Évaluation en milieu paysan de biopesticides à base de *Trichoderma asperellum* et de *Beauveria bassiana* pour la lutte intégrée contre les maladies et les ravageurs dans les systèmes agroforestiers cacaoyers au Cameroun

Field evaluation of *Trichoderma asperellum* and *Beauveria bassiana*-based biopesticides for integrated management of pests and diseases in cocoa-based agroforestry systems in Cameroon

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RÉSUMÉ. L'efficacité des formulations combinées de biopesticides à base de *Trichoderma asperellum* (souche PR11) et de *Beauveria bassiana* (souche BIITA 6.2.2) a été évaluée en milieu paysan dans trois plantations cacaoyères agroforestières à Ntui, dans la région du Centre, Cameroun avec un dispositif expérimental en blocs complets randomisés comprenant 27 parcelles et la collecte mensuelle sur 20 arbres par parcelle de l'incidence et la sévérité de la pourriture brune, des dégâts de mirides et la productivité des cacaoyers. Les résultats montrent qu'aucune différence significative n'a été trouvé entre les traitements biologiques et les traitements chimiques concernant l'incidence et la sévérité de la pourriture brune et des dégâts de mirides. La sévérité des dommages est restée faible pour l'ensemble des traitements. La productivité s'est montrée plus élevée dans les parcelles traitées avec les biopesticides (0,80 kg/cacaoyer). Ces résultats suggèrent que l'application combinée de *Trichoderma asperellum* et de *Beauveria bassiana* est une alternative aux pesticides chimiques pour la gestion intégrée des bioagresseurs dans les systèmes agroforestiers cacaoyers.

ABSTRACT. The efficacy of a combined biopesticide formulation based on *Trichoderma asperellum* (strain PR11) and *Beauveria bassiana* (strain BIITA 6.2.2) was evaluated in a farmer setting on three agroforestry cocoa plantations in Ntui, Central Region, Cameroon. A randomized complete block design was used, comprising 27 plots, with monthly data collection from 20 trees per plot to assess the incidence and severity of black pod rot, mirid insect damage, and cocoa tree productivity. The results showed no significant difference between the biological and chemical treatments regarding the incidence and severity of black pod rot and mirid insect damage. Damage severity remained low for all treatments. Productivity was higher in the plots treated with biopesticides (0.80 kg/cocoa tree). These results suggest that the combined application of *Trichoderma asperellum* and *Beauveria bassiana* is an alternative to chemical pesticides for the integrated management of pests in cocoa agroforestry systems.

MOTS-CLÉS. Gestion Intégrée des ravageurs, *Trichoderma asperellum*, *Beauveria bassiana*, pourriture brune, attaques de mirides, systèmes agroforestiers cacaoyers, Cameroun.

KEYWORDS. Integrated pest management, *Trichoderma asperellum*, *Beauveria bassiana*, black pod disease, mirids damages, cocoa-based agroforesty systems, Cameroon.

1. Introduction

Cocoa (*Theobroma cacao*) is one of the most important agricultural products traded and provides a vital income source for millions of smallholder farmers [FAO, 23]. In addition, cocoa beans have nutritional and health benefits. In West and Central Africa, which accounts for over 70% of global production, cocoa systems face unique and aggressive biotic pressures. Unlike other regions, the cocoa landscape here is dominated by *Phytophthora megakarya*, the most virulent agent of Black Pod Disease (BPD). This specific pathogen is significantly more aggressive than *P. palmivora*, causing yield losses between 30% and 90% at the farm level [ADE, 23; TOR, 23]. Similarly, mirids (*Sahlbergella singularis* and *Distantiella theobroma*) remain the most devastating insect pests in the region, capable of reducing productivity by up to 75% by destroying immature pods and vegetative tissues [NKA, 07; BOA, 23].

To mitigate these losses, farmers have historically relied on synthetic pesticides. However, the misuse of these chemicals presents a risk of causing pesticide resistance, environmental degradation, and health risks [AFR, 11]. Crucially, broad-spectrum pesticides often harm non-target beneficial insects, such as cocoa flower pollinators, which are essential for pod set and overall yield [TOL, 17]. Furthermore, chemical residues increasingly threaten access to international markets due to stringent legislation by importing countries [AGR, 13; TIJ, 19] then prompt numerous efforts to develop alternative pest and diseases control approaches, including host plant resistance [REG, 23], cultural control through shade management and biological control. Biological control offers a sustainable alternative, leveraging the natural antagonism of microbial agents. Biopesticides derived from natural organisms offer a viable alternative, particularly in tropical regions where pest pressure is high and ecological sensitivity is critical [GLA, 12].

