Agro Bali : Agricultural Journal
Vol. 9 No. 2: 390-406, July 2026

e-ISSN 2655-853X
https://doi.org/10.37637/ab.v9i2.2845

Microencapsulated *Piper colubrinum* Volatiles as Sustainable Fruit Fly Attractants in Tropical Horticulture

Cico Jhon Karunia Simamora[1♥], Eva Pramuni Oktaviani Sitanggang[2], and Febrina Feby[1]
[1]Department of Agrotechnology, Faculty of Agriculture, University of Tanjungpura, Pontianak, Indonesia
[2]Department of Chemical Engineering, Faculty of Engineering, University of Tanjungpura, Pontianak, Indonesia
[♥]Corresponding author email: csomamora@faperta.untan.ac.id

Article history: submitted: June 6, 2026; accepted: July 25, 2026; available online: August 11, 2026

Abstract. Volatile compounds from tropical aromatic plants act as important semiochemical signals in agroecosystems, but their tendency to volatilize and oxidize limits their use as fruit fly attractants. This study developed a microencapsulation approach to stabilize Melada (*Piper colubrinum*) volatiles for practical field-level fruit fly attraction. A Completely Randomized Design (CRD) was employed, comprising four microencapsulation formulations with varying maltodextrin-gum arabic (MD-GA) ratios (2:10, 5:10, 10:10, and 12:10) and one petrogenol control, each replicated three times. Physicochemical properties and biological effectiveness were evaluated against fruit flies on chili pepper, guava, and papaya. Higher MD-GA ratios reduced surface oil content while improving encapsulation efficiency (EE), loading capacity (LC), and yield. Formulation F4 (12:10) performed best overall, with EE of 85.14%, LC of 1.39%, and yield of 82.38%, and was optimal for a wall structure giving strong volatile retention while sustaining adequate release for field attractiveness. Uniform microcapsule morphology confirmed good structural integrity, supporting sustained release under open field conditions. Field trials using 45 traps across three locations showed that encapsulated Melada volatiles effectively attracted *Bactrocera umbrosa* and *Bactrocera melastomatos*, remaining active up to 10 days longer than the petrogenol control, with F4 producing the highest catch across host plants and observation days. Attractiveness was highest on chili pepper, followed by guava and papaya, indicating synergy between host-plant volatiles and Melada's bioactive compounds. Overall, MD-GA microencapsulation enhances both the chemical stability and biological efficacy of Melada volatiles, showing strong potential as an eco-friendly attractant for sustainable fruit fly management in tropical horticulture.

Keywords: attractant; horticulture; microencapsulation; stability; volatile

1. Introduction

Fruit flies (*Bactrocera* spp.) are key pests in tropical horticultural farming systems, causing significant economic losses. Female oviposition and larval development within fruit tissue result in premature decay and yield losses that can reach 30-70% at the farmer level (Clarke, 2019; FAO, 2022). These losses are particularly severe in major crops such as chili peppers (*Capsicum frutescens* L.), guavas (*Psidium guajava* L.), and papayas (*Carica papaya* L.), which serve as the preferred hosts for *Bactrocera dorsalis*. The humid, high-temperature tropical climate accelerates the insect's life cycle, making it a pest that is difficult to control year-round. According to data from Badan Pusat Statistik (2023), pest infestations, including those by fruit flies, have reduced national horticultural productivity by up to 18.4%, while FAO (2022) reports that approximately 25 million tons of horticultural produce in Southeast Asia are damaged annually due to fruit fly infestations. These impacts are not limited to reduced crop yields but also pose a serious obstacle to the trade and export of tropical fruits due to strict quarantine regulations (Clarke *et al*., 2005).

Current fruit fly control efforts still rely heavily on the use of synthetic insecticides and methyl eugenol-based attractants. Although effective in the short term, repeated use has led to insect behavioral resistance, environmental degradation, and pesticide residues exceeding safe consumption thresholds (Fang *et al*., 2011). Reliance on imported commercial attractants also reduces farmers' economic efficiency in tropical countries. Within the framework of sustainable agriculture, the exploration of natural volatile compounds from local plants represents a strategic approach in developing efficient, environmentally friendly, and

e-ISSN 2655-853X
https://doi.org/10.37637/ab.v9i2.2845

adaptive biological attractants for tropical agroecosystems (Ahmad *et al*., 2023). The utilization of natural volatile compounds not only strengthens biological control approaches but also aligns with the principles of green pest management, which emphasize the efficiency and sustainability of production systems in tropical ecosystems.

The Melada plant (*Piper colubrinum* Link), a member of the Piperaceae family, is known to produce various secondary metabolites such as ferulic acid, gentisic acid, and methoxy-phenolic derivatives that share aromatic structural similarities with methyl eugenol (Afroz et al., 2021). Volatiles from the genus Piper have long been known to act as semiochemical signals mediating plant-insect interactions, particularly in the olfactory mechanisms that regulate host orientation and preference (Kessler *et al*., 2023). However, natural volatiles have a major limitation in that they are highly volatile and susceptible to oxidative degradation, resulting in low field efficacy and the need for repeated applications (Bahadir & Pfister, 1990). Therefore, formulation innovations are needed that can maintain the chemical stability of volatiles while controlling their release rate to sustain attractiveness to target insects. Nevertheless, despite this ecological potential, no publication or report has ever been found evaluating whether microencapsulation can effectively stabilize Melada volatiles for practical, field-level fruit fly management on horticultural host plants. This represents a clear knowledge gap, and the novelty of the present study lies in coupling MD-GA microencapsulation of Melada volatiles with a comparative, multi-host field evaluation, which has never previously been found in the available literature.

Maltodextrin and gum arabic (MD-GA) based encapsulation technology is a potential approach to protect volatile compounds from degradation and regulate their gradual release (controlled release) (Ozdemir *et al*., 2021; Sahlan *et al*., 2019). The MD-GA ratio governs release behavior primarily through its effect on wall architecture. Because maltodextrin contributes low viscosity and high solubility while gum arabic supplies emulsifying and film-forming capacity, shifting their relative proportion changes the density, cohesiveness, and continuity of the deposited wall matrix around the volatile core: a wall-material-rich formulation tends to form a thicker, more compact shell with lower porosity, whereas a core-material-rich formulation produces a thinner, looser, more porous wall (Choudhury *et al*., 2021; Kurniati *et al*., 2025). This porosity difference determines the diffusion pathway available to volatile molecules; a denser, less porous wall lengthens the tortuous path and reduces the effective diffusion coefficient through the matrix, while a more porous wall shortens it, consistent with the Higuchi-type diffusion model in which release rate is a function of wall porosity, tortuosity, and the diffusion coefficient of the encapsulated compound (Singh *et al*., 2010). Empirically, this mechanism has been demonstrated in wall-to-core ratio studies where thicker walls slowed volatile diffusion and produced lower release rates, while thinner walls allowed faster release, with direct consequences for the biological activity of the released compound against target insects (Kanmaz *et al*., 2026). The formation of microcapsules with specific physicochemical characteristics, such as particle size, porosity, and surface morphology, therefore determines the diffusion kinetics of volatile compounds, which are directly related to the physicochemical dynamics of their release in an open environment. Quantitatively, these microcapsule characteristics can influence the intensity, duration, and frequency of fruit fly behavioral responses to attractant sources over a specific time period (temporal response).

A comparative study of the effectiveness of the volatile attractant Melada on three different host plant commodities, chili peppers, guavas, and papayas, is crucial for elucidating the relationship between microcapsule structure, volatile stability, and

e-ISSN 2655-853X
https://doi.org/10.37637/ab.v9i2.2845

the cross-host orientation behavior of fruit flies. This approach not only highlights the slow-release mechanism and the physicochemical dynamics of the volatiles but also provides a new scientific foundation for the development of next-generation biological attractants based on local, efficient, and sustainable resources in tropical agricultural systems. Accordingly, this study aimed to formulate and physicochemically characterize microencapsulated Melada volatiles at four MD-GA ratios (2:10, 5:10, 10:10, and 12:10) and to evaluate their field attractiveness against fruit flies on three horticultural host plants (chili pepper, guava, and papaya), thereby providing baseline data to support further development of a locally sourced, encapsulation-based biological attractant.

