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Bamboo vinegar as a sustainable botanical alternative for managing pineapple mealybugs, *Dysmicoccus brevipes* (Hemiptera: Pseudococcidae)

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Abstract. *Rosli R, Abd Latip NF, Abdullah MA. 2026. Bamboo vinegar as a sustainable botanical alternative for managing pineapple mealybugs,* Dysmicoccus brevipes *(Hemiptera: Pseudococcidae). Asian J Agric 10 (1): g100133. https://doi.org/10.13057/asianjagric/g100133.* The pineapple mealybug, *Dysmicoccus brevipes*, is a persistent pest that threatens pineapple production worldwide and is commonly managed using synthetic insecticides. However, intensive chemical use raises concerns related to environmental contamination, pest resistance, and residue accumulation. Botanical products such as Bamboo Vinegar (BV) have emerged as sustainable alternatives, yet evidence of their multifaceted bioactivity against mealybugs remains limited. This study evaluated the laboratory insecticidal and repellent efficacy of BV against *D. brevipes* using controlled bioassays. Mortality and survival were assessed over 24-120 h, while repellency was determined using an area-preference assay at 1 h and 6 h post-treatment. Kaplan-Meier survival analysis revealed a clear time-dependent reduction in mealybug survival, with median survival declining from 120.00±15.02 h to 72.00±11.30 h across BV concentrations. Differences among BV concentrations were modest, indicating consistent toxic effects within the tested range. In addition to mortality, BV induced consistent behavioral avoidance. Repulsion indices ranged from 0.26 to 0.52 across all concentrations, with 20% BV achieving the highest repellency (74.41±10.64%), exceeding that of white oil (60.80±19.58%). All treatments were classified within repellency Categories 3 and 4, reflecting moderate but reliable repellency. The primary novelty of this study lies in providing laboratory evidence that BV exhibits dual insecticidal-repellent activity against *D. brevipes*, combining lethal and sublethal effects within a single botanical input. While field validation and formulation optimisation are required, these results provide strong evidence that BV could be integrated into pineapple IPM programs as an eco-friendly tool to suppress mealybug populations and reduce reliance on synthetic insecticides.

Keywords: Bamboo vinegar, mortality effect, pineapple mealybug, repellent effect

INTRODUCTION

Pineapple (*Ananas comosus*) is a high-value tropical fruit cultivated extensively across Asia, Africa, and Latin America, where production systems have increasingly intensified to meet domestic consumption and export demand. In Malaysia, pineapple remains a strategically important horticultural crop, particularly with the expansion of premium cultivars such as MD2 under national agricultural development initiatives (Carlos 2021; MPIB 2021). While varietal improvement and intensified crop management have enhanced productivity, these changes have also increased exposure to insect pests and strengthened reliance on chemical insecticides. As a result, sustainable pest management has become a critical challenge for contemporary pineapple production systems.

Among the most economically damaging pests of pineapple is the pineapple mealybug, *Dysmicoccus brevipes*, a cosmopolitan species prevalent in tropical and subtropical regions (Beardsley 1993). Mealybugs cause direct damage through phloem feeding, leading to reduced plant vigour, stunted growth, and deterioration of fruit quality (Egelie and Gillett-Kaufman 2015). More importantly, *D. brevipes* is a vector of Mealybug Wilt of Pineapple (MWP), a destructive viral disease complex that poses a serious threat to crop survival and yield stability (Sether et al. 1998). MWP is typically characterised by leaf reddening, loss of turgidity, and wilting, which can result in plant death or severely reduced fruit size and yield (Jahn et al. 2003; Viorenta et al. 2025). Yield losses of up to 35% have been reported, particularly when disease symptoms appear early in the crop cycle (Sether and Hu 2002). In Malaysia, the recent detection of pineapple mealybug wilt-associated virus-1 (PMWaV-1) and PMWaV-3 in MD2 cultivars further highlights the growing phytosanitary risk associated with intensified pineapple cultivation (Mohd et al. 2023), complementing earlier reports of PMWaV-2 in local cultivars (Sether et al. 2001).

Management of pineapple mealybug has traditionally relied on systemic insecticides such as imidacloprid, thiamethoxam, clothianidin, and halofenozide, applied through soil or foliar routes (Joy et al. 2013). Although these compounds are effective against sap-feeding insects, their repeated use has raised concerns related to resistance development, non-target impacts, environmental contamination, and pesticide residue issues. These challenges have accelerated the shift toward Integrated Pest Management (IPM), which aims to combine chemical, biological, and cultural strategies to achieve durable and environmentally responsible pest control (N'Guessan et al. 2024). In parallel, alternative approaches such as reduced-risk fumigants for post-harvest disinfestation have also been explored to complement conventional insecticides (Kwon et al. 2024).

Within IPM frameworks, botanical pesticides have gained attention as potential alternatives or complements to synthetic insecticides, particularly for soft-bodied hemipterans such as mealybugs, scale insects, and whiteflies. A wide range of plant-derived products, including neem-based formulations, pyrethrum, essential oils, and garlic extracts, have demonstrated insecticidal or repellent activity in laboratory and, in some cases, field studies (Lira et al. 2020; Folake et al. 2023; Tarasing et al. 2025). Collectively, these studies indicate that botanicals can contribute meaningfully to pest suppression, especially when integrated with other IPM tactics. However, reported efficacy is often inconsistent, varying with plant species, formulation, concentration, and target pest, while short residual activity and phytotoxicity may limit practical application (Avila et al. 2023; Mariyam and Paul 2024). These limitations underscore the importance of evaluating botanicals within specific crop-pest systems using targeted bioassays.

Bamboo Vinegar (BV), a condensate by-product of bamboo charcoal production, has emerged as a promising botanical input due to its broad bioactivity and low-residue profile. BV has been reported to exhibit antimicrobial, antifungal, and insecticidal or antifeedant effects across diverse agricultural contexts (Mu et al. 2004; Sulaiman et al. 2005; Ho et al. 2013; Chen et al. 2025). Studies have also suggested potential roles for BV in enhancing plant resilience and suppressing insect pests, with preliminary evidence indicating repellent activity against certain species (Alias et al. 2020; Abd Latip et al. 2024). Despite increasing interest and availability in Southeast Asia, empirical evidence supporting the use of BV against pineapple mealybug remains limited, particularly studies that jointly evaluate lethal and behavioural responses relevant to IPM decision-making.

