

Research Article

Whitefly–Natural Enemy Dynamics and Cassava Mosaic Disease Evaluated Under Field Condition in Sierra Leone

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Abstract

Bemisia tabaci is a major pest of cassava in sub-Saharan Africa, causing yield losses through direct feeding and its role in transmitting cassava mosaic disease (CMD). Natural enemies such as lacewings, ladybird beetles, and spiders provide valuable biological control services, yet their interactions with different whitefly developmental stages and plant structural traits remain insufficiently characterized. This study examined the dynamics among natural enemies, whitefly eggs, nymphs, adults, and plant height across 3, 6, 9, and 12 months after planting (MAP) under field conditions. The trial was conducted under natural cassava production conditions during 2020/2021 cropping season at the upland experimental site of the School of Agriculture and Food Sciences, Njala University. A total of 270 cassava genotypes comprising 268 local varieties and 2 improved checks (SLICASS 4 and SLICASS 6) were laid out in an augmented randomized design with four blocks. Results showed that lacewings and spiders strongly tracked nymph and adult whitefly populations, while ladybird beetles showed weaker associations. Principal Component Analysis (PCA) revealed alignment of predators with pest pressure during mid- and late season, whereas plant height exhibited minimal influence. Findings underscore the central role of lacewings and spiders in early and sustained suppression of whitefly populations, highlighting the importance of conservation-based integrated pest management (IPM) strategies. Findings serve as useful guide for conservation biological control as a primary IPM strategy for the enhancement of habitats for effective predators (lacewings and spiders) of the whitefly through reduced pesticide use, ground vegetation retention, intercropping, and maintenance of natural refuge habitats.

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Received: 11 December 2025; **Accepted:** 25 December 2025; **Published:** 19 January 2026



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Keywords

Natural Enemies, Whitefly Developmental Stages, Cassava Mosaic Disease, Prevalence, Correlation, Cassava

1. Introduction

Bemisia tabaci (Gennadius) (Hemiptera: Aleyrodidae) is an insect pest species complex that causes widespread damage to cassava cultivated around the globe including Africa [1, 2]. *Bemisia tabaci* directly damages the cassava during fecundation, and the excretion of a sugar-rich honey dew acts as a substrate for development of sooty mould that reduces both respiration and photosynthesis [3]. In addition, the *B. tabaci* serves as a vector of many plant viruses that cause the cassava mosaic disease (CMD) and cassava brown streak disease (CBSD), that in combination lead to significant storage root yield loss in cassava [4, 5]. Despite substantial efforts deployed in developing virus-resistant cassava genotypes, more research efforts aimed at understanding the whitefly vector, which can reduce yields by 40% are still needed [6]. This disproportionation technique to managing insect vectored plant diseases is usual, leading to management strategies that are unsustainable.

Arthropod parasitoids and predators are ubiquitous and operate continuously on all life stages of the *B. tabaci*, and function as control factors in the process. Biological control strategy often targets better exploitation of this behavior in order to more effectively manage pests and reduce insecticide use. Biological control of whiteflies and other pests has been pursued through observation and utilization of natural enemies [7], through analysis of existing agroecosystems [8] or through search for and introduction of natural enemies [9], indicating which key factors control the pest. Natural enemies such as lacewings (Chrysopidae), ladybird beetles (Coccinellidae), and spiders (Araneae) can significantly reduce whitefly populations through predation on eggs, nymphs, and occasionally adults. Lacewings have been known for their voracious larval feeding on soft-bodied insects [10], whereas spiders function as generalist predators capable of suppressing early pest colonization [11]. On the other hand, Ladybird beetles exhibit broader prey preferences, which may reduce their functional overlap with whitefly control [12]. Implementation of the biological control has resulted from habitat manipulation to favor or conserve existing species, introduction of new species, and mass rearing and release of both [7, 9, 13, 14].

The choice of which natural enemy or combination to use, and whether to only conserve the existing complex or augment numbers or species is often complex. Decisions should be made only after analysis of the efficacy of present pest-enemy interactions, including specific observations and life-table analytical studies. For instance, Naranjo *et al.* [12, 15] have shown, using life table analysis, a marked influence of factors

such as plant species upon effectiveness of the natural enemy complex in managing *B. tabaci*.

The driving force behind conducting biological studies on *B. tabaci* enemies is, in addition to overall scientific interest, the desire to improve pest control. This is reflected in both the organisms studied and the kinds of studies conducted. Predators that have proven to be readily exploitable for mass culture— and manipulation in greenhouse agriculture— have been used most often in mass rearing and behavior investigations following host plant and compatibility studies. Studies on parasitoids, of which only three species have been commercially employed so far, incorporate several additional well-known and “hopeful” species. These studies include additional basic behavioral observations disclosing why these species do not always provide adequate control. Indigenous predators and parasitoids are present and active in all agroecosystems, even if in low numbers.

A number of factors, working either in isolation or combination, influence the abundance of *B. tabaci* in cassava [16]. These factors include the biotic (cassava cultivar, cassava age, cassava virus infection status, non-cassava host plants, natural enemies, competition with other herbivores and endosymbionts), abiotic (altitude, climate and weather) and other factors such as pesticides and hybridization [16]. Over the years, whitefly outbreaks have intensified due to climate variability, changing cropping systems, and expansion of susceptible cassava cultivars [17]. Plant structural traits, including height and canopy architecture, have also been noted to influence predator access, microhabitat suitability, and whitefly colonization [18]. However, dearth of information exists on the prevalence of natural enemies of whitefly developmental stages and the degree to which plant height shapes seasonal predator-prey interactions in cassava. In the present study, it was hypothesized that functional relationship exists among whitefly developmental stages, natural enemies and cassava mosaic disease (CMD) across key cassava growth phases. Moreover, Predator Abundance influences whitefly population dynamics under field conditions. The unraveling of such knowledge would contribute to conservation biological control that is imperative in the IPM strategy for the suppression of pest populations. Thus, the objective of this study was to assess the prevalence of natural enemies of whitefly developmental stages and cassava mosaic disease in cassava grown under field conditions.