Two microorganisms with fungicidal and insecticidal potential have been attracting increasing attention in recent years for the development of biopesticides: *Trichoderma asperellum* and *Beauveria bassiana*. Their integration into crop protection strategies is supported by numerous studies highlighting their multiple roles as biostimulants and biopesticides [OUD, 25; MOU, 07; MAH, 25; MEM, 25]. In global agriculture, Trichoderma species are among the most studied antagonistic fungi. In global agriculture, *Trichoderma spp*. are widely recognized as versatile biocontrol agents that function through mycoparasitism, competition for nutrients, and the induction of systemic resistance in the host plant [GLA, 12]. More specifically, *T. asperellum* is known for its aggressive mycoparasitism: it secretes enzymes that degrade the cell wall to parasitize soilborne and foliar pathogens and induces systemic resistance (ISR) in the host plant, thus strengthening the natural defenses of the cacao tree against Phytophthora species [TCH, 11; CHO, 12]. Similarly, *Beauveria bassiana* is an established entomopathogenic fungus that infects a wide range of insect pests by penetrating the cuticle and releasing toxins, making it a staple in Integrated Pest Management (IPM) strategies. Indeed, *B. bassiana* is a basic mycoinsecticide, particularly effective against hemipteran pests such as mirid bugs. Its mode of action is both mechanical and biochemical: upon contact with the insect, the conidia adhere to its cuticle, germinate, and penetrate the hemocoel via specialized structures called appressoria. Once inside, the fungus releases secondary metabolites, such as beauvericin, which disrupt the host's immune system and lead to fatal sepsis [CLA, 96].

In Cameroon, research has identified specific potent strains: *T. asperellum* (strain PR11) against *P. megakarya* [TON, 07] and *B. bassiana* (strain BIITA 6.2.2) against *S. singularis* [MAH, 19]. Despite the proven potential of these individual strains in controlled environments, there is a critical knowledge gap regarding their co-application as formulated products under the heterogeneous and unpredictable conditions of real-world farmer fields. Most existing studies focus on single-pathogen or single-pest interventions and in laboratory, failing to address the simultaneous pressure of BPD and mirids that farmers face daily.

This research, beyond laboratory efficacy studies, aims to evaluate the effectiveness of biopesticides formulated with *B. bassiana* and *T. asperellum*, applied together, for the sustainable protection of cocoa trees under farmer conditions in Cameroon. The impact of these combined applications on the incidence of BPD, mirid infestation levels, and the yield of cultivated plots will be compared to traditional chemical treatments and monitoring carried out by cocoa farmers. Our hypothesis is that the combined application of the *B. bassiana* and *T. asperellum* formulation will have a similar effect to that of synthetic pesticides on the incidence of BPD, mirid damage, and yield, thus constituting a viable pathway for the sustainable intensification of cocoa farming.

2. Materials and methods

2.1. *Study area*

The study was conducted in the locality of Ntui, found in the Mbam et Kim division of the central region of Cameroon, in the bimodal humid forest [IRA, 08]. It is situated about 100 km North from Yaoundé with geographical coordinates between 4°19′- 5°00′N and 11°30’-11°50′E, covering an area of about 430 km^2. The climate is classified as a dry winter savannah climate [MAN, 24], characterized by two distinct rainy and two dry seasons. The major rainy season occurs from mid-August to mid-November, followed by a major dry season from mid-November to mid-March. A minor rainy season takes place from mid-March to mid-June, succeeded by a minor dry season from mid-June to mid-August. The mean annual rainfall is 1232 mm [OLI, 18]. The vegetation presents three distinct ecosystems namely: the semi-deciduous forest zone (FZ), the forest-savannah transition zone (FSTZ), and the savannah zone (SZ), enabling the cultivation of both perennial and annual crops. The dominant vegetation is a dense forest which turns into a mangrove in contact with water bodies. The soils are predominantly brown, eutrophic andosols with a homogeneous profile developed on basic volcanic formations and generally associated with the raw mineral soils [OLI, 18]. The soils are rejuvenated and depleted orthic Ferralsols in the savannah area, and the red orthic Ferralsols soils in the forest area [ONA, 18].

2.2. *Experimental design*

The experimental study was conducted in two cocoa plantations located in Nkouloutou and one located in Bivouna villages, selected based on previous research conducted during the Cocoasoils project from 2018 to 2023. The selection criteria were primarily based on criteria as accessibility, plot age, plot size, the cocoa farmer's collaborative spirit, vegetation type, and farming system (agroforestry). Table 1 shows some of the criteria of all the three chosen farms.

Name of farmer	BEKALA Victor (CBI 3)	MANGON Didier (CBI 1)	BEKALA Marc (CBI 2)
Location	Nkouloutou Village	Bivouna Village	Nkouloutou Village
Year of creation	2009	1996	2010
Area	2ha	16ha	1.5ha
Agrosystem	Forest zone (FZ)	Transition zone (FSTZ),	Forest zone (FZ)
Shade level	Shaded	Shaded	Full sun
Prior farming practices	Forest	Forest	Forest

Tableau 1. *Characteristics of selected farms.*

Once selected, these plantations underwent an initial characterization to gather information on their history including origin of the planting material, variety, weed management practices, timing of sanitary and structural pruning, pest management, disease management, fertilizer application, and yield. Overall, before the trial was set up, the experimental plots were subjected to conventional management practices typical of cocoa production in the region.

The experimental set-up was comprised of a network of 27 plots installed in 3 cocoa plantations. In each of these plantations, all of which were homogeneous in terms of age and type of system, three blocks were established. Each block contained three plots, each measuring 400 m^2 (20 m× 20 m) each, representing three treatments: biopesticide (BT), recommended chemical pesticide (PC), and farmer/producer control (NC). The biopesticides used as biofungicide and bioinsecticide respectively, were locally formulated by the Regional Biocontrol and Applied Microbiology Laboratory of Institute of Agricultural Research for Development (IRAD) and the Entomopathology Laboratory of International Institute of Tropical Agriculture (IITA).