Given the economic importance of *D. brevipes* as both a direct pest and a virus vector, and the growing need for low-risk, locally available pest management tools, a clear research gap exists. The objective of this study was therefore to evaluate, under laboratory conditions, the insecticidal and repellent efficacy of bamboo vinegar against pineapple mealybug. By addressing this gap, the study aims to provide evidence-based insight into the suitability of BV as an eco-friendly component of pineapple IPM programs, supporting efforts to reduce reliance on synthetic insecticides while maintaining effective pest suppression.

MATERIALS AND METHODS

Study site

Sampling of pineapple mealybug for rearing was done at Taman Kekal Pengeluaran Makanan (TKPM) Kampung Kundang, Banting, Selangor, Malaysia (2°42'42.3"N 101°32'47,4"E), while the laboratory experiment to evaluate the mortality and repellent effect of bamboo vinegar on pineapple mealybugs was conducted in Agrotechnology Research Laboratory at Universiti Teknologi MARA Perlis Branch, Arau Campus, Perlis, Malaysia.

Rearing of pineapple mealybug

Pineapple mealybugs (*D. brevipes*) were reared in the laboratory using pumpkin (*Cucurbita moschata*) as an alternative host following established methods (Gopal et al. 2021). Fresh pumpkins were surface-treated with 0.1% carbendazim 50 WP (1 g L^{-1}) for 10s to prevent fungal decay and shade-dried for 4h before use. The short-duration surface dip was applied only to suppress post-harvest fungal contamination; pumpkins were allowed to dry completely before insect introduction, minimizing fungicide residues and avoiding direct exposure of insects. Field-collected mealybugs were introduced onto pumpkins placed in screen cages (30×30×30 cm) and maintained at 25-27°C and 70-80% relative humidity. Cultures were sustained by periodic transfer to fresh pumpkins. Nymphal-stage mealybugs were used in all bioassays. For survival analysis, a total of 50 nymphs per treatment (10 nymphs × 5 replicates; total n=350 across all treatments) were used, whereas for repellency test, a total of 60 nymphs per treatment (10 nymphs × 6 replicates; total of 300 nymphs across all treatments) were used. All procedures complied with institutional and national guidelines for ethical handling of invertebrates.

Preparation of treatments

Pure Bamboo Vinegar (BV) purchased from Tadom Eco Living Sdn. Bhd. was used in this study. The characteristics of the stored bamboo vinegar were determined prior to the experiment. The pH value of bamboo vinegar was measured by a calibrated pH meter. The acetic acid and phenolic content of bamboo vinegar was determined following the method by Association of Official Analytical Chemist (AOAC) (1990). The characteristics obtained were pH of 3.04, 8.33% acetic acids, and 13.52% total phenolics. The treatments of BV for the bioassays were prepared in Agrotechnology Research Laboratory according to four different concentrations (v/v); 5%, 10%, 15%, and 20%. A total of five percent solution was prepared by taking 5 mL of pure BV and the volume was completed to 100 mL with distilled water (v/v in water). The same procedure was repeated for 10%, 15%, and 20% by taking 10 mL, 15 mL, and 20 mL of pure BV, respectively.

Mortality bioassay of bamboo vinegar on pineapple mealybug

Laboratory bioassays were conducted following procedures modified from Pratami et al. (2018). Pineapple leaf bits (8 cm length) were excised from healthy, pesticide-free plants and immersed in the respective treatment solutions for 10 minutes. Seven treatments were tested: distilled water as control, 5% (v/v) BV, 10% (v/v) BV, 15% (v/v) BV, 20% (v/v) BV, imidacloprid (Linodor 20SL, Li Nong (M) Sdn. Bhd.), and malathion (Hextar® Malathion 84, Hextar Chemicals Sdn. Bhd.). The leaf bits were air-dried for 15 minutes after soaking and individually placed in a sterile Petri dish (90 mm). Ten pineapple mealybug nymphs were transferred onto each leaf bit using a fine brush. Each treatment was replicated five times, with each leaf bit representing one experimental unit. All assays were conducted under controlled laboratory conditions (temperature and humidity as described previously). Mortality was assessed at predetermined observation intervals at 24, 48, 72, 96 and 120 hours after treatment application, and survival analyses were performed using interval-based mortality data, while cumulative mortality percentages were calculated for presentation of treatment efficacy. An insect was considered dead when it turned black or showed no movement upon gentle probing with a fine brush (Kwon et al. 2024). Surviving nymphs that remained alive at the final observation period were treated as censored data for the survival analysis. Time-to-mortality data for individual insects were analyzed using the Kaplan-Meier survival estimator. Kaplan-Meier survival curves were generated for each treatment, and differences in survival distributions were evaluated using the log-rank (Mantel-Cox) test (α=0.05).

Repellency bioassay of bamboo vinegar on pineapple mealybug

The repellency bioassay was conducted following the area preference method described by Obeng-Ofori et al. (1998). Five treatments were tested: 5% (v/v) BV, 10% (v/v) BV, 15% (v/v) BV, 20% (v/v) BV, and white oil (Albarol®, ANCOM Crop Care Sdn. Bhd.). For each assay, a filter paper disc was cut into two equal halves. One half was treated with 1 mL of the respective treatment solution, while the other half received 1 mL of distilled water to serve as the untreated control. The halves were air-dried and then reattached before being placed in a sterile Petri dish (90 mm). Ten pineapple mealybug nymphs were carefully transferred to the centre of each dish using a fine brush, after which the dish was covered. Each treatment was replicated six times. The numbers of mealybugs present on the treated and control halves were recorded after 1 h and 6 h. Mehdi et al. (2022). Repellency was quantified using the Repulsion Index (indicator repellency) and repellency percentage. Repulsion Index (IR) was calculated according to Goeden and Kogan (1970) using the formula:

$$IR = \frac{2G}{G} + p$$

Where:

G: The number of insects on the treated areas

p: The number of insects on the viewing areas

IR: Repulsion Index

The Repulsion Index is classified as follows; for IR value less than 1, the treatment is repellent; for IR value greater than 1, the treatment is attractant; and for IR value equal to 1, the treatment is neutral.

