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Research Article

Yield, Production Losses, Fertility Status, and Soil Microbial Population in Three Different Cocoa (*Theobroma cacao* L.)-Based Cropping Systems in an Oxisol in Southern Cameroon

Pierre Germain Ntsoli,[1] **Idriss Djoko Kouam**,[1] **Roland Wilfried Titti**,[1] **Georges Marius Etame Kossi**,[2] **David Brondon Mouthe**,[1] **and Aoudou Yaouba**[1]

[1]*Phytopathology and Agricultural Zoology Research Unit, Department of Crop Sciences, Faculty of Agronomy and Agricultural Sciences, University of Dschang, P.O. Box 222, Dschang, Cameroon*
[2]*Genetics, Biotechnology, Agriculture and Plant Production Research Unit, Department of Crop Sciences, Faculty of Agronomy and Agricultural Sciences, University of Dschang, P.O. Box 222, Dschang, Cameroon*

Correspondence should be addressed to Pierre Germain Ntsoli; pierrentsoli@yahoo.fr and Aoudou Yaouba; yaoubaaoudou@yahoo.fr

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Cocoa is a vital crop globally, yet its production is influenced by various cropping systems that can significantly affect its field performance and long-term sustainability. This study aimed to evaluate how different cropping systems impact yields, losses from pests and diseases, soil fertility, and microbial populations in cocoa cultivation. Three distinct cropping systems were examined within a 65-ha orchard in southern Cameroon: cocoa monoculture without shade (cropping system 1), cocoa grown alongside forest trees and *Persea americana* (cropping system 2), and cocoa in association with *Inga edulis* and *Dacryodes edulis* (cropping system 3). Data collected on production metrics, soil fertility, and microbial populations revealed significant differences ($p < 0.05$) among the cropping systems. Cropping system 2 demonstrated the highest performance across several production variables, including the number of pods per tree, fresh pod weight, number of beans per pod, and both fresh and dry bean weights. The yield was also notably higher in this system. Conversely, the percentage of losses due to pests and diseases was not significantly different among the three systems, with System 1 at 42.18%, System 2 at 41.21%, and System 3 at 43.09%. In terms of soil fertility, cropping system 2 exhibited superior conditions along with a more diverse microbial population. The dominant bacterial genera identified included *Actinomycetes*, *Azotobacter*, *Bacillus*, *Clostridium*, and *Streptomyces*, while the fungal genera included *Aspergillus*, *Penicillium*, and *Trichoderma*. Interestingly, the soil bacterial load was highest in cropping system 3 at 1.89×10^6 CFU.g^{-1}, whereas cropping systems 1 and 2 had higher fungal loads at 2.09×10^6 CFU.g^{-1} and 1.91×10^6 CFU.g^{-1}, respectively. These findings suggest that cropping systems that integrate cocoa with forest species and *Persea americana* not only yield better results but also enhance ecological functions related to microbial diversity and soil fertility in cocoa plantations.

Keywords: agroforestry; cocoa production; cropping system; microbial population; pest and disease losses; sustainable cocoa farming

1. Introduction

Stimulant plants play an essential role in the human diet due to their high alkaloid and phenolic compound content [1]. Among them is the cocoa tree, a perennial crop native to South America. The cocoa tree is truly famous and appreciated for its beans, which are the raw material for chocolate production [2]. Indeed, chocolate is a source of happiness and is recognized for its benefits to human health [3]. It improves cardiometabolic health by modulating blood

pressure and lipid profiles [4]. Furthermore, chocolate consumption has also been reported to improve cognition in clinical trials [5]. The cocoa beans essential to chocolate production are grown in some 70 countries around the world. Most of these countries are located in the intertropical zone [3, 6], mainly on the African, American, and Asian continents. According to the latest reports from the International Cocoa Organization (ICCO), world cocoa production in 2023 is estimated at 5 million tons [7]. Around 65.70% of the world's cocoa supply comes from rural family farms on the African continent [8], for whom cocoa is a major contributor to their income [9]. Specifically, these production statistics for the African continent are best described with the Ivory Coast (900,000 tons), Ghana (450,000 tons), Nigeria (280,000 tons), and Cameroon (260,000 tons) as the continent's top four producing countries [8].

In Central Africa, Cameroon, known as Africa's fourth-largest cocoa producer and the world's sixth-largest, is currently the subregion's leader in terms of cocoa production [8]. Cocoa farming represents a major economic and social activity for the country [10]. Along with coffee, cotton, and bananas, cocoa is one of the four main sources of revenue from the marketing of agricultural commodities [11, 12].

Over the last few decades, global demand for merchantable cocoa has risen significantly as a result of the high consumption of chocolate products worldwide [13, 14]. Despite this increase in demand for market cocoa, production in Cameroon has been revised downward across the production basin particularly due to many factors intrinsic and extrinsic to cocoa farmers. Some of these factors are linked to the economy and independence of cocoa farmers, through the price per kilogram of commercial cocoa, which has fallen as a result of the government's liberalization of the sector, leading cocoa farmers to abandon the sector and concentrate on more profitable perennial crops such as cashew nuts, palm oil, and rubber trees. Other factors are linked to the production environment influenced by recent climate change, aging plantations, degraded soil, pest, and, above all, diseases such as black pod disease [15–18].

As previously reported, cocoa farming in Cameroon faces numerous constraints and significant challenges due to unsustainable farming practices applied to address these constraints, which often lead to the degradation of the production environment. In fact, these practices manifest as farmers' dependence on synthetic inputs, leading to the deterioration of soil fertility and microbial biodiversity, which are essential to the maintenance of healthy agroecosystems. These forms of degradation are often irreversible or extremely difficult to rectify over time, posing a major threat to the sustainability of cocoa farming [19, 20].

To address the issues of degradation and ensure sustainable yields, implementing and understanding cocoa-based cropping systems is essential. Agroforestry practices such as shade-grown cocoa, alley cropping with nitrogen-fixing trees, and multistory cropping have shown promise in improving both ecological balance and economic viability [21]. These systems not only mitigate the adverse effects of monoculture but also contribute to carbon sequestration and biodiversity conservation. The design, understanding of the functioning and adoption of efficient and innovative cropping systems, is important to ensure sustainable agricultural production, particularly in cocoa production, which requires deforestation during plant stand development [18]. At the same time, it involves taking into account aspects of production and system sustainability through the impact on the production environment [20, 22–25]. This is the rationale behind the present study, which was conducted to assess yields, pest-related yield losses, fertility status, and soil microbial population of three cocoa-based cropping systems, involving an unshaded monocropping, a conventional agroforestry system, and a system involving a tree legume.

2. Materials and Methods

2.1. Location and Description of the Study Area. The study was conducted in Nkolandom, located in the southern region of Cameroon, within the bimodal rainforest zone (geographical coordinates: 2° 29′02 N and 11° 57′35 E). This area experiences a Guinean climate, characterized by average annual temperatures around 25°C and annual rainfall ranging from 1700 to 1800 mm. The vegetation in the study region comprises Congolese forest formations, also referred to as dense evergreen rainforest, interspersed with semi-deciduous forest. This ecosystem is notable for its high tree density per hectare, with a canopy height reaching approximately 50 m. The predominant botanical families include *Combretaceae*, *Sterculiaceae*, and *Ochnaceae*, which shed their leaves during the dry season [26, 27].

The soil is dominated by ferrallitic tropical soils, which degrade rapidly in the absence of forest cover. These types of soils are characterized by low organic matter and silt content, variable clay content, acid pH, and low nutrient retention capacity [28]. The relief is dominated by the South Cameroon plateau, with altitudes of up to 1000 m, although the various cropping systems are located in the flat zone. The average altitude varies between 600 m and 675 m, although here and there are hills of varying size, separated by valleys of varying depth [27]. The weathering profiles across much of the plateau are notably thick and feature the widespread presence of ferruginous nodules and cuirass blocks, all covered by loose clayey material of varying thickness [29].

2.2. Plant Material, Experimental Site, and Trial Design. The plant material for this study consists of cocoa trees aged between 8 and 12 years, cultivated under various cropping systems on a 65-ha peasant farm. The farm features a mix of cocoa clones, including SNK 413, TAFO 79/501, IMC 67, and UPA 109. The cropping systems evaluated are illustrated in Figure 1. For data collection, three plots of 1000 m^2 were established within each cropping system of the plantation, with each plot carefully marked using BTP tape. Each designated plot was homogeneous in terms of both age and the type of cropping system employed. The rectangular shape of the plots was intentionally selected to encompass a more heterogeneous area, thereby enhancing the representativeness of the sample compared to square or circular

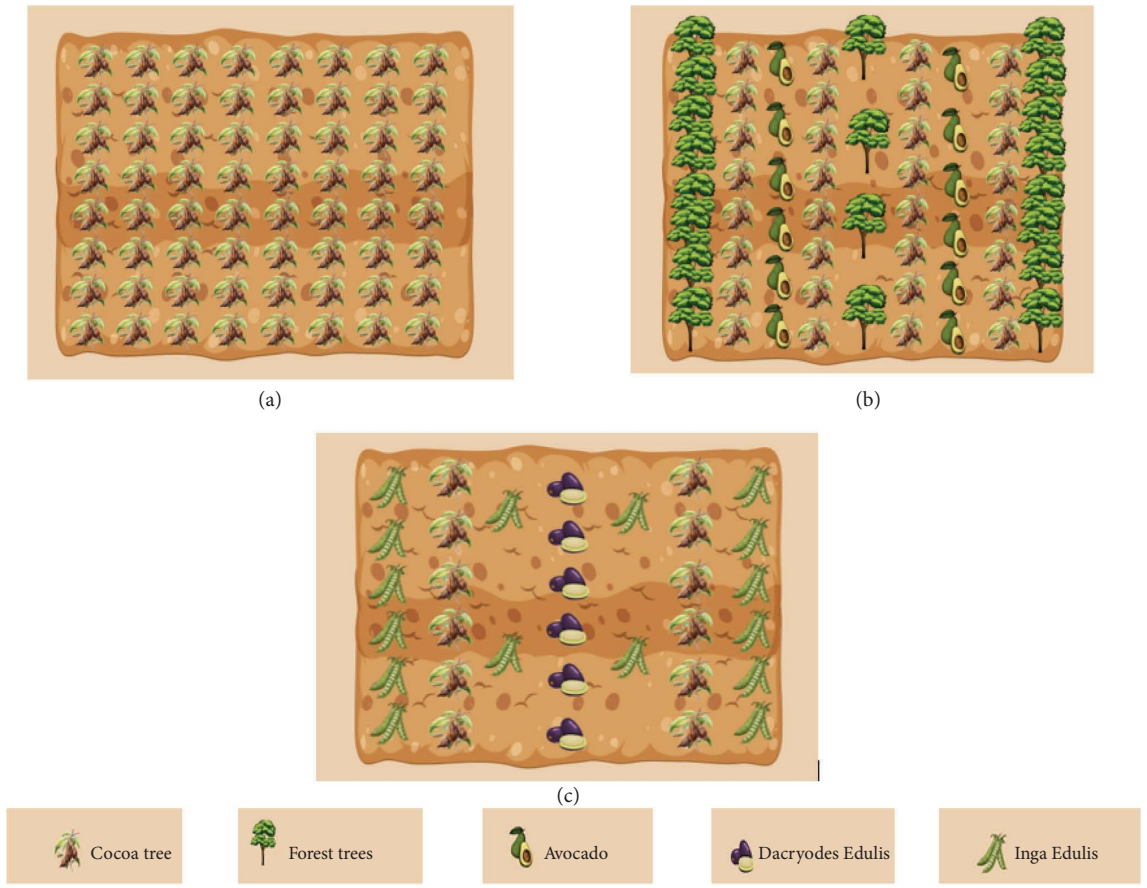


Figure 1: Illustration of the different cropping systems. (a): Monoculture cocoa without shade (cropping system 1), (b): cocoa + forest trees (> 30 m) + *Persea americana* (cropping system 2), (c): cocoa + *Inga edulis* + *Dacryodes edulis* (cropping system 3).

plots of the same size [30]. This design choice aims to capture the variability inherent in the agroecosystem, which is crucial for accurately assessing the impacts of different cropping systems on cocoa production. The densities and spacings of cocoa trees and associated trees in the different cropping systems are presented in Table 1.

