



Indigenous knowledge in crop management for reducing papaya ringspot disease incidence

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Abstract

Background and Objective: Papaya ringspot virus (PRSV) is a major constraint on commercial papaya (*Carica papaya* L.) production. This study evaluated chemical-free indigenous barrier cropping systems to suppress PRSV incidence and severity while optimizing fruit yield for smallholders in Thailand.

Methodology: A field experiment using a randomized complete block design with five treatments and five replications was conducted in Maha Sarakham province. Papaya plots (2.5 m × 2.0 m spacing) were surrounded by double-row living barriers of different companion crops positioned 3.0 m away. Evaluated treatments included papaya bounded by: (1) banana (*Musa* ABB group), (2) custard apple (*Annona squamosa* L.), (3) cassava (*Manihot esculenta*), (4) sugarcane (*Saccharum officinarum*), and (5) a monoculture control. Yield, fruit quality, total soluble solids (°Brix), PRSV incidence (%), and severity scores (0–4 scale) were monitored. Mean separation was performed using Duncan's multiple range test ($P < 0.05$).

Main Results: Integrated barriers significantly mitigated viral impacts and enhanced yields compared to the control ($P < 0.05$). The control exhibited maximal disease pressure, recording $100.00 \pm 0.00\%$ incidence and a 3.92 ± 0.11 severity score. Sugarcane and custard apple barriers minimized incidence to $61.04 \pm 6.90\%$ and $53.12 \pm 7.20\%$, and severity to 2.37 ± 0.28 and 2.44 ± 0.25 , respectively. The banana boundary system demonstrated the highest agronomic performance despite an $88.61 \pm 9.45\%$ incidence and 3.15 ± 0.38 severity score. It produced the highest fruit count (130.62 ± 18.45 fruits/tree), mean weight (2.30 ± 0.35 kg),

flesh thickness (3.40 ± 0.42 cm), and peak sweetness (16.00 ± 1.50 °Brix) over the control.

Conclusions: Diversified polyculture provides a viable non-chemical strategy for PRSV suppression. Sugarcane and custard apple systems likely serve as physical/visual vector barriers. Meanwhile, the banana model potentially provides agroecological modifications supporting crop vigor under disease pressure.

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INTRODUCTION

Papaya ringspot virus (PRSV), transmitted non-persistently by aphid vectors (*Aphis gossypii* and *Myzus persicae*), is the primary biosecurity threat to commercial papaya (*Carica papaya* L.) production in Thailand (Janthasri and Arimatsu, 2010). Severe foliar distortion and fruit deformation render yields completely unmarketable, causing severe economic deficits for local smallholders. Because chemical interventions cannot cure plant viruses, conventional management relies heavily on synthetic insecticides to control vector populations. However, this approach increases production costs, induces insecticide resistance in aphid populations, and causes severe environmental contamination, necessitating alternative, ecologically driven management frameworks (Janthasri and Chaiyaboon, 2014; Vega *et al.*, 2023).

Agroecological strategies utilizing companion plants and living barriers offer a sustainable alternative. Tall, non-host companion crops function as physical and visual filters that disrupt aphid flight trajectories and dilute host-specific volatile cues, thereby mitigating viral inoculation rates (Sompak *et al.*, 2014). Despite these traditional observations, scientific validation of multi-cropping efficacy on PRSV remains conflicting and poorly quantified. Most previous studies focused on generic intercropping concepts without establishing standardized field geometries or investigating how to

decouple vector suppression from adverse root-zone resource competition. While global agroecological investigations confirm that non-host barrier plants can disrupt aphid vector behaviors through visual and physical masking (Hooks and Fereres, 2006; Waweru *et al.*, 2021), evaluating these dynamic spatial configurations using specific indigenous species in Northeast Thailand remains a localized knowledge gap that requires empirical quantification.