The Biofungicide was made from *Trichoderma asperellum* PR11 strain stored in the laboratory. This strain was isolated from the top 8 cm of agricultural soil in Cameroon and its ability to protect the cocoa tree and common bean respectively against black pod disease and angular leaf spot, respectively has been demonstrated [TON, 07; MBA, 14; CHA, 25]. The Bioinsecticide was based on *Beauveria bassiana*, isolated from soil and identified using the [HUM, 12] identification key, then preserved at 80^{o}C as conidia suspension. This isolate was selected according to previous studies on entomopathogenic activity against *Sahlbergella singularis* and *Cosmopolites sordidus* [MAH, 19, 25; MEM, 20, 25]. The two biopesticides, formulated as described in [MAH, 25] were applied at a rate of 120mL per 15L sprayer at a concentration of 1.10^8 spores/mL to treat one elementary plot of 400m^2. The chemical phytosanitary treatments involved the application of insecticides and fungicides sourced from the local market. The selected insecticides included thiamethoxam, cypermethrin, and imidacloprid, while the fungicidal protection was ensured using cuprous oxide, Metalaxyl-M + Mancozeb, and copper oxide + metalaxyl. Additionally, all experimental plots systematically received a foliar fertilizer application of NPK 20-20-20 as indicated by the supplier, to ensure uniform nutrient supply. Treatments were administered using a 15-liter back-sprayer, with specific dosages calibrated for application per plot. For insecticidal control, the concentrations used per 15L of water were 7.5 mL of thiamethoxam, 44.1 mL of cypermethrin, and 13.2 mL of imidacloprid. Regarding fungicidal applications, the dosages per 15L sprayer consisted of 25 g of cuprous oxide, 12.5 g of metalaxyl-M + mancozeb, and 18.75 g of the copper oxide + metalaxyl mixture. Producers managed the control plot using their own agricultural practices, which also included the application of their selected chemical pesticides. Plots receiving conventional pesticides were designated as PC, those receiving biopesticides BT, and those under product monitoring NC. In the center of each plot, 20 cocoa tree stems were randomly selected to assess disease incidence and severity and mirid damage. The experiment spanned nine months, from April to December 2024. Although for technical constraints limiting data collection only from August to December, the various treatments were applied according to a well-defined schedule. All activities carried out on the PC and BT plots are detailed in Table 2.

Activities	April	May	June	July	Aug	Sept	Oct	Nov	Dec
Farm selection	×								
Plot delimitation and labelling		×							
Initial site characterization		×							
Structural pruning		×							
Weed control		×		×			×		×
Sanitary pruning		×	×	×	×	×	×	×	
Pest management (application of conventional and biological insecticide)		×			×		×		×
Disease management (application of conventional and biological fungicide)					×	×	×	×	×
Fertilization (high-efficiency foliar fertilizer Agro Vert Special cocoa granules)		×	× ×	× ×	× ×				
Yield					×	×	×	×	×

Table 2. *Annual timeline of activities*

2.3. Incidence and severity of black pod disease and mirids damage

Assessments of BPD and mirid damage were conducted visually by simple observation [MAH, 15, 20] at monthly intervals from August to December 2024. Green and ripe Cocoa pods from each of the 20 selected cocoa tree were inspected for symptoms of BPD. Infected cocoa pods were assessed and the extent of damage inflicted by the disease described by scores from 0 to 5 according to [AKR, 15]. Mirid damage was assessed only on cocoa pods due to the high preference of the targeted pest for this organ [BIS, 11; YED, 16]. Damage scores represented the percentage of pod surface with typical mirid damage, with the values of 0, 1, 2, 3, 4 assigned, respectively, to 0%, ≤25%, >25% and <50%, ≥50% and ≤75%, and >75% of pod surface presenting typical mirid damage. These damage scores were used to calculate damage incidence and severity, for each cocoa tree, according to the following formula [AKA, 09], then extrapolated at the plot level:

$$I = N/(Total\ number\ of\ inspected\ cocoa\ pods\ on\ a\ tree)\ X100$$

The disease and mirid damage severity on each pod was calculated according to the following formula developed by [TCH, 90].

$$S = \Sigma ab/N$$

Where:

I = Incidence;

S = severity of the infection;

a = Number of infected pods;

b = Degree of infection corresponding to (a);

N = Total number of diseased pods.

2.4. *Cocoa trees productivity*

Yields were assessed using the pod-counting method. All selected cocoa trees were labelled for differentiation. Then, pods ≥ 10 cm in length from each selected cocoa tree were counted and marked with paint of varying colors according to indicate different assessment periods **[JAG, 11]**. The total number of pods was recorded on a special sheet. Pods longer than 10 cm were unlikely to be affected by physiological wilt (Lachenaud, 1991).

Annual cocoa pod production and the associated cocoa bean yield were estimated over the course of a production cycle as the "accessible" pod production, from which we then derived the "accessible" cocoa bean yield [SAJ, 17]. The accessible yield was calculated as follows:

$$\text{Productivity (kg / cocoa tree)} = \text{Number of pods per cocoa tree} \times \text{W beans} \times \text{TC}$$

Where:

Number of pods' is the total number of pods counted on the cocoa tree;

'W beans' is the average fresh bean/pod weight (kg);

and TC is the marketable cocoa transformation coefficient/fresh bean weight (0.35) **[LAC, 91]**. Average cocoa productivity (kg per cocoa tree) was calculated by dividing the total number of pods counted by the number of cocoa trees selected (20 stems) at the plot level.