To measure the repulsion force, repellency percentage is calculated based on the number of pineapple mealybugs on the treated areas and the observed areas. Repellency Percentage (PR) was calculated following the equation by Tapondjou et al. (2005):

$$PR = \frac{(NC - NT)}{(NC + NT)} \times 100$$

Where:

NC: The number of mealybugs in the observed areas

NT: The number of mealybugs in the areas treated with the extract.

PR: Repellency percentage

The repellency percentage is classified into five categories (Table 1), where the repulsion force increases with the increase in the category number, and the fifth category is the most repelling (Jilani and Su 1983).

Data analysis

For statistical analysis, the data from the two time intervals (1 h and 6 h) were treated as a paired dataset, and normality was first assessed using Shapiro-Wilk tests. Because the data were not normally distributed, Wilcoxon Signed-Rank Tests were used to compare repellency responses between the two time points for each treatment. Differences among the five treatments were analyzed using the Kruskal-Wallis H test. Pairwise comparisons were performed using Mann-Whitney U tests with Bonferroni correction. All analyses were considered significant at α=0.05.

Table 1. Five categories of repulsion force based on Repellency Percentage (PR)

Repellency percentage (PR)	**Category number**
<0.1%	Category 0
0.1-20%	Category 1
20.1-40%	Category 2
40.1-60%	Category 3
60.1-80%	Category 4
80.1-100%	Category 5

RESULTS AND DISCUSSION

Mortality effect of bamboo vinegar on pineapple mealybugs

The mortality percentage of pineapple mealybug over exposure time under different treatments is presented in Figure 1. Mortality increased progressively with exposure time across all Bamboo Vinegar (BV) treatments, whereas mortality in the water control remained negligible throughout the observation period. A clear separation was observed between the control and all BV treatments, confirming the biological activity of BV against pineapple mealybug under laboratory conditions. Mortality rose rapidly during the first 48-72 hours following exposure and then increased more gradually toward the later assessment periods. Although higher BV concentrations (15% and 20% v/v) tended to produce slightly faster initial mortality during the early exposure period, the survival curves of 10%, 15%, and 20% BV converged over time. By 96-120 hours, mortality levels among these concentrations were broadly comparable, suggesting that increasing concentration above 10% did not result in proportionally higher final mortality within the tested range. The 5% BV treatment exhibited a slower and more moderate increase in mortality, but followed a similar temporal pattern. In contrast, the synthetic insecticides imidacloprid and malathion induced rapid and near-complete mortality within the early exposure period, demonstrating substantially faster toxic action compared to BV treatments. Overall, the temporal pattern indicates that BV exerts a time-dependent toxic effect on pineapple mealybug, with mortality accumulating progressively following exposure. While slight differences in the speed of initial response were apparent among concentrations, the higher BV concentrations did not produce markedly greater ultimate mortality than intermediate concentrations, suggesting a possible threshold or plateau effect within the tested concentration range.

Kaplan-Meier survival curves (Figure 2) demonstrated clear treatment-related differences in pineapple mealybug survival over the 120-hour observation period. Survival remained consistently highest in the water control, with a substantial proportion of individuals surviving until the end of the experiment. In contrast, all Bamboo Vinegar (BV) treatments and the synthetic insecticide standards produced more rapid declines in survival probability. The log-rank test indicated a significant overall difference among treatments (χ^2=17.935, df=6, p=0.006), confirming that exposure to BV and insecticide treatments altered survival relative to the control. Visual inspection of the survival curves showed a distinct separation between the water control and all other treatments beginning at the early exposure intervals and widening over time. This separation indicates that BV exposure reduced mealybug longevity under laboratory conditions. Within the BV treatments, survival curves followed broadly similar trajectories. Although minor variation in the steepness of decline was observable during the early exposure period, the curves for 10%, 15%, and 20% BV converged over time and remained closely aligned throughout the majority of the observation period. The 5% BV treatment exhibited a slightly more gradual reduction in survival initially, but by 72 hours and beyond, survival probabilities were comparable to those observed in the higher BV concentrations.