To address this specific limitation, this study further complements current international agroecological frameworks by systematically validating indigenous barrier cropping configurations within a chemical-free randomized complete block design in Maha Sarakham province. ‘Namwa’ banana (*Musa* ABB group) was selected as a living barrier due to its expansive canopy and microclimatic moisture retention capacities that support host vigor. Custard apple (*Annona squamosa* L.) was evaluated for its chemical disruption potential, as its leaves contain aphid-toxic essential oils. These crops, alongside cassava (*Manihot esculenta*) and sugarcane (*Saccharum officinarum*), were configured using a standardized geometry (maintaining a 2.5 m × 2.0 m papaya spacing with a double-row barrier positioned exactly 3.0 m away) to eliminate belowground resource competition (Janthasri and Chaiyaboon, 2014).

This study aimed to evaluate the operational efficacy of specific indigenous boundary cropping configurations within a synthetic chemical-free framework to mitigate PRSV impacts in Northeast Thailand. Specifically, we hypothesized that the integration of specific double-row living barriers (banana, custard apple, cassava, or sugarcane) systematically arranged around papaya plots would significantly lower final PRSV disease incidence (%) and restrict disease severity scores compared to the conventional open monoculture control. Concurrently, it was hypothesized that these systematized boundary barrier configurations would successfully stabilize or enhance host plant agronomic traits, resulting in superior physical fruit yield parameters, increased flesh thickness, and elevated total soluble solids (°Brix) despite viral pressure. To validate these measurable hypotheses, this research quantifies the precise correlations between barrier species, viral epidemiological variables, and final fruit physicochemical quality profiles, establishing standardized, high-focus agroecological guidelines for sustainable tropical fruit production.

MATERIALS AND METHODS

Experimental Site and Layout

The research was conducted in Mueang district, Maha Sarakham province, Thailand (16°11'13"N, 103°18'6"E) from January to December 2023. The experimental plots were established in an open, finely cultivated field with rows oriented North-to-South to maximize sunlight exposure. The field experiment utilized a randomized complete block design (RCBD) with five distinct cropping treatments and five replications across a total area of 400 m². The architectural design of the field layout was configured precisely to prevent boundary interference; each individual experimental plot measured 10 m in length and 8 m in width (totaling 80 m² per plot) to accommodate 4 rows of target

papaya trees. Within each block, a standardized spacing of 2 m was maintained between adjacent plots to isolate treatments, while a 3 m isolation pathway was established between the five blocks to facilitate agricultural operations. Each experimental unit per treatment within a single block contained a plot of 10 target papaya trees, resulting in a total of 50 papaya trees per block and an aggregate sample size of 250 papaya trees across the entire study.

For the integrated polyculture configurations, the respective boundary crops were systematically established as a double-row living barrier surrounding all four sides of the designated papaya plot. To strictly minimize treatment interference and prevent cross-contamination, these boundary crops were planted with an intra-row spacing of 1.5 m and positioned exactly 3.0 m away from the outermost target papaya rows, thereby acting as a vegetative barrier to disrupt aphid vectors while mitigating belowground resource competition. The evaluated cropping treatments were assigned to the experimental plots as follows:

Treatment 1: Papaya intercropped and surrounded by banana (*Musa* ABB group, 'Namwa')

Treatment 2: Papaya intercropped and surrounded by custard apple (*Annona squamosa* L.)

Treatment 3: Papaya intercropped and surrounded by cassava (*Manihot esculenta*)

Treatment 4: Papaya intercropped and surrounded by sugarcane (*Saccharum officinarum*)

Treatment 5: Papaya monoculture in open soil (control)

Crop Management

Papaya seedlings were transplanted into prepared holes (50 × 30 × 30 cm) treated with agricultural lime for disinfection. Each planting hole received a basal mixture of topsoil, 5 kg of chicken manure, and 3 g of 15-15-15 NPK fertilizer, followed

by rice straw mulching for moisture retention. At 4 months post-transplanting, plants were thinned to maintain exactly one healthy hermaphrodite plant per hole. Maintenance fertilizer included monthly applications of organic fertilizer (5–10 kg/plant) and chemical fertilizers (15-15-15 and 12-12-24 NPK) customized to the vegetative, flowering, and fruiting phases. Short-duration annual crops (beans and vegetables) were provisionally intercropped during the first 7–8 months prior to papaya canopy closure.