2. Materials and Methods

2.1 Research Location and Design

The study was conducted at two main locations: the Agricultural Biotechnology and Horticultural Land Laboratory at Tanjungpura University, Pontianak, for encapsulate formulation and characterization activities; and horticultural fields in Sungai Selamat Village, North Pontianak District, and in Rasau Jaya, Kubu Raya Regency, West Kalimantan (Figure 1), for field efficacy testing. The study design used a Completely Randomized Design (CRD) with four microcapsule formulation treatments and one commercial control, each replicated three times. In total, the microcapsule characterization experiment comprised 15 experimental units (4 formulations×3 replicates), and the field efficacy trial comprised 5 treatments (F1-F4 and the petrogenol control)×3 replicates×3 host-plant sites, yielding 45 traps in total (15 traps per host-plant site).

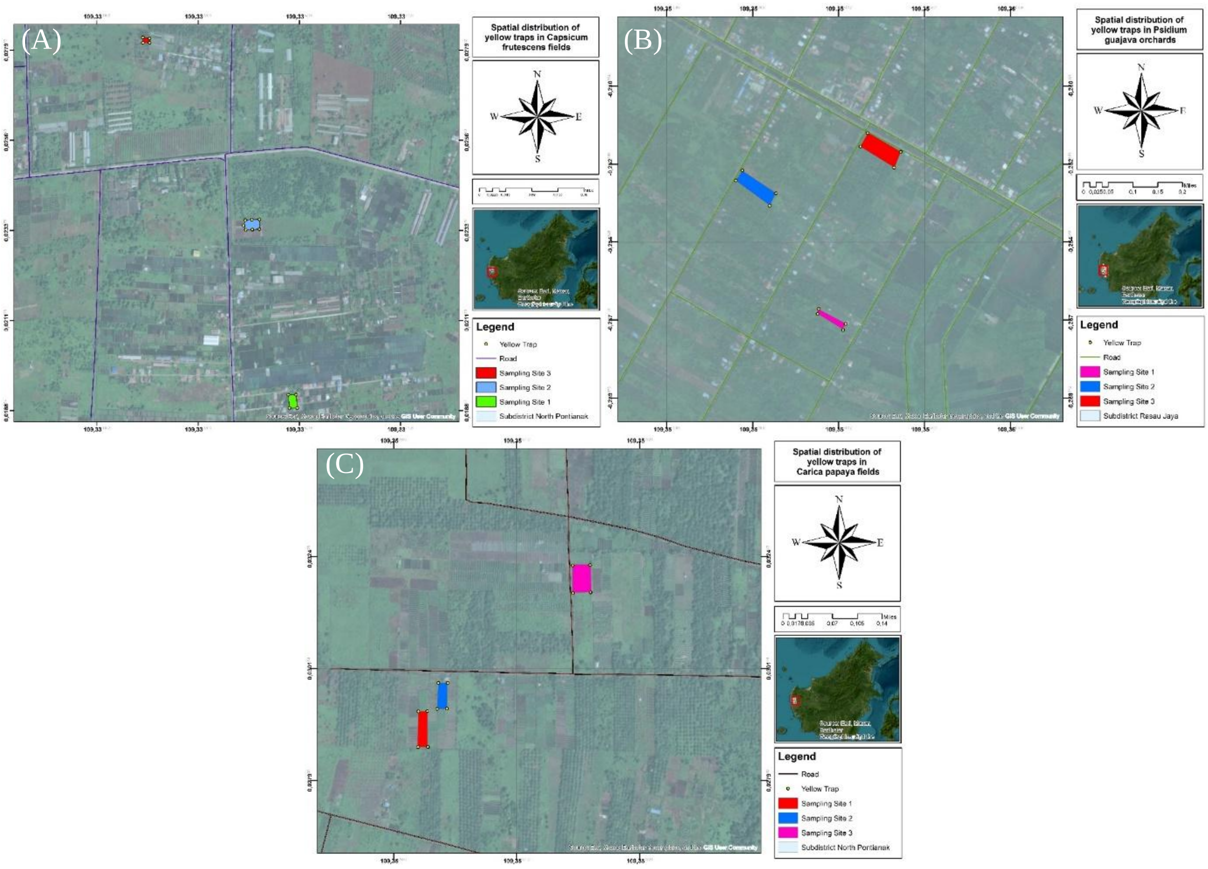

Figure 1. Map of Fruit Fly Trap
Note: A, C = Sungai Slamet; C = Rasau Jaya Villages

e-ISSN 2655-853X
https://doi.org/10.37637/ab.v9i2.2845

2.2 Materials and Equipment

The main material consisted of *Piper colubrinum* Link leaves collected from Rasau Jaya 3 Village, Kubu Raya Regency, West Kalimantan. The chemicals used included maltodextrin (MD), gum arabic (GA), 70% ethanol, technical n-hexane, distilled water, and the reference attractant petrogenol. All materials were of analytical grade (Merck, Germany). The equipment used included a drying oven (DHG 9030A), a rotary vacuum evaporator (EYELA, Japan), an orbital shaker (AMTM 10), a 60-mesh sieve (KZM-test sieve), an OHAUS analytical balance, a scanning electron microscope (Hitachi TM-3000), and a Particle Size Analyzer (Malvern Mastersizer, UK).

2.3 Preparation and Melada Leaf Crude Extract

Fresh, healthy, and contaminant-free Melada leaves were thoroughly washed, cut into small pieces (2-3 cm), and dried at room temperature for 3-4 days until the moisture content reached ±10%. The dried leaves were ground into a fine powder and then sieved using a 60-mesh sieve. The crude drug powder is stored in an airtight container to prevent the degradation of volatile compounds (Sahlan *et al*., 2019).

2.4 Preparation and Formulation of Encapsulates

The coating solution was prepared by mixing 5 g of maltodextrin and 5 g of gum arabic dissolved in 20 mL of distilled water, stirred using a magnetic stirrer. The Melada leaf crude drug was then mixed with the encapsulation medium at four different ratios: F1 (2:10), F2 (5:10), F3 (10:10), and F4 (12:10). The homogeneous mixture was dried at 60-70°C for 48 hours in an oven. The dried samples were then finely ground to obtain microcapsule powder ready for characterization (Sahlan *et al*., 2019).

2.5 Analysis of Microcapsule Characteristics

The physicochemical characteristics of the microcapsules were determined using the following parameters:

2.5.1 Surface Oil Content

Measured using a modified maceration method (Sahlan *et al*., 2019). A total of 1 g of microcapsules was extracted with 10 mL of n-hexane for 15 minutes and shaken in a shaker for 2 minutes. The filtrate was filtered using Whatman No. 42 filter paper and dried at 60°C for 24 hours. The surface oil content was calculated from the difference in weight before and after drying relative to the initial total oil.

2.5.2 Encapsulation Efficiency (EE)

The EE value was calculated from the ratio of total oil content to surface oil content according to the equation (Rao *et al*., 2016):

$$EE\ (\%) = \frac{Total\ oil\ -\ Surface\ oil}{Total\ oil} \times 100$$

2.5.3 Loading Capacity (LC)

LC was measured to determine the amount of volatile oil trapped in the microcapsules based on the ratio of oil weight to total microcapsule weight (Sahlan *et al*., 2019).

2.5.4 Microcapsule Yield

Yield is calculated from the ratio of the dry weight of the microcapsules to the total weight of the forming materials (MD-GA and crude drug) multiplied by 100% (Mahdavi *et al*., 2016).

