DAMAGE ASSESSMENT OF COCOA SWOLLEN SHOOT VIRUS DISEASE (CSSVD) ON COCOA PRODUCTION IN COCOA HEALTH AND EXTENSION DIVISION (CHED), COCOBOD, NHYINAHIN DISTRICT

By:
AMPRATWUM MUBARACK – ORCID: 0009-0002-5843-3127
MENSAH DOUGLAS – ORCID: 0009-0004-2206-0618
KOLAN DAWUDA - ORCID:
0009-0005-0549-4307

ABSTRACT
Cocoa Swollen Shoot Virus Disease (CSSVD) causes canopy loss and yield collapse in Ghana. This study assessed its prevalence and damage severity in 40 smallholder farms in CHED COCOBOD, Nhyinahin, Ashanti Region. Farms were stratified into 20 traditional and 20 hybrid, further grouped as young (<6 years) and mature (>10 years). Five visual indicators were scored: stem swelling (SS), red vein banding (VB), chlorosis (LC), dieback (DB) and mottled pods (MP).

Traditional farms had 100% prevalence and hybrid 95%. Pearson Chi-Square test showed no significant difference, $\chi^2(1) = 1.026$, $p = 0.311$. Infection intensity differed significantly by age, $F(3,36) = 7.72$, $p < 0.001$. Mature traditional (28.80 ± 11.20) and mature hybrid (27.50 ± 10.40) recorded higher composite scores than young traditional (16.00 ± 10.30) and young hybrid (11.40 ± 6.35). Damage severity did not differ by variety, $t(38) = 0.77$, $p = 0.445$, 95% CI [-4.78, 10.68].

Correlation analysis identified SS ($r = 0.90$) and VB ($r = 0.87$) as the strongest severity indicators. PCA explained 66.13% variance and HCA clustered farms by age, not variety. Mature farms are primary reservoirs requiring prioritized surveillance and barrier cropping.

Keywords: CSSVD, Theobroma cacao, CHED, prevalence, farm age, Ghana

CHAPTER ONE: INTRODUCTION

1.1 Background of the Study

The agricultural sector remains the cornerstone of Ghana's macroeconomy, with cocoa (*Theobroma cacao*) acting as the primary driver of rural economic growth, employment, and foreign exchange earnings. Ghana is globally recognized for producing premium-quality bulk cocoa, sustaining the livelihoods of over 800,000 smallholder farming families. However, the sustainable production of this strategic cash crop is severely threatened by persistent phytosanitary challenges. Among these, Cocoa Swollen Shoot Virus Disease (CSSVD) stands out as the most destructive viral threat to cocoa yields and tree survival across West Africa.

CSSVD is caused by a complex of badnavirus species within the family *Caulimoviridae*. These are plant viruses containing non-enveloped, bacilliform particles with a double-stranded DNA genome. The virus is transmitted natively by semi-persistent mealybug vectors belonging to the family *Pseudococcidae*. In Ghanaian cocoa landscapes, species such as *Planococcus citri*, *Formicococcus nialensis*, and *Ferrisia virgata* are the primary vectors responsible for spreading the virus.

Once inoculated into host tissue, CSSVD causes severe structural and physiological damage. It disrupts chlorophyll synthesis, reduces vascular nutrient transport, and limits resource allocation. This leads to characteristic symptoms including nodal or internodal stem swelling, root necrosis, foliar chlorosis, red vein banding on young flushes, distorted mottled pods, systemic canopy dieback, and eventual tree death within two to five years.

To combat this epidemic, the Ghana Cocoa Board (COCOBOD), through its Cocoa Health and Extension Division (CHED), has implemented several intervention policies. These include wide-scale eradication programs ("cut-and-replant" strategies) and the distribution of early-maturing, high-yielding hybrid cocoa varieties. These hybrids are designed to outpace historical yield baselines and exhibit improved vigor under field conditions. However, despite these continuous investment cycles, CSSVD outbreaks remain a critical problem in highly endemic areas like the Nhyinahin District of the Ashanti Region.

1.2 Problem Statement

Despite institutional interventions and continuous financial investments by COCOBOD, Cocoa Swollen Shoot Virus Disease outbreaks continue to expand in the Nhyinahin District, directly threatening smallholder income stability and overall regional yields. Although the Cocoa Health and Extension Division actively promotes early-maturing hybrid varieties, these modern fields show widespread infection. This situation highlights a distinct lack of empirical, field-level data on how genetic variety and farm lifecycle stages interact to drive disease progression.

1.3 Justification of the Study

The persistence of Cocoa Swollen Shoot Virus Disease (CSSVD) in the Nhyinahin District highlights a critical gap between institutional breeding expectations and smallholder field realities. This study justifies empirical field-level research to optimize extension allocations, refine replanting policies, and secure vulnerable smallholder livelihoods. By establishing a clear metric-driven approach to tracking damage severity, COCOBOD can shift from broad reactive cutting programs to localized, preventative vector containment strategies, maximizing the structural survival rates of newly established farms.

1.4 Goal of the Study

The overarching goal of this study is to quantify the field-level epidemiological footprint and

structural damage severity of Cocoa Swollen Shoot Virus Disease (CSSVD) within smallholder farming systems in the Nhyinahin District of CHED, COCOBOD. By establishing an empirical baseline, this research aims to provide actionable insight into how farm maturation cycles and genetic selections interact to influence disease dynamics.

1.5 Research Objectives

To achieve the primary goal, the study is guided by the following specific objectives:

- To determine and compare the absolute prevalence rates of CSSVD between traditional cocoa varieties and modern hybrid varieties within the Nhyinahin District.
- To evaluate the influence of farm age profile (young vs. mature) and genetic variety (traditional vs. hybrid) on composite infection intensity scores.
- To identify and rank the strongest visual diagnostic symptoms that drive cumulative damage assessments.
- To map and cluster local farm typologies using multivariate analysis to isolate the primary viral reservoirs requiring prioritized surveillance.

1.6 Research Hypotheses

Based on the field-level objectives and the statistical design of the study, the following hypotheses were tested:

- **Hypothesis 1:**
  - *Null Hypothesis (H_0):* There is no significant difference in absolute CSSVD prevalence rates between traditional and hybrid smallholder farms.
  - *Alternative Hypothesis (H_1):* There is a significant difference in absolute CSSVD prevalence rates between traditional and hybrid smallholder farms.
- **Hypothesis 2:**
  - *Null Hypothesis (H_0):* Infection intensity scores do not differ significantly based on the age profile of the farm.
  - *Alternative Hypothesis (H_1):* Infection intensity scores differ significantly based on the age profile of the farm, with mature stands recording higher values.
- **Hypothesis 3:**
  - *Null Hypothesis (H_0):* Hybrid varieties exhibit significantly lower damage severity scores than traditional varieties under field conditions.
  - *Alternative Hypothesis (H_1):* Damage severity scores do not differ significantly

between traditional and hybrid varieties once infection is established.