2.5. *Statistical Analysis*

Monthly counts of healthy and damaged cocoa pods were compiled and cumulated over the five-month study period in Microsoft Excel. The accessible cocoa yield was also cumulated over the same period. Because incidence and damage severity data did not follow a normal distribution, Generalized Linear Models (GLM) were fitted separately for each response variable using appropriate distribution families. Specifically, treatment effects on disease and mirid incidence and severity were analysed using a GLM with a quasibinomial distribution and logit link function, which is appropriate for overdispersed proportional data. Cocoa accessible yield (kg/tree), which is a continuous positive variable, was analysed using a GLM with a gamma distribution and log link function. For each model, treatment, exploitation (CBI1, CBI2, CBI3), and their interaction (treatment × farm) were included as explanatory factors; Model structure: response ~ treatment * exploitation. Each GLM was followed by an analysis of deviance (ANOVA with Chisq test) to assess the significance of explanatory factors. Post-hoc pairwise comparisons were performed using the HSD.test function from the 'agricolae' package in R. All statistical analyses were performed in R version 3.4.3, with a significance level of $\alpha = 0.05$ for all tests.

3. Results

3.1. *Black pod disease incidence and severity*

The results from the field experiment indicated variability in the incidence of cocoa BPD across treatments from August to December 2024 (Figure 1A). The highest incidence was registered in the recommended fungicide treatment (15.40%) while the lowest was in the biofungicide treatment (13.5%). Overall, BPD manifested itself with a low mean severity ranging from 0.10 to 0.11. Despite the low incidence levels and mostly damage severity, statistical analysis revealed that these two responses were not significantly affected by applied treatments whatever the exploitation considered (for incidence: Chisq test, p = 0.63, df = 2; for severity: Chisq test, p > 0.82, df = 2). Statistical analysis revealed no significant differences between treatments within each exploitation regarding both disease incidence and severity.

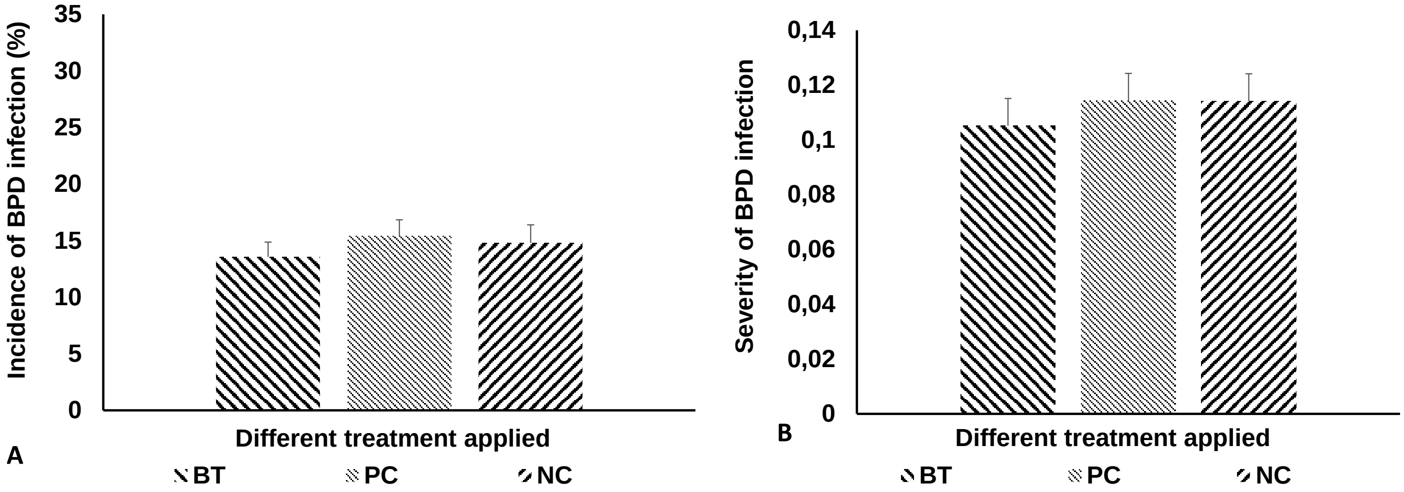

Figure 1. *BPD incidence (A) and damage severity (B) across the three experimental farms (CBI1, CBI2, CBI3) treated with biofungicide (BT), recommended chemical fungicide (PC), or under farmer control (NC). Bars represent mean values per farm; error bars indicate ± standard deviation.*

Statistical analysis showed that interaction treatments versus exploitation were significant for incidence (Chisq test, p = 0.04, df = 4), then for damage severity (Chisq test, p = 0.03, df = 4). In addition, exploitation effect was highly significant in term of damage incidence (Chisq test, p < 0.05, df = 2) with CBI2 (8.9%) significantly different to CBI1 (17.0%) and CBI3 (17.7%). As for incidence, result showed that damage severity significantly differed between exploitation (Chisq test, p < 0.05, df = 2) with CBI2 (0.06), CBI1 (0.13) and CBI3 (0.13) (Figure 2A and B).