2.5.5 Morphological and Particle Size Analysis

The microcapsule surface was analyzed using a Scanning Electron Microscope (SEM) at 30,000× magnification, while particle size was determined via the Dynamic Light Scattering (DLS) method using a Particle Size Analyzer at 25°C for 70 seconds. Particle size distribution was expressed as the Z-average and the polydispersity index (PI).

2.5.6 Field Testing of Attractant Effectiveness

Field testing was conducted in fields planted with chili peppers (*Capsicum frutescens* L.), guavas (*Psidium guajava* L.), and papayas (*Carica papaya* L.). The attractants were installed at a height of 1.5 m with a distance of 20 m between traps. Field conditions during the trial period were consistent with the typical tropical climate of

e-ISSN 2655-853X
https://doi.org/10.37637/ab.v9i2.2845

the West Kalimantan lowlands, with a mean air temperature of 27-31°C, a mean relative humidity of 75-88%, cumulative rainfall of approximately 40-120 mm over the 10-day observation period, and an average wind speed of 1-3 m/s. Each treatment (F1-F4) and control was replicated three times, with a total of 15 traps per location. Observations were made on days 1, 5, and 10. The number of fruit flies captured was counted, identified, and grouped by sex and species based on A Manual of Fruit Flies and Fruit Flies (*Tephritidae*): Phylogeny and Evolution of Behavior (Yong *et al.*, 2016).

2.6 Data Analysis

Data on microcapsule characterization (encapsulation efficiency, loading capacity, yield, and particle size) were analyzed using one-way Analysis of Variance (ANOVA). Meanwhile, data on attractant effectiveness were analyzed for each host plant separately using two-way ANOVA (Formulation×Observation time). Post-hoc tests were conducted using the Honestly Significant Difference (HSD) test at the 5% level to determine significant differences between treatments. The relationship between microcapsule characteristics and fruit fly preference levels was analyzed using Pearson's correlation. The selection of the best formulation was based on the Effectiveness Index Method (De Garmo *et al*., 1984) with weighting of physicochemical parameters and insect behavior. All statistical analyses were performed using SPSS ver. 26, with differences considered significant at $p<0.05$.

3. Results and Discussion

3.1 Identification of Melada Plants

The leaves of *Piper colubrinum* Link (family Piperaceae) are simple and arranged alternately along the stem, with a distinct pinnatifid or pinnatisect primary venation pattern. The secondary veins are arranged in pairs, radiating from the midrib toward the leaf margin. The leaf blade texture ranges from coriaceous to somewhat thick; the adaxial surface is glossy, while the abaxial surface tends to be paler with clearly visible fine veins. The leaf blade is lanceolate to elliptic-lanceolate, generally ranging from 15-20 cm in length, with entire margins and an acuminate apex (Figure 2). These morphological characteristics align with the general traits of the genus Piper, characterized by alternate leaves with distinct venation and leaf surfaces ranging from membranous to coriaceous (Remashre & Ravindran, 1998).

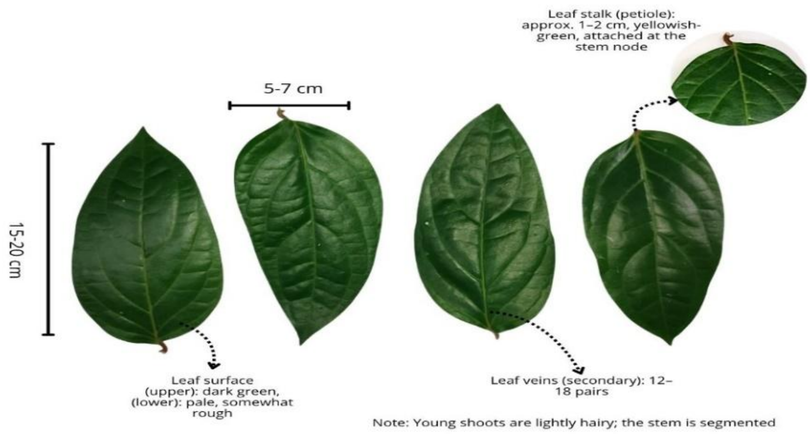

Figure 2. Leaf morphology of *Piper colubrinum* Link

3.2 Physicochemical Characteristics of Melada Volatile Microencapsules

Differences in the MD-GA ratio significantly influence the physicochemical performance of Melada volatile microcapsules, particularly regarding the capsule wall's ability to retain active aromatic compounds. As shown in Table 1,

e-ISSN 2655-853X
https://doi.org/10.37637/ab.v9i2.2845

formulation F1 (2:10) exhibited the highest surface oil content, at 7.26% on the first day and increasing to 9.62% on the 10th day. This high value indicates that the coating layer has not yet formed completely, causing most of the volatile to migrate to the surface during the drying process. This phenomenon is common in systems with a low coating material ratio, as the emulsion viscosity is insufficient to evenly coat the volatile particles (Mahdavi *et al*., 2016).

In contrast, formulations F3 (10:10) and F4 (12:10) exhibited significantly lower surface oil content (<2.5%), indicating the formation of a tighter and more stable protective layer. The compact microcapsule walls prevent the volatile from easily evaporating or oxidizing, thereby increasing encapsulation efficiency (EE). The highest EE value was recorded for F4 (85.14%), followed by F3 (82.76%), while F1 decreased to 71.21% by the end of the observation period. This inverse relationship between surface oil content and EE confirms that the success of the encapsulation process depends on the polymer system's ability to prevent volatile migration within the matrix (Phanse & Chandra, 2024).

Formulation F4 demonstrated the best balance between emulsion viscosity and particle homogeneity. The 12:10 ratio produced microcapsules with a dense yet sufficiently permeable wall layer, ensuring that volatiles remain well-trapped while still being able to be released gradually in an open environment. Such conditions are ideal for natural compound-based attractants that require controlled release of volatiles to maintain the aromatic stimulus over a longer period (Jeyakumari *et al*., 2016; Rao *et al*., 2016; Simamora *et al*., 2025).

Table 1. Surface oil content and encapsulation efficiency

Encapsulation Formulation (MD-GA)	Surface Oil Content (%)			Encapsulation Efficiency		
	Day 1	Day 5	Day 10	Day 1	Day 5	Day 10
F1 (2:10)	7.262±0.15^{c}	8.620±0.18^{b}	9.622±0.17^{a}	79.475±1.28^{bcd}	77.062±1.07^{cd}	71.213±1.05^{ef}
F2 (5:10)	2.765±0.16^{f}	3.404±0.14^{e}	5.620±0.14^{d}	80.382±1.06^{bc}	77.391±1.10^{cd}	70.409±1.17^{f}
F3 (10:10)	0.705±0.14^{gh}	1.241±0.17^{g}	2.443±0.16^{f}	82.762±1.14^{ab}	80.558±1.09^{bc}	75.288±1.21^{de}
F4 (12:10)	0.933±0.17^{gh}	0.373±0.13^{h}	0.987±0.18^{g}	85.143±1.04^{a}	83.119±1.09^{ab}	79.246±1.12^{bcd}
HSD 5%	**0.607**			**4.548**		

Note: Values are means ± standard error (SE) of three replicates (n = 3). $^{a-h}$Mean values within a column followed by different superscript letters differ significantly ($p < 0.05$), according to the Honestly Significant Difference (HSD) test.