2.3. Crop System Management During the Trial. Throughout the cropping season, the same fertilizer application and pest and disease management methods were used for the three cropping systems. For phytosanitary management, Ridomil Gold Plus 66 WP and Nordox 75 WG were used 6 times at 21-day intervals for control of black pod disease, while imidacloprid and thiamethoxam were used for mirid management 2 times at 2-month intervals. Cocoa trees in the orchard were pruned 2 to 4 times a year, depending on the type of specific pruning required.

2.4. Data Collection. All agronomic data were collected during the 2020–2021 crop year.

2.4.1. Climatic Data. Climatic data (rainfall for 30 years and other parameters for 10 years) were obtained simultaneously from the NASA website (https://power.nasa.gov) by the geographical coordinates of the study site and from the Agricultural Research Institute for Development, Nkoemvone station. Evapotranspiration was estimated using the FAO Penman-Monteith formula in Ketema and Wade [31].

2.4.2. Estimation of Disease Losses and Yield Potential of Cropping Systems. Losses due to the pest and disease were assessed by counting healthy and attacked pods throughout the crop year, following a series of 6 passes at 8-week intervals. To estimate the yield, a total of 270 healthy pods were harvested, at a rate of 30 pods per cropping system and per observation plot. All the following parameters were collected using a Z-shaped sampling procedure: the number of viable and wilted cherelles, healthy and mummified pods, the average weight of the pods, the number of beans per pod, the fresh and dry weight of the beans per pod, and the pod index.

The pod index is the number of pods (NbPods) needed to produce 1 kg of merchantable cocoa. It was calculated using the following formula:

$$\text{Pod index} = \frac{1\,\text{kg}}{\text{dry weight of beans in a pod}}. \quad (1)$$

Potential yield (PYield) and disease losses were estimated following the formula of Jagoret et al. [32] by the following mathematical relationship:

Table 1: Density and spacing in the different cropping systems studied.

	Density per ha (spacings)				
	Cocoa	**Forest trees**	***Persea americana***	***Inga edulis***	***Dacryodes edulis***
Cropping system 1	1600 (2.5 × 2.5 m)	\	\	\	\
Cropping system 2	1111 (3 × 3 m)	123 (9 × 9 m)	123 (9 × 9 m)	\	\
Cropping system 3	1111 (3 × 3 m)	\	\	156 (8 × 8 m)	123 (9 × 9 m)

Note: Cropping system 1: monoculture cocoa without shade. Cropping system 2: cocoa + forest trees (> 30 m) + *Persea americana*. Cropping system 3: cocoa + *Inga edulis* + *Dacryodes edulis*.

$$\text{Yld} = [(\text{Nmc} \times \text{Pmf} \times \text{Ct} \times \text{Nc})]. \quad (2)$$

Yld represents the yield measured in kilograms per hectare, while Nmc refers to the average NbPods per cocoa tree, which can be quantified by counting the pods. This count is based on the number of fruits exceeding 10 cm in length, as these are less likely to be affected by physiological wilt [33, 34]. Pmf denotes the average weight of fresh beans per pod (in kg), and Ct is the transformation coefficient that relates the weight of fresh beans to the weight of merchantable cocoa, a variable considered constant at a value of 0.35 [35, 36]. The variable Nc indicates the number of cocoa trees per hectare, also referred to as the density of cocoa trees. This can be quantified by counting the plants within a specified area. The total number of cocoa trees in each plot was recorded, and the density was extrapolated from these counts.

2.4.3. Collection of Soil Samples. Soil samples were collected from the three cropping systems using a Z-sampling method. In each cropping system, a total of fifteen partial samples, each weighing 500 g, were gathered. Prior to sampling, the soil surface was cleared of any dead leaves and plant debris. The samples were taken from the upper soil layers, specifically at a depth of 5–10 cm.

After collecting the partial samples, composite samples weighing 1000 g were prepared for each cropping system. Each composite sample was thoroughly mixed and then divided into two equal portions, which were placed in plastic bags for storage. The samples were kept at room temperature, and microbiological analyses were conducted on the 14th day of storage. This duration was deemed necessary to allow for the re-establishment of microbiological equilibrium, as recommended by Ziemiecka [37].

2.4.4. Physicochemical Analysis of Soil Samples. Physicochemical analyses were conducted at the Research Unit of Soil Analysis and Environmental Chemistry of the Faculty of Agronomy and Agricultural Sciences (FAAS) of the University of Dschang using the standard procedures suggested and explained in the handbook of Pauwels et al. [38]. The results of the physicochemical analysis were appreciated using the Land Evaluation Manual by Beernaert & Bitondo [39].

2.4.5. Isolation, Quantification, and Identification of Microorganisms of Rhizosphere. Soil microbiological analyses were carried out at the Plant Pathology Laboratory of the FAAS at the University of Dschang. For this purpose, the decimal dilution principle was applied. Ten grams of composite sample from the rhizosphere of each cocoa-based cropping system studied were introduced into an Erlenmeyer flask containing 90 mL of sterile distilled water, then mixed, and vortexed, and dilutions were made up to 10^{-7}. Next, 100-µL aliquots from the 10^{-4}–10^{-7} dilutions were plated with replicates in Petri dishes containing nutrient agar and PDA medium, respectively, for isolation and quantification of bacteria and fungi.

Colonies were differentiated through visual inspection, focusing on their morphology and pigmentation. Selected individual colonies were then cultured separately to obtain pure strains. Each pure fungal strain was identified based on macroscopic and microscopic characteristics, utilizing the identification keys provided by Barnett and Hunter [40]. A similar identification process was followed for bacteria, incorporating Gram staining as outlined by Vincent and Humphrey [41], along with additional biochemical tests, including catalase, Simmons citrate, urease, and motility tests, conducted according to the protocols in Bergey's Manual of Systematic Bacteriology [42]. All incubations were performed at 37°C for 24–48 h for bacterial cultures, while fungal cultures were incubated at a temperature of 25 ± 2°C for a period of 5–7 days. This systematic approach ensured the accurate identification of both fungal and bacterial strains.

2.4.6. Enumeration of Colonies. Colonies were counted, and the results were expressed as colony-forming units (CFU) per gram of soil. The number N (estimate of the microbial population) was calculated using the following formula [43]:

$$\text{CFU.g}^{-1} = \frac{(A \times B \times C)}{(D \times E)}, \quad (3)$$

where A is the number of colonies, B is the volume of sterilized water added (mL), C is the dilution factor, D is the weight of the soil subsample (g), and E is the volume of soil solution spread (mL).

2.5. Data Analysis. Statistical analyses were performed using R software version 4.3.1 [44], using the packages *Agricolae* [45], *FactoMineR* [46], and *Stats* [44]. Statistical comparison between cropping systems was performed using the least significant difference (LSD) test for $p < 0.05$. Principal component analysis (PCA) and heat mapping were

performed on all collected data to systematically assess the distinct mode of action of different cropping systems on all measured variables.

3. Results

3.1. Climate of the Study Area During the Trial Period. Climatic conditions at the study site are presented in Table 2. During the year, two distinct wet periods (Prec. > ETP) were observed. The first, from the beginning of March to June, coincides with the first peak in production, and therefore in harvesting; and the second, from August to November, corresponds to the second peak in production, the most important in terms of harvesting during the year. As a result, the zero-water reserve from January to February becomes strictly positive from March to early December. Similarly, the average annual relative humidity (RH) fluctuates around 87.3%, with peaks of more than 90% observed during the two wet periods of the year.

Table 2: Precipitation, evapotranspiration, and relative humidity throughout the study period.

Month	Prec. (mm)	ETP (mm)	SWR (mm)	HR (%)
January	32.1	152.5	0	79.6
February	55.1	130.5	0	82.1
March	140.8	131.9	9	87.2
April	185.1	118.4	75.7	90.5
May	172.4	119	100	91.1
June	123.6	111.1	100	88.9
July	86.6	119.1	67.5	87.1
August	129.4	124	72.8	87.7
September	205.1	117	100	90.2
October	273	119.8	100	91.6
November	175.9	126.5	100	89.4
December	51.7	145.6	6.1	82.5
Mean	1630.9*	126.3	60.9	87.3

Note: Prec. = precipitation, ETP = evapotranspiration.
Abbreviations: RH = relative humidity, SWR = soil water reserve.
*Sum of monthly precipitation.

3.2. Percentage of Viable and Wilted Cherelles and Mummified Pods. Table 3 shows the proportions of viable, wilted, and mummified pods according to the cropping system. In all three cropping systems, wilting of cherelles due to mirid attacks, internal cocoa tree factors, and environmental factors was observed. The percentage of wilted cocoa cherelles was significant ($p < 0.05$). The unshaded monocropping system (85.68%) had the highest percentage of wilted cherelle cushions, while the cocoa + forest trees + *Persea americana* system and the cocoa + *Inga edulis* + *Dacryodes edulis* system had similar percentages of wilted cherelle cushions (77.46% and 77.33%). Regarding the number of viable cherelles, the unshaded monoculture system, the cocoa + forest trees + *Persea americana* system, and the cocoa + *Inga edulis* + *Dacryodes edulis* system had 14.31%, 22.54%, and 22.67%, respectively. However, the proportion of viable cherelles capable of becoming pods was not significantly different between the different cropping systems ($p > 0.05$). There was no significant difference in the proportions of mummified pods between the cropping systems studied ($p > 0.05$). Therefore, the proportions of mummified pods recorded were 42.18% in the monoculture system without shade, 41.21% in the cocoa + forest trees + *Persea americana* system, and 43.09% in the cocoa + *Inga edulis* + *Dacryodes edulis* system.