2. Materials and Methods

2.1. Experimental Site

The field trial was established at the upland experimental site of the School of Agriculture and Food Sciences Experimental site, Njala University, Njala Campus, Njala, Southern Sierra Leone during the 2020/2021 cropping season. The site is located at an elevation of approximately 50 meters above sea level, at latitude 8°6' N and longitude 12°6' W. The experimental site is predominantly covered by secondary bush vegetation. The area experiences a rainy season from April to November and a dry season extending from October to May. The soil type, temperature range, and prevailing humidity during the experimental season were typical of cassava-producing regions in sub-Saharan Africa and comparable to environmental conditions noted in previous whitefly-CMD epidemiological studies [19, 20]. The region experiences a wet season from May to October, with rainfall often exceeding 2,000 mm annually, while temperature ranges between 25–29 °C and a dry season from November to April, marked by reduced precipitation and occasional dry winds [2].

2.2. Experimental Material, Design, Layout and Management

The experimental materials included stem cuttings of 268 cassava genotypes, collected from all districts of Sierra Leone and 2 improved released varieties (SLICASS 4 and SLICASS 6) utilized as checks. The experiment was laid out in an augmented randomized design with four blocks, each measuring 28 m × 10 m with 1 m distance between the blocks. This enabled robust assessment of block effects (microenvironment) and treatment effects (genotype), consistent with modern entomological field methods [22]. The total experimental area utilized was 43 m × 28 m. About 10 stem cuttings per genotype, each measuring 30 cm in length, were planted on a standard plot size of 10 m long ridges while uniform plant-to-plant and row spacing was used 1 m × 1 m spatial arrangement. No irrigation was done and manual weeding schedule was employed monthly with no fertilizer and pesticide application to avoid interference with the natural whitefly vectors and the resultant disease dynamics. Sampling took place at 3, 6, 9, and 12 months after planting (MAP), representing early, mid, peak, and late cassava growth stages.

2.3. Data Collection

2.3.1. Assessment of Whitefly Developmental Stages and Natural Enemies

Whitefly eggs, nymphs, and adults were counted directly from the abaxial surfaces of leaves following standard procedures recommended for cassava entomological surveillance [23]. Using a hand lens with 20x magnification, large and visible whitefly

nymphs between the central and left-side main veins on the underside of the fifth main stem were tallied across experimental sites [24]. Ten leaves per plant (top, middle, bottom strata) were assessed to capture vertical distribution.

Natural enemies such as lacewings (Chrysopidae), ladybird beetles (Coccinellidae), and spiders (Araneae) were visually counted on sampled plants. Predators were identified to family level using field keys developed by Kumar et al. [25]. Sampling was conducted during morning hours to minimize disturbance.

2.3.2. Assessment of Cassava Mosaic Virus Infection and Plant Height Parameters

CMD severity was scored on a 1–5 scale using the IITA standard scoring system [26]. Incidence was calculated as the percentage of plants showing symptoms within each plot.

Plant height was measured from soil surface to the apical meristem using a meter rule. Plant height was included as a plant architectural variable influencing pest and predator dynamics [27].

2.4. Statistical Analysis

The principal component analysis (PCA) of the key traits studied was done using the stats and factoextra packages [28] and the correlation coefficient for the association between different traits in R version 1.0.5.999 [29]. The PCA was carried out to explore multivariate structure and identify dominant interactions. The statistical significance of the correlations was determined based on the standard guideline by Ratner [30] where sets of traits with r -values ranging from 0 – 0.3 = weak positive or low color intensity, 0.3 – 0.7 medium positive or medium color intensity, and from 0.7 – 1 = strong positive or high color intensity; whereas those ranging from 0 – -0.3 = weak negative or low color intensity, -0.3 – -0.7 medium negative or medium color intensity, and from -0.7 – -1 = strong negative linear relationship or high color intensity. ANOVA was used to determine block and treatment effects on natural enemy abundance [31].

3. Results

3.1. Correlation Among Whitefly Developmental Stages and Natural Enemies

Whitefly developmental stage infestation and natural enemies' parameters show dynamic correlations across the four growth phases of cassava (3, 6, 9 and 12-MAP) (Table 1). As the crop ages, these correlations were observed to change, providing insight on pest pressure and the role of natural enemies throughout sampling time. At 3 MAP (the early growth stage of the crop), whitefly nymphs and whitefly eggs had a medium positive association ($r = 0.63^{***}$), suggesting early reproductive buildup or coordinated development between both life stages, whereas adults exhibited weak positive correlations with lacewing, lady bird beetle, and spider. Additionally,

there is a weak positive correlation between adult whiteflies and nymphs ($r = 0.22^{***}$) and eggs ($r = 0.13^*$), indicating that early infestation is well established throughout all stages.

Table 1. Correlation coefficient among whitefly developmental stages and natural enemies sampled at 3, 6, 9 and 12 MAP.