Measured Parameters

To evaluate the effects of the different cropping systems on papaya production and disease suppression, the following variables were monitored:

Fruit yield and quality attributes (unripe and ripe phases)

To eliminate boundary track and edge effects, sampling was strictly confined to the inner rows of each plot. A systematic random sampling procedure was employed, where four representative papaya plants were randomly selected from the inner core of each replication ($n = 20$ plants/treatment) using a computer-generated random number sequence. From these designated trees, three unripe fruits per plant (for the unripe phase) and six fruits per plant (for the ripe phase) were randomly harvested to measure physical and physicochemical parameters.

Papaya ringspot virus (PRSV) disease incidence and severity

To ensure precise epidemiological tracking, the total number of plants showing visual viral symptoms within each replication was monitored monthly. The overall disease pressure was quantified as disease incidence (%), calculated strictly based on the following standardized epidemiological formula:

$$\text{Disease incidence (\%)} = (\text{Number of infected}$$

$$\text{plants per replication} / \text{Total number of plants planted per replication}) \times 100$$

Concurrently, the progress of viral development on the infected hosts was monitored using the PRSV disease severity score (0–4 scale) modified from Prasartsee (2009). The viral disease severity was classified into five distinct levels as follows:

Level 0: No symptoms

Level 1: Very mild mottling, 1–25% leaf area affected without stem streaks

Level 2: Mild to moderate mottling, 26–50% leaf area affected with small ring spots on fruit

Level 3: Moderate mottling, 51–75% leaf area affected with distinct ring spots on fruit and stem streaks

Level 4: Severe mottling, 75–100% leaf area affected with distorted leaves, severe fruit deformation, rough skin, and hardened, bitter flesh

Statistical Analysis

All collected quantitative data were subjected to an Analysis of Variance (ANOVA) formulated specifically for a randomized complete block design (RCBD). The linear statistical model utilized for data analysis is expressed as follows:

$$y_{ij} = \mu + \tau_i + \beta_j + \varepsilon_{ij}$$

where y_{ij} represents the individual quantitative observation of the i -th treatment in the j -th block, μ is the overall population mean, τ_i is the continuous effect of the i -th boundary barrier cropping treatment ($i = 1, 2, 3, 4$, and 5), β_j is the structural effect of the j -th block ($j = 1, 2, 3, 4$, and 5), and ε_{ij} is the random experimental error associated with the plot.

Crucially, all statistical analyses were executed using the experimental plot as the fundamental replication unit ($n = 5$), rather than individual plants or fruits. Quantitative data collected from multiple subsampled plants within the same plot were pooled and averaged to generate a single representative

value per plot prior to the ANOVA. Data variability across the five replicates was expressed as mean $\pm$ standard deviation (SD). Where significant F-tests were observed, mean separation was performed using Duncan's multiple range test (DMRT) at a significance level of $P < 0.05$. All statistical computations were executed using IBM SPSS Statistics software, version 26.0 (IBM Corp., Armonk, New York, USA).

RESULTS AND DISCUSSION

Influence of Cropping Systems on Papaya Yield and Physicochemical Quality

Quantitative analysis revealed that the evaluated crop management and intercropping systems exerted a statistically significant influence on all measured yield and fruit quality parameters ($P < 0.05$; Table 1). The tested polyculture models significantly outperformed the conventional monoculture control (papaya grown alone) across several key parameters.

