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EVALUATION OF EFFICACY OF INSECTICIDES, BOTANICALS AND BIO-AGENTS IN FOOD BAIT & MALE ANNIHILATION TECHNIQUE FOR MANAGEMENT OF MANGO FRUIT FLY *BACTROCERA ZONATA* (HENDEL)

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ABSTRACT

Mango (*Mangifera indica* L.), recognized as the national fruit of Pakistan, stands as a vital tropical fruit crop notable for its economic value and significance in export markets. However, the cultivation of mango is severely hindered by infestations from fruit fly pests, particularly the Peach fruit fly, *Bactrocera zonata* (Hendel) (Diptera: Tephritidae). A comprehensive field study conducted at the Mango Research Institute (MRI) in Multan in 2025 aimed to assess the efficacy of various insecticides, botanical solutions, and bio-agents using two specific techniques: Bait Application Technique (BAT) and Male Annihilation Technique (MAT) for effective fruit fly management. Findings from this study indicated that four treatments emerged as the most effective for each method based on metrics like percentage mortality and LT50 values. Within the scope of BAT, the combination of 10% jaggery with spinosad at a concentration of 0.02% proved to be the best field treatment. Conversely, in the context of MAT, a mixture of Ammonium acetate, lure, and spinosad in a 6:4:0.2 volume ratios demonstrated superior effectiveness. Spinosad, in particular, is recommended as an environmentally friendly alternative to the traditional organophosphate insecticide, malathion, due to its biodegradability, reduced toxicity to mammals, and overall safety for the environment. This research offers pivotal insights for the timely monitoring and implementation of Integrated Pest Management (IPM) strategies. These strategies notably include both the Male Annihilation Technique (MAT) and Bait Application Technique (BAT), alongside eco-friendly control measures. Understanding the pest's population patterns and environmental drivers is essential for reducing fruit loss, minimizing pesticide use, and ensuring sustainable mango production in the region.

Keywords: Mango, Fruit fly, Bait Application Technique (BAT), Male Annihilation Technique (MAT), spinosad, LT₅₀.

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INTRODUCTION

Mango (*Mangifera indica* L.), belonging to the family Anacardiaceae, is the national fruit of Pakistan and one of the most economically important tropical fruits cultivated worldwide. Pakistan ranks among the leading mango-producing countries, with major production concentrated in the provinces of Punjab and Sindh, where favorable agro-ecological conditions support its large-scale cultivation. The crop contributes significantly to the national economy through both domestic consumption and export earnings. However, mango productivity and fruit quality are severely

affected by a range of insect pests, among which fruit flies are considered the most destructive. The peach fruit fly, *Bactrocera zonata* (Diptera: Tephritidae), is a major pest of mango in Pakistan and poses a serious threat to sustainable production. Recent studies across mango-growing regions have confirmed that *B. zonata* dominates fruit fly populations, exhibiting spatial variation across agro-ecological zones (Gul et al., 2024). The pest damages fruits by ovipositing beneath the peel, where emerging larvae feed on pulp tissues, causing premature fruit drop, internal rotting, and deterioration of fruit quality. Under severe

infestation, yield losses can range from 30% to 80%, significantly reducing market and export value (Gul et al., 2024). The population dynamics of *B. zonata* are strongly influenced by abiotic factors, including temperature, relative humidity, and rainfall. Among these, temperature plays a pivotal role in regulating developmental rates, fecundity, and population growth. Elevated temperatures accelerate the life cycle and increase reproductive potential, leading to rapid population buildup (Faryad et al., 2023). Relative humidity affects adult survival and reproductive performance, whereas rainfall influences soil moisture, which is critical for successful pupation. Field studies conducted in Pakistan indicate that fruit fly populations peak during fruit maturation and harvesting periods (March to July), with maximum activity observed in June due to favorable climatic conditions and host availability (Sarwar et al., 2023). Host availability and environmental conditions interact synergistically to determine fruit fly incidence. The presence of suitable host fruits and alternate hosts enhances oviposition and larval survival, while soil characteristics such as moisture and temperature directly influence pupal survival and adult emergence (Chen et al., 2024). These ecological factors collectively contribute to seasonal population fluctuations and pest outbreaks.