Trait	LW	LBB	SP	NWE	NWN	NWA
Correlation coefficient at 3 MAP						
LW	1.00					
LBB	0.06	1.00				
SP	0.22 ^{***}	0.16 [*]	1.00			
NEW	0.09	0.09	0.15 [*]	1.00		
NWN	0.21 ^{***}	0.19 ^{**}	0.23 ^{***}	0.63 ^{***}	1.00	
NWA	0.13 [*]	0.15 [*]	0.23 ^{***}	0.13 [*]	0.22 ^{***}	1.00
Correlation coefficient at 6 MAP						
LW	1.00					
LBB	0.17 ^{***}	1.00				
SP	0.12 [*]	0.17 ^{***}	1.00			
NEW	0.10	0.07	0.14 [*]	1.00		
NWN	0.21 ^{***}	0.11	0.10	0.40 ^{***}	1.00	
NWA	0.22 ^{***}	0.05	0.17 ^{***}	0.22 ^{***}	0.49 ^{***}	1.00
Correlation coefficient at 9 MAP						
LW	1.00					
LBB	0.23	1.00				
SP	0.22 ^{***}	0.33 ^{***}	1.00			
NEW	-0.07	-0.15 [*]	0.08	1.00		
NWN	0.12	0.09	0.13 [*]	0.24 ^{***}	1.00	
NWA	0.28 ^{***}	0.08	0.07	0.13 [*]	0.59 ^{***}	1.00
Correlation coefficient at 12 MAP						
LW	1.00					
LBB	0.34 ^{***}	1.00				
SP	0.43 ^{***}	0.47 ^{***}	1.00			
NEW	0.16 ^{**}	0.42 ^{***}	0.30 ^{***}	1.00		
NWN	0.35 ^{***}	0.24 ^{***}	0.26 ^{***}	0.03	1.00	
NWA	0.42 ^{***}	0.24 ^{***}	0.30 ^{***}	-0.001	0.42 ^{***}	1.00

*, **, and *** = significant at $p < 0.05$, 0.01 , 0.001 , respectively; LW=lacewing, LBB=lady bird beetle, SP=spider, NWE=number of whitefly eggs, NWN=number of whitefly nymph, NWA=number of whitefly adults

Interestingly, adult whiteflies had a weak and positive correlation with number of whitefly adults ($r = 0.13^*$), ladybird beetles ($r = 0.15^*$) and spider ($r = 0.23^{***}$), respectively, suggesting that pest pressure is influenced by the occurrence,

prevalence and activities of natural enemies. At 6-MAP, correlation patterns changed considerably. Adult whiteflies and nymphs ($r = 0.49^{***}$), and between the eggs and nymphs ($r = 0.40^{***}$) had a positively intermediate correlations, whereas

their associations with their natural enemies were relatively weak positive ($r < 0.30$), highlighting the extent of influence of the natural enemies on the pest pressure. At 9-MAP, Correlations between natural enemy parameters and whitefly stages started to declining the mid-reproductive stage. The total strength of the correlations between adult whiteflies and nymphs ($r = 0.59^{***}$) and illness severity ($r = 0.17^{**}$) decreases. Additionally, a modest decrease in the correlation between severity and incidence ($r = 0.17^{**}$) was observed suggesting a possible change in host resistance or disease progression.

Pest pressure was increasingly indicative of outcomes of the natural enemies at the transitional phase. The correlation between number of adult whitefly and ladybird beetle occurrence increased from $r = 0.13^*$ (3 MAP), $r = 0.22^{***}$ (6 MAP), $r = 0.28^{***}$ (9 MAP) to ($r = 0.42^{***}$) at 12-MAP, the late growth stage, highlighting the incremental effect of ladybird beetle natural enemy on whitefly insect attacks. The correlations between adult whiteflies and ladybird beetle ($r = 0.42^{***}$), spiders ($r = 0.30^{***}$), number of whitefly nymphs ($r = 0.42^{***}$); and between spiders and ladybird beetles ($r = 0.47^{***}$), between spiders and lacewing ($r = 0.43^{***}$); between ladybird beetle and lacewing ($r = 0.34^{***}$); and between spiders and number of whitefly eggs ($r = 0.30^{***}$) were intermediately positive. Findings imply that, especially during the early and late phases of cassava development, tracking the numbers of whitefly and their natural enemies may be a useful early warning system for their infestation and resultant disease outbreaks caused by the vector insects.

3.2. Variability in Whitefly Developmental Stages and Natural Enemies

The principal component analysis (PCA) illustrates how natural enemies, different developmental stages of whitefly, and plant height at 3 months after planting (MAP) are classified into primary components that account for the variability in the dataset (Table 2). The PC1, PC2, and PC3 had the highest eigenvalues (2.092, 1.659, and 1.312), and together represent approximately 56% of the total variance, with PC1 accounting for 23.2%, PC2 for 18.4%, and PC3 for 14.6%. Smaller eigenvalues, such as those for PC8 and PC9, contributed little and mainly captured minor variations. PC1 is heavily linked to whitefly stages, particularly nymphs and eggs, along with spiders and lacewings, signifying that these variables are the most significant contributors to the primary variation axis. PC2 is primarily influenced by disease severity mean and incidence, indicating that this component reflects the effect of CMD. PC3 is predominantly associated with plant height, demonstrating that growth performance is measured separately from pest pressures. Other components such as PC4 and PC5 reveal particular associations; for instance, ladybird beetles and spiders exhibit negative values, while plant height and lacewings show moderate associations. In summary, the analysis indicates that whitefly developmental stages and natural enemies are the principal factors driving variation in the system, whereas indicators of plant health like severity and incidence form a separate dimension, and plant height represents another distinct axis of variability.

Table 2. Variabilities in natural enemies and whitefly development stages sampled at 3 months after planting.