1.7 Significance of the Study

This research bridges the gap between controlled research station trials and the practical realities of smallholder cocoa farming in the Ashanti Region.

- **For CHED-COCOBOD Administrators:** It provides a data-driven framework to optimize extension efforts and prioritize the "cut-and-replant" rehabilitation policy in areas identified as primary viral reservoirs.

- **For Extension Officers:** It ranks the most accurate visual diagnostic markers (Stem Swelling and Red Vein Banding), helping field teams identify infections early before severe canopy loss occurs.
- **For Smallholder Farmers:** It highlights how farm maturity acts as a disease reservoir, paving the way for community-based containment programs and barrier-cropping designs that protect new investments.

1.8 Scope of the Study

This study was conducted within smallholder cocoa farms in the Nhyinahin District, an operational zone under the Cocoa Health and Extension Division (CHED) of COCOBOD in the Ashanti Region of Ghana.

- **Analytical Scope:** The study focuses on evaluating five macroscopic visual symptoms of CSSVD: stem swelling (SS), red vein banding (VB), leaf chlorosis (LC), canopy dieback (DB), and mottled pods (MP).

- **Population Scope:** The assessment was balanced across 40 randomly selected smallholder farms divided equally by genetic background (20 traditional, 20 hybrid) and age profile (20 young at <6 years, 20 mature at >10 years).

- **Exclusions:** Molecular identification of specific badnavirus strains and detailed chemical soil analyses were outside the scope of this field-level assessment.

1.9 Organization of the Study

This research paper is structured into six distinct chapters: Chapter One (Introduction) outlines the study foundations; Chapter Two (Literature Review) frames the theoretical and empirical baseline; Chapter Three (Materials and Methods) maps the experimental architecture; Chapter Four (Results) details analytical scores; Chapter Five (Discussion) interprets patterns; and Chapter Six concludes with concrete action plans.

CHAPTER TWO: LITERATURE REVIEW

2.0 Introduction

This chapter provides a comprehensive review of the theoretical and empirical literature

surrounding Cocoa Swollen Shoot Virus Disease (CSSVD) and its impact on *Theobroma cacao* production systems. It establishes a multi-dimensional baseline that links ecological theories with practical field epidemiology. By reviewing badnavirus pathology, vector behaviors, host plant genetics, and farm structural aging, this chapter clarifies the mechanisms that drive the high CSSVD saturation observed within smallholder configurations in the Nhyinahin District of Ghana.

2.1 Theoretical Framework: Habitat Selection Theory

The spatial propagation and field-level severity of CSSVD can be explained through Fretwell's **Habitat Selection Theory** (specifically the Ideal Free and Ideal Despotic Distribution models), adapted to plant-insect-pathogen micro-ecosystems. In an agricultural landscape, the host plant canopy acts as a living habitat for the primary mealybug vectors (*Pseudococcidae* family). According to Habitat Selection Theory, insect vectors do not distribute themselves randomly across a landscape. Instead, they actively select habitats that maximize fitness, reproductive capacity, and protection from environmental stressors. In smallholder cocoa systems, mature farms with dense, interlocking canopies create an ideal habitat. This structure offers a stable microclimate, protection from heavy rainfall, and food sources from mature vascular tissues. As mealybugs settle into these preferred habitats, they create dense populations that accelerate the transmission of semi-persistent badnaviruses. This theoretical framework underscores that managing CSSVD requires looking beyond individual plant biology to address the broader structural dynamics of the farm habitat.

2.2 Empirical Review

2.2.1 Global Distribution and Economic Impact of CSSVD

CSSVD is recognized as the most economically damaging viral disease affecting cocoa globally, restricted primarily to West African producing nations, notably Ghana, Côte d'Ivoire, and Togo. First identified in the Eastern Region of Ghana in 1936, the disease has expanded from a localized infection into a widespread regional epidemic. Within individual smallholder farms, systemic infection causes typical yield losses between 15% and 50%, which can escalate to complete collapse within two to three years as canopy dieback progresses.

2.2.2 Biology and Transmission Ecology of the Virus-Vector Complex

The disease is caused by a complex of badnavirus species within the *Caulimoviridae* family. These plant viruses are characterized by non-enveloped, bacilliform particles containing a circular, double-stranded DNA genome. Transmission occurs via semi-persistent mealybug vectors, including *Planococcoides njalensis*, *Planococcus citri*, and *Ferrisia virgata*. These insects feed on the sap of all plant parts, including leaves, stems, cherelles, and pods.

2.2.3 Infection Patterns in Hybrid and Traditional Cocoa Systems

In response to the vulnerability of traditional Amelonado cocoa selections, breeding programs

introduced high-yielding Upper Amazon hybrids. These hybrid lines are designed for improved field vigor, rapid canopy establishment, and early pod production. However, field evaluations show that these hybrids exhibit high infection rates under intense regional disease pressure. While hybrids may grow faster during their early years, they still show high infection rates when established near older, active disease reservoirs.

2.2.4 Visual Symptoms and Damage Classification Metrics
Field identification relies on identifying macroscopic symptoms caused by viral replication in plant tissues:

- **Stem Swelling (SS):** Hypertrophied nodal or internodal tissues along branches or chupons, indicating severe cambial disruptions.
- **Red Vein Banding (VB):** Anthocyanin accumulation outlining leaf veins, visible during early leaf flush cycles.
- **Leaf Chlorosis (LC):** Interveinal clearance patterns caused by disrupted chlorophyll production.
- **Dieback (DB):** Progressive necrosis moving from terminal shoots downward through the canopy.
- **Mottled Pods (MP):** Growth distortions, mosaic patterns, and reduced pod size.

2.2.5 Comparative Analysis of Variety Susceptibility
Comparative studies show that traditional Amelonado selections lack effective tolerance mechanisms, leading to rapid tissue death once infected. Modern Upper Amazon hybrids often show a delayed onset of severe symptoms due to high early tree vigor. However, long-term statistical evaluations demonstrate that this vigor does not significantly reduce ultimate tissue damage or lower absolute prevalence rates under high vector pressure.

2.2.6 Influence of Farm Age Cohorts on Disease Progression
Farm age is a primary structural driver of CSSVD epidemiology. Mature farms (>10 years old) feature closed, interlocking canopies that allow mealybugs to move easily from tree to tree, facilitating rapid contact transmission. These older fields often accumulate asymptomatic infections over time, turning them into high-volume viral reservoirs.

2.2.7 Environmental and Cultural Practices Driving Outbreaks
The spread of CSSVD is influenced by local environmental conditions and farming practices. High tree density and the absence of non-host barrier crops allow vector populations to grow unchecked. Shade management also plays a role. Research indicates an optimal canopy shade around 45% to 53% helps to balance tree stress and vector activity.