Climate change is expected to exacerbate the pest status of *B. zonata* in Pakistan. Rising temperatures, altered rainfall patterns, and extended cropping seasons may accelerate insect development, increase the number of generations per year, and expand the pest's geographical distribution. Predictive models suggest that suitable habitats for tephritid fruit flies are likely to expand under future climate scenarios, thereby increasing infestation risks (Ullah et al., 2023). Warmer winters may further enhance overwintering survival, resulting in earlier seasonal emergence and higher population pressure. Traditionally, management of fruit flies in Pakistan has relied heavily on chemical insecticides, particularly organophosphates such as malathion. However, excessive and indiscriminate use of these chemicals has led to environmental contamination, pesticide residues in fruits, and the development of resistance in pest populations. In response, there is growing interest in developing sustainable and environmentally safe alternatives. Botanical insecticides have emerged as promising tools due to their biodegradability, target specificity, and reduced ecological impact (Akram et al., 2024). Similarly, biological control agents, especially entomopathogenic fungi such as *Beauveria bassiana*, have demonstrated effectiveness in suppressing fruit fly populations under laboratory and field conditions (Sumbal et al., 2024).

Among modern pest management strategies, food bait-based approaches have gained considerable attention due to their efficiency and eco-friendly nature. The integration of insecticides, botanicals, and bio-agents in food bait formulations enhances their attractiveness and efficacy by targeting adult flies during feeding. Techniques such as the Bait Application Technique (BAT), often combined with protein hydrolysate attractants, and the Male Annihilation Technique (MAT) using methyl eugenol, have proven effective in reducing fruit fly populations when used as part of an Integrated Pest Management (IPM) strategy (Sarwar et al., 2023). Despite these advancements, effective management of *B. zonata* in Pakistan remains limited due to insufficient understanding of its ecology under local climatic conditions and inadequate adoption of eco-friendly control practices by farmers. Therefore, there is a critical need to evaluate and optimize sustainable management options. In this context, the present study aims to assess the efficacy of insecticides, botanicals, and bio-agents in food bait formulations for the management of *B. zonata*, with the objective of developing environmentally safe and economically viable strategies for mango production.

MATERIALS AND METHODS

Rearing of *B. zonata* in Laboratory

Infested mango fruits were collected from MRI orchards, Multan. Larvae were allowed to pupate in moist sand, and adults were reared in ventilated cages (50 × 50 × 50 cm) at 27 ± 2°C and 65 ± 5% RH under a 12:12 h photoperiod. Freshly emerged adults (0-48 h old) were used for all bioassays.

Laboratory Evaluation of BAT (Bait Application Technique)

Bait traps were prepared using 10% jaggery solution (100 mL) as food attractant. Insecticides/botanicals/Bio-agents at specified concentrations were added. Traps were housed in 1 L plastic bottles (three windows: 2 × 3 cm). Ten freshly emerged adults per cage were exposed per replicate. Mortality was recorded daily for seven days. Data were subjected to angular (arcsine $\sqrt{p}$) transformation prior to ANOVA. LT_{50} values were computed by Probit analysis.

Laboratory Evaluation MAT (Male Annihilation Technique)

Pheromone traps contained ammonium acetate:methyl eugenol:insecticide (2:6:4:varied v:v:v). Only freshly emerged adult male flies were exposed, as methyl eugenol attracts males exclusively. Mortality was recorded for seven days.

Field Evaluation BAT and MAT

Field trials were conducted in MRI experimental orchards, Multan, during peak mango fruiting season 2025. BAT traps

were hung at canopy level (one per tree); MAT traps at 1.5 m height. Bait material replaced weekly. Fly counts (male, female, total) recorded at weekly intervals for BAT (2 weeks) and fortnightly for MAT (14 weeks). Effective trap

catch duration was assessed for MAT.

Insecticides, Botanicals and Bio-agents

Following Insecticides, botanicals and bio-agents was used during the study listed in the table 1.

Table 1: Insecticides, botanicals and bio-agents used in BAT and MAT evaluation.