The consistency of the results for F4 is also reflected in the graph data (Figure 3). Loading capacity (LC) and drying yield increased with the addition of coating material proportion. F4 showed the highest values (LC = 1.39%; yield = 82.38%), confirming it as the most efficient formulation for volatile retention and material conversion. Its higher core-to-wall ratio (12:10) allowed more Melada extract to be incorporated per batch without compromising encapsulation efficiency. Since F4 also recorded the highest EE of all formulations (85.14%), indicating that the wall remained permeable enough to sustain an effective release profile rather than becoming so thick that diffusion was excessively impeded (Yang *et al*., 2025).

e-ISSN 2655-853X
https://doi.org/10.37637/ab.v9i2.2845

Figure 3. Loading Capacity and Yield Encapsulation

Balancing retention efficiency and release capacity, the F4 encapsulation formulation is confirmed as the most optimal formulation. Its wall structure is sufficiently dense to protect the volatile from thermal and oxidative degradation, yet it retains adequate porosity to support slow, gradual release as required for attractant applications (Huang *et al*., 2023; Jyothi *et al*., 2012). This pattern confirms that microcapsule performance is determined not only by the quantity of the final product but also by the suitability of its physicochemical properties to the expected biological function. In the context of environmentally friendly pest control, the F4 formulation represents the optimal balance between stability, efficiency, and the effectiveness of Melada volatiles in tropical agroecosystems. In mechanistic terms, F4's higher encapsulation efficiency (85.14%) relative to F3 (82.76%) is consistent with its superior field performance: its release kinetics evidently matched the olfactory response window of the target fruit flies across the full 10-day observation period, rather than under-delivering volatile concentration at the trap surface as might be expected from an excessively dense wall. This is consistent with Fickian diffusion behavior, in which a wall matrix that is dense enough to slow surface volatilization, without fully impeding diffusion, sustains a detectable odor plume for longer under field conditions (Phanse & Chandra, 2024). This interpretation is directly consistent with Tangpao *et al*. (2021), who similarly reported that increasing wall material improved attractant persistence in basil essential oil traps, reinforcing that a higher-loading, denser-walled formulation such as F4 can enhance rather than compromise field-level attractant performance when the wall remains sufficiently permeable. Biological variation among the three field replicates at each site, arising from local microclimate, background host-volatile emission, and fruit fly population density, also contributed to the variability captured by the HSD post-hoc comparisons, underscoring the value of replicated field trials in distinguishing true treatment effects from site-level noise.

3.3 Morphological Stability and Encapsulate Structure

Morphological analysis indicates that variations in the MD-GA ratio significantly influence the homogeneity and physical structure of the Melada volatile microcapsule walls. Particles from formulation F1 exhibit an uneven surface with indications of fine cracks, whereas F3 and F4 display a spherical shape with a smoother and more uniform surface. These differences indicate varying degrees of matrix co-precipitation and solidification during the spray-drying process. The smooth and dense wall layer observed at these higher MD-GA ratios, most pronounced in F4, reflects a balanced emulsion viscosity, enabling effective encapsulation of the volatile without causing particle aggregation (Shamaei *et al*., 2017).

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https://doi.org/10.37637/ab.v9i2.2845

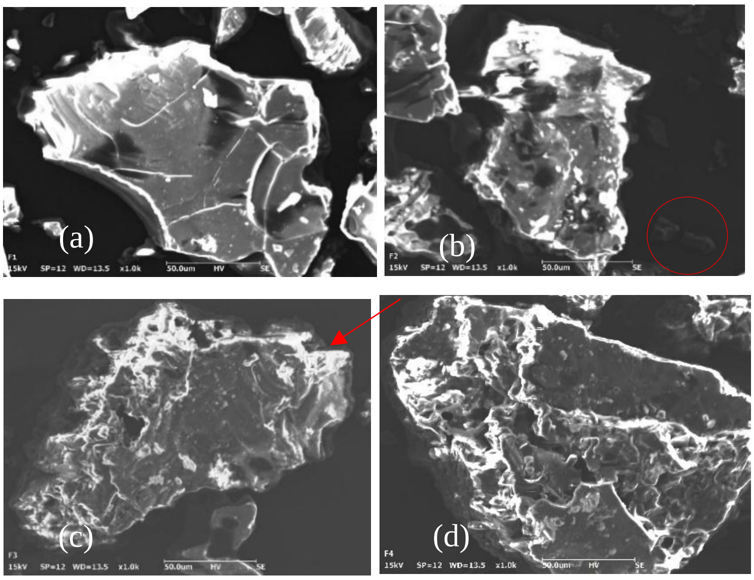

Figure 4. (a) F1 (02:10), (b) F2 (05:10), (c) F3 (10:10), (d) F4 (12:10) white particles indicate MD-GA particles and black particles indicate Melada leaf crude extract particles

The particle size distribution of the microcapsules (Figure 4) shows a diameter range of 201-253 µm, with a polydispersity index of 396-490 µm. Formulation F2 (201.2 µm) has the smallest average particle size, which theoretically increases the surface area to volume ratio, thereby enhancing contact between the microcapsule walls and the external medium and accelerating the mass transfer of volatile molecules from the core to the external environment. Physically, smaller particles have a relatively larger surface area, which supports an increased diffusion rate of volatile molecules through the microcapsule walls compared to larger particles, due to a more intense concentration gradient at the solid-liquid interface (Chen *et al*., 2022).

Particle size correlates with release behavior (Figure 5), smaller particles increase the active surface area and can result in faster and more homogeneous release due to shorter diffusion paths (Yang *et al*., 2025), where control of particle size distribution can determine the intensity and duration of core material release. Thus, F2 (the smallest average size) is predicted to have the highest capacity to retain volatiles through a wide surface distribution, while formulations with larger sizes tend to have slower and less consistent release kinetics. This approach is consistent with the fundamental principle of the surface-to-volume ratio in controlling release rates, which is a key parameter in the design of effective microcapsule systems (Alves *et al*., 2014).

The combination of particle morphology and size determines the performance of biological attractants in tropical horticultural ecosystems. Microcapsules with a dense surface and a narrow size distribution provide better thermohygroscopic stability, keeping the volatiles active for longer despite temperature fluctuations and high humidity. These conditions are crucial for maintaining the attractant's odor gradient within the trap area. ensuring consistent effectiveness in attracting fruit flies throughout the application period (Alves *et al*., 2014). Ecologically, the combination of a smooth surface, low porosity, and uniform particle size distribution provides high resistance to tropical humidity and temperature fluctuations, ensuring the sustained activity of volatiles in open environments (Alves *et al*., 2014; Jyothi *et al*., 2012).

e-ISSN 2655-853X
https://doi.org/10.37637/ab.v9i2.2845

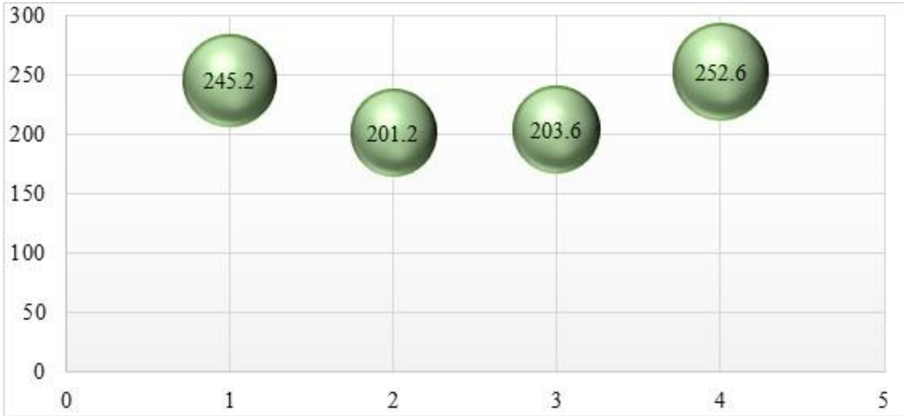

Figure 5. Microcapsule Size Distribution Based on Volume Diameter

3.4 Formulation Effectiveness Index

Analysis of the formulation effectiveness index (Table 2) shows that F4 has the highest value (0.581), followed by F3 (0.500). This numerical ranking is consistent with F4's superior performance across the physicochemical and field-efficacy parameters reported above, confirming F4 as the most ideal formulation overall, as its volatile release remained the most consistent across the observation period. A diffusion rate that is too slow can reduce the olfactory stimulation of insects, reinforcing that F4's balance of retention and permeability, rather than a slower-releasing alternative, represents the optimal outcome (Liu *et al*., 2022; Xu *et al*., 2024). Similarly, the stable release in F4 maintains the aroma intensity within the optimal threshold for the fruit fly's sensory system. The positive correlation between encapsulation efficiency and yield indicates that good volatile retention contributes to the functional stability of the attractant in the field (Singh *et al*., 2020; Zabot *et al*., 2022).

