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Eco-Friendly Pest Control Methods for German Chamomile (*Matricaria chamomilla*): Effects on Pest Infestation, Yield, Soil Microbial Activity, and Beneficial Insects

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ABSTRACT

The study tested whether neem oil, *Beauveria bassiana*, *Chrysoperla carnea*, and an integrated pest management (IPM) package could control aphids (*Aphis fabae*) and spider mites (*Tetranychus urticae*) in German chamomile (*Matricaria chamomilla*) while maintaining agroecosystem health. The study established a randomized complete block design at *Matricaria chamomilla* with five treatments and four replications, which resulted in 20 experimental units. The experimental treatments included T1 as the untreated control and T2 as neem oil 5% (v/v), T3 as *B. bassiana* at 1×10^8 conidia/mL, T4 as *C. carnea* release at 2 eggs/plant, and T5 as an IPM package that used reduced rates of three biocontrol methods. The researchers measured pest infestation rate, dry aerial yield, soil microbial activity, and beneficial insect count, followed by one-way analysis of variance (ANOVA) analysis of treatment means with Tukey's Honestly Significant Difference (HSD) test at $p \leq 0.05$. The IPM package achieved its best pest control results, which reached 12.50 ± 2.08% while producing its maximum crop output of 42.12 ± 0.98 g/plant and its highest level of soil microbial activity, which measured 31.75 ± 0.62 mg CO_2/g soil/day, and its greatest number of beneficial insects, which reached 19.75 ± 0.96 per plot. Relative to the untreated control, the IPM package reduced combined pest infestation by 82% (from 68.8% to 12.5%) and increased dry aerial yield by 133% (from 18.10 to 42.12 g/plant). The control group demonstrated its greatest pest problems, which reached 68.75 ± 2.99% while producing its least plant output, which measured 18.10 ± 0.61 g/plant. All treatment effects produced highly significant results for pest infestation ($F = 321.43$, $p < 0.001$), yield ($F = 581.59$, $p < 0.001$), soil microbial activity ($F = 541.55$, $p < 0.001$), and beneficial insects ($F = 106.01$, $p < 0.001$). This is a combined incidence. The IPM package, with its synergistic multi-trophic strategy, substantially outperforms the single biological treatments and the untreated control. In conclusion, this IPM approach offers medicinal plant growers an economically and ecologically sustainable alternative to synthetic insecticides that is free of residues in the effort to reconcile crop protection with stringent quality and environmental standards.

1. INTRODUCTION

The supply chains of nutraceutical, pharmaceutical, and cosmetic products rely on the strategic role of medicinal and aromatic plants, but their cultivation practices are increasingly challenged by the insect pest pressure and the market demand for residue-free products and conservation of the bioactive quality. Recent studies indicate that pesticide residues remain a safety hazard for herbal products and plant-based tea products, which calls for the industry to implement residue monitoring and develop systems for cleaner production [1-3]. The agricultural sector now experiences a transformation toward sustainable practices through integrated pest management (IPM), which provides an essential framework for decreasing reliance on traditional insecticides while maintaining agricultural output [4]. Research shows that pesticide exposure leads to detrimental effects on insect pollinators and non-Apis bee populations, which results in the loss of essential ecosystem services that support crop growth and farm productivity [5-8]. Herbicides and pesticides create underground contamination problems, which cause harmful effects on microbial protection of plants and change the composition of microbial communities and decrease the stability of soil functions [9, 10]. The use of neem as a botanical insecticide remains appealing because it effectively controls pests while its active ingredients vanish from the environment faster than most synthetic pesticides, according to recent studies which demonstrate its potential yet require new methods to create and distribute products [11-13]. The two modes of action from entomopathogenic fungi establish direct pathogenicity together with endophytic or plant-based mechanisms, and current research describes these fungi as effective tools that protect crops during IPM practices [14, 15]. The methods show their highest value for medicinal crops, which face aphid and mite attacks, because recent research demonstrated that *Beauveria bassiana* effectively controls

Tetranychus urticae and various lepidopteran insects, while lacewing predators serve as a reliable method to control soft-bodied arthropods [16-18]. The research evidence indicates that the combination of botanical knockout, fungal contamination, and predator release will create better results than using any single method [6]. To our knowledge, this is the first field study in Iraqi chamomile cultivation to combine botanical, fungal, and predator tactics in a single integrated package against *Aphis fabae* and *Tetranychus urticae*. The researchers conducted an assessment that tested neem oil, *Beauveria bassiana,* and *Chrysoperla carnea,* and their lower dosage combination in German chamomile to find out if the sustainable IPM solution would decrease pest problems while boosting crop production, maintaining soil microbial health, and protecting beneficial insects. This study evaluated individual and combined applications of neem oil, *B. bassiana*, and *C. carnea* to optimize German chamomile yield, suppress key pests, and maintain soil and insect biodiversity. This study aimed to (1) evaluate the individual and combined efficacy of neem oil, *B. bassiana*, and *C. carnea* against aphids (*Aphis fabae*) and spider mites (*Tetranychus urticae*) on German chamomile; (2) assess effects on chamomile dry aerial yield; (3) measure soil microbial activity via CO_2 evolution; and (4) monitor beneficial insect populations. We hypothesized that the IPM package, by combining rapid botanical knock-down, delayed fungal pathogenicity, and predator augmentation, would outperform any single tactic while maintaining below-ground microbial function and above-ground beneficial insect diversity [19-21].

2. METHODOLOGY

The field experiment was conducted over a six-month duration from March to August 2024 in Kirkuk, Iraq (Latitude: 35°28′ N, Longitude: 44°19′ E; Altitude: 330 m above sea level). The total experimental area was 450 m^2, arranged in four blocks with 1.0 m alleyways between blocks to minimize spray drift and cross-contamination. The experimental site featured a moderately fertile loam soil. Detailed physicochemical analysis of the topsoil layer (0-30 cm depth) demonstrated a precise particle size distribution of approximately 42% sand, 38% silt, and 20% clay. The chemical properties characterized the environment as having an alkaline soil pH of 7.8, an organic carbon content of 1.15%, and an electrical conductivity (EC) of 1.4 dS/m. The experiment was performed in a field plot where *Matricaria chamomilla* L. (German chamomile) was cultivated under normal agricultural practices, and synthetic insecticides were not applied throughout the study period. Before they got to transplanting, the team created a moderately fertile loam soil by adding a constant base amount of fully rotted farmyard manure. The study employed a spacing method, where seedlings were set at 30 cm between rows and 20 cm between plants, to obtain the desired field density required for chamomile biomass production and pest control research.