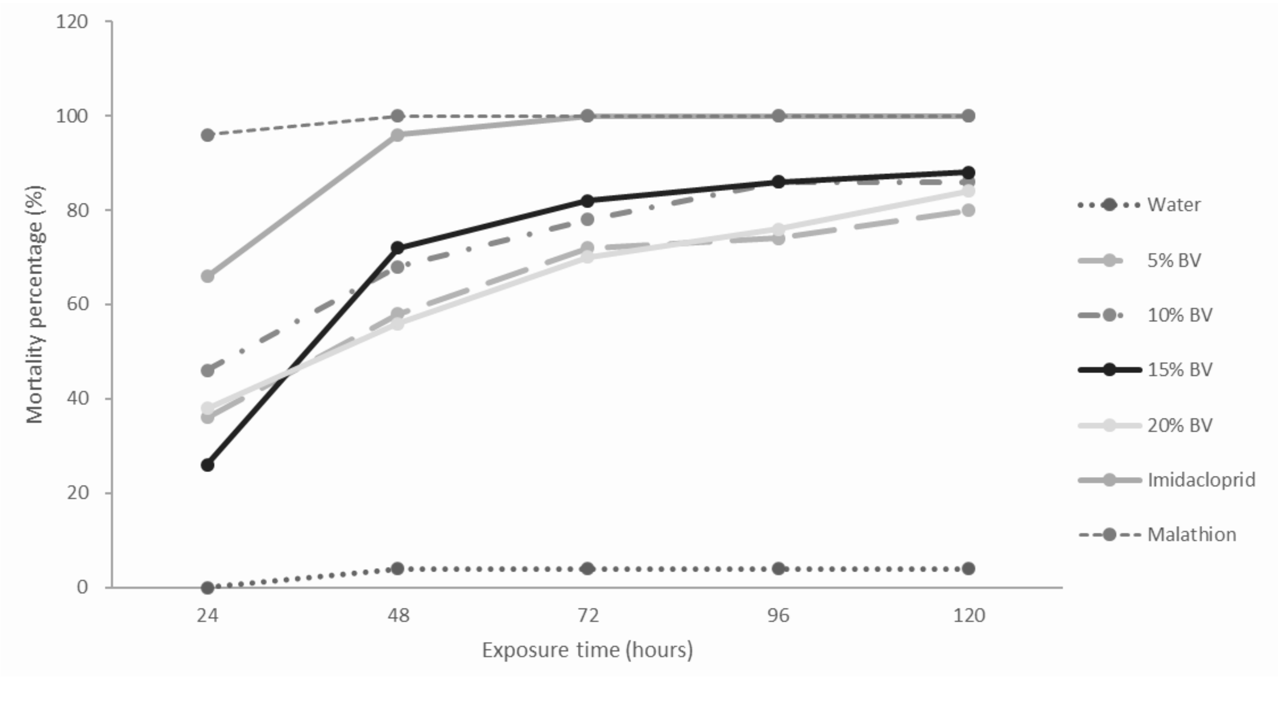

Figure 1. Mortality percentage (%) of pineapple mealybug over exposure time (hours) according to different treatments

This pattern is reflected in the survival time estimates (Table 2). The water control recorded the longest mean survival time (103.30±6.26 h) and the highest median survival (120 h). In contrast, all BV treatments showed reduced mean survival times (ranging from 72.00 to 76.80 h), with identical median survival times of 72 hours across concentrations. The overlapping confidence intervals for mean and median survival among BV treatments further indicate that differences in longevity within the tested concentration range were modest. Similarly, the synthetic insecticide treatments displayed survival estimates comparable to those of the BV treatments over the recorded intervals. By the end of the 120-hour exposure period, survival in all BV and insecticide treatments approached zero, whereas a proportion of individuals in the water control remained alive. Censoring events were minimal and evenly distributed, suggesting that the survival estimates were not biased by differential loss of individuals. Overall, the survival analysis demonstrates that BV exposure significantly shortened mealybug lifespan compared with the untreated control. However, within the tested concentration range (5-20% v/v), survival responses were broadly similar, suggesting that mortality effects may reach a plateau once a threshold concentration is exceeded. These findings indicate that BV exerts a consistent time-dependent toxic effect, with clear separation from the control but limited differentiation among concentrations under the present experimental conditions.

Repellent effect of bamboo vinegar on pineapple mealybugs

Repellency increased significantly between 1 h and 6 h after treatment. The Wilcoxon signed-rank test showed a strong time effect ($Z=-4.102$, $p<0.001$), with most replicates exhibiting higher repellency at 6 h than at 1 h, indicating that repellency strengthened over the observation period. All treatments showed repellent activity, as indicated by Repulsion Index values below 1 (Table 3). Repellency differed significantly among treatments for both repellency percentage and Repulsion Index. Higher BV concentration resulted in stronger repellency, with 20% (v/v) BV producing the greatest behavioral avoidance. This treatment was significantly more repellent than the lower BV concentrations, while white oil showed intermediate repellency and did not differ from the highest BV treatment. Lower BV concentrations did not differ significantly from each other. Effect size estimates ($\eta^2\_H=0.234$ for PR and $\eta^2\_H=0.250$ for IR) indicated biologically meaningful differences among treatments, supporting the robustness of the observed treatment effects. Overall, the results demonstrate a clear concentration-dependent repellency response, with repellency increasing over time and peaking at the highest BV concentration tested.

The Kruskal-Wallis test showed significant differences in repellency among treatments, with 20% (v/v) BV achieving the strongest effect (highest PR rank and lowest IR rank). Post-hoc comparisons confirmed that 20% (v/v) BV is significantly more repellent than 5%, 10%, and 15% (v/v) BV. White oil also displayed high repellency, grouping with 20% (v/v) BV in the post-hoc analysis, while lower concentrations fell into a distinct, less effective cluster. The medium-to-large effect sizes ($\eta^2\_H\approx0.23$-0.25) underscore the biological relevance of these differences. These patterns where repellency strengthening over time, and higher efficacy at a higher concentrations are well aligned with literature on plant-derived repellents. For example, Jaleel et al. (2020) demonstrated clear concentration-dependent repellent effects in botanical extracts using nonparametric analysis. Moreover, recent reviews emphasize the importance of dose-response and temporal dynamics in botanical repellent development (Turan and Çokyiğit 2023; Rault et al. 2024).

Table 2. Means and medians for survival time (hours) of pineapple mealybugs exposed to different BV concentrations

Treatment	Mean ± SE	95% CI (Mean)	Median ± SE	95% CI (Median)
Water	103.30±6.26	91.04-115.56	120.00±15.02	90.56-149.45
5% BV	74.40±6.83	61.01-87.79	72.00±11.52	49.42-94.58
10% BV	72.00±6.93	58.42-85.58	72.00±11.76	48.96-95.05
15% BV	76.80±6.71	63.65-89.95	72.00±11.30	49.85-94.16
20% BV	76.80±6.71	63.65-89.95	72.00±11.30	49.85-94.16
Imidacloprid	72.00±6.93	58.42-85.58	72.00±11.76	48.96-95.05
Malathion	72.00±6.93	58.42-85.58	72.00±11.76	48.96-95.05
Overall	77.46±2.59	72.39-82.54	72.00±4.56	63.06-80.94

Table 3. Mean Repulsion Index (IR) and Repellency Percentage (PR) of pineapple mealybugs under different bamboo vinegar (BV) concentrations

Treatment	Mean IR (%) ± SE	Mean PR ± SE	Repulsion force
5% BV	0.52±0.04	48.44±13.77a	Category 3
10% BV	0.50±0.04	50.07±13.52a	Category 3
15% BV	0.51±0.07	49.38±25.29a	Category 3
20% BV	0.26±0.03	74.41±10.64b	Category 4
White oil	0.39±0.06	60.80±19.58ab	Category 4

Note: Means followed by the same letter are not significantly different according to Mann-Whitney U tests with Bonferroni correction ($p<0.05$, $n=60$)

