; Statista, 2025). In West Africa, numerous factors such as declining soil fertility, uneven rainfall distribution, and low use of mineral and organic fertilizers reduce the performance of agricultural production systems (Cissé *et al.,* 2016). In Côte d'Ivoire, declining soil fertility poses a major challenge to agricultural production, particularly cocoa farming. This decline in soil fertility is a result of heavy human pressure, the absence and/or short duration of fallow periods, the overexploitation of woody resources, and erosion phenomena linked to climate change (Kouadio *et al.,* 2023). Declining soil fertility generally results in the depletion of organic and mineral nutrients in the soil (Kafando *et al.,* 2023). To reverse this trend, various technologies have been tested by both farmers and agronomists (Gnissien, 2018). Among these technologies are compost, agroforestry particularly the introduction of woody species into cocoa plantations and cover crops. Agroforestry, which has been developed for decades as an alternative to deforestation and soil degradation, is a practice designed to reconcile "*responsible intensification and diversification of production in order to increase yields and incomes for cocoa farmers and reduce pressure on forests*" (Cocoa & Forests Initiative 2017). Thus, the woody component in Ivorian cocoa agroforestry systems (AFS) has been the subject of numerous studies revealing that these systems harbour a diversity of forest trees, fruit trees, both native and exotic, which contribute, among other things, to shading cocoa trees, carbon sequestration, and income diversification, and could improve soil fertility according to producers (Cissé *et al.,* 2016 ; Koulibaly *et al.,* 2017).

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Indeed, plant species whose litter decomposes rapidly may be associated with a relatively higher accumulation of nutrients in the soil (Kouadio *et al.,* 2023; Mesele *et al.,* 2025). Nevertheless, this fertilization potential is not sufficiently measured at the local level, particularly in key production areas such as the Nawa region, where the soil is ferralitic (Vroh *et al.,* 2019; Kouadio *et al.,* 2023). The objective of this study is to evaluate the effect of three tree species introduced into cocoa agroforestry systems on soil chemical fertility and cocoa pod yield.

MATERIAL AND METHODS

Study area description

The study was conducted in the Nawa region in southwestern Côte d'Ivoire (Figure 1), specifically in four departments: Gnamanguy, Buyo, Lesseri, and Obrouyo. This region is located between 5°57′57″ west longitude and 6°44′29″ north latitude. The climate of Nawa is sub-equatorial. It has two wet seasons and two dry seasons. The major wet season spans the period from April to July. The minor wet season lasts for three months (September– November). The major dry season begins in December and ends in March, while the minor dry season lasts throughout the month of August (Konan *et al.,* 2021). The average annual rainfall is 1,267 mm. Average temperatures range from to 28 °C, with April being the sunniest month (Climate-Data, 2026). The region's terrain consists of vast plateaus, and the vegetation is partly dense (Taï National Park, a UNESCO Biosphere Reserve and World Heritage Site). The soils of the Nawa are mainly ferrallitic, with textures ranging from clay loam to silty sand (Arcgis, 2026).