The researchers repeated a randomized complete block experimental design of five treatments four times for a total of 20 experimental units. Each block had one plot for each treatment, and the plots within each block were randomized to reduce spatial bias. Plots were 2.0 m by 1.5 m with 0.5 m between plots and 1.0 m between blocks. The experimental treatments were T1, the untreated control; T2, which used *Azadirachta indica* neem oil at 5% v/v; T3, which applied *Beauveria bassiana* at 1×10^8 conidia/mL; T4, which released *Chrysoperla carnea* at 2 eggs per plant; and T5, which used an IPM package that combined neem oil at 2.5% v/v, *B. bassiana* at 5×10^7 conidia/mL, and *C. carnea* at 1 egg per plant. The IPM treatment was designed to exert a reduced-dose complementary control pressure while being compatible with beneficial fauna.

2.1 Pest identification and monitoring

Aphids were identified as *Aphis fabae* Scopoli based on the presence of paired black cornicles, a short finger-like cauda, and transverse dark abdominal bands visible under a stereo-microscope at 40× magnification. Spider mites were identified as *Tetranychus urticae* Koch by dense silk webbing on leaf undersides, two dark pigmented spots on the idiosoma, and tarsal claw morphology examined on slide-mounted specimens. Identification was performed by a staff taxonomist at Kirkuk University and cross-checked against reference specimens. Voucher specimens (aphids: UOK-ENT-2024-17; mites: UOK-ENT-2024-18) were preserved in 70% ethanol and deposited in the College entomological collection. For assessment, 10 plants per plot were randomly selected at each weekly interval. On each plant, three leaves (upper, middle, and lower canopy) were inspected. A plant was scored as aphid-infested if it hosted at least one colony of > 5 aphids on any examined leaf, and as mite-infested if it showed active webbing or >10 motile stages per leaf. The infestation rate per plot was calculated as (infested plants / 10 sampled plants) × 100. Aphid and mite rates were recorded separately; the combined pest infestation rate reported in the initial analysis was the arithmetic mean of the two species-specific rates. Assessments began one week after the first treatment and continued weekly for eight weeks.

2.2 Application of treatments

Neem oil was applied as a fine foliar spray using a knapsack sprayer to run off on the scheduled application dates. The cold-pressed *Azadirachta indica* seed oil contained 0.30% azadirachtin (w/w). For T2, it was applied as a 5% (v/v) aqueous emulsion in 500 L/ha total spray volume (25 L/ha neem oil), with Tween-20 added at 0.1% (v/v) as surfactant. For T5 (IPM), the neem rate was reduced to 2.5% (v/v) (12.5 L/ha). Three neem applications were made at 14-day intervals starting at the 4-leaf stage. *B. bassiana* conidial suspension (strain UOK-Bb01, >95% viability confirmed by 24-h PDA germination count) was prepared freshly and applied in the evening (18:00-19:30 h) at 1×10^8 conidia/mL in 1000 L/ha water (T3) or 5×10^7 conidia/mL (T5) to reduce UV degradation and desiccation losses. Three fungal applications were made at 14-day intervals, synchronized with neem sprays. Chrysoperla carnea eggs (<24 h old) supplied on cardboard strips were obtained from a commercial agricultural supplier in Kirkuk, Iraq, and were released uniformly over the crop canopy at 08:00 h by stapling egg cards to lower leaf surfaces. The supplier specializes in the production and distribution of biological control agents for IPM programs and provides high-quality beneficial insects for agricultural research and sustainable crop protection practices. T4 received 2 eggs/plant and T5 received 1 egg/plant; three releases were performed at 10-day intervals. Larval establishment was checked 48 h after each release by looking at 10 plants per plot for neonate lacewings; establishment averaged 65-70%. All treatments were reapplied at equivalent phenological stages to maintain temporal consistency. T1 (untreated control) received no spray or release; no water-only carrier control was included, which is acceptable for an ecological comparison of bio-control tactics, but means we cannot partition mechanical spray effects from active-agent effects.

2.3 Data collection

The researchers recorded pest infestation rate (%) by counting infested plants per plot at each observation interval and then calculating percentage values before averaging across all assessment dates. The researchers measured plant yield at harvest by recording dry aerial biomass (g/plant) after oven-drying until the weight became constant. The researchers measured soil microbial activity through microbial respiration (mg CO_2/g soil/day), which they assessed using a standard CO_2 evolution method described by Anderson and Domsch [20] on composite soil samples taken from the rhizosphere after the main treatment period. Sampling occurred two days after the final treatment application. Five rhizosphere soil cores (0–15 cm depth) were collected per plot and composited; visible roots were shaken off, and the adhering soil was passed through a 2-mm sieve. A 50 g subsample was incubated at 25 °C for 24 h in a sealed jar with 10 mL of 0.5 M NaOH to trap evolved CO_2. Microbial respiration was expressed as mg CO_2 evolved per g dry soil per day according to the standard soil respiration procedure [20].

2.4 Beneficial insect assessment

Beneficial insects were recorded by direct visual observation and sweep-net sampling during the morning activity window (08:00-10:00 h) on the same days as pest assessments. Observed taxa were grouped as: (1) pollinators — *Apis mellifera* and non-*Apis* bees (Halictidae, Megachilidae); (2) predators — Coccinellidae (adults and larvae), Syrphidae, Chrysopidae, *Orius* spp., and Araneae; and (3) parasitoids — Braconidae (aphid mummies) and Chalcidoidea. On each sampling date, a 3-minute stationary visual count was conducted on each of the 10 plants per plot (30 min/plot), followed by 20 sweep-net strokes per plot with a 38-cm-diameter net. The total beneficial insect count per plot represents the mean of the eight weekly samplings. No killing traps were used during sampling, and all beneficial insects were recorded using non-destructive visual observation and sweep-net techniques.

2.5 Statistical analysis

The researchers analyzed all data through one-way analysis of variance (ANOVA) in SPSS version 28 to evaluate treatment effects on each response variable. Means were separated using Tukey's Honestly Significant Difference (HSD) test at $p \leq 0.05$. The report presents treatment differences as mean values with standard deviation, while Tukey groupings are displayed using lowercase letters.