Variable	PC1	PC2	PC3	PC4	PC5	PC6	PC7	PC8	PC9
PHT	0.227	0.055	0.719	0.107	0.483	0.024	0.418	0.007	0.093
LW	0.503	0.244	0.352	0.48	0.054	0.373	0.415	0.113	0.07
LBB	0.428	0.084	0.231	0.786	0.06	0.325	0.151	0.017	0.078
SP	0.537	0.066	0.17	0.019	0.73	0.041	0.378	0.032	0.013
NEW	0.654	0.145	0.528	0.094	0.289	0.005	0.223	0.189	0.308
NWN	0.763	0.193	0.418	0.065	0.137	0.053	0.067	0.191	0.373
NWA	0.473	0.293	0.337	0.057	0.02	0.705	0.269	0.056	0.039
CMDS	0.269	0.841	0.04	0.011	0.005	0.163	0.023	0.404	0.167
CMDI	0.106	0.857	0.139	0.198	0.011	0.142	0.014	0.374	0.19
EV	2.092	1.659	1.312	0.916	0.875	0.794	0.64	0.393	0.319
PV	23.25	18.44	14.58	10.18	9.72	8.82	7.11	4.36	3.54
CV	23.25	41.68	56.26	66.44	76.16	84.98	92.09	96.46	100

*PHT=plant height, LW=lacewing, LBB=lady bird beetle, SP=spider, NWE=number of whitefly eggs, NWN=number of whitefly nymph, NWA=number of whitefly adults, CMDS= cassava mosaic virus severity, CMDI=cassava mosaic virus incidence, EV=eigen values, PV=proportion of variance, CV=cumulative variance.

At 6 MAP, PC1 had an eigenvalue of 2.567, accounting for the highest share of variance (28.5%), primarily influenced by stages of whiteflies, their severity, and incidence (Table 3). PC2 and PC3, which have eigenvalues of 1.273 and 1.030, contributed 14.1% and 11.4%, respectively, reflecting the impact of natural enemies like ladybird beetles and spiders. Collectively, the first three components encompassed over 54%

of the overall variability, signifying that whitefly development and pest pressure were the primary factors, whereas plant height and specific predators exhibit stronger associations on subsequent components with lower eigenvalues, thereby contributing less to the total variation.

Table 3. Variabilities in natural enemies and whitefly development stages sampled at 6 months after planting.

Variable	PC1	PC2	PC3	PC4	PC5	PC6	PC7	PC8	PC9
PHT	-0.150	0.411	-0.151	0.772	0.328	0.277	-0.052	0.013	0.045
LW	0.375	0.382	0.280	0.135	-0.659	0.288	0.316	-0.003	0.024
LBB	0.170	0.604	0.435	0.061	0.043	-0.607	-0.198	0.065	0.015
SP	0.253	0.483	0.226	-0.501	0.476	0.389	0.107	-0.100	-0.051
NEW	0.463	0.271	-0.623	-0.096	0.094	-0.265	0.430	0.223	0.025
NWN	0.710	0.141	-0.386	0.018	-0.132	-0.071	-0.255	-0.487	-0.046
NWA	0.707	0.012	-0.118	-0.093	-0.104	0.256	-0.497	0.392	-0.007
CMDS	0.760	-0.369	0.256	0.103	0.211	-0.026	0.110	-0.053	0.387
CMDI	0.718	-0.361	0.268	0.281	0.184	-0.068	0.182	0.031	-0.362
EV	2.567	1.273	1.030	0.977	0.886	0.825	0.695	0.459	0.289
PV	28.53	14.14	11.44	10.85	9.84	9.16	7.72	5.10	3.22
CV	28.53	42.67	54.11	64.97	74.806	83.97	91.69	96.79	100

*PHT=plant height, LW=lacewing, LBB=lady bird beetle, SP=spider, NWE=number of whitefly eggs, NWN=number of whitefly nymph, NWA=number of whitefly adults, CMDS= cassava mosaic virus severity, CMDI=cassava mosaic virus incidence, EV=eigen values, PV=proportion of variance, CV=cumulative variance.

The PCA of natural enemies and the developmental stages of whiteflies at 9 MAP indicates that the initial five components collectively accounted for approximately 78% of the total variation, while the subsequent components contributed less (Table 4). The PC1, with an eigenvalue of 2.269, repre-

sents 25.2% of the variance and is characterized by high positive values from factors such as severity mean, the number of whitefly adults, the number of whitefly nymphs, and incidence. This shows that PC1 embodies the aspect of whitefly infestation intensity and disease severity mean, effectively capturing the overall pressure imposed by the pest population.

Table 4. Variabilities in natural enemies and whitefly development stages sampled at 9 months after planting.

Variable	PC1	PC2	PC3	PC4	PC5	PC6	PC7	PC8	PC9
PHT	-0.081	0.332	0.399	0.599	0.464	0.378	0.076	0.022	-0.029
LW	0.317	0.653	0.131	0.33	-0.06	-0.565	0.016	-0.131	0.08
LBB	0.307	0.572	-0.475	-0.213	-0.073	0.207	0.507	0.057	0.001
SP	0.289	0.571	-0.112	-0.461	0.391	0.082	-0.45	0.035	-0.052
NEW	0.262	-0.289	0.489	-0.405	0.523	-0.252	0.322	0.058	-0.013
NWN	0.691	-0.038	0.432	-0.178	-0.254	0.289	-0.02	-0.345	0.187