Table 2. Table of Best Treatment Analysis Using the Effectiveness Index Method

Encapsulated Formulation (MD-GA)	EA	EE	LC	Y	Total Product Value
F1 (2:10)	0.215	0.009	0.028	0.086	0.338
F2 (5:10)	0.090	0.220	0.000	0.037	0.346
F3 (10:10)	0.000	0.400	0.100	0.000	0.500
F4 (12:10)	0.300	0.000	0.081	0.200	0.581

Note: EA: Attractant Effectiveness, EE (%): Encapsulation Efficiency, LC (%): Loading Capacity, Y (%): Yield

The positive correlation between EE and Y values in F3-F4 confirms that the encapsulation efficiency of volatiles contributes to product stability and the consistency of attractant compound release. The higher the ability of the microcapsule walls to retain volatiles during drying, the greater the likelihood that the volatiles will persist under humid tropical agroclimatic conditions. This phenomenon is consistent with the findings of Singh *et al*. (2020), who reported that maltodextrin-gum arabic-based formulations exhibited high thermohygroscopic stability in essential oil-based attractant systems.

e-ISSN 2655-853X
https://doi.org/10.37637/ab.v9i2.2845

Table 3. Fruit Fly Population Counts and Attractant Effectiveness for Microencapsulated Formulation Across Host Plants and Observation Times

Test Plants	Encapsulation Formulation (MD-GA)	Attractant Effectiveness		
		Day-1	Day-5	Day-10
Chili pepper	F0 (Control Petrogenol)	168.00±1.73^{a}	185.33±3.48^{a}	55.00±7.37^{a}
	F1 (2:10)	19.00±2.08^{d}	26.67±2.33^{d}	20.67±1.20^{c}
	F2 (5:10)	54.33±4.48^{c}	60.00±3.79^{c}	52.33±3.53^{b}
	F3 (10:10)	119.00±9.87^{b}	125.67±11.33^{b}	61.67±1.76^{a}
	F4 (12:10)	154.33±4.81^{a}	171.67±4.81^{a}	75.00±4.04^{a}
HSD 5%	**21.680**			
Guava	F0 (Control Petrogenol)	173.00±7.09^{a}	187.67±3.93^{a}	52.67±4.10^{b}
	F1 (2:10)	21.67±2.73^{d}	30.00±3.61^{d}	24.00±1.15^{c}
	F2 (5:10)	56.67±5.24^{c}	64.33±4.33^{e}	53.00±2.52^{b}
	F3 (10:10)	123.67±5.90^{b}	132.00±8.54^{b}	55.33±2.33^{b}
	F4 (12:10)	161.67±4.63^{a}	180.67±4.18^{a}	78.33±4.33^{a}
HSD 5%	**19.176**			
Papaya	F0 (Control Petrogenol)	169.67±3.18^{a}	179.67±2.91^{a}	50.67±2.73^{b}
	F1 (2:10)	20.00±3.21^{d}	24.33±3.76^{d}	18.67±0.88^{c}
	F2 (5:10)	56.67±6.74^{c}	61.33±3.38^{c}	49.00±6.93^{b}
	F3 (10:10)	120.33±11.26^{b}	124.33±12.57^{b}	51.33±7.17^{b}
	F4 (12:10)	155.00±8.08^{a}	163.00±5.13^{a}	79.67±3.18^{a}
HSD 5%	**25.819**			

Note: Values are means ± standard error (SE) of three replicates (n = 3). $^{a-h}$Mean values within a column followed by different superscript letters differ significantly ($p < 0.05$), according to the Honestly Significant Difference (HSD) test.

3.5 Effectiveness of Fruit Fly Attractants and Physicochemical Relationships

The results of field observations (Table 3) show significant differences among formulations within each test plant. The number of fruit flies caught increased as the MD-GA ratio increased. Formulation F4 (12:10) yielded the highest results on cayenne peppers, guavas, and papayas (an average of 75-79 flies), while F1 consistently showed the lowest effectiveness across all host plants and observation days (≤30 flies). This trend confirms that a denser microcapsule layer retains volatile aromas longer in the air (Binyameen *et al*., 2021). F4's consistently highest catch across all three host plants and all three observation days (Day-1, Day-5, and Day-10), rather than only at peak activity, indicates that its release profile sustained a biologically effective odor plume for the full duration of the trial, supporting its selection as the optimal formulation for field deployment. Guava plants showed the highest overall response, particularly on day 5 (180.67 individuals for F4), likely due to a synergy between guava's intrinsic fruit volatiles and Melada's aromatic components. Interactions between aromatic compounds

 e-ISSN 2655-853X
https://doi.org/10.37637/ab.v9i2.2845

from two different sources can enhance the intensity of olfactory signals and accelerate insect orientation (Liu *et al*., 2022; Silva *et al*., 2007). Conversely, chili pepper and papaya showed a comparatively lower overall response, although for F4 the gap between chili pepper and the other host plants narrowed considerably by day 10 (75.00 individuals for chili pepper, compared to 78.33 for guava, and 79.67 for papaya), suggesting that capsaicinoid-related volatiles may help sustain attractant persistence over a longer exposure period, whereas papaya's ester and aliphatic alcohol compounds may partly mask the aroma of Piper (Liu *et al*., 2025).

3.6 Analysis of Fruit Fly Response

The two main species of fruit flies attracted to Melada volatiles are *Bactrocera umbrosa* and *Bactrocera melastomatos*, both of which belong to the Tephritidae family (Figure 6). Both species are known to have high sensitivity to aromatic phenolic compounds such as eugenol and cinnamic acid, which are structurally similar to the volatile components of *Piper colubrinum* (Afroz *et al*., 2021). The stronger behavioral response in female individuals indicates the presence of analog pheromone activity that influences oviposition behavior (Segura *et al*., 2018; Xu *et al*., 2021). This suggests that the encapsulation system is capable of maintaining the chemical integrity of the volatile compounds without altering their bioactive properties as semio-chemical signals.

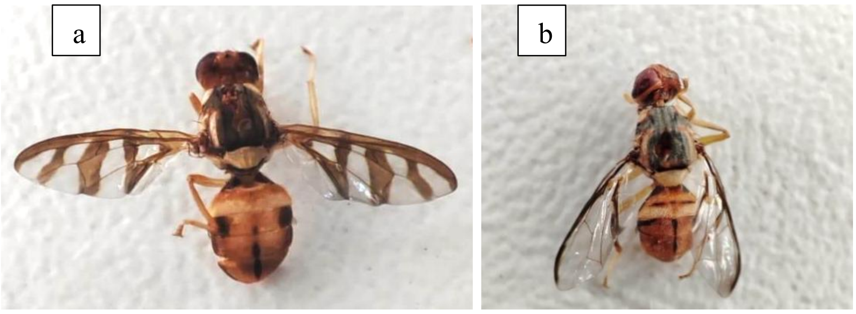

Figure 6. Diversity of Fruit Flies: (a) Adult Bactrocera *umbrosa* and (b) Adult *Bactrocera melastomatos*

Interestingly, the attractant activity of the encapsulated Melada remained high through day 10, whereas that of the Petrogenol control declined sharply after day 5. This indicates that the MD-GA encapsulation system is capable of extending the lifespan of volatiles through a slow-release mechanism (Allwood *et al*., 1999; Tangpao *et al*., 2021). Such a slow-release mechanism is particularly important in tropical regions like West Kalimantan, where high temperatures and humidity often accelerate the degradation of conventional volatile compounds.