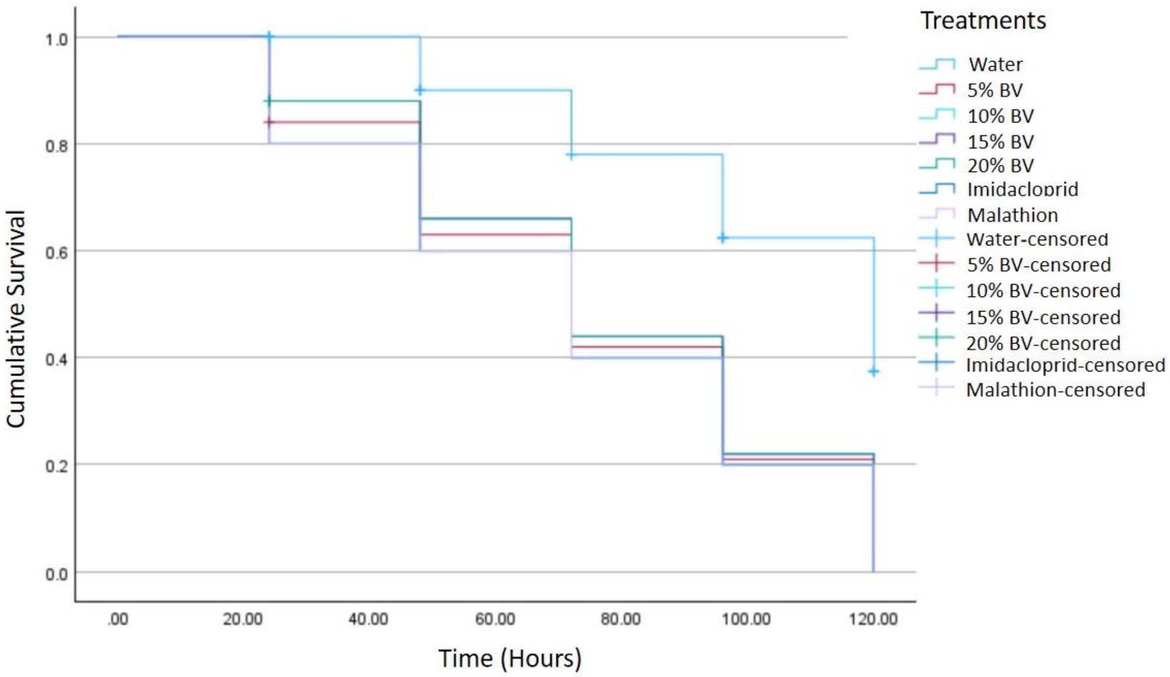

Figure 2. Kaplan-Meier survival curves for pineapple mealybugs exposed to different concentrations of Bamboo Vinegar (BV). Steeper curves indicate faster mortality rates. Tick marks denote censored data points (individuals surviving beyond the observation period)

Discussion

Mortality effect of bamboo vinegar on pineapple mealybugs

The survival analysis demonstrated that exposure to Bamboo Vinegar (BV) significantly reduced the longevity of pineapple mealybugs compared with the untreated control. While all BV concentrations shortened survival time, differences among concentrations were modest, suggesting that once a threshold concentration was reached, additional increases produced limited gains in overall survival reduction within the tested range. This pattern indicates that BV exerts a consistent toxic effect, but its impact may plateau under laboratory conditions. The delayed but progressive mortality observed following BV exposure is consistent with the mode of action commonly attributed to wood- and bamboo-derived vinegars. These products are rich in organic acids and phenolic compounds that disrupt physiological processes gradually rather than inducing rapid neurotoxic knockdown (Yatagai et al. 2002; Oramahi et al. 2023; Suprianto et al. 2023). Unlike synthetic insecticides such as imidacloprid and malathion, which act on specific neural targets and produce rapid mortality, vinegar-based botanicals typically require sustained exposure to achieve maximum efficacy. Similar delayed toxicity patterns have been reported in other studies evaluating botanical formulations (Hutapea et al. 2024; Luis et al. 2024), supporting the interpretation that BV functions through cumulative physiological stress rather than acute intoxication.

The relatively small differences in survival among the 10-20% BV treatments suggest that increasing concentration beyond an intermediate level may not proportionally accelerate mortality under controlled laboratory exposure. This plateau response may reflect saturation of contact activity or limitations in cuticular penetration. Comparable concentration-response patterns have been observed in studies of other plant-derived extracts, where biological efficacy stabilizes once sufficient active compounds are present (Akakabe et al. 2006; Wang et al. 2024). From a practical standpoint, this finding is relevant because it suggests that moderate concentrations may provide similar survival suppression to higher doses, potentially improving cost-efficiency and reducing phytotoxicity risk. Although BV acted more slowly than the synthetic insecticide standards, its consistent reduction of survival time demonstrates measurable insecticidal activity. This supports previous evidence that botanical vinegars can be effective against soft-bodied insects, particularly under conditions of direct contact (Yatagai et al. 2002; Oramahi et al. 2023; Suprianto et al. 2023). The slower action profile should not necessarily be viewed as a limitation, but rather as a functional characteristic aligned with certain Integrated Pest Management (IPM) strategies.

From an IPM perspective, three implications arise. First, BV appears best suited as a short-residual, contact-type biopesticide for suppression rather than rapid knockdown. Its gradual mortality effect suggests usefulness in early-stage infestations or in situations where immediate elimination is not critical. Second, the demonstrated survival reduction supports its potential inclusion in rotation programs aimed at reducing selection pressure on conventional insecticides, thereby contributing to resistance mitigation (Abdelgaleil et al. 2023). Third, BV may serve as an environmentally compatible option in systems where residue concerns and worker safety are priorities (Saleem et al. 2019; Purnama et al. 2024). It is important to note that the present findings are based on laboratory exposure under controlled conditions. Field performance may differ due to environmental factors affecting persistence, coverage, and degradation. Formulation improvements designed to enhance stability or adherence could further strengthen BV efficacy under practical conditions (Akakabe et al. 2006; Wang et al. 2024). Future studies should therefore evaluate optimized formulations and field-level applications to determine its operational role within pineapple production systems.