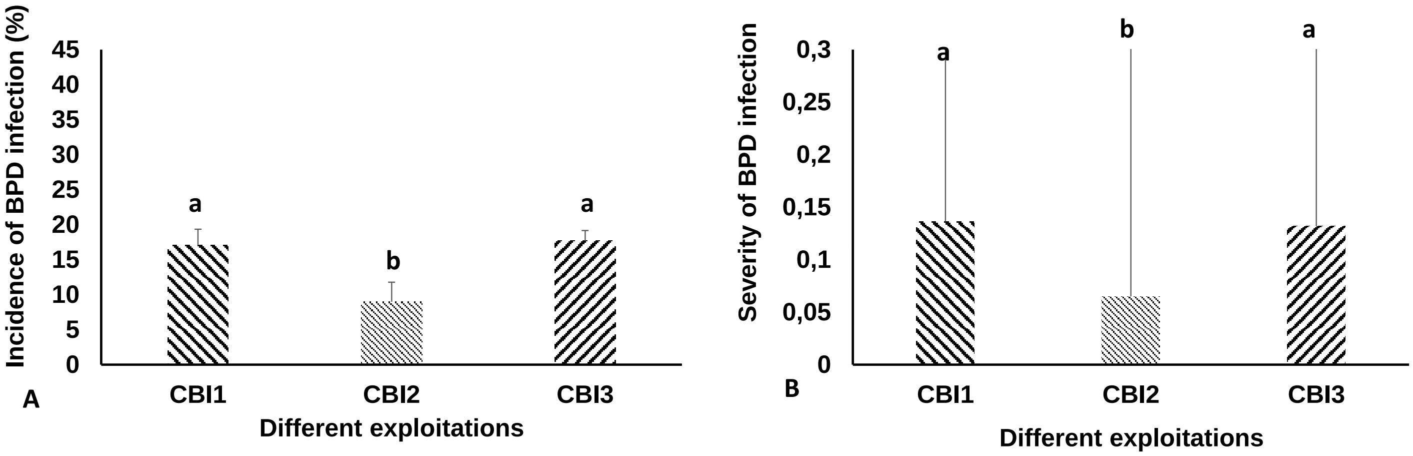

Figure 2. *BPD incidence (A) and damage severity (B) in individual cocoa farms (CBI1, CBI2, CBI3) treated with biofungicide, recommended chemical fungicide, or under farmer control. Bars represent mean values per farm; error bars indicate ± standard deviation. Different letters above bars within each farm panel indicate significant differences between exploitation (post-hoc pairwise comparisons, Tukey contrasts, p < 0.05).*

3.2. *Mirid damage incidence and severity*

The mean incidence of mirid damage on cocoa pods across the farms varied between 23.9% for the recommended insecticide treatment and 28.9% for the bioinsecticide treatment. Severity of mirid attacks on cocoa pods ranged from 0.08 for the recommended insecticide to 0.10 for the bioinsecticide. The severity of damage was very low across all treatments. Both incidence and severity followed the same trend: lower in blocks that received the recommended insecticide and higher in those receiving biopesticides (Figure 3A and B). No significant difference was registered in treatment whatever the exploitation considered (Chisq test, $p = 0.2$, $df = 2$ for incidence and Chisq test, $p > 0.3$, $df = 2$ for severity).

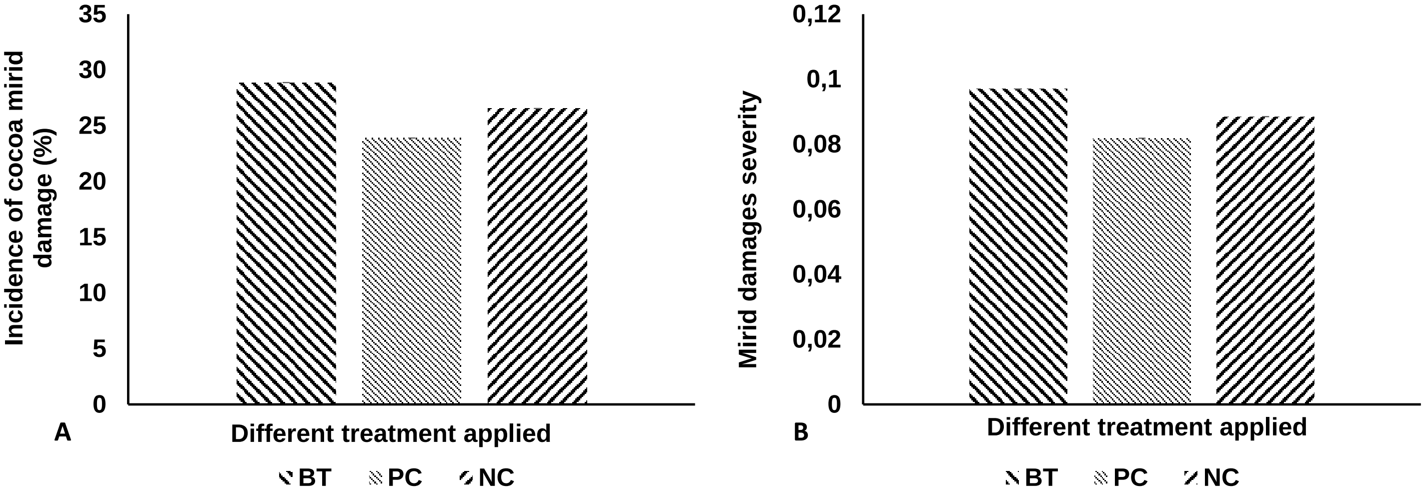

Figure 3. *Mirid damage incidence (A) and severity (B) across the three experimental farms (CBI1, CBI2, CBI3 pooled) in cocoa plots treated with bioinsecticide (BT), recommended chemical insecticide (PC), or under farmer control (NC). Bars represent mean values across plots; error bars indicate ± standard deviation.*