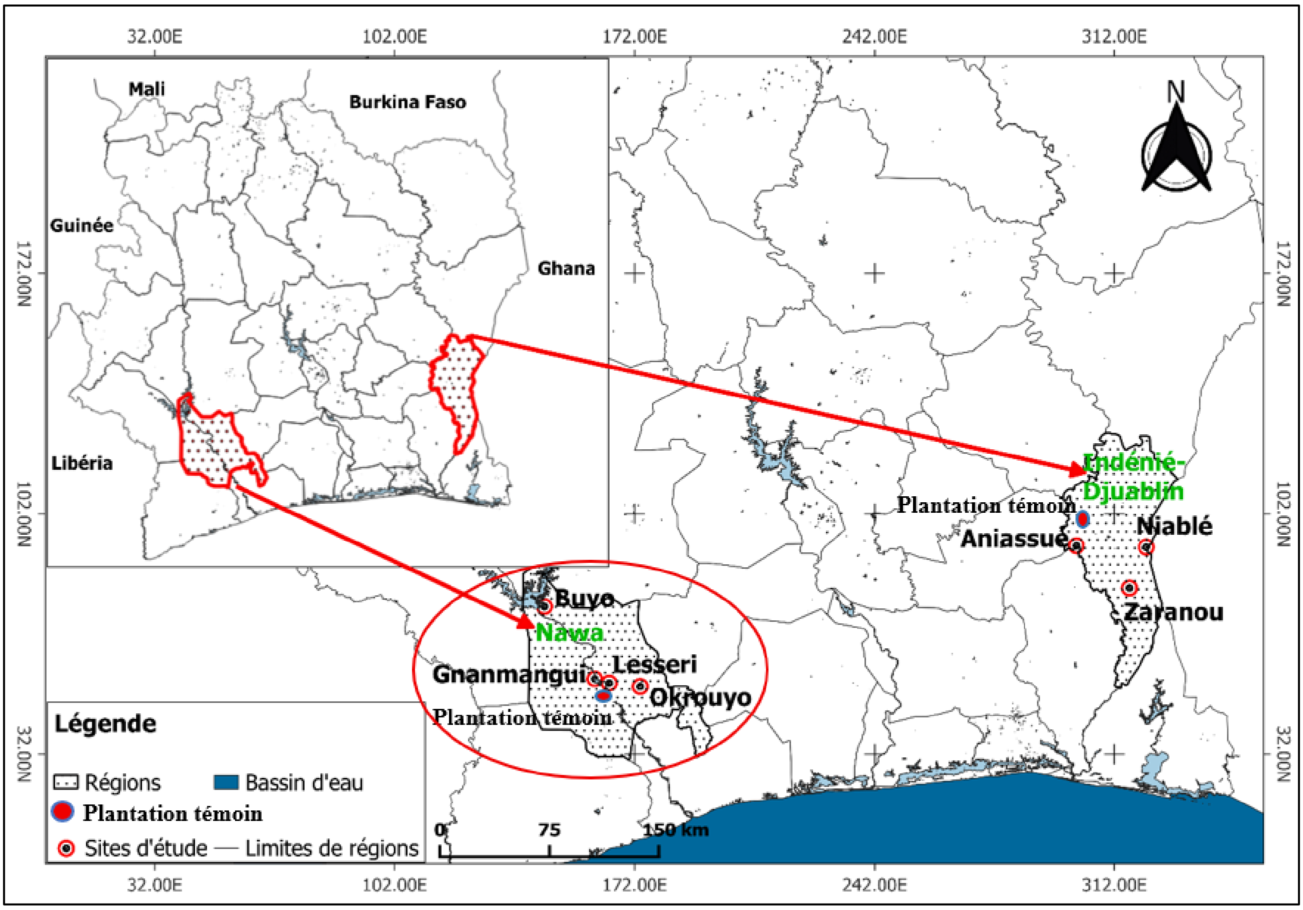

Figure 1: Administrative map of Côte d'Ivoire showing the locations of the sampling areas

Biological material

The plant material used in this study consists of four perennial species, namely the cacao tree (*Theobroma cacao L.*), the Fraké (*Termiliana superba or T. superba*), the Framiré (*Termiliana ivorensis or T. ivorensis*), and the Akpi (*Ricinodendron heudolotii or R. heudelotii*).

The cacao tree is a tree with a taproot system and a dense network of shallow lateral roots (20–30 cm deep). Its root system reaches full development approximately ten years after sowing, and the length of the taproot varies between 0.80 m and 2 m (Mossu, 1990). It is considered a humic shrub because it draws nutrients primarily from the surface horizon, where approximately 85% of its lateral roots are located. The root system of the cacao tree can cover a ground area with a radius of 5 to 6 m around the base of a mature tree (Loor Solorzano, 2007). The cacao tree prefers deep soils of at least 1.5 m, well-drained, preferably sandy loam, and with pH levels close to neutral (Koko, 2014). In addition, the fruit of the cacao tree is called a "chérelle" while it is growing and then a "pod" when it reaches maturity after five or six months, depending on its origin.

A cacao tree can bear an average of 25 pods per year. The loss rate is estimated at between 20 and 30%, and this can vary due to several factors, namely (Loor Solorzano, 2007; Oro, 2011).

The Fraké (*Termiliana superba*) and the Framiré (*Termiliana ivorensis*) are two tree species belonging to the Combretaceae family. They are pioneer and gregarious species that shed their leaves for 2 to 3 months during the dry season. New leaves and flowers appear at the start of the rainy season (Bolza and Keating, 1972; CTFT, 1974; Burkil, 1985). These trees can reach 50 m in height. Their trunks are branchless for the first 35 m, straight and cylindrical, up to 150 cm in diameter, with large buttresses reaching 8 m in height. The bark surface is smooth and gray on young trees. The trees naturally shed their branches, soon developing long, unblemished trunks that can reach 16 m in length by the age of 12 (Burkil, 1985). Furthermore, *Ricinodendron heudelotii*, known locally as Apki in Côte d'Ivoire, is a woody species of the Euphorbiaceae family endemic to the tropical rainforests of Africa. It is a multi-purpose species, identified by the World Agroforestry Centre as suitable for inclusion in multi-layered agroforests and for domestication in West Africa (Leaky, 1998; Leaky & Tomich, 1999). It is a fast-growing tree reaching 20 to 30 m in height, but capable of growing up to 50 m, with a diameter of up to 150 cm (Shiembo, 1994; Akoègnino *et al.,* 2006).

Sampling strategy and data collection

To carry out our study, we began with a field survey in each department (Gnamanguy, Buyo, Lesseri, and Obrouyo). This exploratory phase provided a qualitative overview of agroforestry practices in the cocoa plantations of the study area. Additionally, a field survey identified the tree species in agroforestry systems that producers believe improve soil fertility. Following the survey and fieldwork, we proceeded to select the plantations. The criteria for selecting plantations were accessibility of the field and the producer's willingness to cooperate, a minimum plantation area of 1-hectare, cocoa trees aged 4 years or older, and the presence of target shade trees (*Termiliana superba, Termiliana ivorensis*, and *Ricinodendron heudolotii*) taller than the cocoa trees. Based on these criteria, one AFS was selected per department. Then, a monoculture cocoa plantation was selected in the department of Gnamanguy to serve as a control for the study.

In each agroforestry system, one individual of each species was selected on the basis that there were no other shade trees within 15 meters. The experimental setup was installed beneath these individuals (Figure 2). Thus, the survey plot was marked by three circles around everyone. These three circles of different diameters (5, 10, and 15 m) were delineated using a measuring tape, 0.5m stakes, and string according to the modified method of Isaac *et al.,* (2007) with modifications. To assess the contribution of woody species to soil chemical fertility, composite soil samples were collected at a depth of 0–20 cm from trenches using a shovel and a sample holder within the three circles (ELAW, 2022; EPA, 2023). A total of eighteen (18) soil samples were thus collected.