Variable	PC1	PC2	PC3	PC4	PC5	PC6	PC7	PC8	PC9
NWA	0.715	0.04	0.38	0.071	-0.383	0.031	-0.07	0.408	-0.14
CMDS	0.722	-0.317	-0.351	0.226	0.151	-0.033	-0	-0.215	-0.365
CMDI	0.637	-0.343	-0.434	0.248	0.267	-0.014	-0.07	0.161	0.354
EV	2.269	1.494	1.295	1.039	0.956	0.661	0.579	0.383	0.323
PV	25.21	16.60	14.39	11.55	10.63	7.34	6.44	4.25	3.59
CV	25.21	41.81	56.20	67.75	78.37	85.72	92.15	96.41	100

*PHT=plant height, LW=lacewing, LBB=lady bird beetle, SP=spider, NWE=number of whitefly eggs, NWN=number of whitefly nymph, NWA=number of whitefly adults, CMDS= cassava mosaic virus severity, CMDI=cassava mosaic virus incidence, EV=eigen values, PV=proportion of variance, CV=cumulative variance.

The PC2, with an eigenvalue of 1.494 and 16.6% of the variance, is closely linked to the populations of lacewings, ladybird beetles, and spiders, clearly reflecting the abundance of natural enemies. The third component, possessing an eigenvalue of 1.295 and explaining 14.4% of the variance, indicates positive relationships with plant height, whitefly eggs, and nymphs, while showing negative associations with ladybird beetles and incidence, suggesting a trade-off between plant growth and the initial pest stages on one side and the presence of predators and disease incidence on the other. The fourth component, which has an eigenvalue of 1.039 accounting for 11.5% of the variance, highlights plant vigor, as evidenced by its strong positive relationship with plant height, while contrasting with spider activity and egg density.

The PCA on natural enemies and the various developmental stages of whiteflies at 12 MAP revealed that the first four components collectively accounted for approximately 71.8% of the overall variability, while the remaining components had smaller percentage contributions (Table 5). The primary principal component, which has an eigenvalue of 2.528 accounting for 28.1% of the variance, is significantly influenced by

strong positive associations from lacewing (0.719), ladybird beetle (0.698), spider (0.744), as well as whitefly adults (0.623) and nymphs (0.592). This suggests that PC1 reflects the relationship between predator abundance and the pressure exerted by the whitefly population. The second principal component, with an eigenvalue of 1.738 being responsible for 19.3% of the variance, is marked by very high associations from severity mean (0.888) and incidence (0.869), indicating that PC2 represents the aspects of disease severity and incidence. The third component, possessing an eigenvalue of 1.212 and accounting for 13.5% of the variance, is notably linked to whitefly eggs (0.723) and ladybird beetles (0.344), while showing negative associations with nymphs (-0.457) and adults (-0.456), demonstrating a contrast between early pest stages versus later pest stages or the presence of predators. The fourth component, with an eigenvalue of 0.984 and explaining 10.9% of the variance, is predominantly characterized by plant height (0.959), signifying that PC4 illustrates plant growth independently from dynamics of pests or predators. The remaining components each account for less than 8% of the variance and delineate finer distinctions.

Table 5. Variabilities in natural enemies and whitefly development stages sampled at 12 months after planting.

Variable	PC1	PC2	PC3	PC4	PC5	PC6	PC7	PC8	PC9
PHT	-0.0810	0.3320	0.3990	0.5990	0.4640	0.3780	0.0760	0.0220	-0.0290
LW	0.3170	0.6530	0.1310	0.3300	-0.0600	-0.5650	0.0160	-0.1310	0.0800
LBB	0.3070	0.5720	-0.4750	-0.2130	-0.0730	0.2070	0.5070	0.0570	0.0010
SP	0.2890	0.5710	-0.1120	-0.4610	0.3910	0.0820	-0.4500	0.0350	-0.0520
NEW	0.2620	-0.2890	0.4890	-0.4050	0.5230	-0.2520	0.3220	0.0580	-0.0130
NWN	0.6910	-0.0380	0.4320	-0.1780	-0.2540	0.2890	-0.0190	-0.3450	0.1870
NWA	0.7150	0.0400	0.3800	0.0710	-0.3830	0.0310	-0.0660	0.4080	-0.1400
CMDS	0.7220	-0.3170	-0.3510	0.2260	0.1510	-0.0330	-0.0040	-0.2150	-0.3650
CMDI	0.6370	-0.3430	-0.4340	0.2480	0.2670	-0.0140	-0.0730	0.1610	0.3540

Variable	PC1	PC2	PC3	PC4	PC5	PC6	PC7	PC8	PC9
EV	2.27	1.49	1.30	1.04	0.96	0.66	0.58	0.38	0.32
PV	25.21	16.60	14.39	11.55	10.63	7.34	6.44	4.25	3.59
CV	25.21	41.81	56.20	67.75	78.37	85.72	92.15	96.41	100.00

*PHT=plant height, LW=lacewing, LBB=lady bird beetle, SP=spider, NEW=number of whitefly eggs, NWN=number of whitefly nymph, NWA=number of whitefly adults, CMDS= cassava mosaic virus severity, CMDI=cassava mosaic virus incidence, EV=eigen values, PV=proportion of variance, CV=cumulative variance.

3.3. Analysis of Predator-Prey-Interactions

The multivariate analysis for predator-prey interactions displays distinct seasonal variations in the dynamics between

pests and their natural enemies (Figure 1). The PCA reveals a very broad clustering of data points at 3 MAP, indicating that predator-prey interactions are still in their infancy.