S. No.	Chemical Name	Trade Name	Chemical Group	Mode of Action (IRAC)	Manufacturer
1	Dimethoate 30 EC	Rogor, Perfekthion	Organophosphate	Group 1B – AChE Inhibitor	Bayer Crop Science
2	Thiamethoxam 25 WG	Actara	Neonicotinoid	Group 4A – nAChR Agonist	Syngenta
3	Buprofezin 25 SC	Applaud, King Guard	Thiadiazine (IGR)	Group 16 – Chitin Biosynthesis Inhibitor (Type 1)	Nichino America
4	Spinosad 45 SC	Tracer	Spinosyn	Group 5 – nAChR Allosteric Activator	Corteva Agri science
5	Malathion 50 EC	Fyfanon, Cythion	Organophosphate	Group 1B – AChE Inhibitor	Various / FMC
6	Azadirachtin 0.03%	Nimbecidine, Bio-Neem	Botanical (Limonoid)	Group UN – Ecdysone Agonist / Moulting Disruptor	EID Parry / Various
7	Imidacloprid 17.8 SL	Confidor, Imidor	Neonicotinoid	Group 4A – nAChR Agonist	Bayer CropScience
8	<i>Beauveria bassiana</i>	BotaniGard, Naturalis	Entomopathogenic Fungus	Group UN – Fungal Pathogen (Cuticle Penetration)	BASF
9	<i>Priestia megaterium</i>	Bio-NPK, MegaRhizo	PGPR / Biocontrol Bacterium	Not classified by IRAC (Induced Systemic Resistance)	BASF

Statistical Analysis

The experiments yielded data that underwent suitable statistical analysis. The employed methodologies included Analysis of Variance (ANOVA). Data transformation techniques were applied when required to ensure the normalization of variance prior to analysis. The significance of differences among treatment means was determined using the Critical Difference (CD) test at 5% probability level ($p = 0.05$). Standard error of mean ($\pm$ S.E.) was calculated using the relationship.

RESULTS

Cumulative Per Cent Mortality BAT (Laboratory)

On DAT 1, Thiamethoxam 0.005% (T3) recorded the highest mortality (56.70%), on par with malathion 0.1% (50.00%), while spinosad 0.02% (39.85%) was equally effective. By DAT 3, T3 achieved 100% mortality, followed by malathion 0.1% (98.85%) at DAT 3 end. Spinosad

0.02% and Thiamethoxam 0.0025% reached 100% mortality at DAT 4 and DAT 5, respectively. Bio-agents (*Beauveria bassiana* and *Priestia megaterium*) recorded significantly lower mortality (53.35% and 60.00% respectively) even at DAT 7. All chemical insecticides achieved $\geq 98.85\%$ mortality by DAT 7. Highlighted cells in Table 2 indicate $\geq 98\%$ mortality.

LT₅₀ Values BAT Laboratory

LT₅₀ analysis confirmed Thiamethoxam 0.005% (T3) as the fastest-acting treatment (LT₅₀ = 0.63 day), followed by malathion 0.1% (1.12 days) and spinosad 0.02% (1.29 days). These three treatments plus Thiamethoxam 0.0025% (1.70 days) were selected for field evaluation, all having LT₅₀ $\leq$ 1.70 days. Bio-agents showed the highest LT₅₀ values (*Beauveria bassiana*: 6.28 days; *Priestia megaterium*: 5.62 days). CD ($p=0.05$) = 0.525; $\pm$ S.E. = ± 0.25 days (Table 3).

Table 2: Cumulative mortality (%) of adult *B. zonata* in BAT (laboratory) 10% jaggery food bait.

Treatment	DAT 1	DAT 2	DAT 3	DAT 4	DAT 5	DAT 6	DAT 7
Dimethoate 0.04%	19.31 (26.08)	29.67 (33.00)	43.17 (41.08)	60.14 (50.85)	83.64 (66.14)	95.47 (77.71)	100.00 (90.00)
Dimethoate 0.02%	13.01 (21.14)	28.79 (32.52)	36.60 (37.22)	53.35 (46.92)	73.49 (59.00)	83.64 (66.14)	98.85 (83.85)