Repellent effect of bamboo vinegar on pineapple mealybugs

Recent studies support the repellent and pest-suppressive potential of Bamboo Vinegar (BV) in both laboratory and field contexts. Abd Latip et al. (2024) reported reduced insect abundance in mango orchards following BV application, demonstrating its capacity to deter insect activity under field conditions. Broader reviews have documented the multifunctional role of BV as an insect repellent alongside soil amendment and antimicrobial functions (Rahmat et al. 2014). In the present study, repellency increased over time and was strongest at higher BV concentrations, indicating that BV can induce sustained behavioral avoidance in pineapple mealybugs. This response is consistent with evidence that phenolic-rich botanical products disrupt host-finding and feeding behaviour across diverse insect groups (Dubey and Mostafavi 2023; Kaushik et al. 2023).

Under field conditions, repellency may function through several complementary mechanisms. First, BV may create a behavioral barrier effect, where treated plant surfaces emit volatile compounds that reduce insect landing or probing frequency. Such barrier effects are particularly relevant for crawling or short-distance dispersing pests like mealybugs, where altered surface chemistry may interfere with host acceptance (Zhang et al. 2024). Second, BV may act as a deterrent to settlement, discouraging prolonged feeding and colonization after initial contact. For sap-feeding hemipterans, host selection involves gustatory and olfactory cues; disruption of these cues can reduce successful establishment even if insects temporarily contact treated tissues (Anton and Cortesero 2022; Thompson et al. 2026). Third, vapor-phase activity may influence insect movement within the crop canopy, potentially lowering aggregation intensity and slowing population build-up. These mechanisms align with broader findings that botanical volatiles modify insect orientation, feeding stimulation, and oviposition behaviour (Dubey and Mostafavi 2023; Kaushik et al. 2023). Although specific active constituents of BV were not quantified in this study, its concentration-dependent repellency is consistent with the known bioactivity of organic acids and phenolic derivatives commonly present in bamboo-derived pyrolysis products (Rahmat et al. 2014; Dubey and Mostafavi 2023). Increasing concentration likely enhances volatile emission and surface residue intensity, thereby strengthening behavioral avoidance. However, field persistence remains a key determinant of effectiveness, as many botanical repellents are susceptible to rapid degradation under ultraviolet exposure and rainfall.

From an IPM perspective, several implications emerge. First, BV can be positioned as a contact or vapor-phase repellent suitable for preventive application or early infestation stages, where reducing settlement and colonization pressure is critical. Second, its behavioral mode of action supports its integration alongside other tactics, including biological control and selective insecticides, to reduce reliance on synthetic chemistries. Third, the time-dependent increase in repellency suggests that improvements in formulation-such as encapsulation or adjuvant enhancement-could prolong residual activity and improve field reliability, as emphasized in recent reviews of botanical repellent technologies (Dubey and Mostafavi 2023; Kaushik et al. 2023). Overall, the findings reinforce bamboo vinegar as a promising, eco-friendly behavioral management tool within integrated pineapple mealybug control programs. While further field validation is required, its repellent properties offer a complementary mechanism that could suppress pest establishment and slow population development in sustainable production systems.

In conclusion, Bamboo Vinegar (BV) exhibited clear biological activity against *D. brevipes* under laboratory conditions, reducing survival probability and inducing measurable repellency. Survival analysis confirmed significant shortening of mealybug longevity relative to the control, while behavioural responses intensified at higher concentrations. Differences among BV concentrations were modest for survival but more pronounced for repellency, indicating complementary functional effects. Rather than acting as a rapid knockdown agent, BV appears better suited for suppression and deterrence within integrated pest management systems. However, the effects observed were generated under laboratory conditions, and their durability and consistency under field environments remain untested. The most critical next steps are therefore field validation to assess performance under variable environmental conditions and formulation development to improve stability and persistence, given the likely volatility of BV constituents. These steps are essential to determine whether laboratory efficacy can be translated into reliable on-farm outcomes and integrated effectively with existing pest management practices. In conclusion, bamboo vinegar shows strong promise as a low-residue, plant-derived input for pineapple mealybug management, but its applied value will ultimately depend on successful formulation and field-level validation.

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REFERENCES

Abd Latip NF, Khalib NNA, Omar NF, Azahri MS, Kasim NN, Mohamad Sahal MSA, Abdullah MA. 2024. Investigating the effects of bamboo vinegar as an organic pesticide on insect pests and the nutrient content of Harumanis mango (MA128), *Mangifera indica* L. Pertanika J Trop Agric Sci 47 (3): 591-604. https://doi.org/10.47836/pjtas.47.3.01.

Abdelgaleil SAM, Gad HA, Ramadan GRM, El-Bakry AM, El-Sabrout AM. 2023. Monoterpenes for management of field crop insect pests. J Agric Sci Technol 25 (4): 769-784.

Akakabe Y,Tamura Y, Iwamoto S, Takabayashi M, Nyuugaku T. 2006. Volatile organic compounds with characteristic odor in bamboo vinegar. Biosci Biotechnol Biochem 70 (11): 2797-9. https://doi.org/10.1271/bbb.60317.

Alias NZ., Abdullah S, Shaari SS, Junik JJ, Kamal ML, Masdar ND. 2020. The potential of bamboo vinegar (*Gigantochloa albociliata*) as insecticide. In: Alias NZ, Yusof R (eds.). Charting the Sustainable Future of ASEAN in Science and Technology. Springer Nature, Singapore. https://doi.org/10.1007/978-981-15-3434-8_7.

Anton S, Cortesero AM. 2022. Plasticity in chemical host plant recognition in herbivorous insects and its implication for pest control. Biology 11 (12): 1842. https://doi.org/10.3390/biology11121842.

Association of Official Analytical Chemist (AOAC). 1990. Official Methods on Analysis (18th ed). Benjamin Franklin, Washington DC.

Avila MV, Achimón F, Brito VD, Aguilar R, Pizzolitto RP, Zunino MP, Peschiutta ML. 2023. Insecticidal activity of essential oils against mealybug pests (Hemiptera: Pseudococcidae): A systematic review and meta-analysis. Plants 12 (1): 109. https://doi.org/10.3390/plants12010109.

Beardsley JW. 1993. The pineapple mealybug complex; taxonomy, distribution and host relationships. Acta Hortic 334: 383-386. https://doi.org/10.17660/ActaHortic.1993.334.40.

Carlos J. 2021. Malaysia to Increase the MD2 Pineapple Production to 50%. Tridge. https://www.tridge.com/stories/malaysia-to-increase-the-md2-pineapple-production-to-50.