2.2.8 Surveillance, Integrated Management, and Policy Frameworks
COCOBOD’s historic management policy has centered on the "cut-and-replant" eradication strategy. Modern management frameworks favor Integrated Vector Management (IVM). This approach combines early visual diagnosis, targeted chemical controls for mealybug populations,

maintaining optimal shade canopies, and establishing non-host barrier crops.

2.3 Conceptual Framework

Figure 2.1 presents the conceptual framework for CSSVD damage assessment. Independent Variables consist of Host Factors (Farm Age: Young / Mature, Variety: Hybrid / Traditional), Pathogen Factors (Strain Virulence 1A/1B, Inoculum Pressure), and Environmental Factors (Mealybug Density, Ant Mutualism, Alternative Hosts: Ceiba / Cola). These are filtered through Intervening / Moderating Factors Plantation Indices (Canopy Shade, Nesting Structures), Climatic Profiles (Rainfall, Temperature 24-30°C), and Management Variables (CHED IPDM, Farm Sanitation, Cutting-out Enforcement).

The Process is the Epidemiological Pipeline: Mealybug crawler movement → Phloem sap feeding → Viral incubation → Area-wide transmission. This leads to Outcomes: Infection Levels (Low / Moderate / High), Visual Damage Severity (Red Vein Banding, Leaf Chlorosis, Stem Swellings, Mottled Pods), and Agroecosystem Degradation (Canopy Dieback, Yield Collapse, Socioeconomic Shocks).

A Feedback Loop returns Field Assessment Data → CHED Extension Monitoring → Cutting-out Schedules.

This study operationalizes Host Factors and Visual Damage Severity (SS, VB, LC, DB, MP). Pathogen, Environmental and Intervening factors are retained as contextual moderators from literature (Ollennu 1989; Andres et al. 2018).

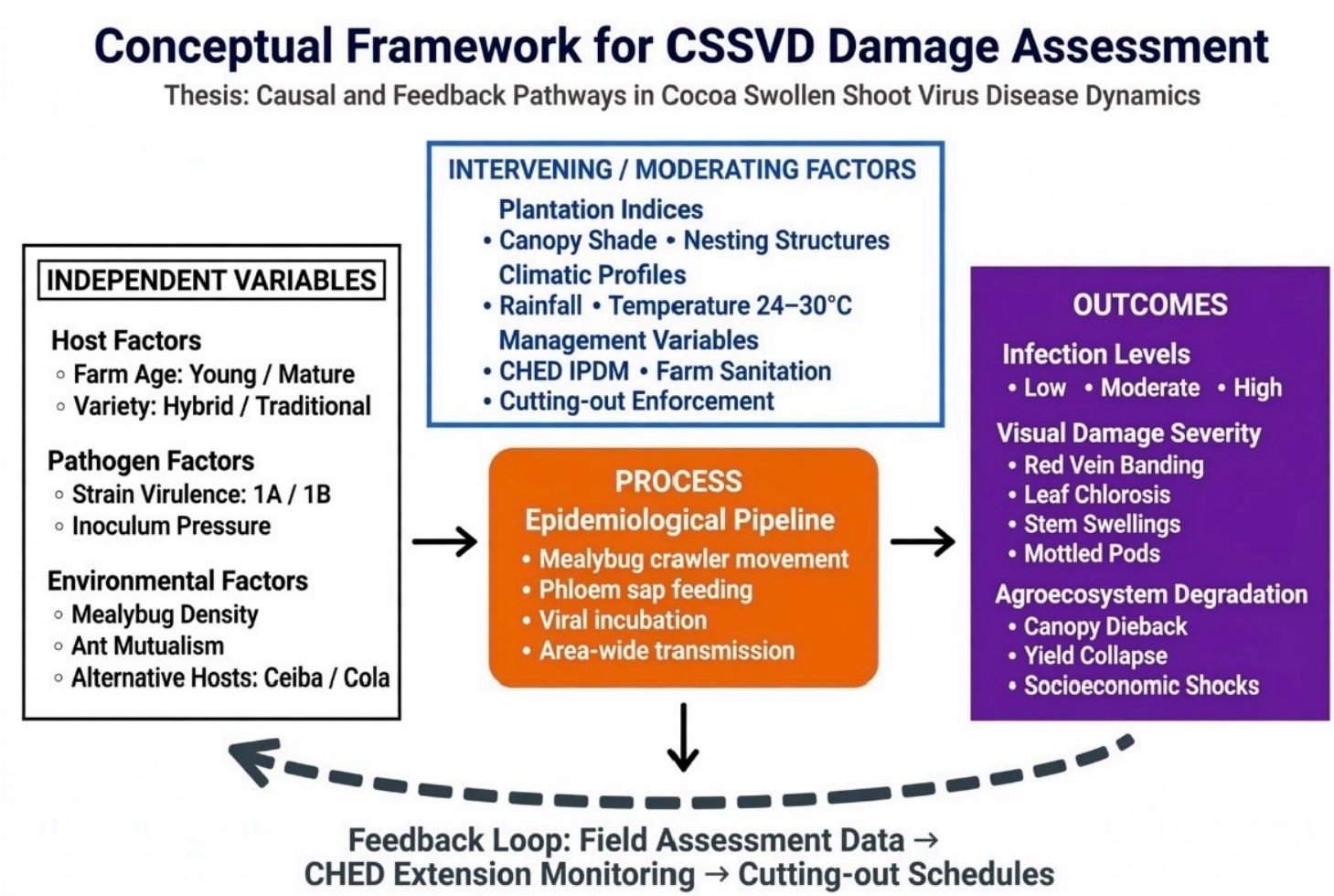


Figure 2.1: Conceptual Framework for CSSVD Damage Assessment – Causal and Feedback Pathways

CHAPTER THREE: MATERIALS AND METHODS

3.0 Introduction

This chapter outlines the structured scientific methodology deployed to evaluate the prevalence, infection intensity, and structural damage severity of Cocoa Swollen Shoot Virus Disease (CSSVD) within the Nhyinahin District of the Ashanti Region.

3.1 Study Area

The study was conducted within the cocoa-growing communities of the Nhyinahin District under the jurisdiction of CHED, COCOBOD in the Ashanti Region of Ghana. The area falls within the moist semi-deciduous forest ecological zone, characterized by a bimodal annual rainfall pattern ranging from 1,200 mm to 1,800 mm. The relative humidity remains high, averaging between 75% and 85%, and temperatures fluctuate between 22°C and 32°C.

3.2 Study Design

This study utilized a cross-sectional, comparative field epidemiological survey design reinforced

by quantitative multivariate statistical modeling. The design evaluated two primary independent factors across smallholder farms: Genetic Variety Accession and Farm Lifecycle Age Profile.