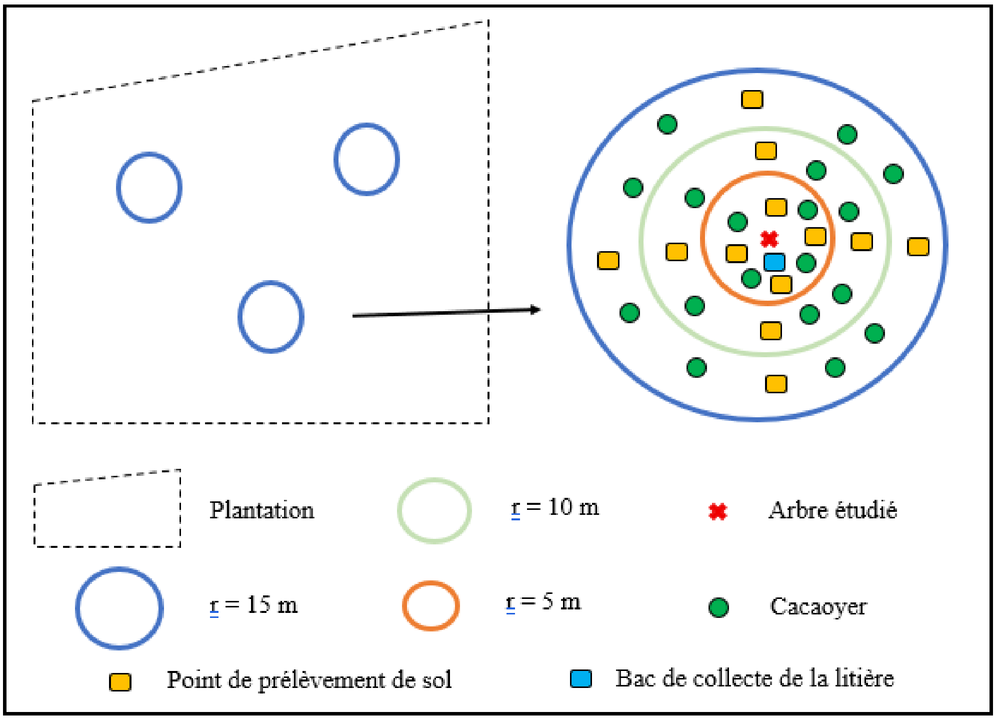

Figure 2: Experimental design in circles set up for species selection and soil sampling

In the AFS plots, litter samples were collected using the same experimental setup as for the soil samples (Figure 2). Litter fall was collected every two weeks from April to May 2025, in 3 bins installed in each AFS plot. Each relatively large bin (65 cm x 65 cm) was positioned close to the ground (approximately 10 cm above the ground) beneath each of the trees under study. Leaves, bark, branches, and miscellaneous material (primarily fruit) were separated manually (Laclau, 2001).

In the control plantations, composite soil samples were collected along diagonals extending from the four cardinal points, with 5 samples per diagonal and one sample at the center (Figure 3). Samples were spaced 50 m apart (Huising and Mesele, 2022). The equipment, method, and sampling depths were the same as in the AFS. A total of 3 composite soil samples were collected in the control plantation.

To determine the pod yield of cocoa trees in the AFS plots, a modified version of Fairtrade's (2025) Method 4 was used. This method utilizes field data collected from groups of producer samples. Following this method, a few cocoa trees was defined within each circle around each target tree. Thus, 4, 6, and 8 cocoa trees were 1 selected within radii of 5, 10, and 15 meters, respectively (Figure 2). On each selected cocoa tree, pods at least 10 cm in length were counted (Jagoret, 2011). Two periods of pod counting took place, the first in February and March 2025, and the second in August and September 2025. The yield of the cocoa trees was determined in each plot completely independently. When counting pods on the trees, those showing no damage were recorded as healthy. Meanwhile, those that were soft, rotten, or gnawed were classified as damaged.

The average number of healthy pods per cacao tree (NMCSC) is the ratio of the sum of the number of healthy pods per cocoa tree to the number of cacao trees sampled, according to the following formula:

$$\text{NMCSC} = \frac{\sum \text{number of healthy pods per cocoa tree}}{\text{number of cocoa tres sampled}}$$

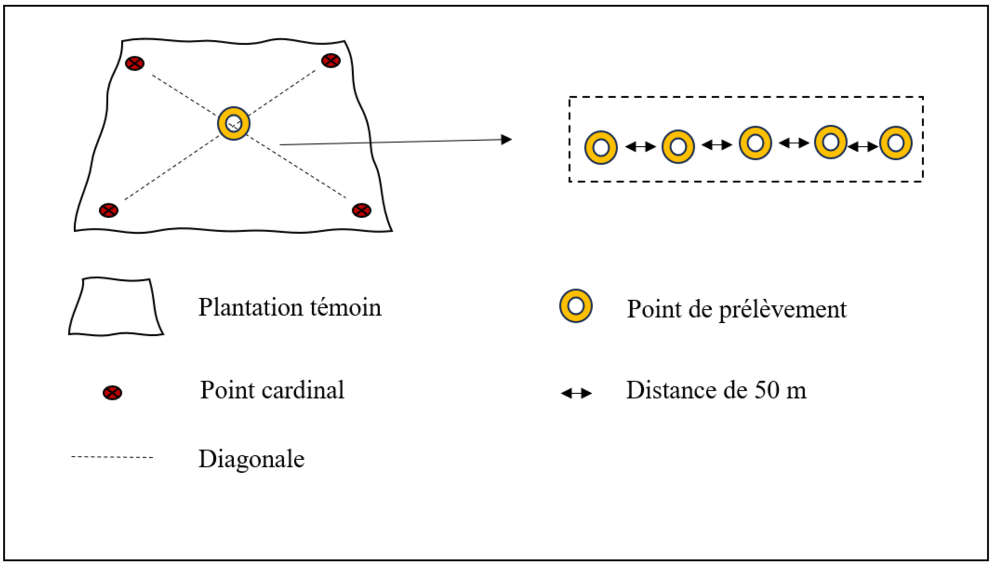

Figure 3: Experimental setup for collecting soil samples in the control plantation

Soil chemical properties

Soil and litter samples were analysed to determine the levels of organic carbon (C), moisture, pH, nitrogen (N), phosphorus (P), exchangeable cations (Ca^{2+}, Mg^{2+} and K^{+}), and cation exchange capacity (CEC).