As in the BPD analysis, the interaction between treatment and exploitations effects was significant for both mirid damage incidence (Chisq test, $p = 0.001$, $df = 4$), and severity damage responses (Chisq test, $p = 0.001$, $df = 4$). Results obtained showed highly significant difference between exploitation in incidence (Chisq test, $p < 0.05$, $df = 2$) and damage severity (Chisq test, $p < 0.05$, $df = 2$). Exploitation

CBI2 has shown the highest damage incidence (CBI2: 39.5%, CBI1: 19% and CBI3: 23.1%) and damage severity (CBI2: 0.14, CBI1: 0.04 and CBI3: 0.07) (Figure 4).

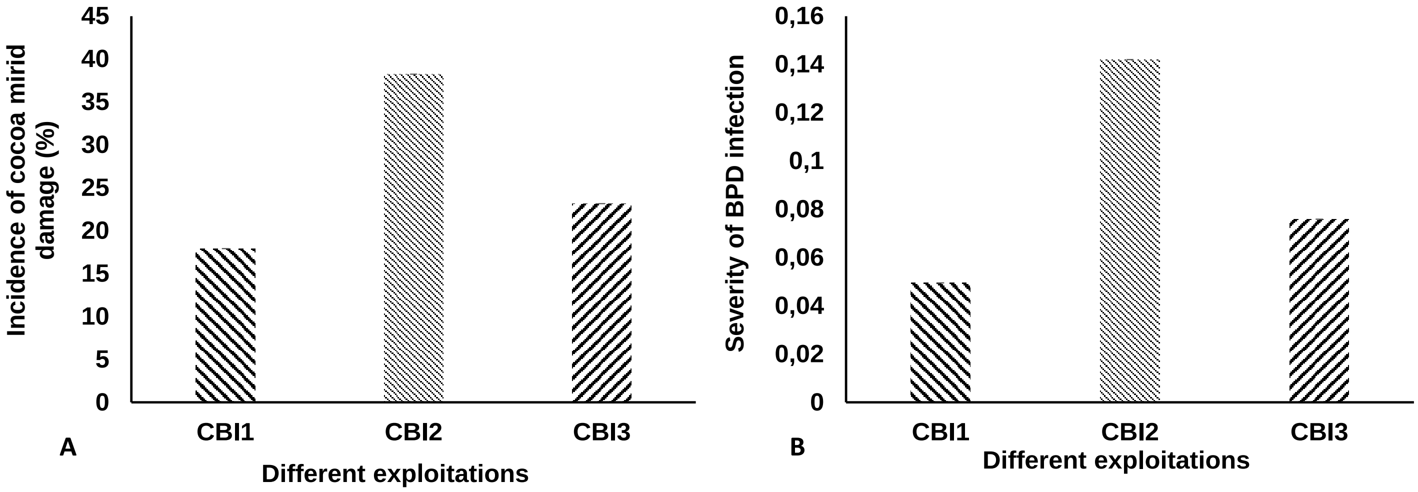

Figure 4 . *Mirid damage incidence (A) and severity (B) in individual cocoa farms (CBI1, CBI2, CBI3) treated with bioinsecticide (BT), recommended chemical insecticide (PC), or under farmer control (NC). Bars represent mean values per farm; error bars indicate ± standard deviation. Different letters above bars within each farm panel indicate significant differences between exploitation (post-hoc pairwise comparisons, Tukey contrasts, p < 0.05).*

3.3. *Cocoa tree productivity*

Globally cocoa productivity means varied from 0.63 kg/tree in the farmer control plots to 0.80 kg/tree in the biopesticide plots. Cocoa plots treated with the recommended pesticides showed a productivity of 0.76kg/tree. The productivity in the biopesticide treatment was significantly higher than in the other two treatments (Figure 5).