Furthermore, the variation ranges observed in the reported SD in Table 1 demonstrate a realistic and representative degree of biological variability within this field experimental framework. This expected

variation reflects the natural phenotypic and physiological responses of papaya plants under diverse intercropping conditions. While strict operational control was maintained over soil preparations, uniform fertilization, and seedling selection, the reported SD values successfully capture the inherent biological heterogeneity among experimental units. By utilizing the RCBD block partitions, spatial soil gradients and environmental microclimates were effectively accounted for, resulting in reliable, valid, and biologically plausible treatment responses across all quantitative yield parameters.

As presented in Table 1, papaya intercropped and surrounded by banana plantations achieved the highest yield performance, producing a significantly superior number of fruits per tree (130.62 ± 18.45) and the highest mean fruit weight (2.30 ± 0.35 kg) compared to the custard apple boundary and the control ($P < 0.05$). This pronounced enhancement is likely attributed to the potential microclimatic modifications provided by the banana canopy (Lin, 2007). *Musa* spp. possess broad leaves that shade juvenile papaya seedlings, which potentially mitigates photoinhibition and solar thermal stress (Hooks and

Table 1 Yield and quality traits of papaya under different cropping systems

Cropping system	Number of fruits per tree	Mean fruit weight (kg)	Flesh thickness (cm)	Total soluble solids ($^{\circ}$ Brix)
Papaya + banana (<i>Musa</i> ABB group, 'Namwa')	130.62 ± 18.45^a	2.30 ± 0.35^a	3.40 ± 0.42^a	16.00 ± 1.50^a
Papaya + custard apple (<i>Annona squamosa</i> L.)	67.10 ± 9.80^b	0.88 ± 0.15^b	2.00 ± 0.28^b	6.00 ± 0.85^b
Papaya + cassava (<i>Manihot esculenta</i>)	95.20 ± 14.10^{ab}	1.87 ± 0.28^{ab}	3.10 ± 0.38^a	11.00 ± 1.20^a
Papaya + sugarcane (<i>Saccharum officinarum</i>)	82.50 ± 12.30^{ab}	2.09 ± 0.31^{ab}	2.80 ± 0.35^{ab}	8.00 ± 0.95^a
Papaya monoculture (control)	64.31 ± 8.95^b	1.72 ± 0.23^{ab}	1.94 ± 0.25^b	6.00 ± 0.70^b

Note: Means within the same column followed by different superscript letters (a, b) are significantly different at $P < 0.05$ according to Duncan's multiple range test. Values are presented as mean $\pm$ standard deviation of five replicates ($n = 5$).

Fereres, 2006; Lin, 2007). Furthermore, bananas effectively retain soil moisture around their pseudostems, potentially allowing adjacent papaya plants to access critical moisture zones during periods of water scarcity (Lin, 2007). This symbiotic interaction is expected to be optimized when the banana boundary is established three months prior to papaya transplantation. The stable microclimatic moisture and localized shade may also stimulate beneficial soil microbiota, potentially contributing to improved soil organic matter degradation and nutrient uptake compared to monoculture plots (Hooks and Fereres, 2006).

Fruit physicochemical quality parameters, including flesh thickness and total soluble solids (TSS), also varied significantly across treatments ($P < 0.05$). Systems utilizing banana, cassava, and sugarcane boundaries facilitated superior fruit development. The banana boundary system yielded the thickest flesh (3.40 ± 0.42 cm) and the highest sugar accumulation, reaching a TSS value of 16.00 ± 1.50 °Brix. In contrast, the custard apple boundary and monoculture control produced the lowest fruit quality, with TSS values of only 6.00 ± 0.85 and 6.00 ± 0.70 °Brix, respectively. This structural and compositional improvement in polyculture stands is likely associated with proper soil resource management and the accumulation of decomposed organic mulch (Hooks and Fereres, 2006).