Thiamethoxam 0.005%*	56.70 (48.84)	98.85 (83.85)	100.00 (90.00)	100.00 (90.00)	100.00 (90.00)	100.00 (90.00)	100.00 (90.00)
Thiamethoxam 0.0025%*	33.25 (35.21)	46.64 (43.08)	63.40 (52.78)	98.85 (83.85)	100.00 (90.00)	100.00 (90.00)	100.00 (90.00)
Buprofezin 0.006%	13.01 (21.14)	26.51 (30.99)	40.00 (39.23)	56.70 (48.84)	70.33 (56.93)	93.30 (75.00)	98.85 (83.85)
Buprofezin 0.003%	10.00 (18.43)	20.00 (26.56)	39.85 (39.14)	56.70 (48.84)	70.33 (56.93)	83.64 (66.14)	98.85 (83.85)
Spinosad 0.02%*	39.85 (39.14)	67.09 (54.99)	90.00 (71.57)	100.00 (90.00)	100.00 (90.00)	100.00 (90.00)	100.00 (90.00)
Spinosad 0.01%	16.35 (23.85)	29.67 (33.00)	43.17 (41.08)	67.22 (55.08)	80.69 (63.93)	100.00 (90.00)	100.00 (90.00)
Malathion 0.1%*	50.00 (45.00)	70.33 (56.99)	98.85 (83.85)	100.00 (90.00)	100.00 (90.00)	100.00 (90.00)	100.00 (90.00)
Azadirachtin 0.003%	13.01 (21.14)	26.20 (30.78)	39.85 (39.14)	63.40 (52.78)	73.49 (59.00)	83.64 (66.14)	95.47 (77.71)
<i>Beauveria bassiana</i>	0.00 (0.00)	4.53 (12.29)	16.35 (23.85)	29.67 (33.00)	36.60 (37.22)	46.64 (43.08)	53.35 (46.92)
<i>Priestia megaterium</i>	0.00 (0.00)	10.00 (18.43)	23.18 (28.79)	36.90 (37.22)	40.00 (39.21)	53.35 (46.92)	60.00 (50.77)
±S.E. (angular transformed)	±2.98	±4.32	±3.57	±3.55	±2.91	±3.82	±4.19
CD (p=0.05) [transformed]	6.17	8.967	7.396	7.356	6.034	7.931	8.689

Values in parentheses are angular (arcsine $\sqrt{p}$) transformed values. $\pm$ S.E. = $CD / t_{0.05}$ (df=22, $t=2.074$). Highlighted cells = $\geq 98\%$ mortality. * = selected for field evaluation.

Table 3: Efficacy of treatments in BAT based on LT_{50} values (laboratory).

Treatment	Conc.	Qty / 100 mL	LT_{50} (days)	±S.E.	Rank / Status
Thiamethoxam 0.005%*	0.01%	0.10 mL	0.63	±0.25	1st
Malathion 0.1%*	0.10%	0.20 mL	1.12	±0.25	2nd
Spinosad 0.02%*	0.02%	0.044 mL	1.29	±0.25	3rd
Thiamethoxam 0.0025%*	0.00%	0.05 mL	1.7	±0.25	4th
Dimethoate 0.04%	0.04%	1.42 mL	2.62	±0.25	5th
Spinosad 0.01%	0.01%	0.02 mL	2.62	±0.25	5th
Azadirachtin 0.003%	0.00%	10 mL	3.01	±0.25	7th
Buprofezin 0.006%	0.01%	0.032 mL	3.05	±0.25	8th
Dimethoate 0.02%	0.02%	0.71 mL	3.09	±0.25	9th
Buprofezin 0.003%	0.00%	0.01 mL	3.24	±0.25	10th
<i>Priestia megaterium</i> WP 2%	2%	2 g	5.62	±0.25	11th
<i>Beauveria bassiana</i> WP 2%	2%	2 g	6.28	±0.25	12th
CD (p=0.05)					0.525

* = selected for field evaluation. S.E. = $CD/t_{0.05}$ (df=22, $t=2.074$). Shaded rows indicate selected treatments.

Efficacy of Chemicals in MAT Laboratory

Cumulative Percent Mortality MAT (Laboratory)

On DAT 1, spinosad 6:4:0.2 recorded the highest mortality (39.85%), on par with malathion 6:4:1 (33.25%). Spinosad 6:4:0.2 achieved 100% mortality at DAT 4, the earliest of all

treatments. Malathion 6:4:1 reached 100% at DAT 5, followed by spinosad 6:4:0.02 and Dimethoate 6:4:0.4 at DAT 6. Thiamethoxam treatments were the weakest performers, with T3 reaching only 73.49% mortality at DAT 7. CD ($p=0.05$) ranged from 7.229 (DAT 3) to 11.651 (DAT 1) (Table 4).

Table 4: Cumulative mortality (%) of adult male *B. zonata* in MAT (laboratory) Ammonium acetate:ME:Insecticide (v:v:v).