3.3. Effect of Cropping System on Yield and Losses due to Pests and Diseases. The results presented in Figure 2 are based on analyses carried out on the pods brought back to the laboratory. The analysis of variance shows that there is a significant difference ($p < 0.05$) between cropping systems for the average NbPods per cocoa tree (Figure 2(a)), the average weight of pods (Figure 2(b)), fresh and dry beans weight (Figures 2(d) and 2(e)), and the NBePods (Figure 2(c)). The fresh weight of the pod was significantly greater ($p < 0.05$) in the cocoa + forest trees + *Persea americana*/cropping system 2 (492.42 g), compared with the unshaded monocropping system (342.94 g), and the cocoa + *Inga* edulis + *Dacryodes edulis system* (348 g). Similarly, the NBePods in the cocoa + forest trees + *Persea americana* system (47) is higher than in the other systems. The same observations were made about the fresh weight and dry weight of the beans (DWBeans). The pod index was significantly different between all the systems studied. The unshaded monocropping and cocoa + *Inga edulis* + *Dacryodes edulis* systems have a higher pod index than the cocoa + forest trees + *Persea americana* system. To produce 1 kg of marketable cocoa, 27 pods are needed in the unshaded monocropping system, 22 pods in the cocoa + forest trees + *Persea americana* system, and 26 cocoa pods for cocoa + *Inga edulis* + *Dacryodes edulis* (Figure 2(f)). Analysis of variance shows that the cropping system has a significant effect ($p < 0.05$) on yield. Over the whole trial system, potential merchantable cocoa yield (Figure 3(a)) was significantly ($p < 0.05$) higher in the cocoa + forest trees + *Persea americana* system, with a mean value of 1041.76 kg.ha^{-1}. The unshaded monocropping and cocoa + *Inga edulis* + *Dacryodes edulis* systems had potential merchantable cocoa yield of 748.99 kg.ha^{-1} and 682.75 kg.ha^{-1}, respectively. The same trend was observed between the three cropping systems for yield losses due to pests and black pod disease (Figure 3(b)). However, there was no significant effect ($p > 0.05$) of the cropping system on the percentage of yield lost to pests and black pod disease. The unshaded monoculture, cocoa + forest trees + *Persea americana* and cocoa + *Inga edulis* + *Dacryodes edulis* systems, respectively, showed percentage losses in merchantable cocoa of 42.18%, 41.21%, and 43.09% (Figure 3(c)). As a result of these losses due to pests and black pod disease, the actual merchantable cocoa yields were, respectively, 425.18 kg.ha^{-1} in System 1, 607.27 kg.ha^{-1} in System 2, and 388.04 kg.ha^{-1} in System 3 (Figure 3(d)).

3.4. Soil Chemical Properties as a Function of Cropping Systems. Significant variations ($p < 0.05$) in soil fertility were observed across different cocoa-based cropping systems. The pH levels indicate that soils under unshaded

Table 3: Percentage of viable and wilted cherelles and mummified pods by cropping system.

	Cropping system 1	Cropping system 2	Cropping system 3
Wilted cherelles	85.68 a	77.46 b	77.33 b
Healthy cherelles	14.31 b	22.54 a	22.67 a
Mummified pods	42.18 a	41.21 a	43.09 a

Note: On the same line, the values followed by the same letter are not significantly different ($p < 0.05$, Kruskal–Wallis test).

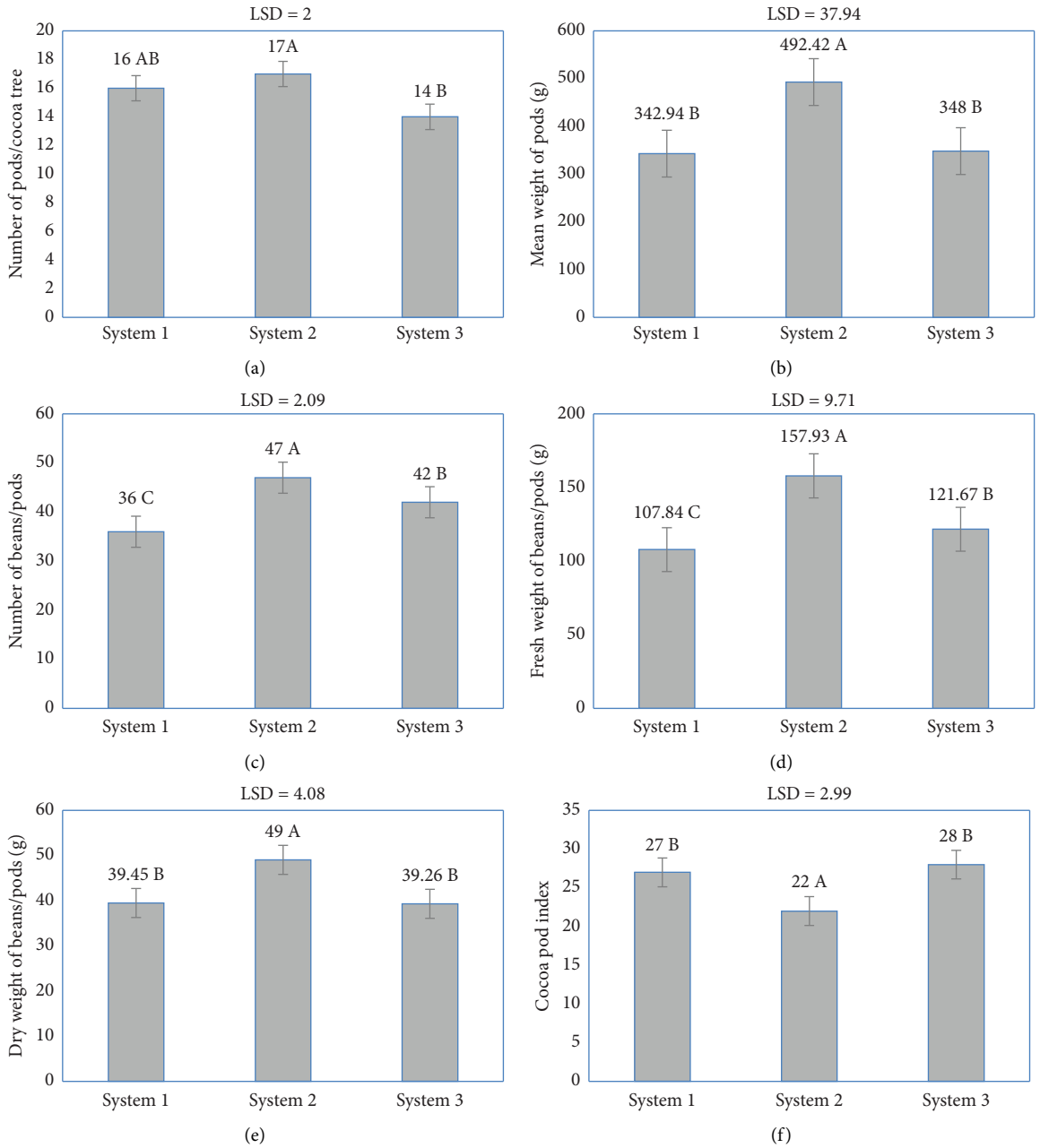


Figure 2: Components of merchantable cocoa yield as a function of cropping systems. Different letters indicate significant differences between cropping systems ($p < 0.05$, LSD test). Error bars indicate ± SD. (a) Number of pods/cocoa tree, (b) average weight of a beans/pod, (c) number of beans/pods, (d) fresh weight of beans/pod, (e) dry weight of beans/pod, (f) pod index. System 1: monoculture cocoa without shade, system 2: cocoa + forest trees (> 30 m) + *Persea americana*, system 3: cocoa + *Inga edulis* + *Dacryodes edulis*.

monoculture (cropping system 1) are very acidic at 4.9, while those in cropping system 2, which combines cocoa with forest trees and *Persea americana*, are moderately acidic at 5.15. In contrast, cropping system 3, featuring cocoa alongside *Inga edulis* and *Dacryodes edulis*, exhibits slightly acidic conditions with a pH of 6.55 (Figure 4(a)). In terms of

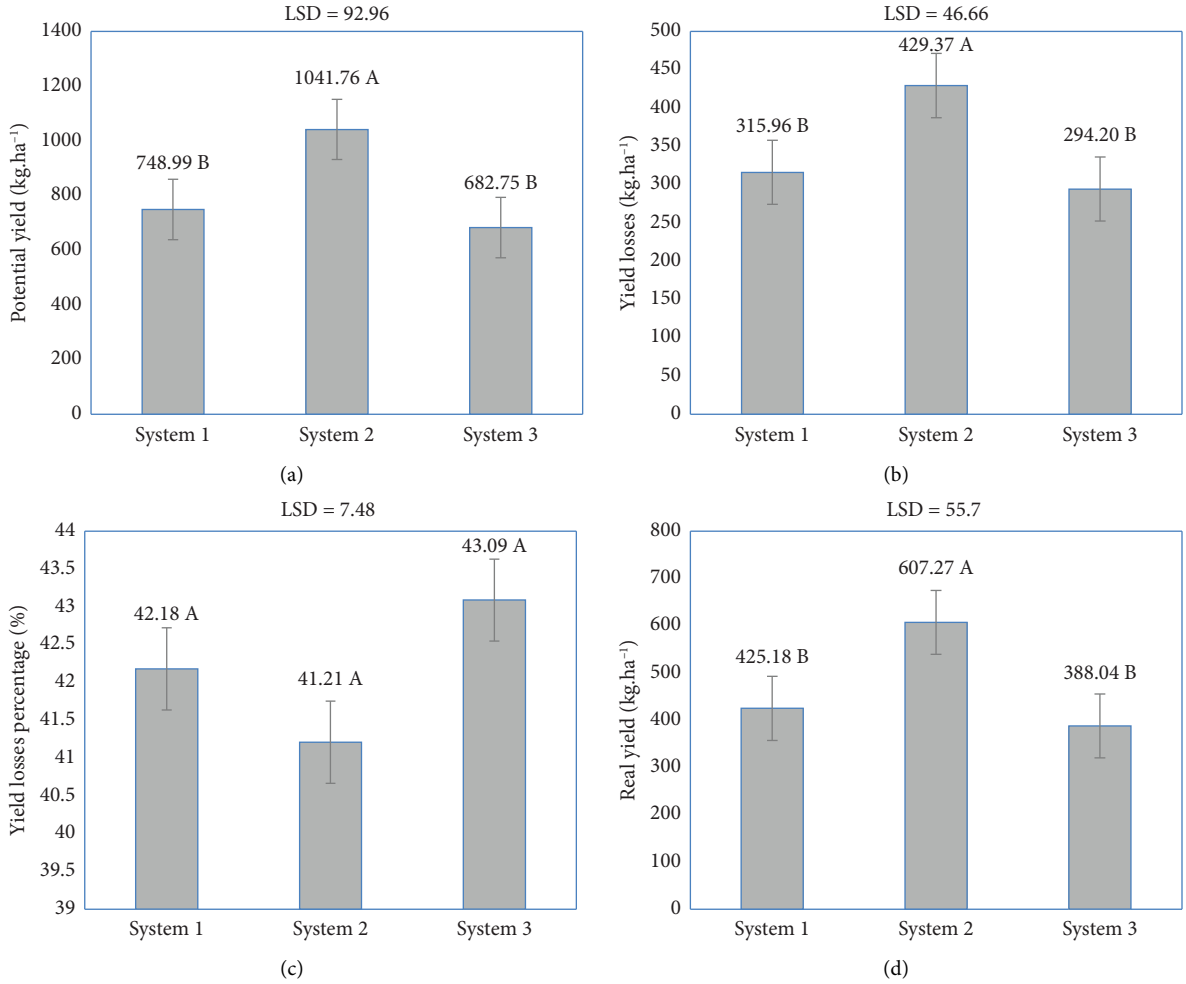


Figure 3: Marketable cocoa yields and losses as a function of cropping systems. Different letters indicate significant differences between cropping systems ($p < 0.05$, LSD test). Error bars indicate ± standard deviation (SD). (a) Potential merchantable cocoa yield, (b) yield loss due to pests and black pod disease, (c) percent yield lost, (d) actual merchantable cocoa yield. System 1: monoculture cocoa without shade, system 2: cocoa + forest trees (> 30 m) + *Persea americana*, system 3: cocoa + *Inga edulis* + *Dacryodes edulis*.

organic matter and available nitrogen, cropping system 2 shows the highest levels, with organic matter at 6.55% and nitrogen at 0.04%. Cropping system 3 follows with organic matter at 4.22% and nitrogen at 0.089%, while cropping system 1 has significantly lower values, with organic matter at only 0.42% and nitrogen at 0.07% (Figures 4(b) and 4(c)). Assimilable phosphorus is notably low in Systems 1 (5.27 ppm) and 2 (13.12 ppm), but markedly high in System 3 at 50.25 ppm (Figure 4(d)). The exchangeable bases also vary significantly among the cropping systems (Figures 4(e), 4(f), 4(g), 4(h)). System 2 has higher levels of sodium (0.04 meq/100 g) and potassium (0.88 meq/100 g), while calcium (6.57 meq/100 g) and magnesium (5.62 meq/100 g) are more abundant in the unshaded monoculture system. Furthermore, the soil cation exchange capacity (CEC) is very high in cropping system 3 at 24.18 meq/100 g, average in System 2 at 13.39 meq/100 g, and very low in System 1 at just 6.22 meq/100 g (Figure 4(i)). These data illustrate the complex interplay between cropping systems and soil fertility dynamics within cocoa cultivation.