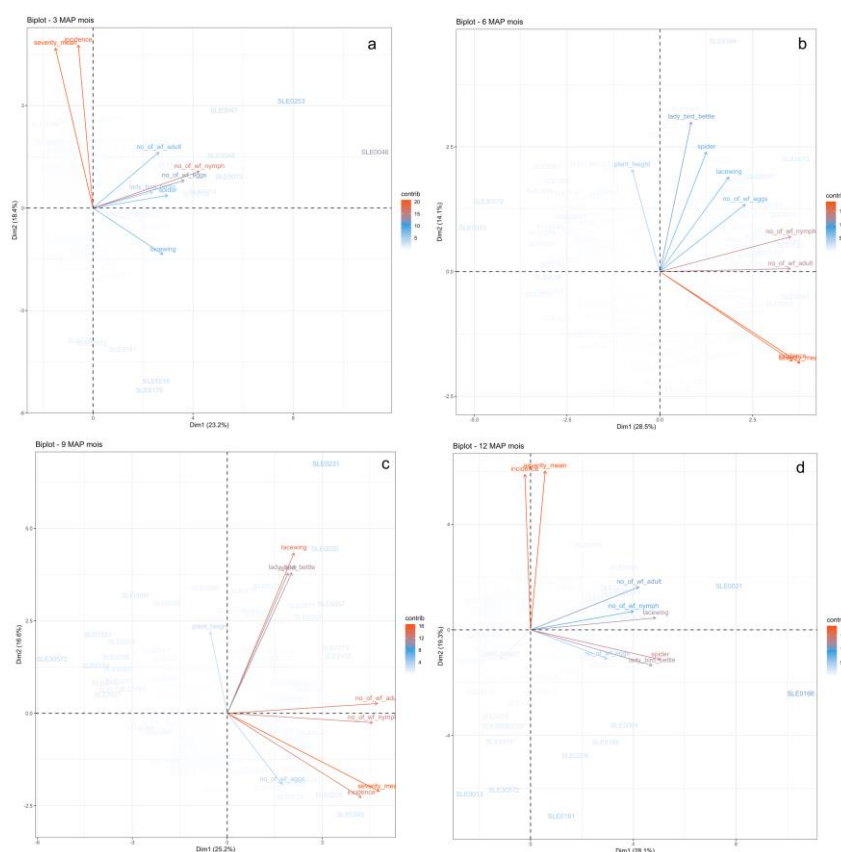


Figure 1. Plots showing contributions of predator-prey interactions of traits to variability in cassava genotypes sampled at 3 MAP (PC1), 6 MAP (PC2), 9 MAP (PC3) and 12 MAP (PC4).

The moderate alignment of the vectors representing variables such as "whitefly adults" and "nymphs" suggests that these life stages co-occur and may be responsible for early pest pressure. Due to their delayed population growth or reduced ability to inhibit pests, natural enemies like lacewings and spiders could show weaker vector contributions at this point. The distance between clusters is more noticeable by 6

MAP. This can indicate a change in the ratio of predators to prey. For example, a rise in the vector strength of spiders and lacewings could be a sign of their increasing power to control whitefly populations. A divergence in ecological processes and active suppression can be seen if the vectors of whitefly eggs and nymphs point in the opposite directions from those

of predators. The start of the effectiveness of biological control may occur at this period. The PCA shows higher vector alignment and closer grouping at 9 MAP, which may be a sign of stabilized predator-prey dynamics. While predator populations increase in response to earlier prey abundance, whitefly populations may have decreased as a result of persistent predation. The principal component, which is probably motivated by predator-prey feedback loops, appears to capture more of the system's structure as the explained variance increases along dimension1. With lengthy, but precisely oriented vectors for both the prey and predator variables, the biplot exhibits the clearest separation between clusters by 12 MAP. This indicates that the system has reached a mature ecological state in which whiteflies are subject to significant regulatory pressure from predator populations. Reduced pest pressure and

successful suppression are indicated if whitefly adult and egg vectors are minimized or orthogonal to predator vectors. Strong predator vectors, on the other hand, can indicate their dominance in determining the dynamics of the agroecosystem.

3.4. Effects of Predator Abundance

Significant block effects were detected for lacewings at all sampling regimes, while ladybird beetles exhibited significant block effects at 6, 9 and 12 MAP (Table 6), and spiders at 3, 9 and 12 MAP (Table 7). Treatment effects were mostly non-significant, underscoring the dominance of spatial and environmental factors over genotype effects.

Table 6. Analysis of variance of lacewing and ladybird beetles sampled across four sampling regimes.

Items	Degree of freedom (MAP)				Sum Sq (MAP)				Mean Sq (MAP)				F value (MAP)				Pr(>F) (MAP)			
MAPs	3	6	9	12	3	6	9	12	3	6	9	12	3	6	9	12	3	6	9	12
Lacewing																				
Block (ignoring Treatments)	3	3	3	3	18.026	2.478	28.757	48.884	6.009	0.826	9.586	16.295	9.931	8.403	42.224	10.863	0.046	0.034	0.002	0.0022
Treatment (eliminating Blocks)	261	260	260	260	87.061	132.944	596.933	187.339	0.334	0.511	2.296	0.721	0.551	5.201	10.113	0.48	0.855	0.058	0.017	0.916
Treatment: Check	1	1	1	1	0.005	1.176	0.68	5.12	0.005	1.176	0.68	5.12	0.008	11.96	2.997	3.413	0.933	0.026	0.158	0.138
Treatment: Test and Test vs. Check	260	259	259	259	87.056	131.768	596.252	182.219	0.335	0.509	2.302	0.704	0.553	5.175	10.141	0.469	0.854	0.058	0.017	0.923
Residuals	3	4	4	4	1.815	0.393	0.908	6	0.605	0.098	0.227	1.5								
Ladybird beetles																				
Block (ignoring Treatments)	3	3	3	3	0.123	0.33	1.288	1.047	0.041	0.11	0.429	0.349	2.244	9.086	28.624	7.156	0.262	0.029	0.004	0.044
Treatment (eliminating Blocks)	261	260	260	260	5.512	16.715	8.572	14.25	0.021	0.064	0.0533	0.052	1.155	5.315	2.198	1.124	0.542	0.056	0.231	0.529
Treatment: Check	1	1	1	1	0.405	0.027	0.085	0.125	0.005	0.027	0.08	0.125	22.091	2.254	5.333	2.564	0.018	0.208	0.082	0.185
Treatment: Test and	260	259	259	259	5.107	16.688	8.492	14.125	0.022	0.064	0.0533	0.051	1.071	5.327	2.186	1.119	0.575	0.055	0.233	0.532