Chen YP, Chen C, Wu H, He Q, Wu J, Yao JY, Chen F. 2025. Bamboo vinegar powder: Unveiling its antioxidant and antifungal efficacy through bioactive compound analysis and mechanistic insights. Food Chem 470: 142718. https://doi.org/10.1016/j.foodchem.2024.142718.

Dubey AK, Mostafavi E. 2023. Phyto-insect repellents: A nanotechnology-based approach of sustainability towards synthetic insect repellents. Curr Opin Green Sustain Chem 41: 100827. https://doi.org/10.1016/j.cogsc.2023.100827.

Egelie AA, Gillett-Kaufman JL. 2015. Pineapple mealybug, *Dysmicoccus brevipes* (Cockerell) (Insecta: Hemiptera: Pseudococcidae): EENY635/IN1106, 10/2015. EDIS 2015 (9): 5. https://doi.org/10.32473/edis-in1106-2015.

Folake AO, Matthew O, Adewale AO, Ibrahim MG. 2023. Insecticidal activity of botanicals and their effectiveness in insects and pests control. South Asian J Agric Sci 3 (2): 88-96. https://doi.org/10.22271/27889289.2023.v3.i2b.95.

Goeden RD, Kogan M. 1970. The host-plant range of *Lema trilineata daturaphila* (Coleoptera: Chrysomelidae). Ann Entomol Soc Am 63 (4): 1175-1180. https://doi.org/10.1093/aesa/63.4.1175.

Gopal GS, Venkateshalu B, Nadaf AM, Guru PN, Pattepur S. 2021. Management of the grape mealybug, *Maconellicoccus hirsutus* (Green), using entomopathogenic fungi and botanical oils: A laboratory study. Egypt J Biol Pest Control 31: 100. https://doi.org/10.1186/s41938-021-00444-z.

Ho CL, Lin CY, Ka SM, Chen A, Tasi YL, Liu mL, Chiu YC, Hua KF. 2013. Bamboo vinegar decreases inflammatory mediator expression and NLRP3 inflammasome activation by inhibiting reactive oxygen species generation and protein kinase C-α/δ activation. PLoS One 8 (10): e75738. https://doi.org/10.1371/journal.pone.0075738.

Hutapea D, Rahardjo IB, Rachmawati F, Yulia ND, Budiarto K. 2024. Efficacy of some botanical insecticides against *Aphis gossypii* Glover (Hemiptera: Aphididae) on chrysanthemum. J Entomol Acarol Res 56: 12173. https://doi.org/10.4081/jear.2024.12173.

Jahn GC, Beardsley JW, González-Hernández H. 2003. A Review of the Association of Ants with Mealybug Wilt Disease of Pineapple. Proc Hawaii Entomol Soc 36: 9-28.

Jaleel W, Wang D, Lei Y, Qi G, Chen T, Rizvi SAH, Sethuraman V, He Y, Lu L. 2020. Evaluating the repellent effect of four botanicals against two *Bactrocera* species on mangoes. PeerJ. 8: e8537. https://doi.org/10.7717/peerj.8537.

Jilani G, Su HCF. 1983. Laboratory studies on several plant materials as insect repellants for protection of cereal grains. J Econ Entomol 76 (1): 154-157. https://doi.org/10.1093/jee/76.1.154.

Joy PP, Anjana R, Soumya KK. 2013. Pests of Pineapple and Their Management. Kerala Agricultural University, Kerala.

Kaushik M, Yadav J, Singh A, Dubey MK. 2023. A systematic review of plant-based mosquito repellents and their activity. Indian J Nat Prod Resour 14 (3): 347-359. https://doi.org/10.56042/ijnpr.v14i3.4615.

Kwon TH, Kim DB, Kim B, Bloese J, Lee BH, Cha DH. 2024. Ethyl formate fumigation against pineapple mealybug, *Dysmicoccus brevipes*, a quarantine insect pest of pineapples. Insects 15 (1): 25. https://doi.org/10.3390/insects15010025.

Lira JA, Pereira RRCC, Costa LO, Nogueira RCC, Pereira CE. 2020. Insecticidal activity of plant extracts on *Dysmicoccus brevipes* in pineapple. Rev Ciênc Agrár 43 (1): 82-90. https://doi.org/10.19084/rca.17598.

Luis VEJ, Orlando MQ, Jenny YV. 2024. Ecological control of aphids in mandarins with pyroligneous acid derived from biomass. J Exp Biol Agric Sci 13 (3): 364-379. https://doi.org/10.18006/2025.13(3).364.379.

Malaysian Pineapple Industry Board (MPIB). 2021. Data Nanas 2021. Malaysian Pineapple Industry Board. https://www.mpib.gov.my/penerbitan/.

Mariyam, Paul N. 2024. Analysis of the insecticidal effect of botanical extracts on mealybugs (*Phenacoccus solenopsis*). Intl J Sci Res Arch 12 (1): 331-338. https://doi.org/10.30574/ijsra.2024.12.1.0770.

Mehdi BY, Oleiwi KA, Salih TA. 2022. Study of the repellent effect of the insect extract of the mealybug *Planococcus cirit* on first-phase nymphs of the mealybug *Nipaecoccus viridis*. Intl J Health Sci 6 (S6): 8746-8753. https://doi.org/10.53730/ijhs.v6nS6.12273.

Mohd ISA, Nusaibah SA, Vadamalai G, Mokhtar AS, Sapak Z. 2023. First report of pineapple mealybug wilt-associated virus 1 and 3 associated with mealybug wilt of pineapple disease on pineapple in Malaysia. New Dis Rep 48 (2): e12231. https://doi.org/10.1002/ndr2.12231.

Mu J, Uehara T, Furuno T. 2004. Effect of bamboo vinegar on regulation of germination and radicle growth of seed plants II: Composition of moso bamboo vinegar at different collection temperature and its effects. J Wood Sci 50 (5): 470-476. https://doi.org/10.1007/s10086-003-0586-y.

N'Guessan L, Chillet M, Chiroleu F, Soler A. 2024. Ecologically based management of pineapple mealybug wilt: Controlling *Dysmicoccus brevipes* mealybug populations with salicylic acid analogs and plant extracts. Horticulturae 10 (3): 227. https://doi.org/10.3390/horticulturae10030227.