3.3 Sampling Technique
A multi-stage stratified random sampling framework was deployed to isolate operational smallholder farm units across the Nhyinahin district.

- *Cohort A:* Young Traditional Farms (<6 years old; n = 10)
- *Cohort B:* Young Hybrid Farms (<6 years old; n = 10)
- *Cohort C:* Mature Traditional Farms (>10 years old; n = 10)
- *Cohort D:* Mature Hybrid Farms (>10 years old; n = 10)

3.4 Materials Used
Field materials included handheld GPS receivers, digital macro-lens cameras, calipers for tracking internodal swellings, and standardized field logs operating within mobile digital collection formats.

3.5 Data Collection

3.5.2 Visual Inspection for CSSVD Symptom Indicators
Field monitoring utilized a systematic diagonal transect method across each of the 40 farms. Within each farm setup, twenty trees were randomly selected and marked along the transect lines to score five symptoms: Stem Swelling (SS), Red Vein Banding (VB), Leaf Chlorosis (LC), Canopy Dieback (DB), and Mottled Pods (MP).

3.5.3 Standardization of the Disease Damage Scoring System
To turn visual observations into quantifiable metrics, an ordinal, five-tier diagnostic scoring matrix was applied to every individual symptom indicator on each sampled tree: Score 0 (Absent), Score 1 (Mild), Score 2 (Moderate), and Score 3 (Severe Systemic).

3.5.4 Documentation and Electronic Data Processing
Field records were normalized daily and backed up to standardized analytical sheets, preventing alphanumeric recording discrepancies across multiple test fields.

3.6 Data Analysis
Statistical models executed included Pearson Chi-Square ($\chi 2 \chi 2$) for testing absolute presence parity, One-Way ANOVA ($F F$) for parsing multi-group age variances, Independent Samples t-test ($t t$) for isolating direct genetic effects, and PCA/HCA multivariate combinations.

3.7 Quality Assurance Measures
Observer validation was kept uniform to remove subjective variance in visual indexing, and all processing equipment underwent rigorous phytosanitary washes using 70% isopropyl alcohol between locations.

3.8 Ethical Considerations
Formal clearances were verified through CHED COCOBOD regional heads. Verbal informed consent was secured from every individual smallholder prior to farm transect indexing.

3.9 Chapter Summary
The experimental approach combined robust stratification metrics with non-parametric and parametric configurations to track CSSVD dynamics across balanced environmental categories.

CHAPTER FOUR: RESULTS

4.1 Introduction
This chapter presents the statistical outputs and analytical findings derived from the epidemiological field data gathered across 40 smallholder cocoa farms in the Nhyinahin District of CHED, COCOBOD.

4.2 Prevalence of CSSVD Infection
Field surveillance data revealed widespread saturation of CSSVD across the district. Out of the 20 traditional smallholder farms sampled, all 20 farms exhibited active viral symptoms (100% prevalence). Among the 20 modern hybrid configurations evaluated, 19 farms displayed active infections (95% prevalence).
The Pearson Chi-Square contingency analysis yielded:
$\chi 2(1) = 1.026$, $p = 0.311$ $\chi 2(1) = 1.026$, $p = 0.311$ Because $p > 0.05$, there is no statistically significant difference in absolute CSSVD prevalence rates between traditional and hybrid smallholder farms.

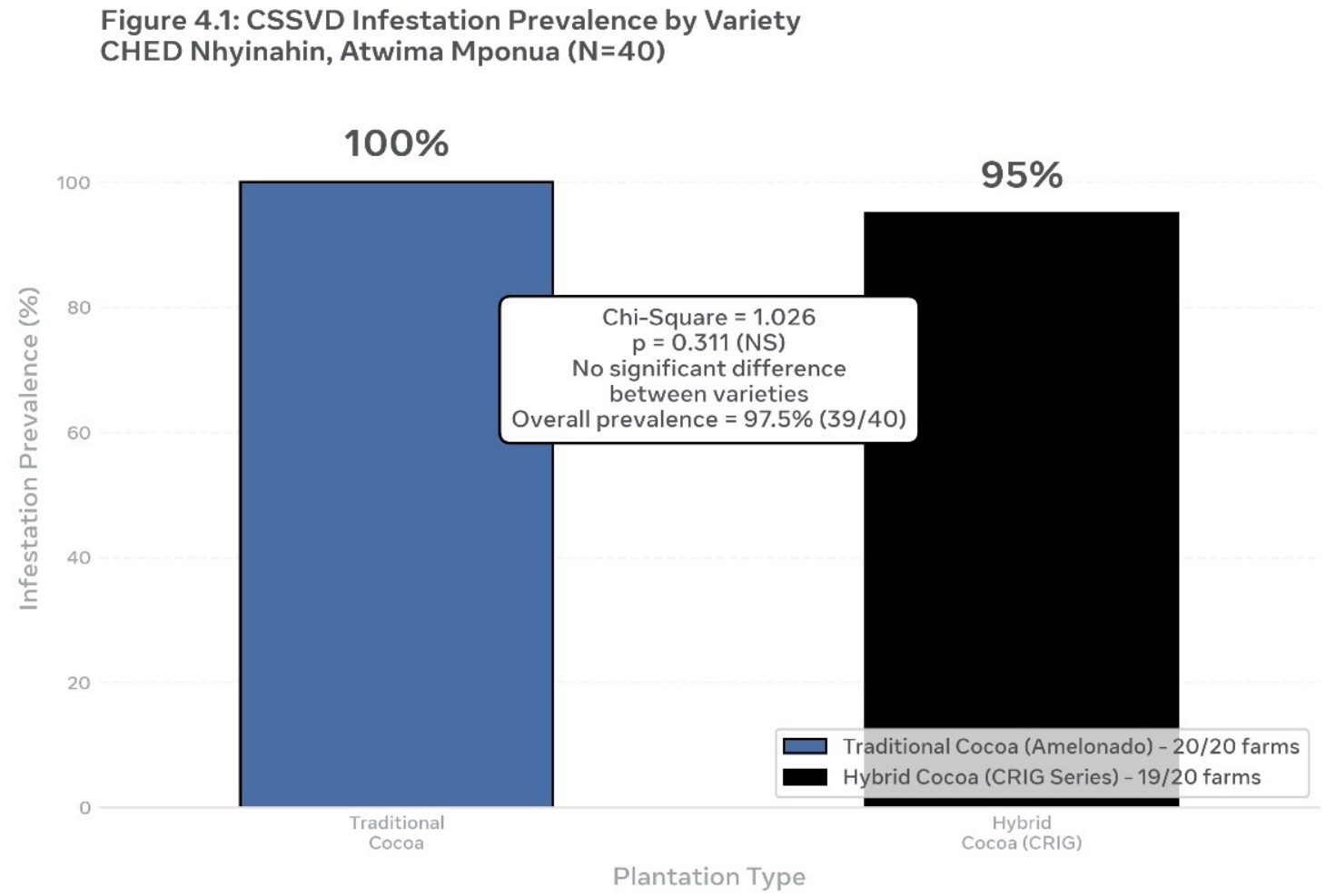


Figure 4.1: CSSVD Infestation Prevalence by Variety CHED Nhyinahin, Atwima Mponua (N=40)

4.3 Infection Indicators Across Variety and Farm Age Groups

Older fields consistently recorded elevated structural scores, particularly along lignified segments showing pronounced internodal swellings. Conversely, younger setups recorded early indicators such as red vein banding on fresh flushes, while showing minor core wood transformations.