3.5. Soil Microbial Population as a Function of Cropping Systems. Figure 5(a) shows the fungal load per gram of soil as a function of the cropping system. After counting colonies on culture medium, the fungal load in soil samples from System 1: unshaded monocropping was 2.09×10^6 CFU.g^{-1}; 1.91×10^6 CFU.g^{-1} in System 2: cocoa + forest trees + *Persea americana*; and 9×10^5 CFU.g^{-1} in System 3: cocoa + *Inga edulis* + *Dacryodes edulis*. On the other hand, a variable bacterial load was observed according to the different cropping systems (Figure 5(b)). Cocoa + *Inga edulis* + *Dacryodes edulis* (1.89×10^6 CFU.g^{-1}) had the highest bacterial population, followed by unshaded monocropping (4.7×10^5 CFU.g^{-1}) and cocoa + forest trees + *Persea americana* (4.9×10^5 CFU.g^{-1}). However, microbial diversity was greater in the latter system, with at least 9 different microbial genera observed.

Bacteria of the genus *Actinomycetes* were found in greater abundance in the system including *Inga edulis*, whereas in the system including the association of cocoa with forest species, the genera *Azotobacter*, *Bacillus*,

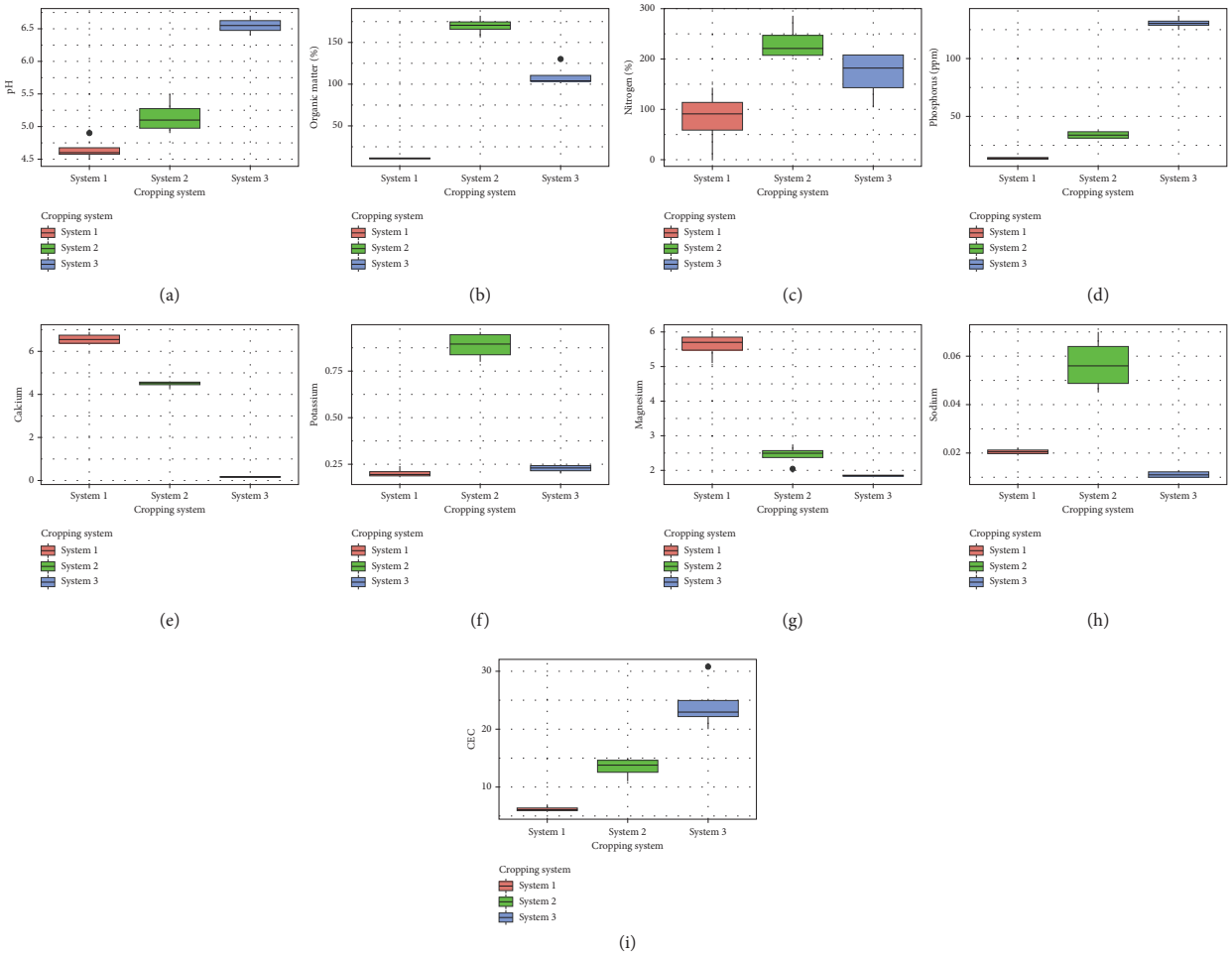


Figure 4: Box plot of the chemical properties of the soil as a function of the cropping system. Calcium, potassium, magnesium, sodium, and cation exchange capacity (CEC) are in meq./100 g of soil. (a) pH, (b) organic matter, (c) percent available nitrogen, (d) available phosphorus, (e) calcium, (f) potassium, (g) magnesium, (h) sodium, (i) soil CEC. System 1: monoculture cocoa without shade, System 2: cocoa + forest trees (> 30 m) + *Persea americana*, System 3: cocoa + *Inga edulis* + *Dacryodes edulis*.

Clostridium, and *Streptomyces* were found in addition to *Actinomycetes*. However, no *Pseudomonas* bacteria were found in the samples from the latter system. As far as soil fungi are concerned, the genus *Aspergillus* remains by far the most abundant, in particular the species *Aspergillus niger* and *Aspergillus carbonarius*, whatever the cultivation system used. The abundance of the *Penicillium* genus is equally balanced in all cropping systems, while the genus *Trichoderma*, particularly *Trichoderma harzianum*, is more abundant in the system combining cocoa with forest species and *Persea americana*. The *Cercospora* genus is only found in System 3 (Figure 6).

3.6. Relationship Between Cropping System, Yield Components, Fertility Status, and Soil Microbial Population. Detailed and visual evaluations of the relationships among various cropping systems, yield, yield loss, soil fertility, and microbial populations are presented through PCA and a heat map correlation. The PCA results, depicted in Figure 7(a), indicate that the first two dimensions account for 100% of the variability captured, with Dimension 1 explaining 61.27% and Dimension 2 38.72%. The most significant variables represented in these dimensions are summarized in Table 4. In the heat map shown in Figure 7(b), the explanatory variables are plotted along the *y*-axis, while the response variables are positioned on the *x*-axis. A color gradient ranging from red to blue illustrates the strength of correlations between these variables. Darker shades of red signify stronger positive correlations, whereas darker shades of blue indicate stronger negative correlations. This visual representation facilitates an intuitive understanding of how different factors interact within the studied cropping systems.

Analysis of Figures 7(a) and 7(b) reveals that all production variables, including NbPods, mean weight of pods (MWPods), NBePods, fresh weight of beans (FWBeans), DWBeans, cocoa pod index (CPodsI), PYield, and loss yield (LYield), exhibit strong correlations with cropping system 2, which integrates cocoa trees with forest trees and *Persea americana*. In contrast, the CPodsI and the percentage of losses attributed to pest and disease (LYieldP) show a significant correlation with cropping system 3, characterized by the combination of cocoa trees, *Inga edulis*, and *Dacryodes*

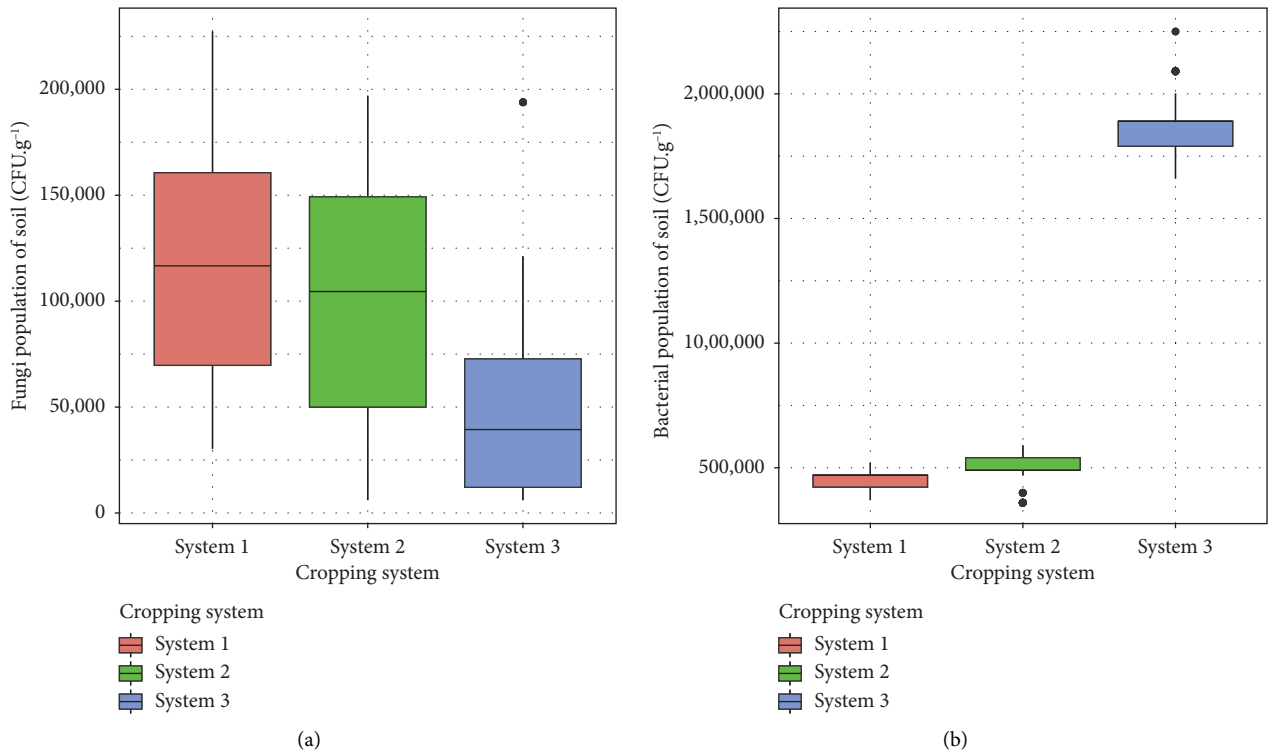


FIGURE 5: Microbial population of soil (CFU.g^{-1}) under different cropping systems. (a) Total fungi population and (b) total bacterial population. System 1: monoculture cocoa without shade, System 2: cocoa + forest trees (> 30 m) + *Persea americana*, System 3: cocoa + *Inga edulis* + *Dacryodes edulis*.