Obeng-Ofori D, Reichmuth CH, Bekele AJ, Hassanali A. 1998. Toxicity and protectant potential of camphor, a major component of essential oil of *Ocimum kilimandscharicum*, against four stored product beetles. Intl J Pest Manag 44 (4): 203-209. https://doi.org/10.1080/096708798228112.

Oramahi HA, Permana RD, Diba F, Indrayani Y. 2023. The composition and termicidal activity of vinegar from medang wood (*Cinnamomum* sp.) under different pyrolysis temperature. Floresta Ambient 30 (3): e20230016. https://doi.org/10.1590/2179-8087-FLORAM-2023-0016.

Pratami GD, Nukmal N, Kanedi M. 2018. Bioassay of leaves extract of gamal (*Gliricidia sepium*) against papaya mealybugs *Paracoccus marginatus* (Hemiptera: Pseudococcidae). Sch J Agric Vet Sci 5 (3): 162-165. https://doi.org/10.21276/sjavs.2018.5.3.6.

Purnama I, Lestari SD, Lidar S, Mutamima A, Suri A, Nelvia N, Malhat FM. 2024. Effectiveness of Wood Vinegar from Torrefied Coconut Shells as an Eco-Friendly Pesticide Against Fall Armyworm (*Spodoptera frugiperda* J.E Smith). E3S Web Conf 593: 03004. https://doi.org/10.1051/e3sconf/202459303004.

Rahmat B, Pangesti D, Natawijaya D, Sufyadi D. 2014. Generation of wood-waste vinegar and its effectiveness as a plant growth regulator and pest insect repellent. Bio Res 9 (4): 6350-6360. https://doi.org/10.15376/biores.9.4.6350-6360.

Rault LC, Morrison WR,,Gerken AR, Bingham GV. 2024. Challenges in assessing repellency via the behavioral response by the global pest *Tribolium castaneum* to protect stored grains. Insects 15 (8): 626. https://doi.org/10.3390/insects15080626.

Saleem MS, Batool TS, Akbar MF,Raza S, Shahzad S. 2019. Efficiency of botanical pesticides against some pests infesting hydroponic cucumber, cultivated under greenhouse conditions. Egypt J Biol Pest Control 29: 37. https://doi.org/10.1186/s41938-019-0138-4.

Sether DM, Hu JS. 2002. Yield impact and spread of pineapple mealybug wilt associated virus-2 and mealybug wilt of pineapple in Hawaii. Plant Dis 86 (8): 867-874. https://doi.org/10.1094/pdis.2002.86.8.867.
Sether DM, Karasev AV, Okumura C, Arakawa C, Zee F, Kislan MM, Busto JL, Hu JS. 2001. Differentiation, distribution, and elimination of two different pineapple mealybug wilt-associated viruses found in pineapple. Plant Dis 85 (8): 856-864. https://doi.org/10.1094/PDIS.2001.85.8.856.
Sether DM, Ullman DE, Hu JS. 1998. Transmission of pineapple mealybug wilt-associated virus by two species of mealybug (*Dysmicoccus* spp.). Phytopatholohy 88 (11): 1224-1230. https://doi.org/10.1094/PHYTO.1998.88.11.1224.
Sulaiman O, Murphy RJ, Hashim R, Gritsch CS. 2005. The inhibition of microbial growth by bamboo vinegar. J Bamboo Rattan 4 (1): 77-81. https://doi.org/10.1163/1569159053444635.
Suprianto A, Oramahi HA, Diba F, Hardiansyah G, Anwari MS. 2023. The antitermitic and antifungal activities and composition of vinegar from durian wood (*Durio* sp.). J Korea Wood Sci 51 (4): 283-294. https://doi.org/10.5658/wood.2023.51.4.283.
Tapondjou AL, Adler C, Fontem DA, Bouda H, Reichmuth C. 2005. Bioactivities of cymol and essential oils of *Cupressus sempervirens* and *Eucalyptus saligna* against *Sitophilus zeamais* Motschulsky and *Tribolium confusum* du Val. J Stor Prod Res 41 (1): 91-102. https://doi.org/10.1016/j.jspr.2004.01.004.
Tarasing PS, Mohi-ud-din S, Gani M, Firdoos M, Srivastava K, Khan AA. 2025. Botanical insecticides: A sustainable alternative for eco-friendly insect pest management. Biol Forum 17 (7): 201-208. https://doi.org/10.65041/BiologicalForum.2025.17.7.30.
Thompson MN, Russavage EM, Bernauer OM. 2026. Making "scents" of how plant volatiles influence agriculturally important insects: A review. Environ Entomol 55 (1): nvaf108. https://doi.org/10.1093/ee/nvaf108.
Turan N, Çokyiğit MA. 2023. A review of plant-based insect repellents, their applications on textiles and repellency test methods. J Eng Sci 6 (1): 33-51. https://doi.org/10.47137/uujes.1251760.
Viorenta, Sartiami D, Maryana N, Watson GW, Zarkani A. 2025. Mealybugs (Hemiptera: Pseudococcidae) on ornamental plants in West Java, Indonesia with a new country species record, and their natural enemies. Biodiversitas 26 (2): 1018-1029. https://doi.org/10.13057/biodiv/d260250.
Wang J, Zhang B, Xun H, Yao X, Tang F. 2024. Simultaneous quantification of twelve compounds from bamboo/wood vinegar by gas chromatography-mass spectrometry. Separations 11 (6): 168. https://doi.org/10.3390/separations11060168.
Yatagai M, Nishimoto M, Hori K, Ohira T, Shibata A. 2002. Termiticidal activity of wood vinegar, its components and their homologues. J Wood Sci 48: 338-342. https://doi.org/10.1007/BF00831357.
Zhang Y, Zhang T, Wang X, , Bian Z, Zhang X, Yang G, Lu Y. 2024. Volatiles from essential oils of three Lamiaceae plants repel the winged cotton aphid, disturb its feeding behavior and reduce its fecundity. Pest Manag Sci 80 (9): 4253-4263. https://doi.org/10.1002/ps.8130.