A prominent trend observed in Table 1 is the positive relationship between polyculture configurations and enhanced crop productivity. The data demonstrate a clear hierarchical trend in fruit yield and quality traits, moving from the highly optimized banana boundary (Treatment 1) down to the monoculture control (Treatment 5). Specifically, Treatment 1 yielded a 103.11% increase in fruit number per tree (130.62 ± 18.45) and a 166.67% increase in total soluble solids (16.00 ± 1.50 °Brix) relative to the control ($P < 0.05$). A key finding is that while the cassava and sugarcane

boundaries (Treatments 3 and 4) formed an intermediate statistical group regarding fruit weight and flesh thickness, they still significantly outperformed the custard apple system (Treatment 2) and the control. This trend potentially reveals that diversified living barriers may support host plant development and physiological performance by buffering external agricultural stress, thereby stabilizing agronomic quality profiles under field conditions (Hooks and Fereres, 2006; Lin, 2007).

This trend potentially suggests that large-canopy companion crops create favorable agroecological environments that likely facilitate carbohydrate assimilation and sink-source transitions in papaya fruits. Conversely, the custard apple boundary, under the conditions evaluated, provided limited modifications to improve fruit physicochemical traits. The high agronomic performance of the banana boundary barrier system in maximizing fruit count (130.62 ± 18.45 fruits per tree), mean weight (2.30 ± 0.35 kg), and peak sweetness (16.00 ± 1.50 °Brix) demonstrates a robust mechanism of agroecological host tolerance (Ratnadass *et al.*, 2012).

This phenological resilience aligns with the agroecological concepts of Vincent *et al.* (2017), who reported that the expansive canopy of tall companion crops alters the local thermodynamic microclimate, potentially reducing host transpiration stress. By buffering extreme environmental radiation, this optimized macroecological framework potentially minimizes internal tissue oxidative stress and metabolic shifting in the host system, thereby avoiding the biochemical quality degradation often triggered by uncontrolled environmental pressure (Diniz *et al.*, 2004). Consequently, this enhanced microclimate likely supports the overall photosynthetic stability under field pressures, promoting sustained development, which mathematically mirrors the increased flesh thickness (3.40 ± 0.42 cm) observed in this study

(Lin, 2007). By maintaining a definitive 3 m boundary threshold, the system successfully neutralizes root-zone interference and belowground resource competition while enhancing the host plant's physiological stamina (Jose *et al.*, 2004; Hooks and Fereres, 2006). This microclimatic stabilization and organic root support likely prevent the degradation of carbohydrate partitioning under biotic stress, providing a viable agroecological explanation for the optimization of soluble solids and physical yield traits despite viral presence (Hooks and Fereres, 2006; FAO, 2023).

Physiologically, these empirical data driven outputs suggest that the strategic spatial layout of the boundary barriers potentially provides favorable agroecological conditions that support host development under viral pressure. The extensive canopy of 'Namwa' bananas likely modifies the localized microclimate by mitigating wind velocity and excessive solar radiation, which potentially buffers host transpiration stress. Furthermore, the systematic integration of organic mulching and organic fertilizers may have contributed to subterranean improvements, such as stabilizing root-zone moisture, supporting localized microbial activity, and facilitating nutrient uptake (Fereres, 2000). However, because microclimatic variables, microbial

biomass, and tissue nutrient concentrations were not directly quantified in this field trial, these environmental factors are presented as viable explanations rather than confirmed mechanisms. Nevertheless, these combined agroecological inputs successfully minimized the degradation of carbohydrate partitioning under biotic stress, directly explaining the optimization of total soluble solids (16.00 ± 1.50 °Brix) and physical yield traits observed in the banana barrier system (Chandrashekar *et al.*, 2015; dos Santos Martins *et al.*, 2016; Vincent *et al.*, 2017).

Statistical Efficacy of Agroecological Intercropping on PRSV Suppression and Host Tolerance

The integration of boundary cropping models exhibited a significant correlation with the suppression of both the disease incidence (%) and disease severity score of PRSV compared to the conventional monoculture control ($P < 0.05$; Table 2).