Composite soil samples were air-dried under shelter, then sieved (2 mm) before being ground. Litter samples were sun-dried, then ground. pH was determined using a glass electrode in a 1:2.5 ratio, as described by Thomas (1996). Soil carbon content was determined using the Walkley and Black method (Nelson and Sommers, 1982). Phosphorus was determined using the method described by Olsen and Sommers (1982). Exchangeable bases (Ca^{2+}, Mg^{2+} dans K^{+}) were determined by extraction with ammonium acetate buffered to pH 7.0 prior to analysis by atomic absorption spectrometry (Ca^{2+}, Mg^{2+}) and flame photometry (K^{+}). N was determined using the Kjeldahl method (Bremner, 1996).

Statistical analyses

All statistical analyses were conducted using R statistical software (version 4.5.0) (R Development Core Team, 2025). All statistical tests were performed at the 5% significance level.

RESULTS

Effects of the three tree species on soil chemical characteristics and mineral balances

The chemical characterization of the soils focused on 10 properties, namely moisture, pH, C, OM, N, P, K^+, Mg^{2+}, Ca^{2+} and CEC (Table I) at a depth of 0 to 20 cm. The soil chemical characteristics revealed variations related to the type of shade tree and radius. Regarding moisture content, soils within a 15-meter radius of *R. heudelotii* and *T. ivorensis* exhibited higher levels than those of *T. superba*, with respective values of 15.88%, 15.62%, and 13.51%. Analysis of deviations from the mean shows that there is a highly significant difference in moisture content, within a 15-meter radius, among the three tree species studied (Table I). Although the 15-meter radius records the highest moisture content levels under all three species, these levels are below 20%.

Regarding pH, the soils under *T. superba and T. ivorensis* exhibit basic pH values (6.23 and 6.18) within a 5-meter radius. Meanwhile, it is within a 10-meter radius that the soils under *R. heudelotii* have a nearly basic pH (6.10). Analysis of deviations from the mean shows that there is a significant difference among the trees, depending on the radius (Table I). Nevertheless, soil pH values under the three tree species ranged from 5.5 to 7.5. The highest

soil organic matter content was observed within a 10-meter radius under *T. ivorensis* (2.15%), and the lowest within a 5-meter radius under *T. superba* (1.77%). Analysis of deviations from the mean shows that there is a significant difference among the trees, depending on the radius (Table I). However, all soil organic matter contents are below 3.5%.

For nitrogen (N), its content in the soils under the three tree species is higher within a 15-meter radius and lower within a 10-meter radius. The highest soil nitrogen content is observed under *T. superba* (0.17%) and *T. ivorensis* (0.17%) within a 15-meter radius. Soils under *R. heudelotii* follow with a content of 0.16% observed within the same radius. Analysis of deviations from the mean reveals a significant difference among the three tree species within a 15-meter radius (Table I). Only the soil nitrogen contents under *T. superba* within a 10-meter radius and under all three trees within a 15-meter radius meet the average threshold values.

The highest phosphorus (P) content in the soil was observed under T. superba (0.62 Cmol/kg of soil) within a 15- meter radius, followed by *R. heudelotii* (0.58 Cmol/kg of soil) within the same radius, and finally *T. ivorensis* (0.58 Cmol/kg of soil) within a 10-meter radius. The lowest phosphorus content in the soil is observed within a 10-meter radius under *R. heudelotii* (0.46 Cmol/kg of soil). Analysis of deviations from the mean highlights that there is a highly significant difference in phosphorus (P) levels in the soils under the different species, depending on the radius (Table I). Only the soils under *T. superba*, within the 15-meter radius, have a phosphorus content exceeding 0.6.

Regarding available potassium, the highest concentration is observed in the soils under *T. ivorensis* (1.38 Cmol/kg of soil), followed by *R. heudelotii* (1.37 Cmol/kg of soil) within a 15-meter radius. Meanwhile, the highest amount of available potassium under *T. superba* (1.36 Cmol/kg of soil) is observed within a 5-meter radius. Analysis of deviations from the mean shows that there is a significant difference between the trees, depending on the radius (Table I). All soils under the three trees have available potassium levels below 3 Cmol/kg.

For magnesium, the highest amounts are 0.50 Cmol/kg and 0.46 Cmol/kg. These are observed, respectively, in the soils under *R. heudelotii* and *T. ivorensis*, within a 5-meter radius. Soils under *T. superba*, within a 15-meter radius, also recorded 0.46 Cmol/kg of magnesium. Analysis of deviations from the mean reveals a significant difference between the trees, depending on the radius (Table I). Magnesium levels in the soils under the three species do not reach the average threshold value of 2.45 Cmol/kg.

Calcium levels are well below 11 Cmol/kg in the soils under the three tree species, with the highest value being 3.27 Cmol/kg under *T. superba* within a 10-meter radius. However, according to the analysis of deviations from the mean, there is a significant difference between the trees, depending on the radius (Table I).

Cation exchange capacity is highest in the soils under *T. ivorensis* (16.81 Cmol/kg) within a 10-meter radius. Next are the soils under *R. heudelotii* (16.70 Cmol/kg) within a 5-meter radius. Finally, soils under *T. superba* (15.98 Cmol/kg) within a 15-meter radius round out the list. Within a 15-meter radius, cation exchange capacity exceeds 15 Cmol/kg in all soils under the three tree species. Analysis of deviations from the mean highlights that there is a significant difference among the trees, depending on the radius (Table I).