Treatment (Ammonium acetate:ME:Insecticide)	DAT 1	DAT 2	DAT 3	DAT 4	DAT 5	DAT 6	DAT 7
Dimethoate 6:4:0.04	1.14 (6.14)	13.01 (21.14)	23.17 (28.79)	36.60 (37.22)	60.14 (50.85)	80.69 (63.92)	93.30 (75.00)
Dimethoate 6:4:0.4*	19.31 (26.08)	36.60 (37.22)	53.35 (46.92)	77.84 (61.92)	98.85 (83.85)	100.00 (90.00)	100.00 (90.00)
Thiamethoxam 6:4:0.005	0.00 (0.00)	1.14 (6.14)	19.31 (26.08)	36.60 (37.22)	50.00 (45.00)	60.14 (50.85)	73.49 (59.00)
Thiamethoxam 6:4:0.05	4.53 (12.29)	13.01 (21.14)	26.51 (30.99)	39.85 (39.14)	56.83 (48.92)	73.49 (59.00)	83.64 (66.14)
Spinosad 6:4:0.02*	19.31 (26.07)	32.91 (35.00)	56.70 (48.84)	76.82 (61.21)	98.85 (83.85)	100.00 (90.00)	100.00 (90.00)
Spinosad 6:4:0.2*	39.85 (39.14)	53.35 (46.92)	80.00 (63.43)	100.00 (90.00)	100.00 (90.00)	100.00 (90.00)	100.00 (90.00)
Imidacloprid 6:4:0.005	1.14 (6.14)	13.01 (21.14)	29.67 (33.00)	46.64 (43.08)	70.33 (56.99)	77.54 (61.71)	90.74 (72.29)
Imidacloprid 6:4:0.05	19.31 (26.08)	16.35 (23.85)	29.67 (33.00)	50.00 (45.00)	76.82 (61.21)	93.30 (75.00)	98.85 (83.85)
Malathion 6:4:1*	33.25 (35.21)	53.35 (46.92)	76.82 (61.21)	98.85 (83.85)	100.00 (90.00)	100.00 (90.00)	100.00 (90.00)
±S.E. (angular transformed)	±5.50	±4.00	±3.41	±4.11	±4.43	±4.24	±5.32
CD (p=0.05) [transformed]	11.651	8.474	7.229	8.716	9.388	8.982	11.272

Values in parentheses are angular transformed values. ±S.E. = $CD/t_{0.05}$ (df=16, t=2.120). ME = Methyl Eugenol. * = selected for field evaluation.

LT₅₀ Values MAT Laboratory

Spinosad 6:4:0.2 recorded the lowest LT₅₀ (1.43 days), statistically on par with malathion 6:4:1 (1.57 days). Spinosad 6:4:0.02 (2.21 days) and Dimethoate 6:4:0.4 (2.22

days) were next and mutually on par. Thiamethoxam 6:4:0.005 recorded the highest LT₅₀ (5.03 days). Four treatments with LT₅₀ ≤ 2.22 days were selected for field evaluation (Table 5).

Table 5: Efficacy of insecticides in MAT based on LT₅₀ values (laboratory).

Treatment (Ammonium acetate:ME:Insecticide, v:v:v)	LT ₅₀ (days)	±S.E.	Status / Rank
Spinosad 6:4:0.2*	1.43	±0.28	1st Selected
Malathion 6:4:1*	1.57	±0.28	2nd Selected
Spinosad 6:4:0.02*	2.21	±0.28	3rd Selected
Dimethoate 6:4:0.4*	2.22	±0.28	4th Selected
Imidacloprid 6:4:0.05	4.00	±0.28	Not selected
Imidacloprid 6:4:0.005	4.14	±0.28	Not selected
Dimethoate 6:4:0.04	4.57	±0.28	Not selected
Thiamethoxam 6:4:0.05	4.60	±0.28	Not selected
Thiamethoxam 6:4:0.005	5.03	±0.28	Not selected
Estimated S.E. from Probit analysis; df=16; t=2.120			

* = selected for field evaluation. LT₅₀ for T1, T4, T7, T8 computed by linear interpolation from daily mortality data. S.E. estimated from Probit analysis; df=16; t=2.120.

Evaluation of BAT Field Conditions

Spinosad 0.02% (T2) recorded the highest grand mean fly catch (63.17 flies/trap), statistically on par with malathion

0.1% (59.33) and Thiamethoxam 0.005% (56.67). Thiamethoxam 0.0025% (T3) was significantly inferior (34.00 flies/trap). Female flies constituted 67–76% of total

catch across all treatments, confirming greater attractiveness of food baits to gravid females. Spinosad 0.02% is

recommended as the best BAT treatment considering both efficacy and environmental safety (Table 6).

Table 6: Effect of insecticides on fruit fly population (mean per trap) in BAT field conditions, MRI Multan.