Items	Degree of freedom (MAP)				Sum Sq (MAP)				Mean Sq (MAP)				F value (MAP)				Pr(>F) (MAP)			
MAPs	3	6	9	12	3	6	9	12	3	6	9	12	3	6	9	12	3	6	9	12
Lacewing																				
Test vs. Check																				
Residuals	3	4	4	4	0.055	0.048	0.06	0.195	0.0	0.012	0.0	0.049								

Table 7. Analysis of variance of spiders sampled across four sampling regimes.

Items	Degree of freedom (MAP)				Sum Sq (MAP)				Mean Sq (MAP)				F value (MAP)				Pr(>F) (MAP)			
MAPs	3	6	9	12	3	6	9	12	3	6	9	12	3	6	9	12	3	6	9	12
Block (ignoring Treatments)	3	3	3	3	1.114	0.23	4.67	6.51	0.371	0.077	1.557	2.17	18.575	1.387	11.974	64.295	0.019	0.368	0.018	0.001
Treatment (eliminating Blocks)	261	260	260	260	35.566	30.509	48.812	42.302	0.136	0.117	0.188	0.163	6.813	2.118	1.444	4.821	0.068	0.244	0.402	0.066
Treatment: Check	1	1	1	1	0.02	0.201	0.02	0.405	0.002	0.201	0.02	0.405	1	3.622	0.154	12	0.391	0.13	0.715	0.026
Treatment: Test and Test vs. Check	260	259	259	259	35.546	30.308	48.792	41.897	0.137	0.117	0.188	0.162	6.836	2.112	1.449	4.793	0.068	0.245	0.401	0.066
Residuals	3	4	4	4	0.06	0.222	0.52	0.135	0.002	0.055	0.13	0.034								

4. Discussion

4.1. Correlations and Variability in Whitefly Developmental Stages and Natural Enemies

This study provides a comprehensive evaluation of interactions among whitefly developmental stages, their natural enemies, plant height, and CMD expression. The results align with recent findings demonstrating that whitefly population peaks and disease spread are closely tied to temporal changes in cassava canopy structure and predator activity [32, 33]. Results demonstrate strong predator–prey synchrony between natural enemies and whitefly developmental stages. Lacewings showed the strongest numerical response to increasing nymph and adult populations, supporting prior findings on their efficiency as biological control agents [10, 34]. Spiders

functioned as consistent generalist predators, maintaining stable correlations across all MAPs [11]. Their early presence is particularly valuable in suppressing initial whitefly colonization. Ladybird beetles exhibited weaker associations with whitefly abundance, consistent with their polyphagous feeding habits [12].

Plant height showed limited influence on predator–prey interactions. While early height influenced whitefly adult colonization, its effect diminished later, aligning with observations that cassava canopy structure influences microclimate more than predator accessibility [35].

Plant height exhibited minimal influence on whitefly life stages or natural enemy populations, especially beyond 6 MAP. Early-season colonization tendencies toward taller plants were evident but did not persist into later growth stages. This suggests that while plant height may influence initial microhabitat preference, other plant traits such as canopy density, leaf hairiness, and architectural complexity have stronger eco-

logical effects on whitefly ecology [36]. These findings support broader evidence that cassava plant architecture affects predator accessibility and microclimate stability more than height alone [35]. Hence, plant height is not a reliable ecological predictor of pest pressure or predator efficacy.

4.2. Analysis of Predator-Prey-Interactions

Lacewings and spiders demonstrated consistent positive correlations with whitefly nymphs and adults across all sampling periods, indicating they respond numerically and functionally to increases in pest density. Their strong association with key vector life stages confirms their importance as natural regulators of whitefly populations. Similar predator tracking behavior has been documented in cassava ecosystems, where lacewings show high predatory efficiency on nymphal whiteflies [35], while spiders maintain stable predatory pressure as generalist hunters [11]. Ladybird beetles, however, showed much weaker correlations across MAPs. This agrees with Santos et al. [37], who opined that coccinellids are highly polyphagous, often feeding on diverse prey types such as aphids, mites, and small caterpillars, thereby reducing their specialization toward whiteflies. Thus, their ecological role may be supplementary rather than central in cassava IPM programs.

The PCA results reveal shifting interactions between whitefly abundance and CMD severity/incidence over time. At 3 MAP, CMD variables are weakly linked with pest abundance, consistent with early, low-level inoculation. At 6 MAP, strong correlations emerge between adults and CMD parameters, aligning with known epidemiological dynamics where adult whiteflies act as principal vectors [17]. At 9 MAP, CMD severity and incidence peak sharply, reflecting cumulative viral infections rather than real-time vector activity. Recent modeling studies confirm that CMD expression intensifies progressively throughout the season, even when vector populations plateau [29, 38]. This explains why CMD variables remain strongly correlated at 12 MAP, even though whitefly reproduction slows. These patterns underline the importance of early and mid-season vector management to reduce long-term disease burden.