3. RESULTS

The ANOVA results in Table 1 showed strong treatment effects for all variables, indicating that the biocontrol strategies altered both pest pressure and crop performance. Yield and soil microbial activity responded particularly strongly, while beneficial insects also differed clearly among treatments.

Aphids were the dominant pest in all treatments, but the IPM package suppressed both pests to levels significantly lower than any single treatment ($p < 0.001$). The combined incidence, previously reported as a single metric, was the arithmetic mean of the two species-specific rates (Table 2).

Table 1. One-way analysis of variance (ANOVA) summary for the four response variables

Parameter	F-Value	DF1	DF2	p-Value	Inference
Pest infestation (%)	321.43	4	15	<0.001	Highly significant
Plant yield (g/plant)	581.59	4	15	<0.001	Highly significant
Soil microbial activity	541.55	4	15	<0.001	Highly significant
Beneficial insects (per plot)	106.01	4	15	<0.001	Highly significant

Note: DF: Degrees of freedom

Table 2. Effect of eco-friendly pest control methods on aphid (*Aphis fabae*) infestation rate

Treatment	Mean ± SD (%)	Tukey Group
T1 Control	72.50 ± 3.12	e
T2 Neem oil 5%	45.00 ± 2.65	d
T3 *B. bassiana*	36.00 ± 2.20	c
T4 *C. carnea*	30.50 ± 1.85	b
T5 IPM package	14.00 ± 2.10	a

Note: Different letters indicate significant differences among the treatments (Tukey's HSD, $p < 0.05$). IPM: Integrated pest management.

Table 3. Effect of eco-friendly pest control methods on spider mite (*Tetranychus urticae*) infestation rate

Treatment	Mean ± SD (%)	Tukey Group
T1 Control	65.00 ± 2.85	e
T2 Neem oil 5%	38.50 ± 2.35	d
T3 *B. bassiana*	31.00 ± 1.95	c
T4 *C. carnea*	26.00 ± 1.55	b
T5 IPM package	11.00 ± 1.80	a

Note: IPM: Integrated pest management.

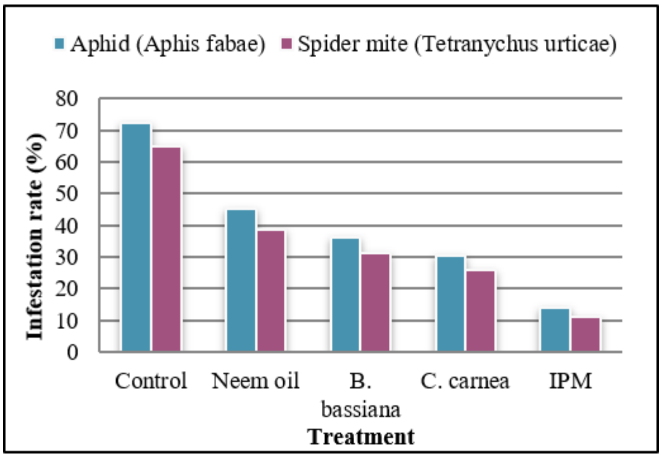

Figure 1. Mean aphid (*Aphis fabae*) and spider mite (*Tetranychus urticae*) infestation rates (%) in *Matricaria chamomilla* under different eco-friendly pest-control treatments

Figure 1, Tables 2, and 3 present the mean aphid and spider mite infestation rates side-by-side, illustrating the differential suppression achieved by each treatment. The IPM package achieved its maximum effectiveness when it decreased pest infestation to levels that were lower than any of its individual control methods. The control plots showed extreme pest infestation because the study area had no pest control methods to reduce the strong aphid and spider mite infestation.

Table 4. Effect of eco-friendly pest control methods on dry aerial yield of *Matricaria chamomilla* (g/plant)

Treatment	Mean ± SD (g/plant)	Tukey Group
T1 Control	18.10 ± 0.61	e
T2 Neem oil 5%	27.55 ± 0.58	d
T3 *B. bassiana*	30.60 ± 0.61	c
T4 *C. carnea*	33.75 ± 0.79	b
T5 IPM package	42.12 ± 0.98	a

Note: Values are means ± SD of four replicate plots. Means followed by different lowercase letters differ significantly by Tukey's HSD test at $p \leq 0.05$. Yield was recorded at harvest after oven-drying to constant weight. IPM: integrated pest management.

The 2.3-fold yield increase in T5 relative to T1 is large but biologically plausible given the severe aphid and mite pressure in the control (combined incidence > 68%), which would have drastically reduced photosynthetic leaf area and assimilate allocation. In unprotected chamomile stands under comparable pest pressure in the region, yield losses of 60-70% are commonly reported by local growers. The tight standard deviations reflect the uniformity of the experimental loam and the consistent stand establishment, not artificial precision.

Figure 2 and Table 4 visualize the yield gradient across treatments, with the IPM bar standing approximately 2.3-fold above the control.

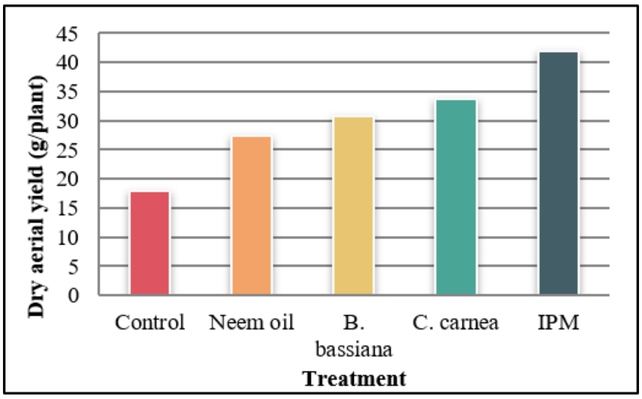

Figure 2. Mean dry aerial yield (g $plant^{-1}$) of chamomile aerial parts across treatments

The increase of soil respiration by 74% in the IPM package relative to the control is large but within the range reported for reduced-pesticide management in Mediterranean herbaceous systems (typically increases of 50-100% over conventionally sprayed controls) [21]. The mechanism probably involves less chemical disturbance of the rhizosphere microbiome and increased root exudation from healthier plants, providing more labile carbon substrates for microbial turnover. However, we recognize that respiration is a single proxy for soil biological activity; we did not measure microbial diversity, enzyme activities, or nutrient cycling rates, so our inference about "soil health" is necessarily narrow.