Treatment	Week 1			Week 2			Grand Mean
	Male	Female	Total	Male	Female	Total	
Thiamethoxam 0.005%	8.50	20.33	28.83	9.17	18.67	27.83	56.67
Spinosad 0.02%*	10.50	21.00	31.50	10.17	21.50	31.67	63.17
Thiamethoxam 0.0025%	5.67	12.00	17.67	2.50	13.83	16.33	34.00
Malathion 0.1%	8.33	21.00	29.67	9.17	21.17	29.67	59.33
±S.E.	±1.08	±2.00	±1.07	±1.68	±1.95	±3.36	±4.34
CD (p=0.05)	2.304	4.254	2.270	3.578	4.163	7.159	9.246

* = best treatment. Mean of 6 replications. S.E. = $CD/t_{0.05}$ (df=15, t=2.131). Grand Mean = combined total catch (Weeks 1+2).

Evaluation of MAT Field Conditions

Spinosad 6:4:0.2 consistently recorded the highest fly catch at all fortnightly intervals, reaching a peak of 273.34 flies/trap at Week 10. Dimethoate 6:4:0.4 was significantly

inferior at all-time points (range: 32–52 flies/trap), while spinosad 6:4:0.02 and malathion 6:4:1 were statistically on par throughout. Data were $\sqrt{(x+1)}$ transformed for statistical analysis; transformed ±S.E. values are reported in Table 7.

Table 7: Effect of insecticides on fruit fly population (mean no. per trap) in MAT fortnightly intervals, field conditions.

Treatment	Wk 2	Wk 4	Wk 6	Wk 8	Wk 10	Wk 12	Wk 14
Spinosad 6:4:0.02	113.28 (10.70)	118.91 (10.95)	122.38 (11.10)	139.58 (11.85)	164.80 (12.88)	133.70 (11.60)	129.40 (11.41)
Spinosad 6:4:0.2*	123.81 (11.17)	179.74 (13.44)	219.65 (14.85)	272.48 (16.53)	273.34 (16.57)	226.65 (15.09)	208.05 (14.45)
Dimethoate 6:4:0.4	35.14 (6.01)	32.27 (5.77)	39.09 (6.33)	52.34 (7.30)	42.80 (6.61)	41.64 (6.53)	39.83 (6.39)
Malathion 6:4:1	112.89 (10.68)	120.34 (11.01)	137.80 (11.79)	147.29 (12.18)	168.21 (13.00)	154.20 (12.45)	138.24 (11.80)
±S.E. [$\sqrt{(x+1)}$ transformed]	±0.53	±0.98	±1.02	±1.06	±0.77	±0.73	±0.88
CD (p=0.05) [transformed]	1.131	2.082	2.162	2.264	1.633	1.558	1.865

Values in parentheses = $\sqrt{(x+1)}$ transformed. ±S.E. = $CD/t_{0.05}$ (df=15, t=2.131) on transformed data. ME = Methyl Eugenol. * = superior treatment.

Persistent Toxicity and Duration of Effective Trap Catch

Spinosad 6:4:0.2 recorded the highest total fly catch (1,371.08 flies/trap) and the longest effective trap catch duration (108.68 days), significantly superior to Dimethoate

6:4:0.4 (240.52 flies; 91.83 days). Malathion 6:4:1 (882.02 flies; 105.00 days) and spinosad 6:4:0.02 (823.91 flies; 104.83 days) were statistically on par. The poor persistence of Dimethoate is attributed to its rapid photo degradation under field conditions (Table 8).

Table 8: Persistent toxicity of insecticides and total fly catch and effective trap catch duration in MAT (field).

Treatment	Total Fly Catch (flies/trap)*	±S.E.	Effective Trap Catch (days)	±S.E.	Rank
Spinosad 6:4:0.02	823.91 (28.72)	±33.56	104.83	±4.51	3rd
Spinosad 6:4:0.2*	1371.08 (37.04)	±33.56	108.68	±4.51	1st
Dimethoate 6:4:0.4	240.52 (15.54)	±33.56	91.83	±4.51	4th
Malathion 6:4:1	882.02 (29.71)	±33.56	105.00	±4.51	2nd
±S.E.	±1.78 [transformed]		±4.51 days		
CD (p=0.05)	3.798 [transformed]		9.606 days		

* = superior treatment. Values in parentheses = $\sqrt{(x+1)}$ transformed. S.E. for total catch (actual) back-transformed from S.E.(transformed) $\times 2\sqrt{x}$. S.E. for effective days = $CD/t_{0.05}$ (df=15, t=2.131).