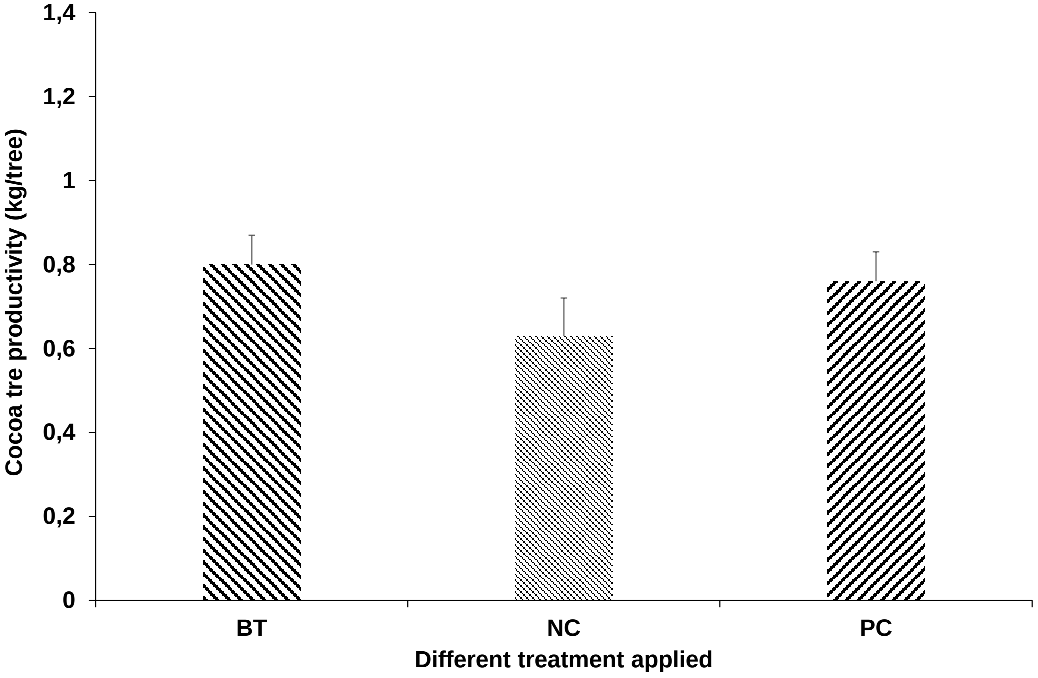

Figure 5. *Cocoa trees productivity according to treatment bioinsecticide (BT), recommended chemical insecticide (PC), or under farmer control (NC) across the three farms (CBI1, CBI2, CBI3 pooled). Bars represent mean values; error bars indicate ± standard deviation.*

Analysis of Generalized Linear Models (GLM) reveals that the effect of Exploitation is the main driver of variability for all structural and biodiversity parameters studied, while the effect of Treatment remains statistically insignificant for all variables. More specifically, exploitation highly significantly influences biomass, above ground carbon, and basal area, with a marked superiority of CB1 site over CB2 site, CB3 remaining intermediate. Cocoa productivity, tree cover (Shade Cover) and taxonomic diversity (Shannon Index) are also impacted by the exploitation factor, always with the superiority of CB1. Finally, a significant interaction between treatment and exploitation was observed only for biomass and above ground carbon (Table 3).

	Treatment	**Exploitation**	**Treatment*Exploitation**
Productivity	0.44	0.027*	0.51
Shade Cover	0.50	0,16*	0.74
Biomass	0.40	0.0049**	0.039*
Above Ground Carbon	0.40	0.0049**	0.040*
Basal Area	0.34	0,0044**	0.067
Shannon Index	0.97	0.036*	0.892

Table 3. *Results of Generalized Linear Models (GLM) and Tukey's HSD post-hoc run on attribute of associated trees stand and productivity according to the treatment and exploitation *: $p < 0.05$ significant.*

4. Discussion

The results demonstrate that bio-fungicides and chemical fungicides yield statistically comparable results in controlling Black Pod Disease (BPD) incidence and severity. This parity suggests that biological alternatives can reach the threshold of conventional chemical efficacy. Our findings align with [PUR, 18], who noted that *Trichoderma viride* enhances systemic resistance in plants. [MBA, 19] revealed similarity between the use of fungicide and local oil based-*Trichoderma asperellum* PR11 formulation in the consistent reduction of BPD in the field. The globally low severity (0.10–0.11) observed across all treatments suggests that all treatments effectively limited the progression of the disease within the pods, even if the infection was not entirely prevented. It should be noted, however, that these low severity values may have reduced the statistical power to detect treatment effects. The significant interaction between sites and treatment in damage incidence and severity confirms that the effectiveness of biopesticides depends strongly on the microclimate of the farm and, likely, on the vegetation structure of the sites. The Ntui area is a perfect example of the forest-to-savannah transition.

Although variability in BPD incidence and severity was observed among farms, no significant differences between the three treatments with respect to either incidence or severity. The significant difference between exploitation in term of Black Pod Disease damage incidence and severity could suggest that under specific environmental conditions—such as those found in the forest or savannah zone of Ntui—different treatment may outperform each them, highlighting the importance of vegetation structure in determining management response. The lower incidence of BPD at CBI2 compared to other sites can be attributed to its "full sun" position. As [MFE, 12] demonstrated, *Phytophthora* pressure is intrinsically linked to high humidity. The increased solar radiation at CBI2 likely reduced the ambient humidity, creating a sub-optimal environment for Oomycete sporulation.

Regarding mirid management, although numerical results showed a slightly lower incidence for chemical insecticides, the lack of statistically significant difference in treatment confirms that *B. bassiana*-based formulations are a viable alternative. Similarly, [HLE, 17] found no significant difference in insect damage on sweet potato between chemical treatment and spraying with *B. bassiana*. [MAH, 25] reported that the *B. bassiana* formulation with soybean oil significantly reduced mirid populations compared to the control group, by 100% thirty-six days after the application of the biopesticide, reducing associated damage [MAH, 25; AWU, 16].

The slight numerical advantage of chemical insecticides may be explained by the slower mode of action of entomopathogenic fungi (EPFs). Unlike the immediate neurotoxic effect of molecules like thiamethoxam or cypermethrin, the infection process of *B. bassiana* involves complex biological stages: adhesion, germination, penetration, and dissemination [MOH, 12]. This lag time explains why the reduction of mirids bites on cocoa pods is not immediate but takes time; then damages recorded in Biopesticide becoming comparable to chemical treatments over the duration of the trial. The higher incidence of mirid attacks at farm CBI2 (the sunniest farm) further validates the ecological observations of **[BAB, 09]**, who established that mirids prefer areas with maximum sunlight exposure.