Figure 3 and Table 5 show the response of soil microbial activity. The IPM treatment was 31.75 mg CO_2 g^{-1} day^{-1}.

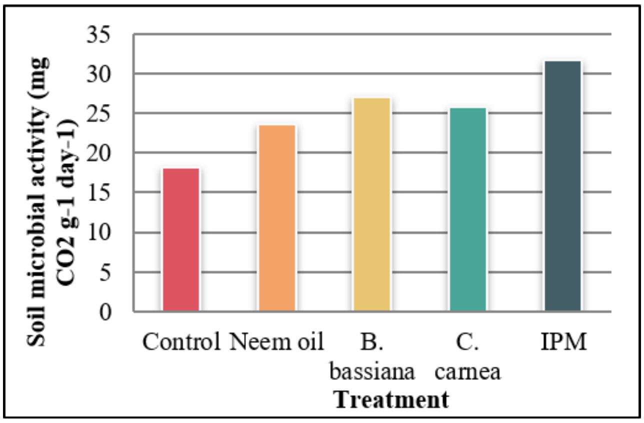

Figure 3. Mean soil microbial activity (mg CO_2 g^{-1} day^{-1}) under the tested treatments

Table 5. Effect of eco-friendly pest control methods on soil microbial activity (mg CO_2 g^{-1} day^{-1}) as measured by 24-h CO_2 evolution from rhizosphere soil collected 2 days after the last treatment

Treatment	Mean ± SD (mg CO_2/g soil/day)	Tukey Group
T1 Control	18.27 ± 0.35	e
T2 Neem oil 5%	23.60 ± 0.39	d
T3 *B. bassiana*	27.02 ± 0.30	b
T4 *C. carnea*	25.92 ± 0.38	c
T5 IPM package	31.75 ± 0.62	a

Note: Values are means ± SD of four replicate plots. Different lowercase letters above bars denote significant differences by Tukey's HSD test at $p \leq 0.05$. IPM: integrated pest management.

Table 6. Effect of environmentally friendly pest control methods on the number of beneficial insects (individuals per plot) averaged over eight weekly samplings (visual counts + sweepnet)

Treatment	Mean ± SD (per plot)	Tukey Group
T1 Control	8.00 ± 0.82	d
T2 Neem oil 5%	11.00 ± 0.82	c
T3 *B. bassiana*	12.75 ± 0.96	c
T4 *C. carnea*	16.75 ± 0.96	b
T5 IPM package	19.75 ± 0.96	a

Note: Values are means ± SD of four replicate plots. Different lowercase letters above bars denote significant differences by Tukey's HSD test at $p \leq 0.05$. IPM: integrated pest management.

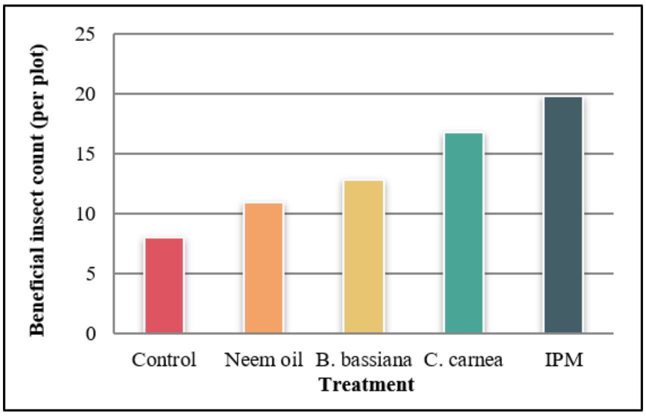

Figure 4. Mean beneficial insect count per plot in response to the eco-friendly treatments

The IPM plots supported the highest abundance of pollinators and predators, reflecting both the intentional *C. carnea* releases and the compatibility of selective biological treatments with non-target taxa. Coccinellidae and Syrphidae were the most frequently recorded predator groups, while *A. mellifera* dominated pollinator counts.

Figure 4 and Table 6 show the beneficial insect count per treatment, while Figure 5 breaks down the functional-group composition in T1 versus T5, revealing that predators (Coccinellidae and Syrphidae) accounted for the largest share of the increase.

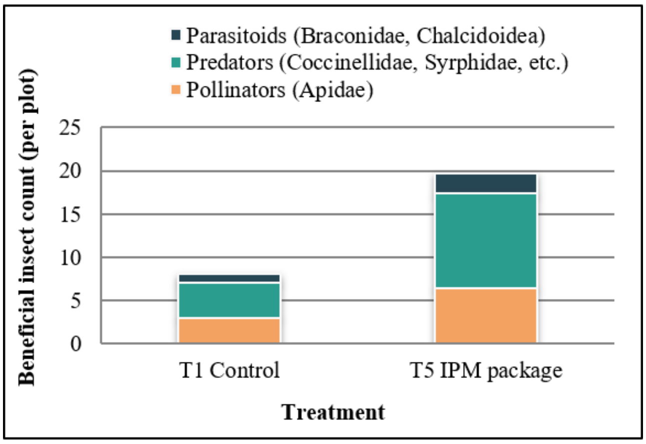

Figure 5. Composition of beneficial insect functional groups in the untreated control (T1) versus the IPM package (T5)

Note: Groups are: pollinators (Apidae), predators (Coccinellidae, Syrphidae, Chrysopidae, *Orius* spp., Araneae), and parasitoids (Braconidae, Chalcidoidea). Values are means averaged across eight weekly samplings.

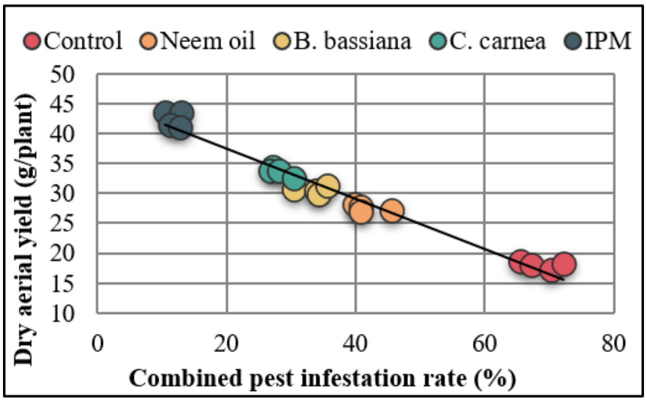

Figure 6. Scatter plot of combined pest infestation rate versus dry aerial yield for the 20 individual experimental plots (n = 20)

Note: Each symbol represents one plot; colors denote treatments. The dashed line is the linear regression fit. Inset: Pearson r = –0.985, p < 0.001, 95% CI [–0.994, –0.961].