4.4 Damage Severity Distribution

The individual symptom scores were aggregated to generate a Composite Infection Intensity Score for each farm. Mature fields concentrated toward the upper end of the damage scale, while younger fields remained clustered around lower to moderate values.

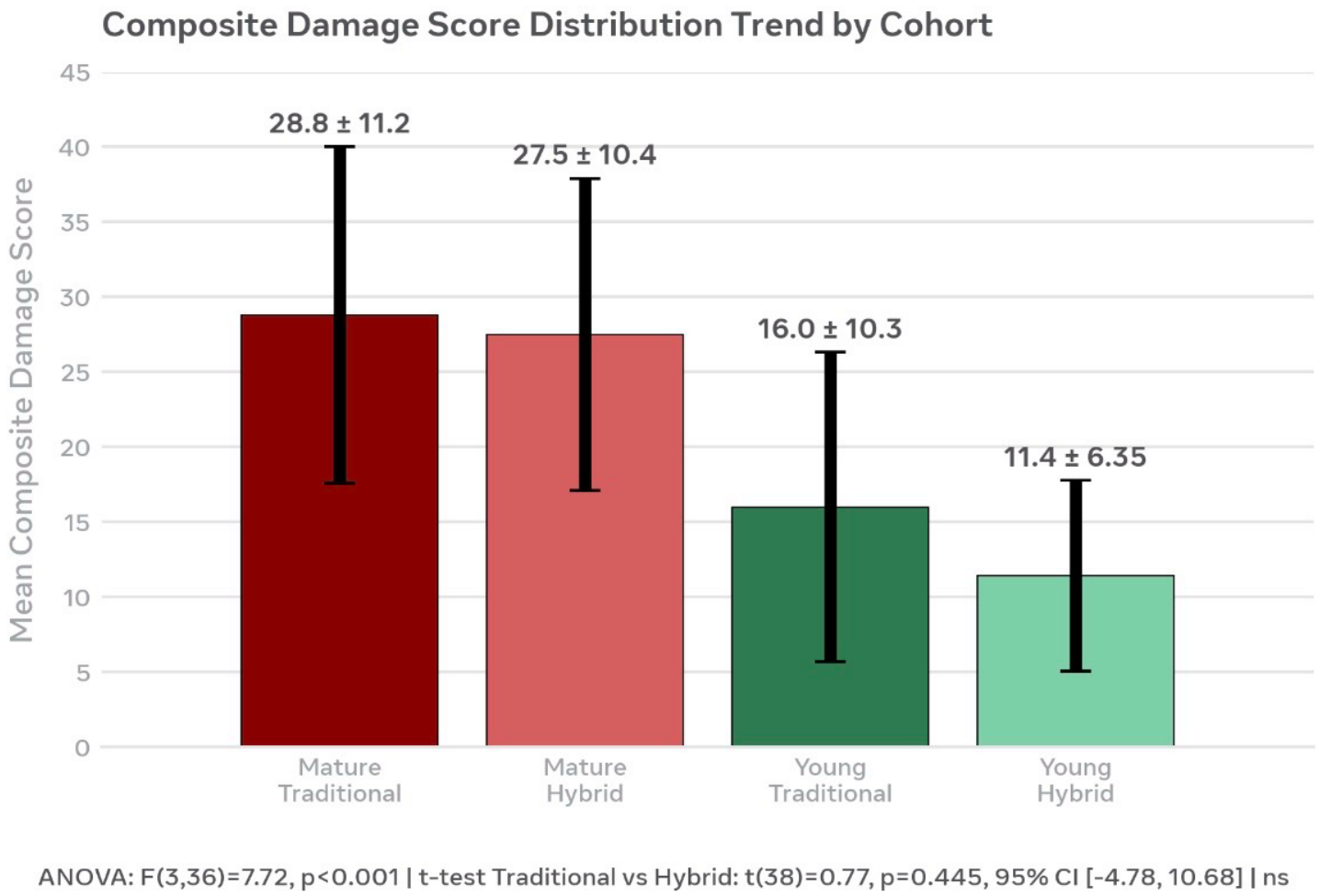


Figure 4.1: Composite Damage Score Distribution Trend by Cohort

4.5 Comparison of Damage Severity Scores
The One-Way Analysis of Variance (ANOVA) confirmed a highly significant difference in infection intensity across the groups:
$F(3,36) = 7.72$, $p < 0.001$

The mean composite scores and standard deviations highlight this gap: Mature Traditional (28.80 ± 11.20), Mature Hybrid (27.50 ± 10.40), Young Traditional (16.00 ± 10.30), and Young Hybrid (11.40 ± 6.35).

Distribution of damage category

Mild damage highest (14 farms, 35%). No Damage 22.5% (9), Moderate 22.5% (9), Severe 20% (8). 77.5% show damage symptoms, but 97.5% are infected.