The significant interaction between farm and treatment could indicate a variable response depending on local farm conditions.

Productivity levels were notably higher in the biopesticide treatment group, likely explained the by the combined health benefits associated with these formulations. This superiority suggests that biopesticides may offer a dual benefit: effective pest suppression and a reduction in the phytotoxic stress often associated with synthetic chemicals. The marked difference in coca productivity can also be attributed to the preservation of tree physiological health. The intensity of mirid damage can lead to leaf desiccation and directly affect tree productivity. **[PRA, 24]** demonstrated higher productivity for sweet potato tubers treated with the *Beauveria bassiana*-based biopesticide, reaching 43 t/ha compared to 20 t/ha with chemical treatment. Biological alternatives—often based on entomopathogenic fungi like *Beauveria bassiana*—tend to be more compatible with the tree's natural defense mechanisms.

Several factors can explain cocoa trees productivity in agroforestry systems, including cocoa and associated tree density and diversity **[VAN, 16]**, soil fertility **[NIJ, 19**; **SAU, 20]**, management practices **[JAG, 18; NDJ, 25]**. The variation in results across different exploitations (CBI1 vs. CBI2 and CBI3) highlights the influence of landscape-level factors and planting density. Further, previous land use can mitigate the effect of age on cocoa production. There is an increase in soil fertility on low clay content due to contribution of associated trees through residue addition **[NIJ, 19; FON, 24]**. The cocoa plantations studied were established under forest conditions (complex systems) that exhibit a good level of fertility, which is expected to remain relatively stable over time compared to simplified and very simplified systems, regardless of the treatments applied. In the case where no significant difference was found between treatments, it is possible that other limiting factors, such as light competition from shade trees or soil nutrient plateaus, masked the potential benefits of the biopesticides. The highly significant influence of the exploitation factor on biomass, above-ground carbon, and basal area highlights the critical role of site-specific conditions in determining the productive capacity of the ecosystem. While, the significant interaction treatment*exploitation, for responses biomass and above ground carbon, could suggest that treatment effectiveness may depend on specific conditions or history of each harvesting site, although this trend does not generalize to other indicators of forest structure.

Compared with chemical pesticides, the performance of biopesticides based on *T. asperellum* and *B. bassiana*, which offer an average productivity of 0.80 kg/tree, provides an alternative to chemical pest control in cocoa agroforestry systems in Ntui, Cameroon. This finding aligns with other studies that emphasize the potential of biopesticides to reduce the use of chemical pesticides in Cameroon's agricultural systems and, consequently, mitigate their adverse effects on human health and the environment [BAY, 24; SOU, 24; COT, 25; TEM, 25]. In addition to their technical performance, biopesticides present an economic opportunity, particularly for cash crops such as cocoa. Access to international markets hinges on compliance with restrictions on pesticide residues [ASS, 22; GAL, 21]. However, farmers must widely adopt biopesticides to capitalize on these benefits. Several levers must be activated to this end, including a regulatory framework, contextualized norms for homologating biopesticides, and support services to develop a local supply chain driven by private firms [SOU, 24; TEM, 25]. Additionally, comparative analysis over several years of the effects of biopesticides and their implications for agricultural labor mobilization and financial profitability is needed, especially in the Cameroonian context where local production of biopesticides is mostly in the prototype phase [TEM, 25].

5. Conclusion

We evaluated the effectiveness of locally formulated biopesticides based on *Beauveria bassiana* and *Trichoderma asperellum* strains against cocoa mirids and Black Pod Disease (BPD) under real farmer field conditions in Cameroon. The combined application of these two Biopesticide achieved results comparable to recommended chemical pesticides in terms of disease incidence (13.5% vs. 15.4%) and mirid damage (28.9% vs. 23.9%). Biopesticide plots in terms of overall productivity (0.80 kg/tree) outperformed both chemical (0.76 kg/tree) and farmer control (0.63 kg/tree) plots. Result also showed that the efficacy of these biological agents may depend on site-specific factors such as microclimate and vegetation structure—notably performing best in shaded forest environments. Although disease severity remained low across all treatments, limiting the statistical power to detect differences, the ability of biopesticides to maintain tree health and boost accessible yields without the environmental and health risks of synthetic chemicals is encouraging.

These results support the integration of locally formulated biopesticides into Integrated Pest Management (IPM) strategies, provided that future efforts focus on establishing regulatory frameworks and local supply chains to facilitate widespread farmer adoption and ensure long-term economic viability. The study shows that the combined application of *Trichoderma asperellum* and *Beauveria bassiana* represents a a promising and sustainable alternative to synthetic pesticides for managing Black Pod Disease and mirid pests in Cameroon’s cocoa agroforestry systems, with significant potential advantages in terms of environmental safety, human and animal health, and resistance management. However, future work is needed on optimizing formulation stability, shelf life and cost-benefit analysis to ensure recommendation and adoption by end users. This work lays the groundwork for a robust technical validation of biopesticides as a cornerstone of sustainable cocoa farming systems in Cameroon.

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