All correlations remain highly significant at the individual-plot level, but the 95% CIs are appropriately wider than those implied by the previous treatment-mean analysis, correctly reflecting the n = 20 sample size (Table 7).

Figures 6 and 7 present scatter plots of the raw plot-level data (n = 20) for the two strongest variable pairs, with regression lines and Pearson statistics inset, confirming the robustness of the correlations beyond the treatment-mean level.

Figure 8 tracks the temporal dynamics of combined pest pressure over the eight weekly assessments, showing that the IPM package maintained the steepest decline from week 1 onward, whereas the control fluctuated around 65-70% throughout the season.

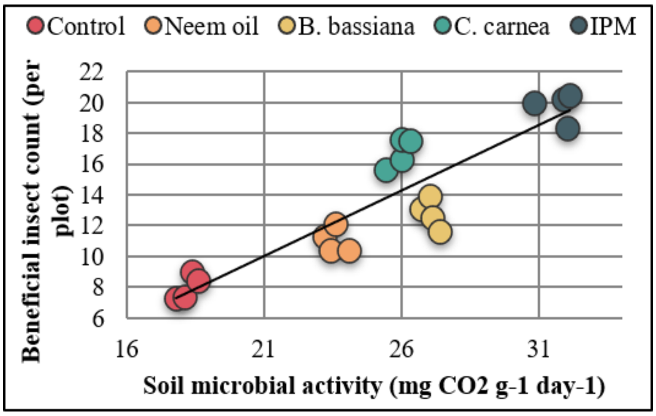

Figure 7. Scatter plot of soil microbial activity versus beneficial insect count for the 20 individual experimental plots (n = 20)

Note: Each symbol represents one plot; colors denote treatments. The dashed line is the linear regression fit. Inset: Pearson r = 0.897, p < 0.001, 95% CI [0.754, 0.959].

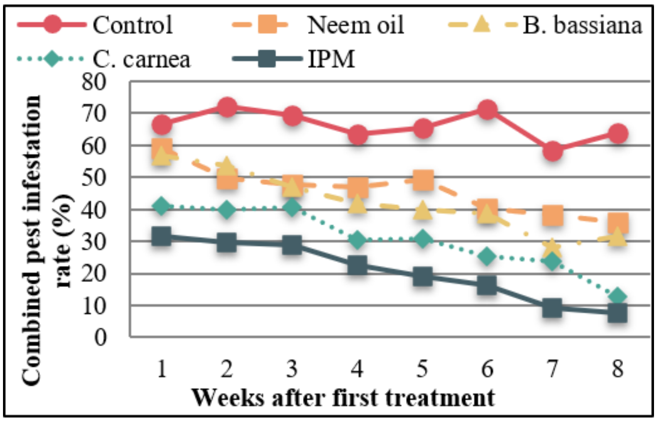

Figure 8. Temporal dynamics of combined pest infestation rate (aphids + spider mites) over the 8-week assessment period

Note: Data points are weekly means; error bars omitted for clarity. The IPM package (T5) shows the steepest sustained decline, while the control (T1) fluctuates around 65–70%.

Table 7. Pearson correlation coefficients among variables across 20 plots (4 replicates × 5 treatments)

Variable Pair	Pearson R	p-Value	95% CI
Pest infestation vs Plant yield	-0.985	<0.001	[-0.994, -0.961]
Pest infestation vs Soil microbial activity	-0.968	<0.001	[-0.988, -0.920]
Pest infestation vs Beneficial insects	-0.927	<0.001	[-0.971, -0.821]
Plant yield vs Soil microbial activity	0.970	<0.001	[0.925, 0.988]
Plant yield vs Beneficial insects	0.954	<0.001	[0.886, 0.982]
Soil microbial activity vs Beneficial insects	0.897	<0.001	[0.754, 0.959]

Note: Values are Pearson's r with two-tailed p-values and 95% confidence intervals. Correlations were computed in IBM SPSS Statistics 28.

The relationships among the measured variables were further examined using Pearson correlation analysis. As shown in Table 7, several significant positive and negative correlations were observed among the evaluated parameters across the 20 plots (4 replicates × 5 treatments).

4. DISCUSSION

The study demonstrated that the IPM package outperformed single-tactic treatments because it integrated three complementary mechanisms: neem oil for rapid antifeedant and growth-disrupting effects, *Beauveria bassiana* for delayed pathogenic suppression, and *Chrysoperla carnea* for direct predation of soft-bodied pests. This finding is consistent with sustainability-oriented IPM approaches that emphasize the advantages of combining multiple compatible control tactics to achieve more durable and environmentally sound pest management outcomes [19]. Furthermore, recent studies have highlighted the importance of reducing pesticide inputs and preserving soil microbial functions and agroecosystem biodiversity through biologically based pest management strategies [22-26]. To our knowledge, this is the first field study conducted on German chamomile cultivation in Iraq that integrates botanical, fungal, and predator-based tactics within a single IPM package against *Aphis fabae* and *Tetranychus urticae* [27-30].

The decrease in infestation, together with the resulting yield increase, supports recent studies that demonstrate that pesticide residues persist as a primary quality problem in medicinal crops, thus proving the benefits of pest management systems that do not leave harmful pesticide traces [18]. The control treatment showed high pest pressure, which decreased both photosynthetic area and assimilate allocation, thus leading to low biomass production. The IPM plots maintained their canopy structure until it became necessary for faster dry matter growth to take place. The control showed no effects from neem, but the neem treatment failed to reach the performance level of the fungal and predator-based methods, which operate at field strength, because botanical treatments deliver quick results that fail to maintain effectiveness during field conditions. The review by Adusei and Azupio [1] and the azadirachtin synthesis study by Kilani-Morakchi et al. [7] demonstrate that neem has minimal environmental impact and serves as an effective insecticide solution, but not as a complete treatment method. The current findings show that neem causes a significant decrease in pest numbers, but *B. bassiana* and *C. carnea* treatments produce better results because the botanical component functions more effectively when used with IPM systems, according to studies [1-7]. The use of *B. bassiana* reduced pest numbers more effectively than neem while increasing both crop yield and soil microorganism activity, according to recent studies, which show that submerged spores at 1×10^8 SS/mL cause high mortality rates in *Tetranychus urticae* and *B. bassiana* metabolites create strong larvicidal effects on various insect pests, according to Basso et al. [4] and Vivekanandhan et al. [15]. Recent reviews demonstrate that entomopathogenic fungi function as insecticides, which also offer biocontrol solutions to plants through endophytic benefits under specific environmental and product application conditions, according to the findings of studies [9, 16, 17]. The fungal and IPM treatments produced higher soil microbial activity because their lower chemical input requirements created less environmental damage while chemical applications protected vital plant root activities [22, 31-38].