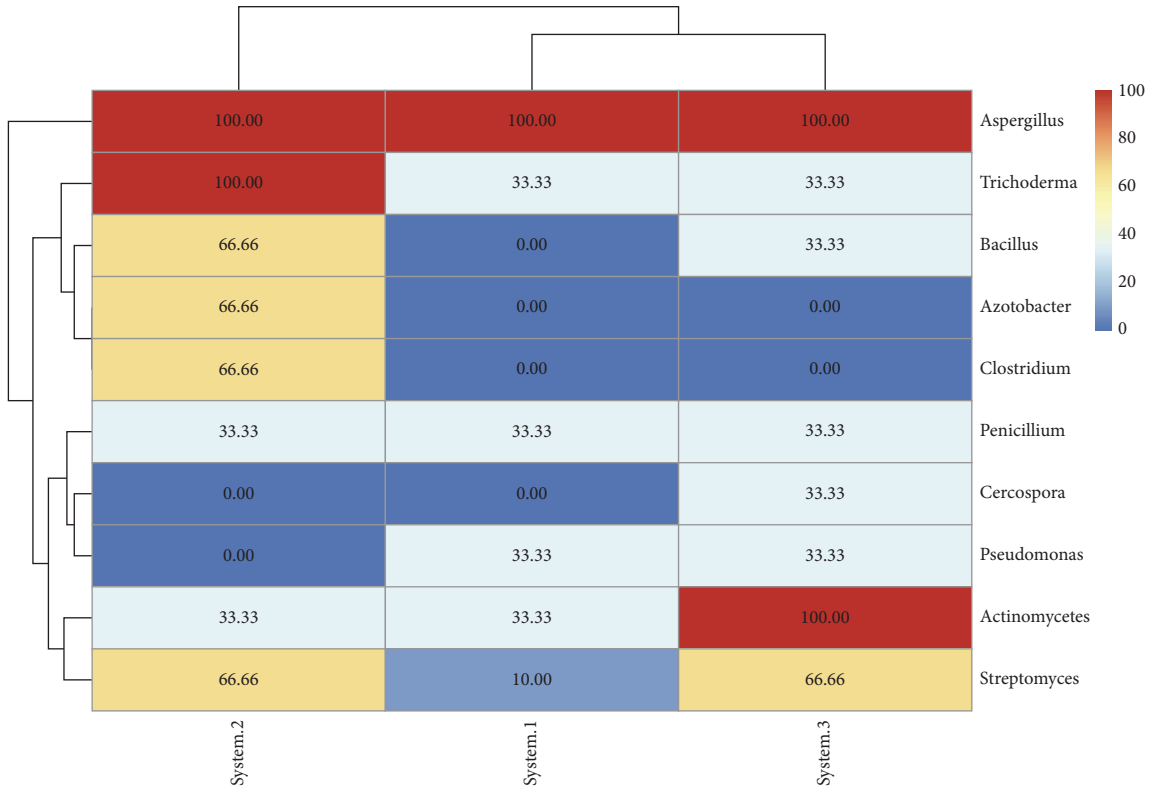


FIGURE 6: Diversity and abundance of microbial gender under different cropping systems. System 1: monoculture cocoa without shade, System 2: cocoa + forest trees (> 30 m) + *Persea americana*, System 3: cocoa + *Inga edulis* + *Dacryodes edulis*.

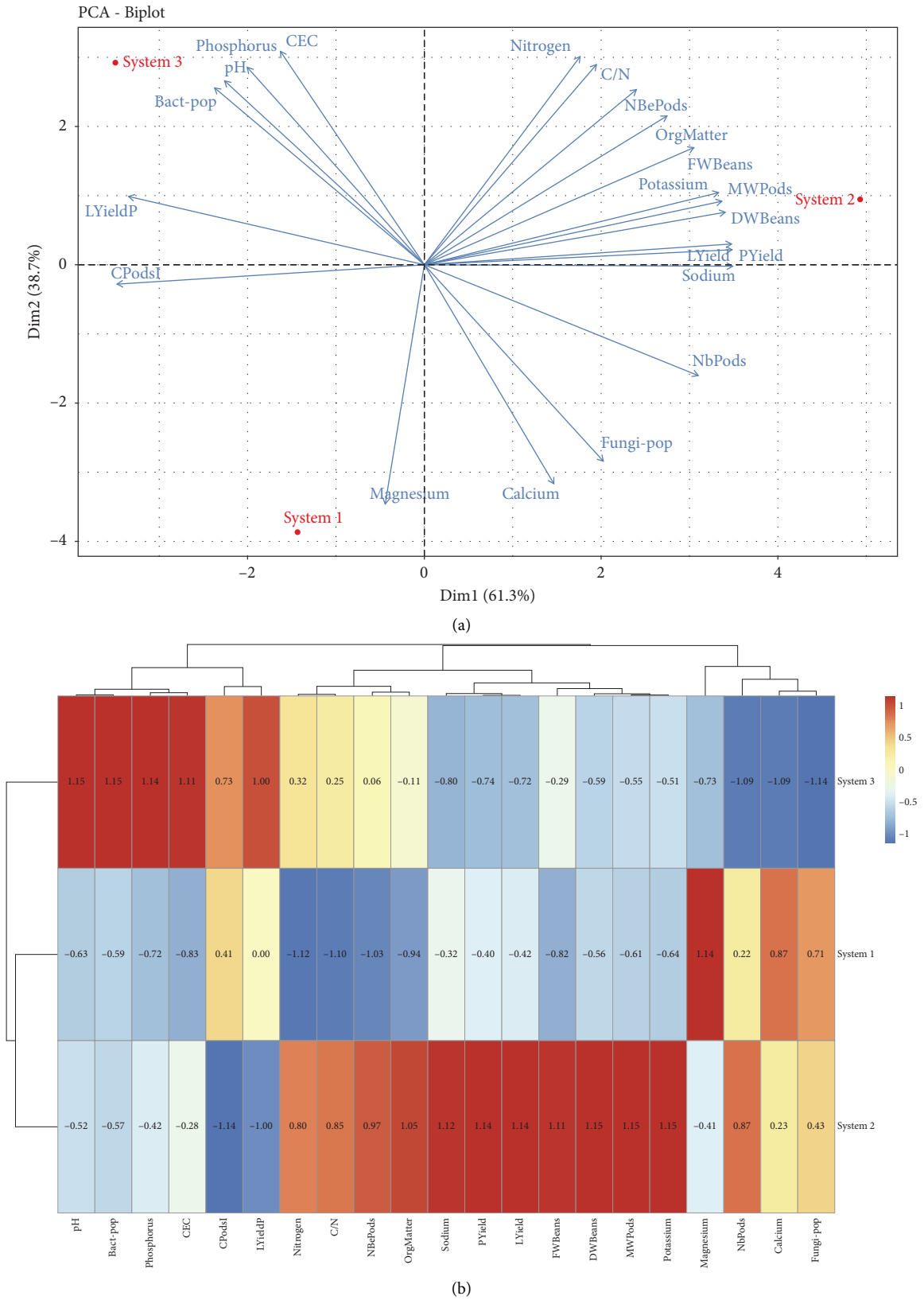


Figure 7: Principal component analysis (a) and heat map (b) based on yield, fertility status, and soil microbial population variables according to cropping systems. NbPods: number of pods/cocoa tree, MWPods: mean weight of pods, NBePods: number of beans/pods, FWBeans: fresh weight of beans/pods, DWBeans: fresh weight of beans/pods, CPodsI: cocoa pod index, PYield: potential yield, LYield: loss yield, LYieldP: loss yield percentage, OrgMatter: organic matter, CEC: cation exchange capacity, C/N: carbon–nitrogen ratio, Fungi-pop: fungi population of soil, Bact-pop: bacterial population of soil. System 1: monoculture cocoa without shade, System 2: cocoa + forest trees (> 30 m) + *Persea americana*, System 3: cocoa + *Inga edulis* + *Dacryodes edulis*.

Table 4: Eigenvectors and eigenvalues of the first two principal components (PCs) with yield variables, soil fertility status, and microbial population variables.

Variables	Dim 1	Dim 2
NbPods	**0.88**	−0.46
MWPods	**0.96**	0.26
NBePods	**0.68**	**0.72**
FWBeans	**0.87**	0.48
DWBeans	**0.97**	0.21
CPodsI	**−0.99**	−0.08
PYield	**0.99**	0.06
LYield	**0.99**	0.08
LYieldP	**−0.95**	0.28
pH	**−0.64**	**0.76**
OrgMatter	**0.78**	**0.61**
Nitrogen	**0.50**	**0.86**
Phosphorus	**−0.57**	**0.81**
Calcium	0.42	**−0.90**
Potassium	**0.95**	0.29
Magnesium	−0.12	**−0.99**
Sodium	**0.99**	−0.005
CEC	−0.46	**0.88**
C/N	**0.55**	**0.82**
Fungi-pop	**0.58**	**−0.81**
Bact-pop	**−0.68**	**0.73**
Eigenvalue	12.86	8.13
Percentage change	61.27	38.72
Cumulative percentage change	61.27	100

Note: Variables with values in bold are those that contribute most to the construction of PCA axes.
Abbreviation: Dim: dimension.

edulis. Regarding soil fertility and microbial populations in cocoa cultivation across different cropping systems, cropping system 2 is distinguished by higher levels of organic matter, available nitrogen, a favorable carbon-to-nitrogen (C/N) ratio, and exchangeable bases. Conversely, cropping system 3, which includes the leguminous tree *Inga edulis*, is noted for its nearly neutral pH, elevated CEC, a more substantial bacterial population, and greater availability of phosphorus. In terms of monoculture systems, these are linked to increased fungal populations alongside higher levels of magnesium and calcium in the soil. Overall, variations in bacterial and fungal populations are influenced by soil pH levels. In cropping system 3, where moderately to slightly acidic pH values are prevalent, bacterial populations are notably high while fungal populations remain low. Conversely, in environments with lower pH levels, there is an observable increase in fungal populations accompanied by a decrease in bacterial counts. This dynamic underscores the complex interplay between soil chemistry and microbial ecology within these agroecosystems.