The various mineral ratios considered in this study are: C/N, N/P, Ca^{2+}/Mg^{2+}, Mg^{2+}/K^+, $K^+/(Ca^{2+}+Mg^{2+})$ and K^+/CEC. The results of these various ratios at a depth of 0 to 20 cm are recorded in Table II. This table reveals that C/N ratio values are optimal only in soils under *T. superba*, within a 5-meter radius ($10 < 11.44 < 12$). The C/N ratio values are very low or too high in the other radii and under the other tree species. Furthermore, the N/P ratio values are well below 1.5 in the soils under all three species; the highest value is 0.29. This value is observed in the soils under *R. heudelotii* and *T. ivorensis* within a 15-meter radius. The Ca^{2+}/Mg^{2+} ratio values are optimal, i.e., between 3 and 7, under *R. heudelotii* (5.56) and *T. ivorensis* (6) within a 5-meter radius. They are also optimal under *R. heudelotii* (6.45) and *T. superba* (6.85) within a 15-meter radius. This result suggests that there is a balance between calcium and magnesium in these soils.

Table II also reveals that the Mg/K ratio values are very low ($Mg^{2+}/K^{+} \leq 4$). The highest value of this ratio (0.39) is observed under *R. heudelotii* within a 5-meter radius. It follows from the above that magnesium is deficient relative to potassium in these soils. Furthermore, the values of the $K^{+}/(Ca^{2+}+Mg^{2+})$ and K^{+}/CEC ratios are very low ($K^{+}/(Ca^{2+}+Mg^{2+}) < 2$ and $K^{+}/CEC < 2$) in the soils under the trees. The highest values of these ratios are 0.41 and 0.14, respectively, observed under *T. ivorensis* within a 5-meter radius. Thus, potassium is deficient relative to the sum of calcium and magnesium on the soil's adsorbent complex.

Chemical properties of the litter of *T. superba, R. heudelotii*, and *T. ivorensis* in AFS

The chemical characterization of the litter focused on properties such as moisture content, pH, C, MO, N, P, K^{+}, Mg^{2+} and Ca^{2+} (Figure 4).

This table shows that the moisture content is higher in the litter of *T. superba* (5.64%) and lower in that of R. *heudelotii* (5.23%). The pH values of the litter from the three species are nearly alkaline (pH > 5.5). The litter of *T. ivorensis* has the highest pH value (6.22), while the litter of *R. heudelotii* has the lowest (5.62). For C and MO, the highest contents are observed in the litter of *R. heudelotii* (49.38 and 85.3, respectively). The lowest contents, however, are observed in the litter of *T. ivorensis* (48.19 and 83.07, respectively).

According to Figure 3, the highest N content is observed in the litter of *T. ivorensis* (3.12). The lowest content is observed in the litter of *T. superba* (2.63). For P, the highest content is observed in the litter of *R. heudelotii* (0.74). The lowest content is observed in the litter of *T. ivorensis* (0.23). Regarding potassium, the litter of *T. ivorensis* contains the highest amount (2.65). And the litter of *R. heudelotii* contains the lowest amount (2.27). For Mg^{2+} and Ca^{2+}, the highest amounts are found in the litter of *R. heudelotii* (0.68 and 2.46, respectively). The litter of *T. superba* contains the lowest amount of magnesium (0.44). The litter of *T. ivorensis* contains the lowest amount of calcium (2.11).

Chemical characteristics and mineral balance in the soil of the control plantation

Table III presents some chemical properties of the soils in the control plot at a depth of 0 to 20 cm. The results show that the moisture content is low, as the observed values are below 20%. Also, the soil is acidic (pH < 5.5). The C and MO contents are low (C < 2 and MO < 3.5). Nitrogen levels are good (0.1 < N < 0.3). P levels are optimal (P ± 0.6). The concentrations of K^{+}, Mg^{2+} and Ca^{2+} are very low ($K^{+} < 3$; $Mg^{2+} < 2$ and $Ca^{2+} < 11$). CEC values are low (CEC < 15).

The various mineral ratios considered in this analysis are: C/N, N/P, Ca^{2+}/Mg^{2+}, Mg^{2+}/K^{+}, $K^{+}/(Ca^{2+} + Mg^{2+})$ and K^{+}/CEC. The results of these ratios are recorded in Table IV.

It appears that the values of the C/N and N/P ratios are low (C/N < 10 and N/P < 1.5). The Ca^{2+}/Mg^{2+} and Mg^{2+}/K^{+} ratios are balanced ($3 < Ca^{2+}/Mg^{2+} < 7$ and $Mg^{2+}/K^{+} \leq 4$). The values of the $K^{+}/(Ca^{2+} + Mg^{2+})$ and K^{+}/CEC ratios are very low ($K^{+}/(Ca^{2+} + Mg^{2+}) < 2$ and $K^{+}/CEC < 2$). Le K^{+} is therefore deficient relative to the sum of Ca^{2+} and Mg^{2+} on the soil adsorbent complex (Table IV).

Table I: Chemical characteristics of the soil beneath the trees studied in the AFS sites in Gnamanguy, Buyo, Lesseri, and Obrouyo