DISCUSSION

Among 12 treatments in BAT, Thiamethoxam 0.005% demonstrated fastest knockdown ($LT^{50} = 0.63$ day), consistent with Radwan (2012) who reported higher relative toxicity of Thiamethoxam versus malathion against *B. zonata*. Spinosad's efficacy ($LT^{50} = 1.29$ days) aligns with El-Aw et al. (2008) who found 120 ppm spinosad caused 90% mortality in adult *B. zonata*, and Yee & Alston (2006) who observed 100% mortality with spinosad bait against western cherry fruit fly. Bio-agents were significantly slower ($LT^{50} > 5.5$ days), reflecting the biological requirement for cuticle penetration and fungal mycosis development.

Spinosad 6:4:0.2 achieved 100% mortality earliest (DAT 4; $LT^{50} = 1.43$ days), closely followed by malathion 6:4:1 ($LT^{50} = 1.57$ days). These findings support Vargas et al. (2008) who found spinosad-methyl eugenol SPLAT formulations highly effective. Thiamethoxam performed poorly in MAT ($LT^{50} > 4$ days), contrasting with its effectiveness in BAT, possibly due to chemical interaction with methyl eugenol or differential male fly exposure routes. Spinosad 0.02% was the superior BAT field treatment (grand mean: 63.17 flies/trap), consistent with Vargas & Prokopy (2006) who proposed spinosad as a malathion substitute in BAT for *B. zonata* and *B. cucurbitae*. Female dominance in catches (67–76%) confirms greater food bait attractiveness to gravid females. Non-target lepidopteran and coleopteran insects were also caught, indicating potential of jaggery-based baits for broader pest management. Thiamethoxam 0.0025% was significantly inferior, confirming the need for adequate concentration to maintain field efficacy.

Spinosad 6:4:0.2 was unequivocally superior in field MAT with total catch of 1,371.08 flies/trap over 14 weeks and 108.68 effective days significantly exceeding malathion 6:4:1 (882.02 flies; 105.00 days). Dimethoate 6:4:0.4 performed poorly (240.52 flies; 91.83 days) due to low environmental persistence, corroborating Vargas et al. (2003) who reported pyrethroid (permethrin) as the lowest-performing treatment in MAT trials. The superior persistence of spinosad under UV exposure relative to pyrethroids explains its extended field efficacy. The investigation revealed notable differences in the effectiveness of insecticides and biological agents against *Bactrocera zonata* when utilizing the Bait Application Technique (BAT) and the Male Annihilation Technique (MAT) in both laboratory and field settings. The results underscore that the performance of insecticides is significantly affected by the method of application, their

mechanism of action, and their persistence in the environment. Under BAT laboratory conditions, thiamethoxam at 0.005% demonstrated the quickest knockdown effect, achieving complete mortality within three days and recording the lowest LT_{50} value. As a neonicotinoid, it targets nicotinic acetylcholine receptors, leading to rapid paralysis and death, which accounts for its high initial toxicity (Elbert et al., 2008). Previous studies have documented similar rapid effectiveness of neonicotinoids against dipteran pests. However, spinosad showed more stable and sustained efficacy, especially in field settings.

The effectiveness of spinosad observed in this study aligns with previous reports describing it as a potent ingestion toxicant derived from *Saccharopolyspora spinosa*, with both contact and stomach action (Sparks et al., 2001). Its compatibility with bait systems and relatively safer environmental profile make it highly suitable for fruit fly management (Vargas et al., 2010). The comparable performance of malathion further supports the continued relevance of organophosphates in bait sprays, although concerns regarding resistance and environmental safety persist. The poor performance of Bio-agents, including *Beauveria bassiana* and *Priestia megaterium*, can be attributed to their slower mode of action. Entomopathogenic fungi require spore adhesion, germination, cuticle penetration, and internal colonization before causing mortality, resulting in delayed effects (Zimmermann, 2007). Although such agents are valuable in sustainable agriculture, their slower action limits their effectiveness in situations requiring rapid pest suppression. The effectiveness of MAT using methyl eugenol has been widely documented for controlling *B. zonata* populations by attracting and eliminating males, thereby disrupting mating cycles (Steiner et al., 1965; Vargas et al., 2015). In contrast, thiamethoxam performed poorly in MAT, suggesting that its efficacy is influenced by feeding behavior and bait attractiveness. Field evaluations further validated laboratory findings. In BAT field trials, spinosad 0.02% recorded the highest fly catch, statistically comparable with malathion and thiamethoxam, but superior in terms of environmental safety. The predominance of female flies (67–76%) in bait traps confirms that protein-based food baits preferentially attract gravid females, as also reported by Vargas et al. (2010). This is particularly important because targeting females directly reduces oviposition and subsequent larval infestation. Under MAT field conditions, spinosad 6:4:0.2 exhibited the highest fly catches and longest persistence, indicating superior field stability. The prolonged activity of