The correlation between attractant effectiveness and different crop commodities (chili peppers, guavas, papayas) reflects the complex interactions between attractant formulations, the physiological characteristics of host plants, and the fruit fly species present on each plant. The two dominant fruit fly species identified in the field trials, *Bactrocera umbrosa* and *Bactrocera melastomatos*, exhibit distinct host preferences both ecologically and taxonomically. Globally, *Bactrocera* sp. are polyphagous but exhibit a certain degree of specialization toward specific plant families, depending on the availability of host volatile compounds, fruit phenology, and fruit peel chemical characteristics that influence oviposition (Allwood *et al*., 1999; Yong *et al*., 2016). Molecular and microbiome ecology data indicate that *B. melastomatos* typically infests plants from the *Melastomataceae* family, whereas *B. umbrosa* is more frequently associated

e-ISSN 2655-853X
https://doi.org/10.37637/ab.v9i2.2845

with Moraceae and other susceptible crops, a pattern that may explain the dominance of certain species in different orchards based on the types of fruit available in the field (Yong *et al*., 2016).

Furthermore, these host preference patterns have implications for population dynamics in the three studied orchards. Chili peppers (*Capsicum* spp.) are plants with thin fruit skins and are susceptible to oviposition by flies of the *Bactrocera* group, which are attracted to specific semiochemical stimuli; Dacini's ecological studies indicate that the physical structure of the fruit and its chemical profile determine the infestation levels of specific species on solanaceous plants compared to fleshy fruit plants such as papaya and guava (Allwood *et al*., 1999; Yong *et al*., 2016). *B. umbrosa* is frequently reported to be attracted by the attractant methyl eugenol and can be found on vegetables or fruits near the host plants (tomatoes and chili peppers) within agroecosystems (Yong *et al*., 2016). On the other hand, *B. melastomatos* appears to have a narrower host range and is associated with specific fruits; its geographic distribution patterns and association with *Moraceae*/*Melastomataceae* suggest ecological tendencies that may influence the dominant species in guava and papaya orchards, which have fruit chemical and physiological characteristics distinct from those of Solanaceae.

Increasing the coating material ratio enhances the structural stability of the microcapsules and prolongs the effectiveness of the aroma. F4 is the most efficient formulation, offering the best balance between physical stability and biological activity among the formulations tested. These findings align with the concept of eco-engineered attractant systems, where formulation design must consider the interactions between the physical properties of the materials, the tropical environment, and the specific behavior of the target insects toward plant species (Haran *et al*., 2019; Pavithran *et al*., 2024). Integrating an understanding of fruit fly host preferences with attractant encapsulation strategies will improve the effectiveness of pest monitoring and control in agricultural practices within tropical agroecosystems.

3.7 Economic Feasibility and Practical Scalability of MD-GA Microencapsulated Melada Attractants

Beyond biological performance, the practical adoption of any locally sourced attractant depends on whether its production can be scaled economically for smallholder and commercial horticultural use. Spray- and oven-based MD-GA microencapsulation is well suited to this purpose: among microencapsulation techniques, drying-based methods using maltodextrin and gum arabic are considered the most industrially scalable and cost-effective, since both wall materials are low-cost, widely available food-grade polysaccharides and the drying process itself is far less energy-intensive than freeze-drying-based alternatives (Luft & Mazutti, 2025). F4's economic case rests on a different logic than a simple least-material argument: although its 12:10 core-to-wall ratio requires 20% more Melada crude extract per batch than F3 to reach the same fixed 10 g wall-material input, this additional feedstock yielded a proportionally larger return across every measured outcome, encapsulation efficiency, loading capacity, drying yield, and field catch, rather than diminishing returns, making the extra raw-material cost per batch economically justified relative to the attractant's functional output per unit produced.

At the same time, several practical constraints must be resolved before commercial-scale production of F4 is feasible. First, moving from the oven-drying protocol used in this study to a continuous spray-drying process, the industry standard for MD-GA microencapsulation, will require re-optimization of feed concentration, inlet temperature, and atomization parameters for F4's specific core-to-wall ratio, since laboratory-scale batches typically yield lower powder recovery (in the range of 20-70%)

e-ISSN 2655-853X
https://doi.org/10.37637/ab.v9i2.2845

than industrial-scale equipment, where losses on the drying-chamber wall represent a proportionally smaller fraction of total output (Luft & Mazutti, 2025). Second, because F4 requires a higher proportion of Melada crude extract relative to wall material than the other formulations tested, consistent year-round supply of Melada leaves becomes proportionally more important; this depends on cultivation or managed wild-harvesting arrangements with local growers in Kubu Raya and surrounding districts, as reliance on unmanaged wild stands would not support predictable production volumes at the scale F4 demands. Third, as with other plant-based attractants, commercialization will require navigating national biopesticide/attractant registration requirements, which in many countries remain slower and less harmonized than those for synthetic agrochemicals and represent a recognized bottleneck for bringing plant-essential-oil-based pest control products to market (Isman *et al*., 2011). Addressing these three constraints, process scale-up, feedstock supply chains, and regulatory registration, represents the logical next step toward translating the F4 formulation from a validated laboratory prototype into a field-deployable commercial product for tropical horticultural pest management.

4. Limitations and Future Directions

This study has several limitations. Field trials were conducted on only three horticultural crops and at two locations in West Kalimantan; therefore, the results cannot yet be generalized to all tropical agroecosystem conditions. Future research should evaluate the effectiveness of the formulation under various environmental conditions and with a wider variety of horticultural crops. In addition, the field trials were conducted within a single observation period and did not capture potential seasonal variation in temperature, rainfall, and humidity across dry and wet seasons, both of which strongly influence volatile emission and fruit fly activity in tropical agroecosystems. The evaluation was also limited to the two predominant species recorded in this study, *B. umbrosa* and *B. melastomatos*, the attractant's effectiveness against other economically important *Bactrocera* species, such as *B. dorsalis* and *B. carambolae*, remains to be verified in future multi-seasonal, multi-species trials.

Two further limitations warrant attention in future work. First, this study evaluated field attractiveness only within a short post-production window and did not assess the long-term storage stability of the F4 microcapsules; volatile retention, moisture uptake, and microcapsule wall integrity during extended storage under tropical ambient conditions (high humidity and temperature) remain unknown and should be examined through accelerated and real-time storage-stability trials before commercial shelf-life claims can be made. Second, the present evaluation relied entirely on whole-organism field catch as a proxy for attractiveness; the underlying olfactory mechanism by which Melada volatiles are perceived and discriminated by Bactrocera olfactory receptors remains unexplored. Molecular studies coupling electroantennography or heterologous receptor-expression assays with the specific volatile constituents of Melada would clarify which odorant receptors mediate the observed behavioral response, providing a mechanistic basis for future formulation optimization beyond the empirical wall-ratio approach used here (Xu *et al*., 2024).