The yield response — a 133% increase in the IPM package over the untreated control — is large but not unprecedented for heavily infested medicinal herbs. In the control, combined aphid and mite incidence exceeded 68%, which would have led to severe reductions in photosynthetic leaf area and assimilate allocation. Extension records from local unprotected chamomile in northern Iraq show yield losses of 60-70% under similar pest pressure, suggesting our control performance is representative of the growers' experience. Tight standard deviations reflect consistent loam texture and transplant establishment and are not artificially constrained variability.

The IPM treatment showed 31.75 mg CO_2 g^{-1} day^{-1} in soil microbial respiration, which was 74% higher than the control. While this appears to be large, similar increases (50-100%) have been reported in Mediterranean herbaceous systems following cessation of broad-spectrum pesticides [21]. This likely acts by decreasing chemical disruption of the rhizosphere microbiome and increasing root exudation from healthier plants, providing more labile carbon substrates for microbial turnover. However, we recognize that respiration is a single proxy of soil biological activity, and we did not measure microbial diversity, enzyme activities, or nutrient cycling rates; thus, our inference about "soil health" is necessarily narrow [23-26, 39, 40].

The present experiment demonstrated that the best performance level of *Chrysoperla carnea* was due to its classification as a generalist predator working efficiently in situations of biological control. Recent field and greenhouse studies demonstrate that *C. carnea* larvae can effectively control greenhouse pests through their predation abilities while they function as conservation biological control agents under suitable habitat and attractant conditions [5-14, 41-43].

The lacewing and IPM plots showed higher numbers of beneficial insects, demonstrating that the management program maintained compatibility with non-target species. Coccinellidae and Syrphidae were the dominant free-living predators, while *Apis mellifera* accounted for the majority of pollinator observations. The absence of broad-spectrum insecticides likely allowed these populations to persist, in contrast to the pest-dominated control canopies where heavy honeydew and mite webbing created unsuitable microclimates for natural enemies.

The recent studies about pollinators have established that pesticides cause decreases in population numbers and changes in behavior and survival rates for non-Apis bees and other beneficial insects [3, 11]. The present results show that biologically based pest control successfully transformed pest-dominated conditions into resilient agroecosystems. The IPM package demonstrated ecological validity, establishing an inverse relationship where reduced pest pressure directly maximized yield, microbial activity, and beneficial insect biodiversity. The treatment protects underground processes and aboveground biocontrol services while controlling pest populations. The integrated result of current soil-health research shows that pesticide pressure disrupts microbial activities that protect plants, but selective management methods maintain ecological functions. The research results demonstrate that an IPM package that combines botanical elements with microbial biopesticides and augmentative predators provides a strong solution for producing medicinal plants [31-33, 44].

5. LIMITATIONS

We acknowledge several constraints. First, the experiment ran for a single six-month growing season, so we cannot infer long-term stability of the IPM effects or potential pest resurgence in subsequent cycles. Second, we did not include a synthetic insecticide comparator, which means we can claim superiority over the untreated control and over single biological tactics, but we cannot directly benchmark against conventional chemical standards. Third, with four replicates per treatment, power is adequate for the large effect sizes observed but may be insufficient for subtler interactions. Fourth, although we frame the IPM package as "residue-free," we did not perform chemical residue analysis on the harvested biomass; this claim rests on the known degradation profiles of neem azadirachtin and biological agents, not on direct assay. Finally, pest assessments were based on presence/absence per plant rather than absolute density counts, which is practical for field scouting but sacrifices information on population dynamics within infested plants.

Future work should test the package across multiple environments and growing seasons, measure the persistence of biological agents under local climatic conditions, assess effects on essential oil content and flavonoid profiles, and evaluate the economic costs of labor and materials relative to conventional spraying. Such data would be essential for convincing local medicinal-plant growers to adopt the integrated strategy at scale.

6. CONCLUSION

The research shows that an ecologically designed pest control system can effectively reduce aphid and spider mite populations while enhancing German chamomile agricultural results. The IPM package reduced combined pest infestation by 82% compared to the control (from 68.8% to 12.5%) and increased dry aerial yield by 133% (from 18.10 to 42.12 g/plant). It also produced the greatest soil microbial activity (31.75 mg CO_2/g soil/day) and the largest population of beneficial insects (19.75 individuals per plot) across all four measured variables. The combined use of neem oil, *Beauveria bassiana*, and *Chrysoperla carnea* produced better results than each individual component because their different modes of action created effective synergies in actual farming environments. For growers, this suggests that biologically based management can achieve marketable yields while avoiding the negative effects typically associated with broad-spectrum chemical insecticides — particularly important for medicinal crops where residue limits are strict, and consumer acceptance depends on clean raw material. However, we did not directly measure residues, essential oil quality, or production costs, so the practical recommendation is framed as a promising implication rather than a proven economic certainty. The evidence is especially relevant in regions where crop quality assessment considers yield, phytochemical purity, biodiversity preservation, and supply-chain safety together.