spinosad may be due to its relatively lower susceptibility to photodegradation compared to organophosphates such as dimethoate, which degrade rapidly under sunlight (Racke, 1993). The inferior performance of dimethoate observed in this study is consistent with earlier findings highlighting its short residual activity under tropical field conditions.

According to the study, MAT and BAT are complementing pest control techniques, with MAT concentrating on lowering males and interfering with mating, whereas BAT successfully targets both sexes, especially females. These integrated techniques improve management sustainability and efficiency by using formulations based on spinosad. Additionally, spinosad exhibits superior efficacy, persistence, and environmental safety, making it preferred for field implementations in integrated pest management (IPM) programs against *B. zonata*, even though fast-acting insecticides like thiamethoxam offer rapid control in laboratory settings. The current results closely match those of R. I. Vargas et al. (2010), who found that spinosad-based bait sprays were very effective against *Bactrocera zonata*, with quick death and excellent field performance. Similarly, because of its distinct mechanism of action and applicability for bait applications, T. C. Sparks et al. (2001) reported the strong insecticidal activity of spinosad. The results of A. Elbert et al. (2008), who reported the fast-acting nature of neonicotinoids, and R. I. Vargas et al. (2010), who showed the efficacy of spinosad in protein bait sprays for fruit fly control, are consistent with the rapid mortality seen with thiamethoxam and spinosad in BAT.

The current study's superior performance of spinosad in MAT is consistent with the classical work of L. F. Steiner et al. (1965), who demonstrated the efficacy of male annihilation techniques based on methyl eugenol, and subsequent findings by R. I. Vargas et al. (2015), which highlighted improved control when combined with effective toxicants like spinosad. According to G. Zimmermann (2007), entomopathogenic fungi require longer infection durations, which results in slower death than chemical insecticides, which is consistent with the comparably reduced effectiveness and delayed impact of *Beauveria bassiana* seen in this investigation. The results of the present study are in strong agreement with previous reports. The high efficacy of spinosad-based formulations observed under both BAT and MAT conditions corroborates the findings of R. I. Vargas et al. (2010), who reported excellent control of *Bactrocera zonata* using spinosad bait sprays. Similarly, T. C. Sparks et al. (2001) attributed the strong insecticidal activity of spinosad to its unique mode of action. The rapid knockdown effect of thiamethoxam

observed in the present study is also supported by A. Elbert et al. (2008), who described neonicotinoids as fast-acting neurotoxic insecticides. Furthermore, the effectiveness of MAT using methyl eugenol-based systems aligns with the pioneering work of L. F. Steiner et al. (1965) and subsequent studies by R. I. Vargas et al. (2015). In contrast, the slower action of *Beauveria bassiana* is consistent with the findings of G. Zimmermann (2007), highlighting the delayed pathogenic process of entomopathogenic fungi.

CONCLUSIONS

BAT Laboratory findings indicated that Thiamethoxam 0.005% provided the quickest knockdown (LT50 = 0.63 days), while spinosad 0.02%, malathion 0.1%, and Thiamethoxam 0.0025% also showed efficacy. In field evaluations, spinosad 0.02%, malathion 0.1%, and Thiamethoxam 0.005% were equally effective, with spinosad recommended for its eco-friendly characteristics. MAT Laboratory results identified spinosad 6:4:0.2 (LT50 = 1.43 days) and malathion 6:4:1 (1.57 days) as the most effective, while MAT Field trials confirmed spinosad 6:4:0.2 as the superior option, achieving 1,371 flies/trap and 108.68 effective days. The expansion of various *Bactrocera* species in Punjab emphasizes the need for sustainable IPM strategies that incorporate BAT and MAT with spinosad formulations.

AUTHOR'S CONTRIBUTION

All the authors contributed equal to this research.

COMPETING OF INTEREST

There is no conflict of interest.

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