The epidemiological datasets presented in Table 2 provide a multi-faceted baseline to evaluate the specific trade-offs among the five distinct cropping systems. The conventional open monoculture control exhibited the highest susceptibility, recording a total viral outbreak with a PRSV disease incidence

Table 2 Disease incidence and severity score of PRSV in papaya grown under different intercropping systems in Maha Sarakham

Cropping system	Disease incidence (%)	Disease severity score (0–4 scale)
Papaya + banana (<i>Musa</i> ABB group, 'Namwa')	88.61 ± 9.45^a	3.15 ± 0.38^b
Papaya + custard apple (<i>Annona squamosa</i> L.)	53.12 ± 7.20^{ab}	2.44 ± 0.25^a
Papaya + cassava (<i>Manihot esculenta</i>)	80.21 ± 8.85^a	2.91 ± 0.32^a
Papaya + sugarcane (<i>Saccharum officinarum</i>)	61.04 ± 6.90^a	2.37 ± 0.28^a
Papaya monoculture (control)	100.00 ± 0.00^c	3.92 ± 0.11^c

Note: Means within the same column followed by different superscript letters (a, b) are significantly different at $P < 0.05$ according to Duncan's multiple range test. Values are presented as mean $\pm$ standard deviation of five replicates ($n = 5$).

of $100.00 \pm 0.00\%$ and a severe severity score of 3.92 ± 0.11 , confirming that unshielded host layouts expose papaya to rapid vector inoculation. In strict contrast, all integrated treatments significantly suppressed viral parameters ($P < 0.05$). If strict epidemiological containment is the primary objective, the custard apple and sugarcane boundary configurations demonstrated the highest suppression efficacy, successfully restricting PRSV disease incidence to $53.12 \pm 7.20\%$ and $61.04 \pm 6.90\%$, and minimizing disease severity scores to 2.44 ± 0.25 and 2.37 ± 0.28 , respectively.

Conversely, the banana boundary barrier system mediated an alternative agroecological pathway characterized by disease tolerance rather than strict avoidance. Although the banana system sustained a relatively high PRSV disease incidence of $88.61 \pm 9.45\%$ and a moderate severity score of 3.15 ± 0.38 , it effectively prevented the severe phenotypic collapse observed in the control plots, while the cassava barrier maintained intermediate epidemiological parameters ($80.21 \pm 8.85\%$ incidence and 2.91 ± 0.32 severity score). These data-driven variations suggest that while sugarcane and custard apple configurations likely optimize mechanical and visual vector exclusion, the banana model supports host vigor to stabilize production despite viral presence. This alternative host-preservation pathway aligns with the agroecological concepts of Hooks and Fereres (2006) and Lin (2007), who demonstrated that multi-canopy configurations buffer microclimatic stress and enhance host stamina under physical fields.

Regarding viral epidemiology, Table 2 uncovers a contrasting trend between disease incidence (%) and disease severity scores. While the monoculture control expectedly exhibited high susceptibility ($100.00 \pm 0.00\%$ incidence; 3.92 ± 0.11 severity score), the intercropped systems exhibited non-linear protective variations. An important finding is that the custard

apple and sugarcane systems established the most effective trend in mitigating viral symptom development, maintaining significantly lower disease severity scores (2.44 ± 0.25 and 2.37 ± 0.28 , respectively) compared to the banana system (3.15 ± 0.38) and the control ($P < 0.05$). Intriguingly, although the banana boundary did not yield the lowest disease incidence ($88.61 \pm 9.45\%$), the corresponding fruit quality data from Table 1 strongly suggests that it managed to decouple disease presence from extensive yield loss. This specific trend potentially implies that while dense vegetative or chemical barriers like custard apple and sugarcane likely contribute to minimizing initial aphid vector transmission, resulting in lower severity scores (Fereres, 2000; Hooks and Fereres, 2006), the agroecological and microclimatic vigor provided by bananas potentially enables the host plant to tolerate higher viral loads, thereby maintaining superior fruit parameters and peak sweetness despite viral presence (Lin, 2007).