Species	***5-meter radius***			***10 m radius***			***15 m radius***			***MTV***
Parameters	***T. superba***	***R. heudelotii***	***T. ivorensis***	***T. superba***	***R. heudelotii***	***T. ivorensis***	***T. superba***	***R. heudelotii***	***T. ivorensis***	
Humidity (%)	7.44b	13.54a	13.55a	7.54b	13.63a	15.46a	13.51b	15.88a	15.62a	20 - 40
pH	6.23a	5.85b	6.18a	6.21a	5.84b	6.12a	5.95a	6.10a	5.64b	5.5 – 7.5
C (%)	1.03b	1.22a	1.18a	1.06b	1.11b	1.25	1.19a	1.17ab	1.16b	2
MO (%)	1.77b	2.10a	2.03a	1.82b	1.91b	2.15a	2.05a	2.01b	1.99b	3.5
N (%)	0.09ab	0.09ab	0.08b	0.05b	0.08b	0.15a	0.17ab	0.17ab	0.16b	0.1 - 0.3
P (%)	0.47b	0.53a	0.55a	0.49b	0.46b	0.58a	0.62a	0.58ab	0.55b	0.6
K^{+} (Cmol/kg)	1.36a	1.28b	1.35a	1.14b	1.29a	1.33a	1.35b	1.37ab	1.38a	3.075
Mg^{2+} (Cmol/kg)	0.44b	0.50a	0.46b	0.44a	0.39b	0.38b	0.46ab	0.48a	0.44b	2.45
Ca^{2+} (Cmol/kg)	3.26a	2.78b	2.76b	3.27a	2.88b	3.16a	3.14b	3.10b	3.24a	11
CEC (Cmol/kg)	13.58a	16.70a	9.55b	14.54a	10.65b	16.81a	15.98a	16.12a	15.75b	15-25

Means followed by the same letters on the same row are not significantly different at the 5% level according to the t-test; MTV: mean threshold value

Table II: Soil mineral balance under the trees studied in the AFS of the departments of Gnamanguy, Buyo, Lesseri, and Obrouyo

	5 m radius			*10 m radius*			*15 m radius*			*MTV*
Chemical properties	***T. superba***	***R. heudelotii***	***T. ivorensis***	***T. superba***	***R. heudelotii***	***T. ivorensis***	***T. superba***	***R. heudelotii***	***T. ivorensis***	
C/N	11.44	13.55	14.75	21.2	13.8	8.33	7.00	6.88	7.25	10 – 12
N/P	0.19	0.16	0.14	0.10	0.17	0.25	0.27	0.29	0.29	1.5 – 2
Ca^{2+}/Mg^{2+}	7.40	5.56	6	7.43	7.38	8.31	6.82	6.45	7.36	3 – 7
Mg^{2+}/K^+	0.32	0.39	0.34	0.31	0.3	0.28	0.34	0.35	0.31	≤ 4
$K^+/(Mg^{2+}+Ca^{2+})$	0.36	0.39	0.41	0.37	0.39	0.37	0.37	0.38	0.37	>2
K^+/CEC	0.1	0.07	0.14	0.09	0.12	0.07	0.08	0.08	0.08	>2

MTV: mean threshold value

Effects of the three tree species on cocoa yield

The results presented in Figure 5 show a highly significant effect of companion tree species on the average number of healthy pods per cacao tree at distances of 5 and 10 meters in the Nawa region ($P < 0.0001$). According to Figure 4, Akpi (*R. heudelotii*) had the highest average number of healthy pods per cacao tree within a 15-meter radius (NMCSC = 45 pods), while Framiré (*T. ivorensis*) had the lowest average number of healthy pods per cacao 301 tree within this radius (NMCSC = 40 pods).

For the 10-meter radius, Fraké (*T. superba*) had the highest average number of healthy pods per cacao tree (NMCSC = 62 pods), while Framiré (*T. ivorensis*) had the lowest average number of healthy pods per cacao tree (NMCSC = 27 pods). Regarding the 5-meter radius, the Akpi (*R. heudelotii*) had the highest average number of healthy pods per cocoa tree (NMCSC = 85 pods), while the Framiré (*T. ivorensis*) had the lowest average number of healthy pods per cocoa tree (NMCSC = 27 pods).