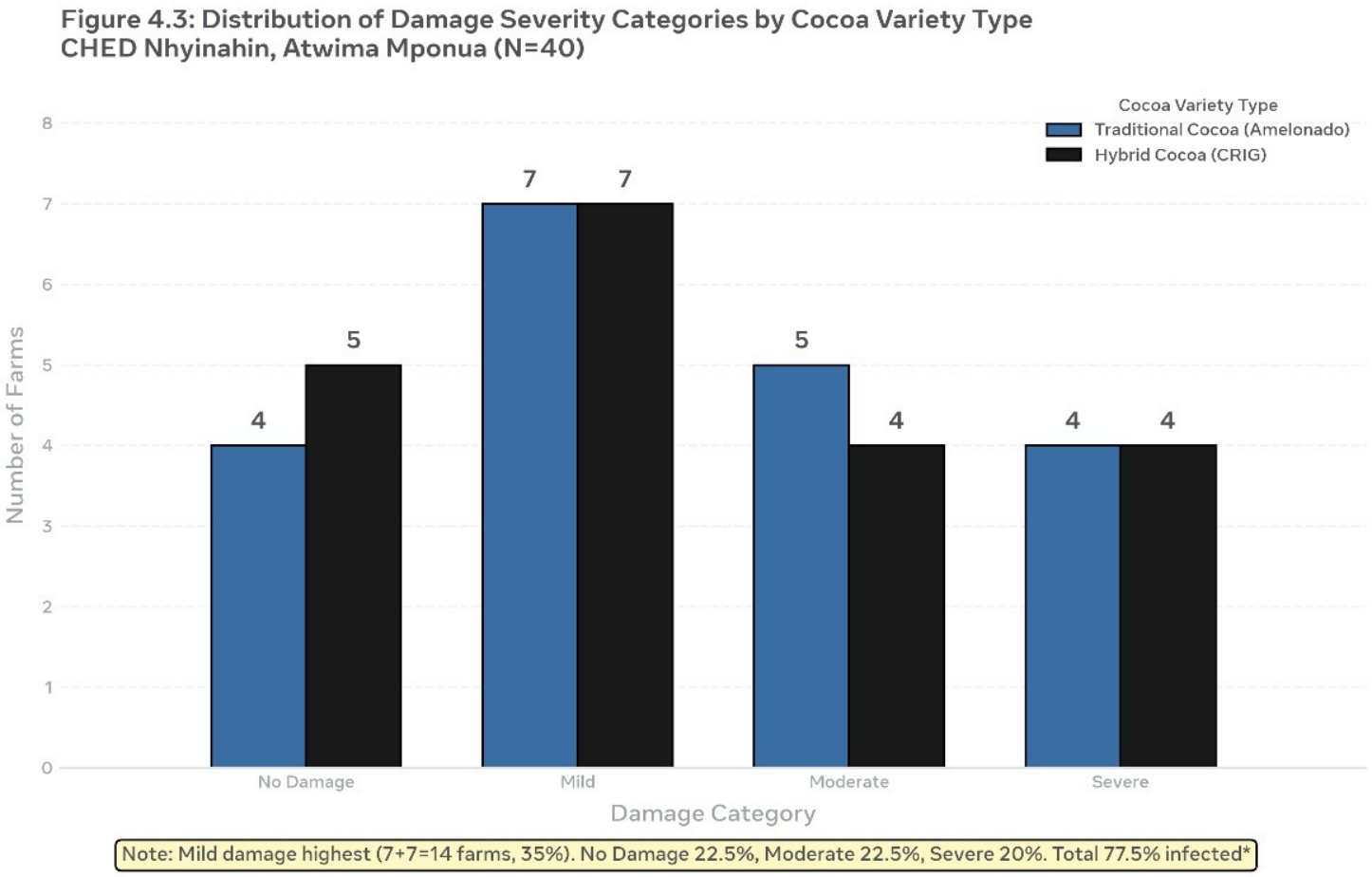


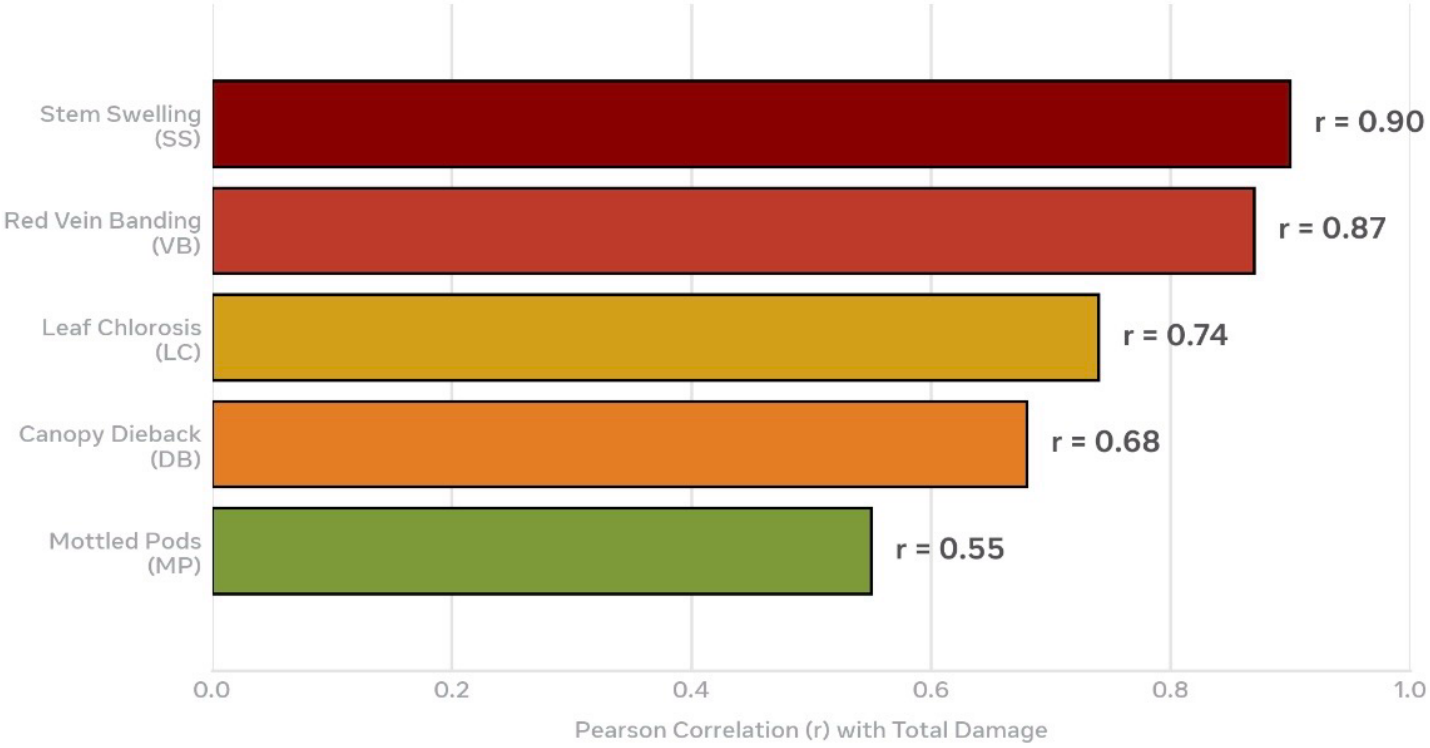
Figure 4.3: Distribution of Damage Severity Categories by Cocoa Variety Type

The Independent Samples t-test directly comparing all traditional farms against all hybrid setups yielded:
t(38) = 0.77, p = 0.445, 95% CI [-4.78, 10.68]

Because p > 0.05, hybrid varieties do not achieve a significant reduction in tissue damage severity compared to traditional crops once an infection is established.

4.6 Correlation Analysis
The analysis identified Stem Swelling as the strongest overall indicator (r = 0.90), followed closely by Red Vein Banding
(r = 0.87).