The combined findings strongly support the use of conservation biological control as a core component of cassava IPM. Strategies that enhance lacewing and spider populations such as reduced pesticide use, maintenance of ground vegetation, intercropping, and inclusion of floral strips can greatly strengthen natural pest suppression. These recommendations align with updated IPM guidelines that emphasize ecological intensification and reduced chemical reliance in African agriculture [39].

4.3. Effects of Predator Abundance

The findings of the analysis of variance indicate that block effects were consistently significant for lacewings, ladybird

beetles, and spiders across the four sampling regimes, suggesting strong spatial heterogeneity influencing predator abundance. Treatment effects (cassava variety) were largely non-significant, indicating varietal differences did not meaningfully shape predator populations. This supports the conclusion that environmental variation—such as microclimate, soil conditions, or vegetation structure—is a stronger determinant of predator activity than genotype [40].

5. Conclusions

This study provides a comprehensive, season-long assessment of interactions among whitefly developmental stages, natural enemies, plant height, and cassava mosaic disease (CMD) expression across key cassava growth phases. The findings clearly demonstrate that lacewings and spiders are the most ecologically influential natural enemies associated with whitefly suppression. Their consistent positive correlations with nymphs and adults from 3 to 12 MAP indicate that these predators respond numerically and functionally to whitefly abundance, making them critical allies in natural pest regulation.

Ladybird beetles, though present, exhibited weaker and inconsistent associations with whitefly stages, suggesting a limited role in suppressing vector populations. Their polyphagous behavior likely reduces their effectiveness as specialized whitefly predators. Plant height, while having minor early-season influence on adult whitefly colonization, did not significantly affect predator or pest abundance during mid- to late-season stages. This indicates that more complex architectural traits—such as canopy density, leaf arrangement, and microclimate—likely exert stronger ecological influence than height alone.

The PCA results reveal that CMD severity and incidence become highly associated with adult whitefly abundance particularly from 6 to 9 MAP, reflecting peak disease transmission during the period of highest vector pressure. By 12 MAP, CMD remained strongly expressed even though whitefly reproduction slowed, consistent with cumulative viral load and established infection. Strong block effects across MAPs highlight the major role of environmental heterogeneity and microhabitat conditions—such as shade, soil fertility, adjacent vegetation, and field structure—in shaping natural enemy communities. These environmental factors often outweigh cassava genotype effects. Overall, the study emphasizes the importance of ecological processes driving predator–prey dynamics, CMD spread, and plant–insect interactions. The results support integrating conservation biological control as a central pillar of cassava IPM programs, alongside targeted vector monitoring and landscape management.

The exploitation of conservation biological control as a primary IPM strategy could enhance habitats for lacewings and spiders—the most effective predators—through reduced pesticide use, ground vegetation retention, intercropping, and maintenance of natural refuge habitats. Strengthening of

early-season monitoring programs (3–6 MAP) for whitefly adults and nymphs at early growth stages strongly predict CMD spread. Regular monitoring can guide timely interventions and prevent epidemic-scale disease transmission. Increase habitat complexity within and around cassava fields necessitates the incorporation of flowering strips, hedgerows, or cover crops that provide shelter and alternative food sources for predators, supporting their persistence even during low prey availability. Incorporation of landscape-level management strategies including spatial heterogeneity strongly influences predator abundance. Field layout optimization, maintenance of semi-natural habitats, and reduction of bare-field zones can improve natural enemy colonization. Promotion of farmer capacity building through training on predator identification, CMD symptom recognition, whitefly scouting techniques, and responsible pesticide use are imperative to avoid disrupting beneficial arthropods. Integration of resistant or tolerant cassava varieties in IPM packages can contribute to reduce CMD burden and complement biological control. Regional coordination of CMD and whitefly management through coordinated surveillance and synchronized community-based planting can minimize vector sources and disease reservoirs.

Abbreviations

CMD	Cassava Mosaic Disease
IPM	Integrated Pest Management
MAP	Month After Planting
PCA	Principal Component Analysis
SLICASS	Sierra Leone Improved Cassava

Acknowledgments

The authors acknowledge the Njala University field staff for their technical support during sampling and natural enemies surveillance. Special appreciation is extended to the entomology and pathology research teams for their insight into whitefly and natural enemies monitoring methods. Gratitude is also expressed to local farmers for their collaboration and logistical assistance.

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Data Availability Statement

The data is available from the corresponding author upon reasonable request.

Conflicts of Interest

The authors declare no conflicts of interest.

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Biography



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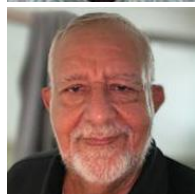


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Prince Emmanuel Norman (PhD) is a Chief Research Officer and Deputy Director General, Research, Technology and Innovation Development at Sierra Leone Agricultural Research Institute (SLARI). He completed his PhD in Plant Breeding from University of Ghana in 2019, and his Master of Science in Plant Breeding from the University of KwaZulu-Natal, South Africa in 2011. Recognized for his exceptional contributions, Rev. Dr. Prince Emmanuel Norman has been honored with the INV Awards 2025 International Research and Invention Award, and Academic Awards ACH Awards 2025, etc. Dr. Norman's research has primarily centered around the genetic improvement of staple crops, particularly the white Guinea yam, cassava, sweet potato, cocoyam, cereals, etc. as well

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