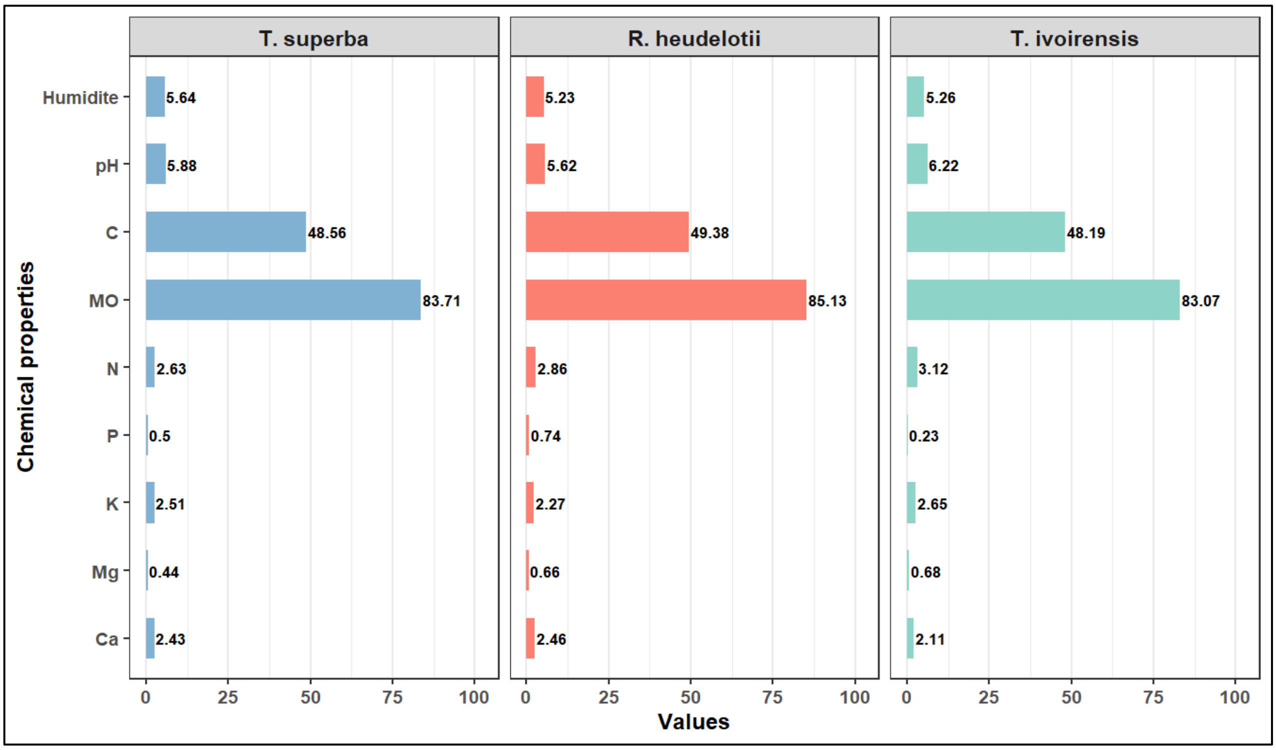

Figure 4: Chemical characteristics of the litter of the three shade trees studied in the AFS plantations in the departments of Gnamanguy, Buyo, Lesseri, and Obrouyo

Tableau III: Chemical properties of soils in the control plantation

Chemical properties	**Humidity (%)**	**pH**	**C (%)**	**MO (%)**	**N (%)**	**P (%)**	**K^+ (Cmol/kg)**	**Mg^{2+} (Cmol/kg)**	**Ca^{2+} (Cmol/kg)**	**CEC (Cmol/kg)**
Concentrations	15.73	5.12	1.11	2.01	0.17	0.63	1.41	0.48	2.84	11.34
MTS	20-40	5.5-7.5	2	3.5	0.1-0.3	0.6	3.07	2.45	11	15-25

MTS : mean threshold value

Tableau IV*: Balance of soil minerals in the control plantation*

Chemical properties	**C/N**	**N/P**	**Ca^{2+}/Mg^{2+}**	**Mg^{2+}/K^{+}**	**K^{+}/(Ca^{2+}+Mg^{2+})**	**K^{+}/CEC**
Concentrations	6.52	0.26	5.91	0.34	0.42	0.12
VSM	10-12	1.5-2	3-7	≤ 4	>2	>2

MTS : mean threshold value

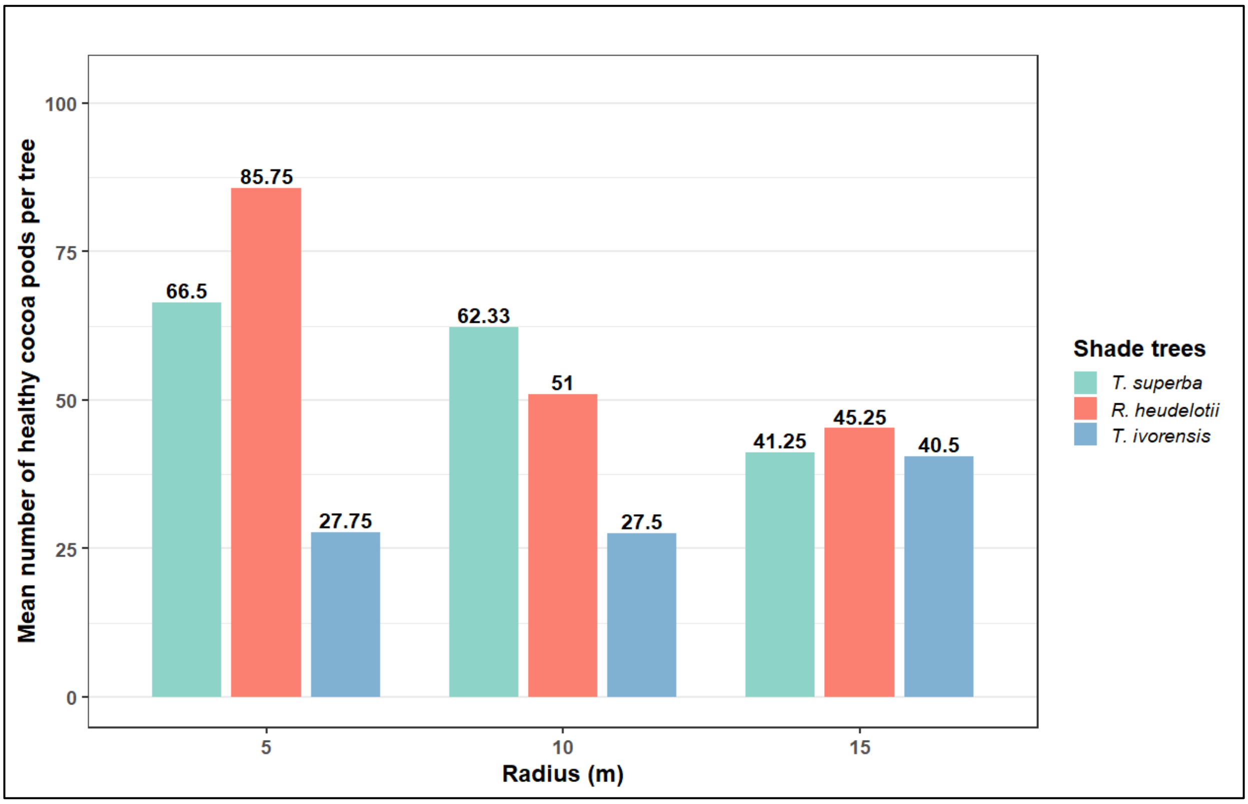

Figure 1: Average number of healthy pods per cacao tree around the shade trees studied in the AFS plantations in the departments of Gnamanguy, Buyo, Lesseri, and Obrouyo

DISCUSSION

Effects of the three tree species on soil chemical characteristics and mineral balances