Figure 4.4: Correlation Strength of Visual Symptoms with Total Damage



Visual Diagnostic Symptom	Pearson Correlation (r) with Total Damage	Statistical Strength Profile	Field Utility Ranking
Stem Swelling (SS)	r = 0.90	Very Strong Positive	Primary Diagnostic Indicator
Red Vein Banding (VB)	r = 0.87	Very Strong Positive	Early Warning Flush Marker
Leaf Chlorosis (LC)	r = 0.74	Strong Positive	Secondary Interveinal Marker
Canopy Dieback (DB)	r = 0.68	Moderate-to-Strong Positive	Advanced Structural Decliner
Mottled Pods (MP)	r = 0.55	Moderate Positive	Crop Yield Impact Indicator

4.7 Principal Component Analysis (PCA)

The first two principal components accounted for 66.13% of the total cumulative sample variance, heavily driven by the co-loading behaviors of Stem Swelling and Red Vein Banding across the spatial orientation axes.

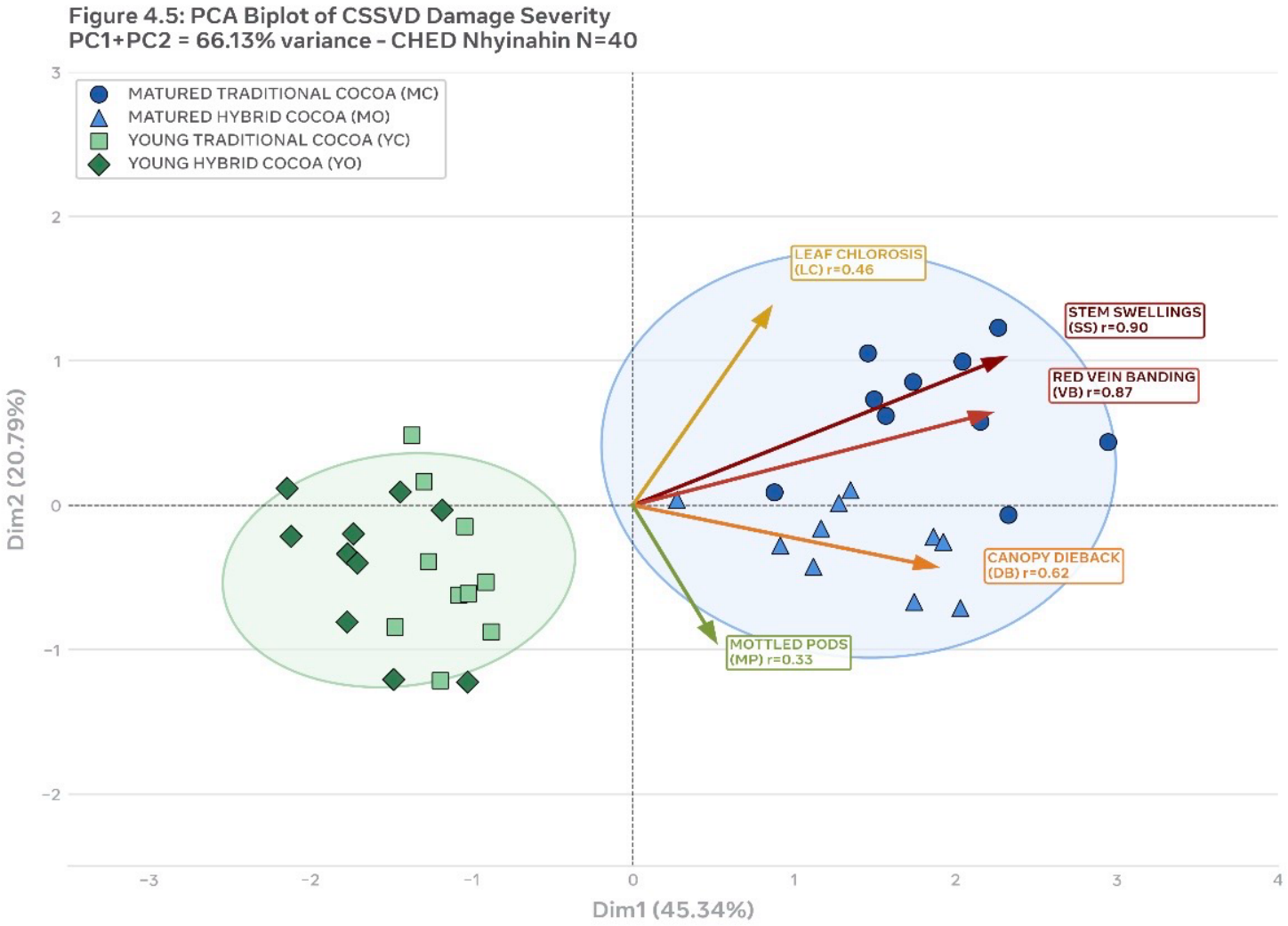
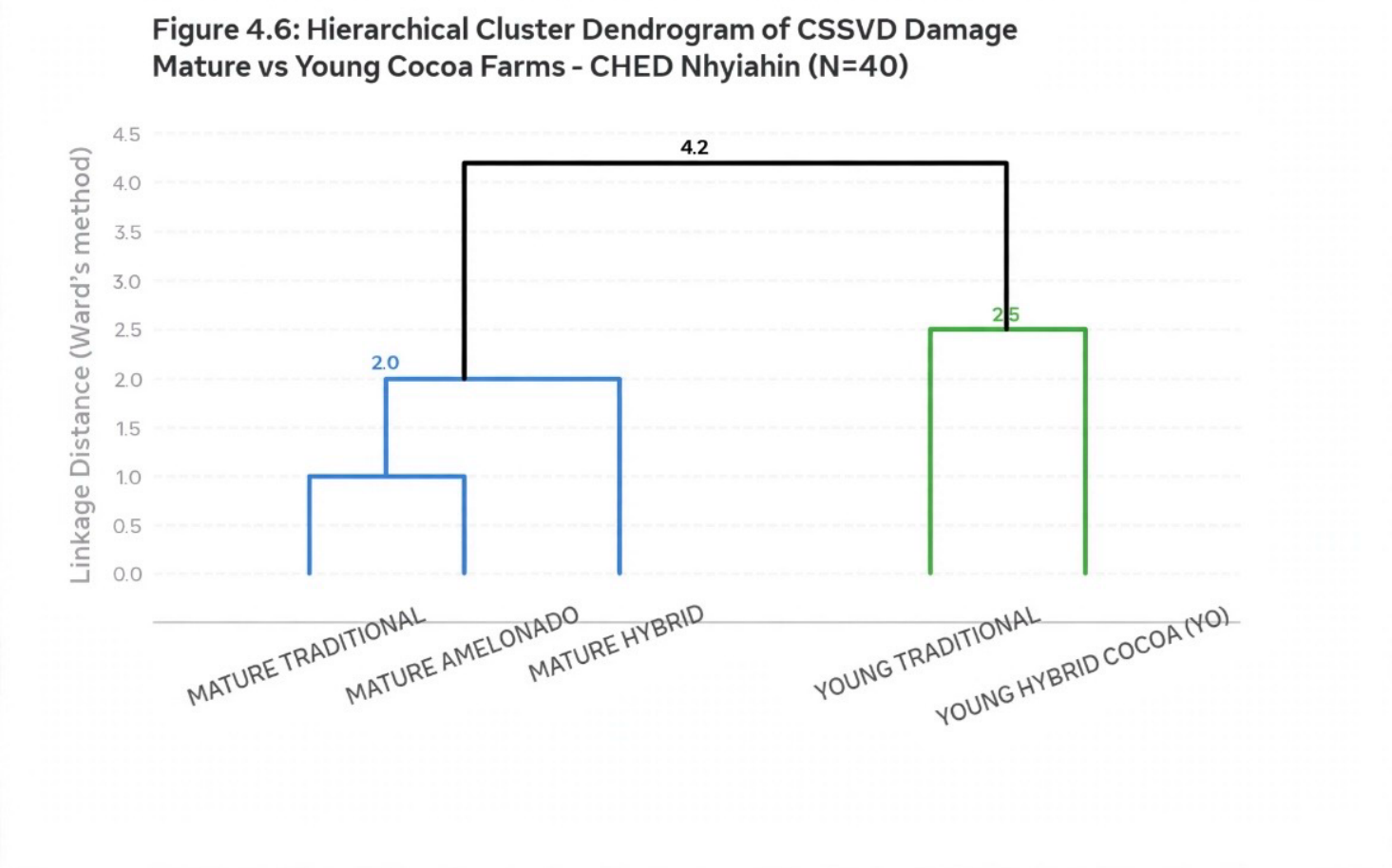