4. Discussion

The notion of the cropping system is essential in the management of a plant stand. In the case of cocoa farming, it has an influence on the crop of interest (cocoa tree) due to interactions between environmental modifications related to the absence or presence of associated species in the cropping system [32, 47]. Moreover, the predominant methods of cocoa cultivation vary considerably, from monoculture systems that expose crops to sunlight to more diversified agroforestry systems that integrate other plant species [48, 49]. In this study, significant differences were observed between the cropping systems implemented with regard to merchantable cocoa yields and associated yield variables. Cocoa production across different cropping systems reveals that the cocoa association with forest trees and *Persea americana* system significantly outperforms both the unshaded monocropping (425.18 kg.ha^{-1}) and the cocoa + *Inga edulis* + *Dacryodes edulis* (388.04 kg.ha^{-1}) systems. Specifically, cocoa trees in association with forest trees and *Persea americana* produced heavier beans (492.42 g) and achieved superior yields (607.27 kg.ha^{-1}) compared to those grown in full-sun conditions. Results concerning the influence of cropping systems established on cocoa tree performance have been reported in numerous studies. Indeed, Andres et al. [50] report that cocoa yields were 12%–46% higher in agroforestry systems than in monocultures in the Ivory Coast and Bolivia after a trial. Moreover, the yield performance in favor of the cultivation system that maintained forest species in association with *Persea americana* to the detriment of the full-sun system was a major result and contradictory to other studies. Niether et al. [51] noted that cocoa trees cultivated under shade exhibited yields that were 25% lower than their counterparts grown without shade. Yet, while it is generally accepted that unshaded cocoa farms generally produce the highest yields. In unshaded systems, enhanced photosynthesis and floral induction lead to increased pod production as reported by Koko et al. [52] and Trazié et al. [53]. Lachenaud [34] attributes these variations to several critical nutritional factors in the plant's environment, including climatology, planting density, shade, and soil fertility. Yet, these essential factors are closely linked to the cropping system, which involves modifications to the associated species interacting with the cocoa trees. Nevertheless, it should not be forgotten that, while monoculture systems may give better results in the short term, they often lead to an increase in pest pressure and a decline in soil quality over time [54, 55]. Conversely, agroforestry systems, which combine cocoa with other crops or trees, can enhance biodiversity, improve soil health, and provide additional sources of income for farmers.

To further explain the differences in effective yields observed between the cropping systems studied, it remains important to highlight the losses linked to diseases and pests. Indeed, the action of diseases and pests in cocoa-based agroecosystems contributes to reducing their performance in terms of yields. Despite the higher yield losses in the system associating cocoa trees with forest trees + *Persea americana*, the results of this study indicate that the pest pressure and the percentage/ratio of pest/disease-related cocoa losses do not vary significantly regardless of the cropping system implemented. This observation corroborates the results obtained by Armengot et al. [2], who were able to demonstrate that cocoa-based agroforestry systems do not increase the incidence of pests and diseases compared with monoculture systems when the same management methods are applied, which is the case in this study. While

shading in general does not have a direct effect on pest and disease incidence and cocoa productivity, other factors may explain pathogen dynamics in different cropping systems. Gidoin et al. [19] explain the dynamics of the disease in the field on the basis of the abundance or availability of susceptible tissues. Since there is high production in unshaded cocoa farms, the probability of contamination of other pods is high, particularly through the secondary inoculum already present on the tree, which can increase the rate of black pod disease. Disease emergence is due to inoculum stored on the field, either in the soil, in apparently healthy organ tissues, or on dead organ tissues such as leaves, dead branches, or infected mummified pod [19, 56, 57]. In this sense, whatever cropping system is implemented for cocoa cultivation, the presence of a secondary source of inoculum in the field can, to a lesser extent, induce the same disease rate despite the absence or presence of shade and the type of associated species. On the other hand, Monteith & Butler [58] explain the high level of black pod disease on the basis of the speed of dew formation in the pods. According to the same author, dew formation is defined by the rate of change of temperature and RH. The fact that temperature is lost rapidly between different systems, with or without shading, results in a sudden drop in temperature. Rapid changes in temperature, as in the less shaded systems, favor the formation of dew on the pods, whereas in the shadier systems, shading reduces the formation of dew, and in turn the chances of infection of the pods by *Phytophthora* spp. In shadier cropping systems, the rate of black pod disease rot is generally high due to shading, which can favor the living conditions of the pathogen through high RH [19].

The observed differences in soil fertility and microbial populations underscore the influence of cropping systems on these critical indicators of agroecosystem effectiveness and viability. This assertion is supported by recent findings from Augarten et al. [59] which highlight the significant role that plant stands play in shaping soil health within perennial cropping systems in Wisconsin. In terms of soil fertility, the elevated levels of organic matter found in cropping systems that integrate cocoa with forest cover and *Persea americana* can be attributed to the substantial litter accumulation over years of cultivation. Indeed, Matos et al. [60] report results in favor of agroforestry, showing that the establishment of agroforestry systems on areas previously occupied by extensive pasture improves soil fertility and soil physical indicators. This result is at odds with those of Morales-Belpaire [61] in Bolivia, who showed that soil organic matter and enzyme activity were higher in fallow plots than in monocultures and that agroforestry showed intermediate values, not significantly higher than monocultures. The capacity of soils to sequester carbon and supply essential nutrients for crop productivity is largely determined by the dynamics of organic matter within the soil [62]. On this basis, Condron et al. [63] further emphasize that to enhance the sustainability of agricultural production systems, it is crucial to continuously renew soil organic matter, as it drives essential ecosystem processes such as primary productivity and decomposition. Similarly, phosphorus, which is a major component of several biomolecules [64], and the main element most deficient or unavailable in ferrallitic tropical soils [28, 65], was found strongly in the cultivation system associating cocoa with a shrub legume such as *Inga edulis*. The presence of plant cover alongside cocoa trees significantly influences the availability of both macro- and micronutrients, thereby enhancing overall soil fertility. More than ever, the availability of these elements necessary for the growth, development, and good yield of the plant is also influenced by life in the soil, in particular the microbial population (quantity and diversity), which in turn is influenced by the technical model for exploiting agricultural land through the cropping system.

Moreover, soil microbial communities are integral to nutrient cycling and ecosystem functioning. As highlighted by Trivedi et al. [66], microorganisms are sensitive indicators of soil health due to their rapid response to environmental changes. A diverse microbial community contributes to multiple ecosystem functions, including nutrient retention and plant productivity [67]. The loss of microbial biodiversity can severely impair these functions, leading to decreased soil fertility and agricultural productivity [68]. The interplay between cropping systems, soil fertility, and microbial populations is critical for maintaining healthy agroecosystems. As Doran and Zeiss [69] suggest, understanding these relationships can inform better management practices that enhance soil health and agricultural sustainability. Therefore, adopting integrated cropping systems that promote biodiversity and organic matter accumulation is essential for improving soil fertility and ensuring long-term productivity in cocoa production. In this, the desired result for sustainable cocoa production was observed in the following in the cropping system integrating cocoa, forest species, and avocado.

Soil microorganisms, including bacteria and fungi, play a crucial role in ecosystem functioning by facilitating decomposition and nutrient cycling. They also serve as indicators of land-use change and the overall health of agroecosystems [54, 59, 69]. In fact, land use through the cropping system modifies the structure of the soil microbial community through changes in the availability and quality of carbon and pH [70]. In this study, it was interesting to note that the fungal population was higher in the unshaded monocropping and cocoa + forest trees + *Persea americana* systems, and the bacterial population was higher in the system combining cocoa with the shrub/perennial legume *Inga edulis*. However, focusing solely on the quantitative aspects of these populations limits our understanding of how cropping systems influence soil microbial communities. Microbial diversity is another critical indicator that provides insights into soil fertility and productivity. For instance, the presence of diverse bacterial genera such as *Actinomycetes*, *Azotobacter*, *Bacillus*, and *Streptomyces*, along with fungal genera like *Aspergillus*, *Penicillium*, and *Trichoderma*, suggests a robust ecosystem capable of promoting plant growth while suppressing soil pathogens [71, 72]. As for the unshaded monocropping system, its low organic matter content in the soil naturally results in a very low microbial population and diversity compared with systems that have maintained the characteristics of a forest as much as possible. These results are fully in line with those of Koné and Yao [73], who concluded that cocoa monocropping was not conducive to efficient

ecological functioning of the soil. One strategy for solving the problem of organic matter, density, and microbial diversity in cocoa monocropping systems is to introduce cover crops into the system. Indeed, Gentsch et al. [74] show that the use of cover crops in rotation or in conventional farming practices can stimulate the population of beneficial organisms in the rhizosphere through increased carbon input and greater root exudation. Recent research by Baldwin-Kordick et al. [75] further supports this notion by indicating that diverse cover crops can enhance soil microbial diversity and activity, thereby improving soil health and resilience against environmental stresses. They assert that the integration of diverse plant species can lead to synergistic effects on soil microbial communities, which ultimately benefits nutrient cycling and plant productivity. Understanding the dynamics of soil microorganisms within different cropping systems is essential for promoting sustainable agricultural practices. By recognizing the importance of both microbial abundance and diversity as indicators of soil health, we can develop management strategies that enhance ecosystem functioning while ensuring long-term productivity in cocoa cultivation. As noted by Trivedi et al. [66], a healthy soil microbiome is fundamental for maintaining ecosystem stability and resilience, highlighting the need for integrated approaches that foster biodiversity within agricultural landscapes.

5. Conclusion

The establishment of a cocoa orchard requires careful consideration of cropping systems, which significantly influence yields, pest and disease losses, and the physicochemical properties and microbial populations of the soil. Our results indicate that cropping systems incorporating forest species and *Persea americana* alongside cocoa trees markedly outperform unshaded monoculture systems and those combining cocoa with shrub legumes like *Inga edulis* and *Dacryodes edulis*. Specifically, the agroforestry system that minimizes forest destruction not only leads to higher cocoa yields but also fosters greater microbial diversity and enhances soil health. In our study, we observed clear agronomic advantages in terms of pod production, bean weight, and overall yield in systems that integrated cocoa with forest species and *Persea americana*. These systems exhibited superior soil fertility characteristics, as evidenced by improved physicochemical properties and a more diverse microbial community. Moreover, the findings suggest that agroforestry practices, especially cropping systems that integrated cocoa with forest species and *Persea americana*, not only enhance cocoa productivity but also contribute to ecological sustainability by maintaining healthy cocoa agroecosystems. This cropping system aligns with the growing demand for sustainable and multifunctional agricultural systems that support both economic viability and environmental stewardship in cocoa cultivation.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Conflicts of Interest

The authors declare no conflicts of interest.

Author Contributions

Conceptualization: Pierre Germain Ntsoli and Aoudou Yaouba; methodology: Pierre Germain Ntsoli, Idriss Djoko Kouam, Roland Wilfried Titti, Georges Marius Etame Kossi, and Aoudou Yaouba; validation: Pierre Germain Ntsoli and Aoudou Yaouba; investigation: Pierre Germain Ntsoli, Idriss Djoko Kouam, Roland Wilfried Titti, and Georges Marius Etame Kossi; data analysis: Pierre Germain Ntsoli; writing – original draft preparation: Pierre Germain Ntsoli, David Brondon Mouthe, and Aoudou Yaouba; writing – review and editing: Pierre Germain Ntsoli; supervision: Aoudou Yaouba All authors have read and agreed to the published version of the manuscript.