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REFERENCES

[1] Adusei, S., Azupio, S. (2022). Neem: A novel biocide for pest and disease control of plants. Journal of Chemistry, 2022(1): 6778554. https://doi.org/10.1155/2022/6778554

[2] Ayllón-Gutiérrez, R., Díaz-Rubio, L., Montaño-Soto, M., Haro-Vázquez, M.P., Córdova-Guerrero, I. (2024). Applications of plant essential oils in pest control and their encapsulation for controlled release: A review. Agriculture, 14(10): 1766. https://doi.org/10.3390/agriculture14101766

[3] Basu, P., Ngo, H.T., Aizen, M.A., et al. (2024). Pesticide impacts on insect pollinators: Current knowledge and future research challenges. Science of the Total Environment, 954: 176656. https://doi.org/10.1016/j.scitotenv.2024.176656

[4] Basso, V., Pinheiro Dillon, A.J., Toldi, M., Gonçalves Kramer, C., Vicenço Bonato, C. (2023). Beauveria bassiana submerged spores for control of two-spotted spider mite (Tetranychus urticae Koch (Acari: Tetranychidae)): Production, stability, and virulence. Archives of Microbiology, 206(1): 23. https://doi.org/10.1007/s00203-023-03759-7

[5] Berteloot, O.H., Peusens, G., Beliën, T., Van Leeuwen, T., De Clercq, P. (2024). Predation efficacy of Chrysoperla carnea on two economically important stink bugs. Biological Control, 196: 105586. https://doi.org/10.1016/j.biocontrol.2024.105586

[6] Fuchs, B., Saikkonen, K., Damerau, A., Yang, B., Helander, M. (2023). Herbicide residues in soil decrease microbe-mediated plant protection. Plant Biology, 25(4): 571-578. https://doi.org/10.1111/plb.13517

[7] Kilani-Morakchi, S.K., Morakchi-Goudjil, H., Sifi, K. (2021). Azadirachtin-based insecticide: Overview, risk assessments, and future directions. Frontiers in Agronomy, 3: 676208. https://doi.org/10.3389/fagro.2021.676208

[8] Mishra, A.K., Singh, H., Kumar, A., Gupta, H., Mishra, A. (2024). Recent advancements in liquid chromatographic techniques to estimate pesticide residues found in medicinal plants around the globe. Critical Reviews in Analytical Chemistry, 54(8): 2900-2914. https://doi.org/10.1080/10408347.2023.2212049

[9] Panwar, N., Szczepaniec, A. (2024). Endophytic entomopathogenic fungi as biological control agents of insect pests. Pest Management Science, 80(12): 6033-6040. https://doi.org/10.1002/ps.8322

[10] Peng, B., Xie, Y., Lai, Q., Liu, W., et al. (2024). Pesticide residue detection technology for herbal medicine: Current status, challenges, and prospects. Analytical Sciences, 40(4): 581-597. https://doi.org/10.1007/s44211-024-00515-9

[11] Raine, N.E., Rundlöf, M. (2024). Pesticide exposure and effects on non-Apis bees. Annual Review of Entomology, 69(1): 551-576. https://doi.org/10.1146/annurev-ento-040323-020625

[12] Siviter, H., Bailes, E.J., Martin, C.D., Oliver, T.R.,

Koricheva, J., Leadbeater, E., Brown, M.J.F. (2021). Agrochemicals interact synergistically to increase bee mortality. Nature, 596(7872): 389-392. https://doi.org/10.1038/s41586-021-03787-7

[13] Steiner, M., Falquet, L., Fragnière, A.L., Brown, A., Bacher, S. (2024). Effects of pesticides on soil bacterial, fungal and protist communities, soil functions and grape quality in vineyards. Ecological Solutions and Evidence, 5(2): 12327. https://doi.org/10.1002/2688-8319.12327

[14] Tesari, T., Leksono, A.S., Mustafa, I. (2024). Effectiveness of botanical pesticide combined with Beauveria bassiana on mortality, nutritional index and fecundity of Spodoptera litura L. Cogent Food & Agriculture, 10(1): 2320816. https://doi.org/10.1080/23311932.2024.2320816

[15] Vivekanandhan, P., Swathy, K., Alahmadi, T.A., Ansari, M.J. (2024). Biocontrol effects of chemical molecules derived from Beauveria bassiana against larvae of Tuta absoluta (Meyrick) (Lepidoptera: Gelechiidae). Frontiers in Microbiology, 15: 1336334. https://doi.org/10.3389/fmicb.2024.1336334

[16] Wang, L., Keyhani, N.O., Xia, Y., Xie, J. (2024). The potential and limitations of entomopathogenic fungi as biocontrol agents for insect pest management. Entomologia Generalis, 44(4): 797-811. https://doi.org/10.1127/entomologia/2024/2498

[17] Wang, Y., Li, S., Sun, J., Li, Y., et al. (2024). Comprehensive assessment for species authenticity, pesticide residual, and fungal contamination characteristics of Panax herbal tea. LWT - Food Science and Technology, 207: 116688. https://doi.org/10.1016/j.lwt.2024.116688

[18] Zattara, E.E., Aizen, M.A. (2021). Worldwide occurrence records suggest a global decline in bee species richness. One Earth, 4(1): 114-123. https://doi.org/10.1016/j.oneear.2020.12.005

[19] Zhou, W., Arcot, Y., Medina, R.F., Bernal, J., Cisneros-Zevallos, L., Akbulut, M.E.S. (2024). Integrated pest management: An update on the sustainability approach to crop protection. ACS Omega, 9(40): 41130-41147. https://doi.org/10.1021/acsomega.4c06628

[20] Anderson, J.P.E., Domsch, K.H. (1978). A physiological method for the quantitative measurement of microbial biomass in soils. Soil Biology and Biochemistry, 10(3): 215-221. https://doi.org/10.1016/0038-0717(78)90099-8

[21] Gomiero, T., Pimentel, D., Paoletti, M.G. (2011). Environmental impact of different agricultural management practices: Conventional vs. organic agriculture. Critical Reviews in Plant Sciences, 30(1-2): 95-124. https://doi.org/10.1080/07352689.2011.554355

[22] Mello, D.C., Pires, N.L., Evangelista, C.S., Caldas, E.D. (2024). Pesticide residues in dry herbs used for tea preparation by UHPLC-MS/MS: Method validation and analysis. Journal of Food Composition and Analysis, 125: 105817. https://doi.org/10.1016/j.jfca.2023.105817

[23] Jeyaseelan, A., Murugesan, A.G., Kuppusamy, S. (2024). A review of the impact of herbicides and insecticides on the microbial communities. Environmental Research, 245: 118020. https://doi.org/10.1016/j.envres.2023.118020