Figure 4.3: PCA Biplot of CSSVD Damage Severity
PC1+PC2 = 66.13% variance - CHED Nhyinahin N=40

4.8 Hierarchical Cluster Analysis (HCA)

The resulting dendrogram split the 40 farms into two primary clusters defined by operational farm age profile rather than genetic variety, reinforcing that canopy maturity dictates local landscape risk factors.



Interpretation: MC & MO cluster at 2.0 = Mature farms have identical viral profile regardless of variety. YC & YO cluster at 2.5 = Young farms similar. Final split at 4.2 = Dataset partitions by AGE not VARIETY (supports ANOVA F=7.72, p<0.001).

4.9 Chapter Summary

Widespread disease distribution is uniform by variety (p = 0.311), but tissue destruction maps tightly to farm age profile (p < 0.001), identifying mature setups as core reservoirs.

CHAPTER FIVE: DISCUSSION

5.0 Discussion

The absolute prevalence rates recorded 100% across traditional Amelonado farms and 95% within modern hybrid configurations reveal a severe viral saturation in the Nhyinahin District.

The non-significant outcome of the Pearson Chi-Square test ($\chi^2(1) = 1.026$, $p = 0.311$) directly challenges the assumption that deploying modern hybrid varieties alone can mitigate viral transmission under intense field pressure. This aligns with recent epidemiological warnings from West African cocoa systems, which observe that while Upper Amazon hybrids exhibit strong

agronomic vigor and early canopy establishment, they lack absolute genetic immunity to infection when exposed to high vector populations.

The highly significant variance revealed by the One-Way ANOVA ($F(3,36) = 7.72$, $p < 0.001$) underscores that the physical progression of the disease is driven by the structural maturity of the farm landscape, not by variety.

The elevated mean composite score observed in mature traditional (28.80 ± 11.20) and mature hybrid (27.50 ± 10.40) cohorts indicates that older fields serve as highly saturated environmental reservoirs for the virus. This can be explained using Fretwell's Habitat Selection Theory. Over years of uninterrupted growth, mature farms develop dense, interlocking canopies that create an ideal habitat for mealybug vectors (Pseudococcidae), protecting them from heavy rains and solar radiation. These stable conditions facilitate continuous contact transmission between adjacent trees.

Conversely, the younger cohorts recorded lower composite infection scores (Young Traditional: 16.00 ± 10.30; Young Hybrid: 11.40 ± 6.35). This lower baseline reflects their younger age and shorter exposure history, rather than permanent genetic resistance.

This interpretation is supported by the Independent Samples t-test ($t(38) = 0.77$, $p = 0.445$), which showed no statistically significant difference in damage severity between traditional and hybrid varieties once infected. This suggests that the physiological impact of viral replication affects both genetic blocks similarly over time.

CHAPTER SIX: CONCLUSION AND RECOMMENDATIONS

6.1 Conclusion

This study establishes that CSSVD is widespread across both traditional and hybrid smallholder cocoa systems in the Nhyinahin District, with absolute prevalence rates reaching 100% and 95%, respectively.

The statistical analyses demonstrate that while current hybrid selections do not significantly reduce viral infection rates ($\chi^2(1) = 1.026$, $p = 0.311$) or post-infection tissue damage ($t(38) = 0.77$, $p = 0.445$) compared to traditional options, the structural maturity of the farm serves as the major driver of disease severity ($F(3,36) = 7.72$, $p < 0.001$).

Mature farms with dense, closed canopies (28.80 ± 11.20 and 27.50 ± 10.40) function as primary

reservoirs for the virus and its mealybug vectors within the agricultural landscape. Younger farms (16.00 ± 10.30 and 11.40 ± 6.35) show lower damage only because of shorter exposure time, not because of genetic immunity.

Visual diagnosis should prioritize Stem Swelling (r = 0.90) as the primary indicator and Red Vein Banding (r = 0.87) as the early warning marker.

6.2 Recommendations

1. Targeted Replanting Policies:
CHED, COCOBOD should prioritize its "cut-and-replant" rehabilitation resources toward mature fields with composite damage scores above 25. Removing these older, high-volume reservoirs is essential to lower viral pressure on surrounding fields.

2. Establish Non-Host Barrier Strips:
When replanting cleared blocks with young hybrids, farmers should be encouraged to plant non-host barrier crops (such as Citrus species or targeted agroforestry trees) along field borders. These strips help disrupt the movement of mealybug vectors across open ground.

3. Community Early Warning Networks:
Extension teams should train local farming groups to recognize early diagnostic symptoms, such as Red Vein Banding on new leaf flushes. Catching infections early allows for faster intervention before severe stem swelling develops.

4. Integrated Vector Management (IVM):
Field practices should combine early visual monitoring with selective chemical vector controls and active shade management to keep mealybug populations below damaging thresholds.

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