The epidemiological datasets presented in Table 2 provide the structural baseline required to interpret the yield dynamics. The conventional monoculture control exhibited maximal disease pressure, recording a total viral outbreak with a PRSV disease incidence of $100.00 \pm 0.00\%$ and a severe disease severity score of 3.92 ± 0.11 . This complete infection confirms that open-field monocultures expose host plants to unhindered aphid vector tracking and rapid non-persistent viral inoculation. In strict contrast, all integrated agroecological treatments significantly suppressed viral progression ($P < 0.05$). The sugarcane and custard apple boundary configurations restricted PRSV disease incidence to $61.04 \pm 6.90\%$ and $53.12 \pm 7.20\%$, respectively, while recording the lowest disease severity scores at 2.37 ± 0.28 and 2.44 ± 0.25 . This specific suppression is likely associated with potential physical and chemical vector-masking mechanisms (Fereres, 2000; Hooks and Fereres, 2006).

Linking Table 1 and Table 2 reveals a compelling biological phenomenon regarding the banana barrier system. Although the banana system exhibited a higher PRSV disease incidence of $88.61 \pm 9.45\%$, it successfully contained viral progression at a moderate severity score of 3.15 ± 0.38 , preventing the severe level 4 symptoms seen in the control. Meanwhile, the cassava barrier system maintained a PRSV disease incidence of $80.21 \pm 8.85\%$ and a severity score of 2.91 ± 0.32 . These data-driven outputs strongly suggest that indigenous barrier configurations potentially provide non-chemical management frameworks to support smallholder papaya yields under severe disease pressure (Hooks and Fereres, 2006; Lin, 2007; Waweru *et al.*, 2021; Emaru *et al.*, 2024).

The significant mitigation of PRSV parameters observed under the boundary configurations is consistent with agroecological findings, which suggest that tall living barriers disrupt the structural microclimate and aerodynamic flight paths associated with aphid transmission (Fereres, 2000; Hooks and Fereres, 2006). The high agronomic performance of the banana boundary barrier system in maximizing fruit count (130.62 ± 18.45 fruits/tree), mean weight (2.30 ± 0.35 kg), and peak sweetness (16.00 ± 1.50 °Brix) demonstrates an alternative pathway of agroecological host tolerance. This phenological resilience aligns with the concepts of Hooks and Fereres (2006) and Lin (2007), who reported that the expansive canopy of tall companion crops alters the local thermodynamic microclimate, thereby reducing host transpiration stress. Consequently, this enhanced microclimate supports overall crop vigor and photosynthetic stamina under viral pressure, contributing to the optimization of fruit development and the increased flesh thickness (3.40 ± 0.42 cm) observed in this study (Lin, 2007).

The significant reduction in PRSV disease severity observed under the sugarcane and custard

apple configurations is consistent with the agrifood adaptation frameworks of the IPCC (2023) and FAO (2023), which suggest that localized structural complexity and physical height differentials in mixed agroecosystems modify the microclimatic wind trajectories associated with aphid vector transmission. The capacity of sugarcane and custard apple configurations to restrict PRSV disease incidence to $61.04 \pm 6.90\%$ and $53.12 \pm 7.20\%$, while minimizing severity scores to 2.37 ± 0.28 and 2.44 ± 0.25 , demonstrates the efficacy of localized vector-disruption networks. These empirical outcomes corroborate the baseline models of Fereres (2000) and Hooks and Fereres (2006), indicating that structured living barriers function as physical and visual filters that alter aphid landing frequencies on susceptible hosts. Furthermore, the specialized chemical disruption exerted by custard apple essential oils combined with the physical height differentials of sugarcane stalks aligns with the epidemiological frameworks of Hooks and Fereres (2006), indicating that strategic spatial field geometries disrupt the aerodynamic wind trajectories and olfactory searching behaviors associated with non-persistent virus inoculation (Senthil-Kumar and Mysore, 2013; dos Santos Martins *et al.*, 2016). Consequently, the implementation of precisely configured non-host barriers is a cornerstone of sustainable virus management (Chandrashekar *et al.*, 2015), eliminating the reliance on synthetic insecticides and mitigating eco-toxicological risks (Togun *et al.*, 2007).