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References

[1] N. V. D. R. Mudenuti, A. C. de Camargo, S. M. de Alencar, et al., "Phenolics and Alkaloids of Raw Cocoa Nibs and Husk: The Role of Soluble and Insoluble-Bound Antioxidants," *Food Bioscience* 42 (2021): 101085, https://doi.org/10.1016/J.FBIO.2021.101085.

[2] L. Armengot, L. Ferrari, J. Milz, F. Velásquez, P. Hohmann, and M. Schneider, "Cacao Agroforestry Systems Do Not Increase Pest and Disease Incidence Compared With Monocultures Under Good Cultural Management Practices," *Crop Protection* 130 (2020): 105047, https://doi.org/10.1016/j.cropro.2019.105047.

[3] N. Badrie, F. Bekele, E. Sikora, and M. Sikora, "Cocoa Agronomy, Quality, Nutritional, and Health Aspects," *Critical Reviews in Food Science and Nutrition* 55, no. 5 (2015): 620–659, https://doi.org/10.1080/10408398.2012.669428.

[4] L. C. García and A. N. M. Hernández, "Beneficial Effects of Cocoa and Dark Chocolate Polyphenols on Health," *The FASEB Journal* 34, no. S1 (2020): 1, https://doi.org/10.1096/FASEBJ.2020.34.S1.07187.

[5] D. J. Lamport, E. Christodoulou, and C. Achilleos, "Beneficial Effects of Dark Chocolate for Episodic Memory in Healthy Young Adults: A Parallel-Groups Acute Intervention With a White Chocolate Control," *Nutrients* 12, no. 2 (2020): 483, https://doi.org/10.3390/NU12020483.

[6] F. Amiel, Y. Laurans, and A. Muller, "Agricultural Value Chains Facing the Challenge of Biodiversity: Cocoa-Chocolate. IDDRI," *Study* 5 (2019).

[7] ICCO International Cocoa Organization Statistics, "International Cocoa Organization," (2023), https://www.icco.org/statistics/.

[8] E. Bomdzele and E. L. Molua, "Assessment of the Impact of Climate and Non-Climatic Parameters on Cocoa Production: A Contextual Analysis for Cameroon," *Frontiers in Climate* 5 (2023): 1069514, https://doi.org/10.3389/fclim.2023.1069514.

[9] M. Wessel and P. M. F. Quist-Wessel, "Cocoa Production in West Africa, a Review and Analysis of Recent Developments," *NJAS-Wageningen Journal of Life Sciences* 75 (2015): 1–7, https://doi.org/10.1016/j.njas.2015.09.001.

[10] A. L. Nlend Nkott, S. Mathé, L. Temple, and M. Geitzenaeur, "Institutional and Organizational Determinants for the Development of Cocoa Certification in Cameroon: Case of the Certification System," (2017), https://www.researchgate.net/publication/370318135_Cocoa_Certification_in_Cameroon_Socioeconomic_Determinants_and_Performance_of_Producers_in_Mbam_Division_Center_Region.

[11] J. A. Mouen Bedimo, D. Bieysse, C. Cilas, and J. L. Nottéghem, "Spatio-Temporal Dynamics of Arabica Coffee Berry Disease Caused by *Colletotrichum kahawae* on a Plot Scale," *Plant Disease* 91, no. 10 (2007): 1229–1236, https://doi.org/10.1094/PDIS-91-10-1229.

[12] E. W. Ouokam, Y. Yunxian, M. Y. James, M. O. Appiah, and G. Motlehewa, "Assessment of Agricultural Practices for Improving Quality of Cocoa Beans: South-West Cameroon," *International Journal of Environment, Agriculture and Biotechnology* 4, no. 3 (2019): 767–777, https://doi.org/10.22161/IJEAB/4.3.25.

[13] L. Armengot, P. Barbieri, C. Andres, J. Milz, and M. Schneider, "Cacao Agroforestry Systems Have Higher Return on Labor Compared to Full-Sun Monocultures," *Agronomy for Sustainable Development* 36, no. 4 (2016): 70–10, https://doi.org/10.1007/s13593-016-0406-6.

[14] P. Jagoret, H. T. Ngnogue, E. Malézieux, and I. Michel, "Trajectories of Cocoa Agroforests and Their Drivers over Time: Lessons From the Cameroonian Experience," *European Journal of Agronomy* 101 (2018): 183–192, https://doi.org/10.1016/J.EJA.2018.09.007.

[15] O. G. Maledy, R. Adengoyo, M. Ndoumbè Nkeng, and J. A. Mouen Bedimo, "Adaptation Strategies for the Adverse Effects of Climate Disruptions on Coffee and Cocoa Trees Productivity in Cameroon," *International Journal of Biological and Chemical Sciences* 16 (2023): 2516–2535, https://doi.org/10.4314/IJBCS.V16I6.5.

[16] M. Ndoumbe Nkeng, I. B. Efombagn Mousseni, L. Bidzanga Nomo, I. Sache, and C. Cilas, "Spatio-Temporal Dynamics on a Plot Scale of Cocoa Black Pod Rot Caused by Phytophthora Megakarya in Cameroon," *European Journal of Plant Pathology* 147, no. 3 (2017): 579–590, https://doi.org/10.1007/S10658-016-1027-2.

[17] A. R. Tsufac, N. P. Awazi, and B. P. K. Yerima, "Characterization of Agroforestry Systems and Their Effectiveness in Soil Fertility Enhancement in the South-West Region of Cameroon," *Current Research in Environmental Sustainability* 3 (2021): 100024, https://doi.org/10.1016/j.crsust.2020.100024.

[18] P. Jagoret, I. Michel-Dounias, D. Snoeck, H. T. Ngnogué, and E. Malézieux, "Afforestation of Savannah With Cocoa Agroforestry Systems: A Small-Farmer Innovation in Central Cameroon," *Agroforestry Systems* 86, no. 3 (2012): 493–504, https://doi.org/10.1007/s10457-012-9513-9.

[19] C. Gidoin, R. Babin, L. Bagny Beilhe, C. Cilas, G. M. Ten Hoopen, and M. A. N. Bieng, "Tree Spatial Structure, Host Composition and Resource Availability Influence Mirid Density or Black Pod Prevalence in Cacao Agroforests in Cameroon," *PLoS One* 9, no. 10 (2014): e109405, https://doi.org/10.1371/JOURNAL.PONE.0109405.

[20] D. Tilman, K. G. Cassman, P. A. Matson, R. Naylor, and S. Polasky, "Agricultural Sustainability and Intensive Production Practices," *Nature* 418, no. 6898 (2002): 671–677, https://doi.org/10.1038/nature01014.

[21] D. Snoeck, L. Koko, J. Joffre, P. Bastide, and P. Jagoret, "Cacao Nutrition and Fertilization," *Sustainable Agriculture Reviews* 9 (2016): 155–202, https://doi.org/10.1007/978-3-319-26777-7_4.

[22] S. Gaba, F. Lescourret, S. Boudsocq, et al., "Multiple Cropping Systems as Drivers for Providing Multiple Ecosystem Services: From Concepts to Design," *Agronomy for Sustainable Development* 35, no. 2 (2015): 607–623, https://doi.org/10.1007/s13593-014-0272-z.

[23] P. Jagoret, J. Kwesseu, C. Messie, I. Michel-Dounias, and E. Malézieux, "Farmers' Assessment of the Use Value of Agrobiodiversity in Complex Cocoa Agroforestry Systems in Central Cameroon," *Agroforestry Systems* 88, no. 6 (2014): 983–1000, https://doi.org/10.1007/s10457-014-9698-1.

[24] E. Malézieux, Y. Crozat, C. Dupraz, et al., "Mixing Plant Species in Cropping Systems: Concepts, Tools and Models: A Review," *Sustainable Agriculture* 43 (2009): 329–353, https://doi.org/10.1007/978-90-481-2666-8_22.

[25] E. Malézieux, "Designing Cropping Systems From Nature," *Agronomy for Sustainable Development* 32, no. 1 (2012): 15–29, https://doi.org/10.1007/s13593-011-0027-z.

[26] D. H. Bisseleua and S. Vidal, "Plant Biodiversity and Vegetation Structure in Traditional Cocoa Forest Gardens in Southern Cameroon Under Different Management," *Biodiversity & Conservation* 17, no. 8 (2008): 1821–1835, https://doi.org/10.1007/s10531-007-9276-1.

[27] C. Santoir and A. Bopda, *South Cameroon Regional Atlas* (Orstom, 1995).

[28] A. Oberson, D. K. Friesen, I. M. Rao, S. Bühler, and E. Frossard, "Phosphorus Transformations in an Oxisol Under Contrasting Land-Use Systems: The Role of the Soil Microbial Biomass," *Plant and Soil* 237, no. 2 (2001): 197–210, https://doi.org/10.1023/a:1013301716913.

[29] D. Bitom, B. Volkoff, A. Beauvais, F. Seyler, and P. D. Ndjigui, "Rôle des Héritages Latéritiques et du Niveau des Nappes Dans l'évolution des Modelés et des sols en Zone Intertropicale Forestière Humide," *Comptes Rendus Geoscience* 336, no. 13 (2004): 1161–1170, https://doi.org/10.1016/j.crte.2004.03.019.

[30] R. Priyadarshini, K. Hairah, D. Suprayoga, and J. B. Baon, "Diversity of Shade Trees on Coffee Based Agroforestry System," in *23rd International Conference on Coffee Science 2010* (Bali, Indonesia, October 2010).

[31] T. Z. Ketema and L. J. Wade, "Evapotranspiration Estimation Using Soil Water Balance, Weather and Crop Data," in *Evapotranspiration-Remote Sens. Model* (IntechOpen, 2012), http://www.intechopen.com/books/evapotranspiration-remote-sensing-and-modeling/evapotranspiration-estimation-using-soil-water-balance-weather-and-crop-data.

[32] P. Jagoret, I. Michel, H. T. Ngnogué, P. Lachenaud, D. Snoeck, and E. Malézieux, "Structural Characteristics Determine Productivity in Complex Cocoa Agroforestry Systems," *Agronomy for Sustainable Development* 37 (2017): 1–12, https://doi.org/10.1007/S13593-017-0468-0/FIGURES/3.

[33] G. Mossu, "The Cocoa Tree Maisonneuve and Larose," *Open Journal of Soil Science* 14 (1990): 159.

[34] P. Lachenaud, *Fruiting Factors in the Cocoa Tree: Influence on the Number of Seeds Per Fruit* (National Agronomic Institute Paris-Grignon, 1991).

[35] J. Braudeau, "The Cocoa Tree. Agricultural Techniques and Tropical Productions Collection," *Maisonneuve and Larose* 304 (1969).

[36] P. Lachenaud, "A Method for Evaluating the Production of Fresh Beans Applicable to Trials Entirely," *Coffee Cacao Tea* 28 (1984): 21–30.

[37] M. J. Ziemiecka, "Land Sampling: Collection and Conservation of Samples, Preparation of Materials to Be Analysed (Suspension and Dilution of Samples)," in *Symp. On*

Microbial Study Methods: From the Ground, ed. P. Simonart (Paris, France: Bulletin of the Belgian society of Pedology, 1957).