In general, the chemical characteristics of the soil, at depths ranging from 0 to 20 cm, indicate that the concentrations of the chemical elements measured are higher within a 5- and 15-meter radius beneath the three tree species in question than within a 10-meter radius. Indeed, several studies conducted to assess the potential of agroforestry systems to improve soil fertility have shown that the presence of trees improves soil chemical properties (Bayala *et al.,* 2003; Grouzis and Akpo, 2006; Kafando *et al.,* 2023). According to Ayi (2017), the moderately high nutrient levels under the trees within a 5-meter radius are linked to factors intrinsic or extrinsic to the tree. The fact that soil pH is nearly neutral under the three species (5.5 < pH < 6.5), unlike soil pH in monocultures (pH = 5.1), could be explained by the chemical composition of the leaves of each species. Indeed, some authors, such as Yélémou *et al.,*(2013), had noted that the acidic nature of tropical ferruginous soils could be the cause of the acidic pH observed in cocoa plantations. However, it appears that despite the proven acidity of the ferruginous soils in the Nawa and Indénié-Djuablin regions, the soils under *Termiliana superba, Termiliana ivorensis*, and *Ricinodendron heudelotii* are nearly neutral.

The increase in soil organic carbon content of 1.19% under *Termiliana superba* (within a 15-meter radius), 1.22% under *Ricinodendron heudelotii* (within a 5-meter radius), and by 1.25% under *Termiliana ivorensis* (within a 10-meter radius) corroborates the findings of Kafando *et al.,*(2023), who reported an improvement in carbon status under the canopy of *P. reticulatum*. Furthermore, similar results were obtained with an increase in organic carbon status under species of the genus Acacia in eastern Burkina Faso by Traoré *et al.,*(2007). According to Yélémou *et al.,*(2013), the high carbon content under the canopy is related to inputs from falling leaves and twigs. For the species *Termiliana ivorensis*, the high carbon content could be explained by the species' abundant leaf biomass, which it renews once a year.

The 0.17% increase in nitrogen content within a 15-meter radius beneath the three tree species corroborates the findings of Yélémou *et al.,*(2013) and Kafando *et al.,*(2023), who reported an improvement in nitrogen status beneath the canopy of *P. reticulatum*. The increase in nitrogen under the three studied species could be linked to the high nitrogen content of their litter, ranging from 2.63% to 3.12% (Burkil, 1985; Djeugap *et al.,* 2013). According to Yélémou *et al.,* (2013), litter decomposition is linked to its nitrogen content and the C/N and lignin/N ratios; litter rich in lignin decomposes more slowly. The leaf biomass of *Termiliana superba, Termiliana ivorensis*, and *Ricinodendron heudelotii* contains a low lignin content (Burkil, 1985; Djeugap *et al.,* 2013; Endamana *et al.,* 2016). The organic matter from these three species is therefore of the soil-improving type, meaning it is easily degradable to facilitate crop growth. Shade trees in agroforestry systems, particularly *Termiliana superba*, *Termiliana ivorensis,* and *Ricinodendron heudelotii*, help improve soil chemistry while maintaining soil humus and moisture (Kagné, 2012). These beneficial effects guide farmers in their choice of species to manage (Larwanou *et al.,* 2010).

Effects of the three tree species on cocoa yield

Unlike soil chemical characteristics, yields of healthy cocoa pods associated with these three tree species are significantly higher (62 to 85 pods) within 5- and 10-meter radii than within a 15-meter radius (45 pods) in the Nawa region. Similarly, within 5-meter and 10-meter radii, yields of healthy cocoa pods vary significantly from one tree species to another. This indicates that these tree species do not influence cocoa productivity in the same way. This result is consistent with that of Kafando *et al.,* (2023), who reported that sorghum grain and dry matter yields varied depending on the woody species under which the plants were located. Yields of healthy pods within the three radii and around the three species are significantly higher than yields in monoculture (20 to 25 pods). Indeed, neutral pH promotes the availability of soil nutrients, especially nitrogen, as acidity hinders cocoa tree nutrition.

CONCLUSION

The objective of this study was, first, to determine the soil fertility status around each shade tree. The soils beneath the shade trees studied are nearly alkaline, in contrast to the soil in the monoculture area. Furthermore, the nitrogen content of the soils under *Termiliana superba* within a 10-meter radius and under the three tree species within a 15-meter radius met the average threshold values ($N > 0.1$). Also, under *Termiliana superba*, the soils within a 15-meter radius had an optimal phosphorus content (0.6%). The cation exchange capacity (CEC) was optimal (CEC > 15 Cmol/kg) in the soils under the three tree species within a 15-meter radius. Furthermore, this study aimed to determine cocoa tree yield based on distance and the type of associated shade trees. To this end, the results showed that *Ricinodendron heudelotii* had the highest average number of healthy pods per cacao tree within a 5-meter radius (NMCSC = 85 pods) and a 15-meter radius (NMCSC = 45 pods). Meanwhile, *Termiliana superba* had the highest average number of healthy pods per cocoa tree within a 10-meter radius (NMCSC = 62 pods). *Termiliana superba, Termiliana ivorensis, and Ricinodendron heudelotii* have positive and significant effects on soil fertility and cocoa yield in cocoa agroforestry systems (SAFc).

Outlook

Despite the interesting results obtained and the lessons learned in this study, the effect of shade trees, forest trees, or fruit trees on the bioavailability of chemical nutrients in soils under cocoa trees warrants further investigation to consolidate sustainability efforts in the cocoa sector. To this end, investigations should not only extend to other woody species associated with cocoa but also to complementary annual crops. Furthermore, modeling tools are needed to predict the effects of these species on cocoa yields over the very long term.

Disclaimer (artificial intelligence)

Authors hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc.) and text-to-image generators have been used during the writing or editing of this manuscript.

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Competing interests

Authors have declared that they have no known competing financial interests or non-financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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