5. Conclusion

The microencapsulation technology of Melada (*Piper colubrinum* Link) volatiles using the MD-GA matrix system has been shown to enhance chemical stability, retention efficiency, and biological efficacy as a fruit fly attractant in tropical environments. Formulation F4 (12:10) was the optimal condition, producing the densest microcapsule wall among the tested formulations, the highest coating efficiency (85.14%), and controlled volatile release with

e-ISSN 2655-853X
https://doi.org/10.37637/ab.v9i2.2845

an activity duration of up to 10 days. The highest response to the attractant occurred in chili pepper plants, followed by guava and papaya, indicating a synergistic effect between the volatile profile of the host plant and the activity of the Melada attractant. Overall, this formulation has strong potential to be applied as an environmentally friendly and sustainable green pest management approach based on local resources for controlling fruit fly pests in tropical horticultural farming systems. Overall, these results indicate that the MD-GA-encapsulated Melada formulation is a promising, locally sourced candidate for environmentally friendly fruit fly management in tropical horticultural systems. However, these conclusions are based on a single 10-day trial conducted at two locations during one observation period; before large-scale practical or commercial adoption, further field validation across multiple growing seasons, agroecological zones, and host-plant systems is recommended to confirm that F4's performance remains consistent under varying tropical environmental conditions. Practically, integrating this formulation into existing trap-based monitoring programs could, following such validation, give smallholder farmers in tropical horticultural regions a lower-cost, non-imported alternative to synthetic lures such as methyl eugenol and petrogenol, supporting broader adoption of green pest management practices.

Declaration of Generative AI and AI-Assisted Technologies in the Writing Process

The authors declare that no generative AI or AI-assisted technologies were used during the preparation of this manuscript.

Authorship Contribution Statement

Cico Jhon Karunia Simamora: Conceptualization, Methodology, Investigation, Resources, Supervision, Project administration (writing, review, and editing); Eva Pramuni Oktaviani Sitanggang: Methodology, Data curation, Investigation, Resources, Supervision (writing, review, and editing); Febrina Feby: Formal analysis, Methodology, Investigation, Visualization (writing, review, and editing).

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The authors gratefully acknowledge University of Tanjungpura for support, permission, and cooperation during the conduct of this research. This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

References

Afroz, M., Rahman, Md. M., & Amin, Md. R. (2021). Insect Plant Interaction with Reference to Secondary Metabolites: A Review. *Agricultural Reviews*, *42*(4). https://doi.org/10.18805/ag.R-200

Ahmad, S., Jaworski, C. C., Ullah, F., Jamil, M., Badshah, H., Ullah, F., & Luo, Y. (2023). Efficacy of lure mixtures in baited traps to attract different fruit fly species in guava and vegetable fields. *Frontiers in Insect Science*, *2*, 984348. https://doi.org/10.3389/finsc.2022.984348

Allwood, A. J., Chinajariyawong, A., Drew, R. A. I., Hamacek, E. L., Hancock, D. L., Hengsawad, C., & Vijaysegaran, S. (1999). Host plant records for fruit flies (*Diptera: Tephritidae*) in Southeast Asia. *The Raffles Bulletin of Zoology*, *27*(Supplement 7), 1–92.

Alves, S. F., Borges, L. L., dos Santos, T. O., de Paula, J. R., Conceição, E. C., & Bara, M. T. F. (2014). Microencapsulation of Essential Oil from Fruits of *Pterodon emarginatus* Using Gum Arabic and Maltodextrin as Wall Materials: Composition and Stability. *Drying Technology*, *32*(1), 96–105. https://doi.org/10.1080/07373937.2013.816315

Badan Pusat Statistik. (2023). *Statistik Pertanian Hortikultura Indonesia 2022*. Badan Pusat Statistik Republik Indonesia.

e-ISSN 2655-853X
https://doi.org/10.37637/ab.v9i2.2845

Bahadir, M., & Pfister, G. (1990). *Controlled Release Formulations of Pesticides* (pp. 1–64). https://doi.org/10.1007/978-3-642-46674-8_1

Binyameen, M., Hamid, A., Afzal, I., Sajjad, M., Azeem, M., Zaka, S. M., Sarwar, Z. M., Shad, S. A., Baker, T. C., & Schlyter, F. (2021). Role of fruit volatiles of different guava varieties in attraction and oviposition behaviors of peach fruit fly, *Bactrocera zonata Saunders*. *Arthropod-Plant Interactions*, *15*(1), 95–106. https://doi.org/10.1007/s11829-020-09796-z

Chen, K., Zhang, M., Adhikari, B., & Wang, M. (2022). Microencapsulation of Sichuan pepper essential oil in soybean protein isolate-Sichuan pepper seed soluble dietary fiber complex coacervates. *Food Hydrocolloids*, *125*, 107421. https://doi.org/10.1016/j.foodhyd.2021.107421

Choudhury, N., Meghwal, M., & Das, K. (2021). Microencapsulation: An overview on concepts, methods, properties and applications in foods. *Food Frontiers*, *2*(4), 426-442. https://doi.org/10.1002/fft2.94

Clarke, A. R. (2019). *Biology and management of Bactrocera and related fruit flies*. CABI

Clarke, A. R., Armstrong, K. F., Carmichael, A. E., Milne, J. R., Raghu, S., Roderick, G. K., & Yeates, D. K. (2005). Invasive Phytophagous Pests Arising Through A Recent Tropical Evolutionary Radiation: The *Bactrocera dorsalis* Complex of Fruit Flies. *Annual Review of Entomology*, *50*(1), 293–319. https://doi.org/10.1146/annurev.ento.50.071803.130428

Fang, C. C., Okuyama, T., Wu, W. J., Feng, H. T., & Hsu, J.-C. (2011). Fitness Costs of an Insecticide Resistance and Their Population Dynamical Consequences in the Oriental Fruit Fly. *Journal of Economic Entomology*, *104*(6), 2039–2045. https://doi.org/10.1603/EC11200

FAO. (2022). *The State of Food and Agriculture 2022*. FAO. https://doi.org/10.4060/cb9479en

Haran, J., Grove, T., Van Noort, S., Benoit, L., & Addison, P. (2019). Natural biocontrol of fruit flies in indigenous hosts: A perspective for population control in the agroecosystem. *Biological Control*, *137*, 104022. https://doi.org/10.1016/j.biocontrol.2019.104022

Huang, K., Yuan, Y., & Baojun, X. (2023). A Critical Review on the Microencapsulation of Bioactive Compounds and Their Application. *Food Reviews International*, *39*(5), 2594–2634. https://doi.org/10.1080/87559129.2021.1963978

Isman, M. B., Miresmailli, S., & Machial, C. (2011). Commercial opportunities for pesticides based on plant essential oils in agriculture, industry and consumer products. *Phytochemistry Reviews*, *10*(2), 197-204. https://doi.org/10.1007/s11101-010-9170-4

Jeyakumari, A., Zynudheen, A. A., & Parvathy, U. (2016). Microencapsulation of Bioactive Food Ingredients and Controlled Release - A Review. *MOJ Food Processing & Technology*, *2*(6). https://doi.org/10.15406/mojfpt.2016.02.00059

Jyothi, S. S., Seethadevi, A., Prabha, K. S., Muthuprasanna, P., & Pavitra. P. (2012). Microencapsulation: A Review. *Journal of Pharmacy and Biological Sciences*, *3*(2), 509–531.