[38] J. M. Pauwels, E. Van Ranst, M. Verloo, and A. D. Mvondo Ze, *Methods of Soil and Plant Analysis, Equipment, Management of Glassware and Chemicals* (Publ. Agric, 1992).

[39] F. Beernaert and D. Bitondo, *Land Evaluation Manual* (Dschang Univ. Center, 1993).

[40] H. L. Barnett and B. B. Hunter, *Illustrated Genera of Imperfect Fungi* (APS, 1998).

[41] J. M. Vincent and B. Humphrey, "Taxonomically Significant Group Antigens in Rhizobium," *Journal of General Microbiology* 63, no. 3 (1970): 379–382, https://doi.org/10.1099/00221287-63-3-379.

[42] P. Vos, G. M. Garrity, D. Jones, N. R. Krieg, W. Ludwing, and K.-H. Scheilfer, *Bergey's Manual of Systematic Bacteriology, Volume 3: The Firmicutes* (Springer, 2010).

[43] A. Arunyanark, S. Jogloy, S. Wongkaew, et al., "Association Between Aflatoxin Contamination and Drought Tolerance Traits in Peanut," *Field Crops Research* 114, no. 1 (2009): 14–22, https://doi.org/10.1016/J.FCR.2009.06.018.

[44] R Core Team, *The R Stats Package* (Cran, 2019), https://stat.ethz.ch/R-manual/R-devel/library/stats/html/00Index.html.

[45] F. de Mendiburu and Y. Muhammad, "Statistical Procedures for Agricultural Research," (2020), https://github.com/myaseen208/agricolae.

[46] S. Lê, J. Josse, and F. Husson, "FactoMineR: An R Package for Multivariate Analysis," *Journal of Statistical Software* 25 (2008): 1–18, https://doi.org/10.18637/JSS.V025.I01.

[47] G. Mattalia, A. Wezel, P. Costet, et al., "Contribution of Cacao Agroforestry Versus Mono-Cropping Systems for Enhanced Sustainability. A Review With a Focus on Yield," *Agroforestry Systems* 96, no. 7 (2022): 1077–1089, https://doi.org/10.1007/s10457-022-00765-4.

[48] F. O. Ruf, "The Myth of Complex Cocoa Agroforests: The Case of Ghana," *Human Ecology* 39, no. 3 (2011): 373–388, https://doi.org/10.1007/s10745-011-9392-0.

[49] P. Jagoret, "Analyse et Évaluation de Systèmes Agroforestiers Complexes sur le Long Terme: {Application} Aux Systèmes de Culture à Base de Cacaoyer au {Centre} {Cameroun}, Montpellier SupAgro," (2011), https://agritrop.cirad.fr/560345/.

[50] C. Andres, H. Comoé, A. Beerli, M. Schneider, S. Rist, and J. Jacobi, "Cocoa in Monoculture and Dynamic Agroforestry," *Sustainable Agriculture Reviews* 19 (2016): 121–153, https://doi.org/10.1007/978-3-319-26777-7_3.

[51] W. Niether, J. Jacobi, W. J. Blaser, C. Andres, and L. Armengot, "Cocoa Agroforestry Systems Versus Monocultures: A Multi-Dimensional Meta-Analysis," *Environmental Research Letters* 15, no. 10 (2020): 104085, https://doi.org/10.1088/1748-9326/ABB053.

[52] L. Koko, R. Yoro, K. N'Goran, and A. Assa, "Evaluation de la Fertilité des sols sous Cacaoyers dans le Sud-Ouest de la Côte d'Ivoire," *Agronomie Africaine* 20, no. 1 (2009): 81–95, https://doi.org/10.4314/aga.v20i1.1738.

[53] J. Trazié, Y. Bohoussou N'Dri, F. Akotto Odi, and A. Yao-Kouamé, "Impact of Associated Trees on Cocoa Farming in Transitional Zones. ForêstSavane: Case of M'Brimbo (South-Central Ivory Coast)," *European Scientific Journal* 13 (2017): 164, https://doi.org/10.19044/esj.2017.v13n1p164.

[54] P. R. Pandey, S. Singh, S. Dubey, et al., "Assessment of Soil Microbial Status Under Different Land Use System at Various Depth," *International Journal of Environment and Climate Change* 13, no. 10 (2023): 603–615, https://doi.org/10.9734/ijecc/2023/v13i102692.

[55] H. Zhang, A. Ghahramani, A. Ali, and A. Erbacher, "Cover Cropping Impacts on Soil Water and Carbon in Dryland Cropping System," *PLoS One* 18, no. 6 (2023): 02867488–e286829, https://doi.org/10.1371/journal.pone.0286748.

[56] J. A. Mouen Bedimo, D. Bieysse, I. Njiayouom, J. P. Deumeni, C. Cilas, and J. L. Nottéghem, "Effect of Cultural Practices on the Development of Arabica Coffee Berry Disease, Caused by *Colletotrichum kahawae*," *European Journal of Plant Pathology* 119, no. 4 (2007): 391–400, https://doi.org/10.1007/S10658-007-9169-X.

[57] M. Ndoumbe-Nkeng, C. Cilas, E. Nyemb, et al., "Impact of Removing Diseased Pods on Cocoa Black Pod Caused by *Phytophthora megakarya* and on Cocoa Production in Cameroon," *Crop Protection* 23, no. 5 (2004): 415–424, https://doi.org/10.1016/J.CROPRO.2003.09.010.

[58] J. L. Monteith and D. R. Butler, "Dew and Thermal Lag: A Model for Cocoa Pods," *Quarterly Journal of the Royal Meteorological Society* 105, no. 443 (1979): 207–215, https://doi.org/10.1002/QJ.49710544313.

[59] A. J. Augarten, L. C. Malone, G. S. Richardson, et al., "Cropping Systems with Perennial Vegetation and Livestock Integration Promote Soil Health," *Agricultural & Environmental Letters* 8, no. 1 (2023): e20100, https://doi.org/10.1002/AEL2.20100.

[60] P. S. Matos, M. R. Cherubin, J. M. Damian, F. I. Rocha, M. G. Pereira, and E. Zonta, "Short-Term Effects of Agroforestry Systems on Soil Health in Southeastern Brazil," *Agroforestry Systems* 96, no. 5-6 (2022): 897–908, https://doi.org/10.1007/s10457-022-00749-4.

[61] I. Morales-Belpaire, A. Alfaro-Flores, K. Losantos-Ramos, O. Palabral-Velarde, P. Amurrio-Ordoñez, and L. Armengot, "Soil Quality Indicators Under Five Different Cacao Production Systems and Fallow in Alto Beni, Bolivia," *Agroforestry Systems* 98, no. 7 (2024): 2517–2532, https://doi.org/10.1007/s10457-024-01048-w.

[62] S. A. Billings and S. E. Ziegler, "Linking Microbial Activity and Soil Organic Matter Transformations in Forest Soils Under Elevated CO2," *Global Change Biology* 11, no. 2 (2005): 203–212, https://doi.org/10.1111/J.1365-2486.2005.00909.X.

[63] L. Condron, C. Stark, M. O'Callaghan, P. Clinton, and Z. Huang, "The Role of Microbial Communities in the Formation and Decomposition of Soil Organic Matter," *Soil Microbiology and Sustainable Crop Production* 5 (2010): 81–118, https://doi.org/10.1007/978-90-481-9479-7_4.

[64] D. W. Hopkins and J. A. J. Dungait, "Soil Microbiology and Nutrient Cycling," *Soil Microbiology and Sustainable Crop Production* 7 (2010): 59–80, https://doi.org/10.1007/978-90-481-9479-7_3.

[65] T. S. George, B. L. Turner, P. J. Gregory, B. J. Cade-Menun, and A. E. Richardson, "Depletion of Organic Phosphorus From Oxisols in Relation to Phosphatase Activities in the Rhizosphere," *European Journal of Soil Science* 57, no. 1 (2006): 47–57, https://doi.org/10.1111/J.1365-2389.2006.00767.X.

[66] P. Trivedi, M. Delgado-Baquerizo, I. C. Anderson, and B. K. Singh, "Response of Soil Properties and Microbial Communities to Agriculture: Implications for Primary Productivity and Soil Health Indicators," *Frontiers of Plant Science* 7 (2016): 990, https://doi.org/10.3389/fpls.2016.00990.

[67] F. Romero, S. Hilfiker, A. Edlinger, et al., "Soil Microbial Biodiversity Promotes Crop Productivity and Agro-Ecosystem Functioning in Experimental Microcosms," *The*

Science of the Total Environment 885 (2023): 163683, https://doi.org/10.1016/J.SCITOTENV.2023.163683.

[68] L. Brussaard, P. C. de Ruiter, and G. G. Brown, "Soil Biodiversity for Agricultural Sustainability," *Agriculture, Ecosystems & Environment* 121, no. 3 (2007): 233–244, https://doi.org/10.1016/J.AGEE.2006.12.013.

[69] J. W. Doran and M. R. Zeiss, "Soil Health and Sustainability: Managing the Biotic Component of Soil Quality," *Applied Soil Ecology* 15, no. 1 (2000): 3–11, https://doi.org/10.1016/S0929-1393(00)00067-6.

[70] W. R. Cookson, M. Osman, P. Marschner, et al., "Controls on Soil Nitrogen Cycling and Microbial Community Composition Across Land Use and Incubation Temperature," *Soil Biology and Biochemistry* 39, no. 3 (2007): 744–756, https://doi.org/10.1016/J.SOILBIO.2006.09.022.

[71] M. A. Boat Bedine, B. Iacomi, S. N. Tchameni, M. L. Sameza, and F. B. Fekam, "Harnessing the Phosphate-Solubilizing Ability of Trichoderma Strains to Improve Plant Growth, Phosphorus Uptake and Photosynthetic Pigment Contents in Common Bean (*Phaseolus vulgaris*)," *Biocatalysis and Agricultural Biotechnology* 45 (2022): 102510, https://doi.org/10.1016/j.bcab.2022.102510.

[72] I. D. Kouam, J. Mabah, P. Germain Ntsoli, et al., "Growth Promotion Potential of Bacillus Spp. Isolates on Two Tomato (*Solanum lycopersicum* L.) Varieties in the West Region of Cameroon," *Open Agriculture* 8 (2023): 1–16, https://doi.org/10.1515/opag-2022-0154.

[73] A. W. Koné and M. K. Yao, "Soil Microbial Functioning and Organic Carbon Storage: Can Complex Timber Tree Stands Mimic Natural Forests?" *Journal of Environmental Management* 283 (2021): 112002, https://doi.org/10.1016/j.jenvman.2021.112002.

[74] N. Gentsch, J. Boy, J. D. K. Batalla, et al., "Catch Crop Diversity Increases Rhizosphere Carbon Input and Soil Microbial Biomass," *Biology and Fertility of Soils* 56, no. 7 (2020): 943–957, https://doi.org/10.1007/s00374-020-01475-8.

[75] R. Baldwin-Kordick, M. De, M. D. Lopez, et al., "Comprehensive Impacts of Diversified Cropping on Soil Health and Sustainability," *Agroecology and Sustainable Food Systems* 46, no. 3 (2022): 331–363, https://doi.org/10.1080/21683565.2021.2019167.