[24] Swaine, M., Bergna, A., Oyserman, B., Vasileiadis, S., Karas, P.A., Screpanti, C., Karpouzas, D.G. (2025). Impact of pesticides on soil health: Identification of key soil microbial indicators for ecotoxicological assessment strategies through meta-analysis. FEMS Microbiology Ecology, 101(6): fiaf052. https://doi.org/10.1093/femsec/fiaf052

[25] Ni, B., Xiao, L., Lin, D., Zhang, T.L., et al. (2025). Increasing pesticide diversity impairs soil microbial functions. Proceedings of the National Academy of Sciences, 122(2): e2419917122. https://doi.org/10.1073/pnas.2419917122

[26] Némethová, E., Řezáč, M., Gryndler, M., Abeyawardana, O.A., Řezáčová, V. (2025). Soil pH mediates the impact of pesticides on bacterial communities. Frontiers in Microbiology, 16: 1670425. https://doi.org/10.3389/fmicb.2025.1670425

[27] Pobożniak, M., Olczyk, M. (2025). Biocontrol in integrated pest management in fruit and vegetable crops. Horticulturae, 11(5): 522. https://doi.org/10.3390/horticulturae11050522

[28] Jalloh, A.A., Uyi, O., Chitturi, A., Basu, S., et al. (2025). Harnessing natural enemies for sustainable management of agricultural insect pests. Frontiers in Agronomy, 7: 1684672. https://doi.org/10.3389/fagro.2025.1684672

[29] Scott-Brown, A.S., Rial-Lovera, K., Giannitsopoulos, M.L., Rickson, J.R., Staton, T., Walters, K.F., Burgess, P.J. (2025). Farmland trees and integrated pest management: A review of pathways for natural-enemy conservation. Ecological Solutions and Evidence, 6(3): e70087. https://doi.org/10.1002/2688-8319.70087

[30] Yarahmadi, F., Rajabpour, A. (2024). Insecticides and natural enemies: Applications in integrated pest management programs - Challenges, criteria, and evaluation for recommendations. In Insecticides in Pest Control - Impact, Challenges and Strategies, pp. 1-19. https://doi.org/10.5772/intechopen.1005830

[31] Gupta, I., Singh, R., Muthusamy, S., Sharma, M., Grewal, K., Singh, H. P., Batish, D.R. (2023). Plant essential oils as biopesticides: Applications, mechanisms, innovations, and constraints. Plants, 12(16): 2916. https://doi.org/10.3390/plants12162916

[32] Mascarin, G.M., Golo, P.S., de Souza Ribeiro-Silva, C., Muniz, E.R., de Oliveira Franco, A., Kobori, N.N., Fernandes, É.K.K. (2024). Advances in submerged liquid fermentation and formulation of entomopathogenic fungi. Applied Microbiology and Biotechnology, 108(1): 451. https://doi.org/10.1007/s00253-024-13287-z

[33] Lou, H., Luo, Q., Guo, Q., Su, R., Liu, J., He, H., Cheng, Y. (2024). Optimization of the culture medium of Beauveria bassiana using agricultural by-products for enhanced sporulation. Fermentation, 10(11): 587. https://doi.org/10.3390/fermentation10110587

[34] Al-Zahrani, J.K., Al-Abdalall, A.H., Osman, M.A., Aldakheel, L. A., et al. (2023). Entomopathogenic fungi and their biological control of Tetranychus urticae two-spotted spider mites. Journal of King Saud University - Science, 35(8): 102910. https://doi.org/10.1016/j.jksus.2023.102910

[35] Zhao, Y., Lou, T., Cao, R., Jiang, L., Xu, Q., Zhan, Q. (2024). Predation efficiency and biological control potential of lacewing predators against aphids. Agronomy, 14(10): 2242. https://doi.org/10.3390/agronomy14102242

[36] Sebaei, R.S. (2024). Efficacy of releasing Chrysoperla carnea (Stephens) against aphid infestation under greenhouse conditions. Annals of Agricultural Science,

Moshtohor, 62(4): 743-752.

[37] Landge, A., Dwivedi, S.A., Landge, S.A. (2024). A review on application of integrated pest management tactics for aphid complex on crop ecosystem. International Journal of Advanced Biochemistry Research, 8(7): 458-468. https://doi.org/10.33545/26174693.2024.v8.i7f.1505

[38] Dhakad, A.K., Kumar, R., Choudhary, R., Singh, S., Khan, S., Poonia, P.K. (2025). Traditional to modern perspectives on neem (Azadirachta indica): Phytochemistry, bioactivity, and agricultural applications. Industrial Crops and Products, 231: 121155. https://doi.org/10.1016/j.indcrop.2025.120701

[39] Cai, C., Zhou, F., Chu, R., Ye, H., Zhang, C., Shui, L., Liu, Y. (2024). Rapid and sensitive in-situ detection of pesticide residues in tea soup using fiber SERS probes. Journal of Food Composition and Analysis, 133: 106384. https://doi.org/10.1016/j.jfca.2024.106384

[40] Knuth, D., Gai, L., Silva, V., Harkes, P., et al. (2024). Pesticide residues in organic and conventional agricultural soils across Europe: measured and predicted concentrations. Environmental Science & Technology, 58(15): 6744-6752. https://doi.org/10.1021/acs.est.3c09059

[41] Sayed, S.M., El Husseini, M.M., Agamy, E. et al. (2025). Field evaluation of entomopathogenic fungi for eco-friendly management of insect pests in crop systems. Scientific Reports, 15: 24044. https://doi.org/10.1038/s41598-025-06100-y

[42] Ali, H.M.S., Kamran, M., Alatawi, F.J. (2025). Evaluation of different larval instars and predator-prey ratios of Chrysoperla carnea against Tetranychus urticae. Acarologia, 65(2): 356-368. https://dx.doi.org/10.24349/lf2w-eh0c

[43] Li, H., Qiao, S., Zhang, S. (2025). Essential oils in grain storage: A comprehensive review of insecticidal and antimicrobial constituents, mechanisms, and applications for grain security. Journal of Stored Products Research, 111: 102537. https://doi.org/10.1016/j.jspr.2024.102537

[44] Riedo, J., Dueñas, J.F., Mbedi, S., Sparmann, S., Rillig, M.C. (2025). Abrupt versus gradual application of pesticides: Effects on soil bacterial and fungal communities. Environmental Pollution, 383: 126859. https://doi.org/10.1016/j.envpol.2025.126859