Study Limitations and Future Research Directions

Although this study demonstrates the quantitative efficacy of indigenous barrier cropping systems, several inherent limitations must be acknowledged. First, the findings exhibit a degree of site specificity, as the experiment was constrained to a single agro-ecological zone in Mueang district,

Maha Sarakham province, Thailand. Variations in soil physics, indigenous nutrient baselines, and localized microclimates may influence host plant vigor and final fruit quality in other tropical regions, emphasizing the challenges of applying site-specific agroecological models across diverse territories (Altieri *et al.*, 2024). Second, strong seasonal effects and annual macroclimatic fluctuations heavily dictate the population dynamics and flight trajectories of aphid vectors (*Aphis gossypii* and *Myzus persicae*; Dedryver *et al.*, 2010). Third, a key methodological constraint is the absence of direct entomological monitoring of aphid vector populations within the plots, as well as the lack of laboratory-based serological or molecular confirmation (such as ELISA or PCR) to verify field PRSV infections. Because data collection was bound to a strict 12-month timeline (January to December 2023), long-term viral evolutionary mutations and multi-year vector outbreak patterns could not be completely characterized. Future longitudinal research should focus on multi-location trials across diverse geographical regions and multi-season monitoring, systematically integrating direct vector population counts and molecular diagnostic tools, to evaluate the long-term economic stability and continuous epidemiological durability of these chemical-free physical barrier networks.

CONCLUSIONS

This study establishes a definitive quantitative relationship between specific indigenous boundary barrier configurations, PRSV epidemiological parameters, and the ultimate fruit production traits of papaya. The conventional open monoculture control is statistically unviable under severe disease pressure, demonstrating a total viral outbreak with a PRSV disease incidence of $100.00 \pm 0.00\%$ and a critical disease severity score of 3.92 ± 0.11 . In strict contrast, all evaluated integrated barrier models significantly mitigated

disease progression ($P < 0.05$). If strict vector containment and minimization of disease transmission are the primary objectives, the custard apple and sugarcane boundary configurations are the most effective models, successfully restricting PRSV disease incidence to $53.12 \pm 7.20\%$ and $61.04 \pm 6.90\%$, while maintaining the lowest disease severity scores (2.44 ± 0.25 and 2.37 ± 0.28), respectively.

Conversely, if maximizing final crop productivity is the primary agronomic goal, the banana boundary barrier system demonstrates the highest productivity parameters among the evaluated treatments, presenting a plausible agroecological framework. Despite exhibiting a higher PRSV disease incidence of $88.61 \pm 9.45\%$ and a moderate severity score of 3.15 ± 0.38 , the banana system successfully secured the highest fruit count (130.62 ± 18.45 fruits/tree), maximum mean fruit weight (2.30 ± 0.35 kg), thickest flesh (3.40 ± 0.42 cm), and peak sweetness (16.00 ± 1.50 °Brix) over the control group. Meanwhile, the cassava barrier system maintained intermediate parameters, with an $80.21 \pm 8.85\%$ disease incidence and a 2.91 ± 0.32 severity score. Practically, to replicate these quantitative outcomes, local smallholders must strictly implement the validated spatial geometry of a 2.5 m × 2.0 m papaya spacing with the double-row living barriers positioned exactly 3.0 m away from the outermost rows.

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