Kanmaz, D., Yildiz, S., Koral Koc, S., Manasoglu, G., Aras, C., Celen, R., Tiritoglu, M., Duzyer Gebizli, S., Vatan, O., & Karaca, E. (2026). Assessment of the oil release and insect repellent activity of spray-dried gum arabic/citronella oil microcapsules. *Polymers*, *18*(2), 285. https://doi.org/10.3390/polym18020285

Kessler, A., Mueller, M. B., Kalske, A., & Chautá, A. (2023). Volatile-mediated plant–plant communication and higher-level ecological dynamics. *Current Biology*, *33*(11), R519–R529. https://doi.org/10.1016/j.cub.2023.04.025

Kurniati, D., Rabani, K. A., Yarlina, V. P., Huda, S., & Saputra, R. A. (2025). Impact of maltodextrin and gum Arabic ratio on freeze dried microencapsulated extract of microgreen kangkong (*Ipomoea reptans* Poir). *Scientific Reports*, *15*, Article

e-ISSN 2655-853X
https://doi.org/10.37637/ab.v9i2.2845

19707. https://doi.org/10.1038/s41598-025-19707-y

Liu, H., Wang, Y. M., Yu, G. F., Chen, Z. H., Ma, M. M., Zhang, K. Y., Zhang, Y. F., Che, Z. P., Hu, Z. J., Chen, G. Q., Liu, S. M., & Deng, S. Z. (2025). Exploitation of Rosmarinus officinalis ct. verbenone essential oil as potential and eco-friendly attractant for *Bactrocera dorsalis* (Hendel). *Ecotoxicology and Environmental Safety*, *300*, 118452. https://doi.org/10.1016/j.ecoenv.2025.118452

Liu, Z., Xie, Q. P., Guo, H. W., Xu, W., & Wang, J.-J. (2022). An odorant binding protein mediates *Bactrocera dorsalis* olfactory sensitivity to host plant volatiles and male attractant compounds. *International Journal of Biological Macromolecules*, *219*, 538–544. https://doi.org/10.1016/j.ijbiomac.2022.07.198

Luft, L., & Mazutti, M. A. (2025). Freeze and spray drying technologies to produce solid microbial formulations for sustainable agriculture. *Processes*, *13*(7), Article 2188. https://doi.org/10.3390/pr13072188

Mahdavi, S. A., Jafari, S. M., Assadpoor, E., & Dehnad, D. (2016). Microencapsulation optimization of natural anthocyanins with maltodextrin, gum Arabic and gelatin. *International Journal of Biological Macromolecules*, *85*, 379–385. https://doi.org/10.1016/j.ijbiomac.2016.01.011

Ozdemir, N., Bayrak, A., Tat, T., Altay, F., Kiralan, M., & Kurt, A. (2021). Microencapsulation of basil essential oil: utilization of gum arabic/whey protein isolate/maltodextrin combinations for encapsulation efficiency and in vitro release. *Journal of Food Measurement and Characterization*, *15*(2), 1865–1876. https://doi.org/10.1007/s11694-020-00771-z

Pavithran, R. K., Reddy, S. G., Siva Kumar, B., & Kugabalasooriar, S. (2024). Enhancing Sustainability in Agriculture: Natural Polymer-Based Controlled Release Systems for Effective Pest Management and Environmental Protection. *ES Food & Agroforestry*, *18*, 1276. https://doi.org/10.30919/esfaf1276

Phanse, S. K., & Chandra, S. (2024). Spray drying encapsulation of essential oils: Insights on various factors affecting the physicochemical properties of the microcapsules. *Flavour and Fragrance Journal*, *39*(2), 93–115. https://doi.org/10.1002/ffj.3774

Rao, J., Ikawa, S., Bekele, A. Z., Samuels, R. I., & Tolosa, L. (2016). The influence of controlled release formulations on the persistence of plant volatiles as potential insect attractants. *Industrial Crops and Products*, *83*, 571–579

Remashre, A. B., & Ravindran, P. N. (1998). Anatomy of *Piper colubrinum* Link. Journal of Spices and Aromatic Crops. *Journal of Spices and Aromatic Crops*, *7*(2), 111–123.

Sahlan, M., Fadhan, A. M., Pratami, D. K., Lischer, K., Wijanarko, A., Hermansyah, H., & Mahira, K. F. (2019). Encapsulation of Agarwood Essential Oil with Maltodextrin and Gum Arabic. *International Journal of Technology*, *10*(8), 1541. https://doi.org/10.14716/ijtech.v10i8.3485

Segura, D. F., Belliard, S. A., Vera, M. T., Bachmann, G. E., Ruiz, M. J., Jofre-Barud, F., Fernández, P. C., López, M. L., & Shelly, T. E. (2018). Plant Chemicals and the Sexual Behavior of Male Tephritid Fruit Flies. *Annals of the Entomological Society of America*, *111*(5), 239–264. https://doi.org/10.1093/aesa/say024

Shamaei, S., Seiiedlou, S. S., Aghbashlo, M., Tsotsas, E., & Kharaghani, A. (2017). Microencapsulation of walnut oil by spray drying: Effects of wall material and drying conditions on physicochemical properties of microcapsules. *Innovative Food Science & Emerging Technologies*, *39*, 101–112. https://doi.org/10.1016/j.ifset.2016.11.011

Silva, J. W. P., Bento, J. M. S., & Zucchi, R. A. (2007). Olfactory response of three parasitoid species (*Hymenoptera: Braconidae*) to volatiles of guavas infested or not with fruit fly larvae (Diptera:

e-ISSN 2655-853X
https://doi.org/10.37637/ab.v9i2.2845

Tephritidae). *Biological Control*, *41*(3), 304–311. https://doi.org/10.1016/j.biocontrol.2007.03.005

Simamora, C. J. K., Utomo, K. P., Jumiati, Pramulya, M., & Wahyuni, N. (2025). Evaluation of growth position and root associative microbes of Mitragyna speciosa on the production of psychoactive, mitragynine and alkaloids. *Notulae Scientia Biologicae*, *17*(1), 12281. https://doi.org/10.55779/nsb17112281

Singh, M. N., Hemant, K. S. Y., Ram, M., & Shivakumar, H. G. (2010). Microencapsulation: A promising technique for controlled drug delivery. Research in Pharmaceutical Sciences, 5(2), 65-77.

Singh, A., Dhiman, N., Kar, A. K., Singh, D., Purohit, M. P., Ghosh, D., & Patnaik, S. (2020). Advances in controlled release pesticide formulations: Prospects to safer integrated pest management and sustainable agriculture. *Journal of Hazardous Materials*, *385*, 121525. https://doi.org/10.1016/j.jhazmat.2019.121525

Tangpao, T., Krutmuang, P., Kumpoun, W., Jantrawut, P., Pusadee, T., Cheewangkoon, R., Sommano, S. R., & Chuttong, B. (2021). Encapsulation of Basil Essential Oil by Paste Method and Combined Application with Mechanical Trap for Oriental Fruit Fly Control. *Insects*, *12*(7), 633. https://doi.org/10.3390/insects12070633

Xu, L., Jiang, H. B., Yu, J. L., & Wang, J. J. (2024). Plasticity of the olfactory behaviors in *Bactrocera dorsalis* under various physiological states and environmental conditions. *Current Opinion in Insect Science*, *63*, 101196. https://doi.org/10.1016/j.cois.2024.101196

Xu, L., Tang, K. Y., Chen, X.-F., Tao, Y., Jiang, H. B., & Wang, J. J. (2021). Comparative transcriptomic analysis reveals female-biased olfactory genes potentially involved in plant volatile-mediated oviposition behavior of *Bactrocera dorsalis*. *BMC Genomics*, *22*(1), 25. https://doi.org/10.1186/s12864-020-07325-z

Yang, X., Liang, Y., Li, K., Hu, Q., He, J., & Xie, J. (2025). Advances in Microencapsulation of Flavor Substances: Preparation Techniques, Wall Material Selection, Characterization Methods, and Applications. *Journal of Agricultural and Food Chemistry*, *73*(16), 9459–9477. https://doi.org/10.1021/acs.jafc.4c11399

Yong, H. S., Song, S. L., Lim, P. E., Eamsobhana, P., & Suana, I. W. (2016). Complete Mitochondrial Genome of Three Bactrocera Fruit Flies of Subgenus *Bactrocera* (*Diptera: Tephritidae*) and Their Phylogenetic Implications. *PLOS ONE*, *11*(2), e0148201. https://doi.org/10.1371/journal.pone.0148201

Zabot, G. L., Schaefer Rodrigues, F., Polano Ody, L., Vinícius Tres, M., Herrera, E., Palacin, H., Córdova-Ramos, J. S., Best, I., & Olivera-Montenegro, L. (2022). Encapsulation of Bioactive Compounds for Food and Agricultural Applications. *Polymers*, *14*(19), 4194. https://doi.org/10.3390/polym14194194