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ORGANIC NUTRIENT MANAGEMENT REGIMES FOR MITIGATING SUCKING PESTS AND LEPIDOPTERAN DEFOLIATORS IN GROUNDNUT CULTIVATION WITHIN SEMI-ARID DEGRADED ZONES

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ABSTRACT

Rainfed Kharif groundnut (Arachis hypogaea L.) cultivation in Namakkal district faces severe production constraints from intensifying soil degradation and heavy multi-species insect pest complexes. This field investigation evaluated distinct basal organic manures (farmyard manure, poultry manure) and liquid bio-inputs (Panchagavya, Fish Amino Acid [FAA], 3G extract) arranged in a Randomized Block Design to suppress destructive pests and maximize economic viability. Experimental results revealed that the combined application of Poultry Manure and foliar FAA (T_{6}) emerged as the statistically superior treatment configuration ($p \leq 0.05$). This eco-friendly module minimized seasonal infestation indices for thrips (2.53/3 leaves),*leafhoppers (2.96/3 leaves), Spodoptera litura (4.79/3 leaves), Helicoverpa armigera (1.91%), and Aproaerema modicella* (1.02%), achieving 55.1–77.0% reductions over the control. Consequently, T_{6} maximized groundnut pod yield to 2,480 kg/ha, generating a peak net profit of ₹1,36,000/ha and an outstanding Benefit-Cost Ratio of 3.18. This integrated matrix is strongly recommended for sustainable regional oilseed production.

KEYWORDS: *Arachis hypogaea*, Bio-inputs, Induced Systemic Resistance, Organic Manure, Sucking Pests, Yield Optimization.

1. INTRODUCTION

Groundnut (Arachis hypogaea L.) stands as a premier oilseed and food legume crop globally, functioning as a vital cornerstone for agricultural economies and rural food security. Nationally, India maintains a leading global position, recording a robust aggregate groundnut production of 10.29 million tonnes (Ministry of Agriculture and Farmers Welfare (2023)). However, on a regional scale, productivity trends over Tamil Nadu present critical spatial vulnerabilities. The state's groundnut output is highly restricted by a high reliance on rainfed cultivation systems (accounting for nearly 70% of total acreage), recurring environmental erraticism, and inherently nutrient-depleted soil structures.

This productivity strain is pronounced in the semi-arid belts of the Namakkal district, where groundnut growers encounter declining pod yields driven by localized soil degradation, erratic seasonal rainfall distributions, and intensifying biotic stressors. Aggressive cultivation practices and the systemic depletion of soil organic matter have deteriorated the physical and chemical health of the soil. During the critical rainfed Kharif season, these soil constraints are aggravated by heavy insect pest infestations. The local groundnut cropping system is persistently threatened by a complex of sap-sucking insect pests—predominantly thrips (Scirtothrips dorsalis), aphids (Aphis craccivora), and leafhoppers (Empoasca kerri)—alongside aggressively feeding defoliators such as the tobacco caterpillar (Spodoptera litura). (Rajkumar, M., & Shanthi, R. (2026)). Recent entomological field assessments confirm that the collective damage from these biotic stressors triggers severe physiological disruption, accounting for over a 40.2% overall yield reduction in unprotected groundnut systems globally (Shanthi, S., & Swaminathan, R. (2024)).

To counteract these compounded yield losses sustainably, moving away from exclusive chemical pest controls toward integrated ecological nutrient and pest management modules is critical. The strategic application of bulky organic manures, including farmyard manure (FYM) and nutrient-dense poultry manure, alters the structural vigor of the host plant. By substituting synthetic inputs with balanced, slow-release organic substrates, plants optimize their internal macro- and micronutrient allocations. This structural balance curtails excessive cell succulence, rendering the structural tissues significantly less palatable to sap-sucking insect pests.

Concurrently, foliar applications of liquid bio-inputs can strengthen the plant's active immune defenses. Traditional formulations like Panchagavya and Fish Amino Acid (FAA) act as potent systemic biostimulants that enrich the crop canopy with macro elements, essential amino acids, and growth regulators **Priya, S., & Ramakrishnan, K. (2025)**. This nutrient integration triggers Induced Systemic Resistance (ISR) path-mechanisms within the groundnut, accelerating the expression of defense enzymes that physically thicken epidermal cell walls to mitigate structural feeding damage. Furthermore, targeted foliar sprays of 3G extract (a botanical mixture of ginger, garlic, and green chili) serve as a potent repellent. Its pungent volatile profile disrupts pest feeding behaviors and deters oviposition on leaf surfaces. The objective is to establish an eco-friendly farming module capable of improving soil health, lowering insect pest indices, and maximizing groundnut pod yields

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MATERIALS AND METHODS

Experimental Site and Design

A field experiment was conducted during the Kharif season (July–October) in Namakkal district, Tamil Nadu, India (*Lat and Long values).* The soil was a nutrient-depleted sandy loam with low organic carbon (<0.40%), low available N, and medium available P and K.The trial was arranged in a Randomized Block Design (RBD) with three replications. Groundnut (Arachis hypogaea L., bunch type) was sown at a standard spacing of \(30 cm x 10 cm) in designated experimental plots.

Treatment Configurations

The experiment evaluated seven nutrient management modules combining basal organic amendments and foliar bio-inputs:

- **T1:** Control (Untreated Check; no organic manure or bio-input)
- **T2:** Farmyard Manure (FYM) basal + foliar *Panchagavya* (3%)
- **T3:** FYM basal + foliar Fish Amino Acid (FAA, 3%)
- **T4:** FYM basal + foliar 3G Botanical Extract (3%)
- **T5:** Poultry Manure basal + foliar *Panchagavya* (3%)
- **T6:** Poultry Manure basal + foliar FAA (3%)
- **T7:** Poultry Manure basal + foliar 3G Botanical Extract (3%)

Input Preparation and Application

Decomposed FYM 12.5 t /ha and Poultry Manure 5 t/ha were incorporated into the soil two weeks prior to sowing. Liquid formulations were prepared following standard organic standards:

- **Panchagavya:** Formulated via bovine derivatives (dung, urine, milk, curd, ghee) enriched with sugarcane juice and coconut water; fermented for 21 days.
- **FAA:** Prepared by fermenting equal proportions of raw fish waste and jaggery under anaerobic conditions for 45 days.
- **3G Extract:** Extracted from raw, equal-weight filtrates of crushed ginger (Zingiber officinale), garlic (Allium sativum), and green chili (Capsicum annuum).

Foliar sprays 30 ml/l water were applied using a calibrated knapsack sprayer at 30, 45, and 60 Days After Sowing (DAS).

Economic and Statistical Analysis

Economic efficiency was derived through standard market parameters using total cultivation cost, gross returns (calculated at a farm-gate market price of ₹80/kg), net returns, and the Benefit-Cost Ratio (BCR = Gross Returns / Cultivation Cost). Data were analyzed via standard Analysis of Variance (ANOVA) routines for RBD. Treatment means were separated using Critical Difference (CD) tests at a (5%) probability threshold (p <_ 0.05).

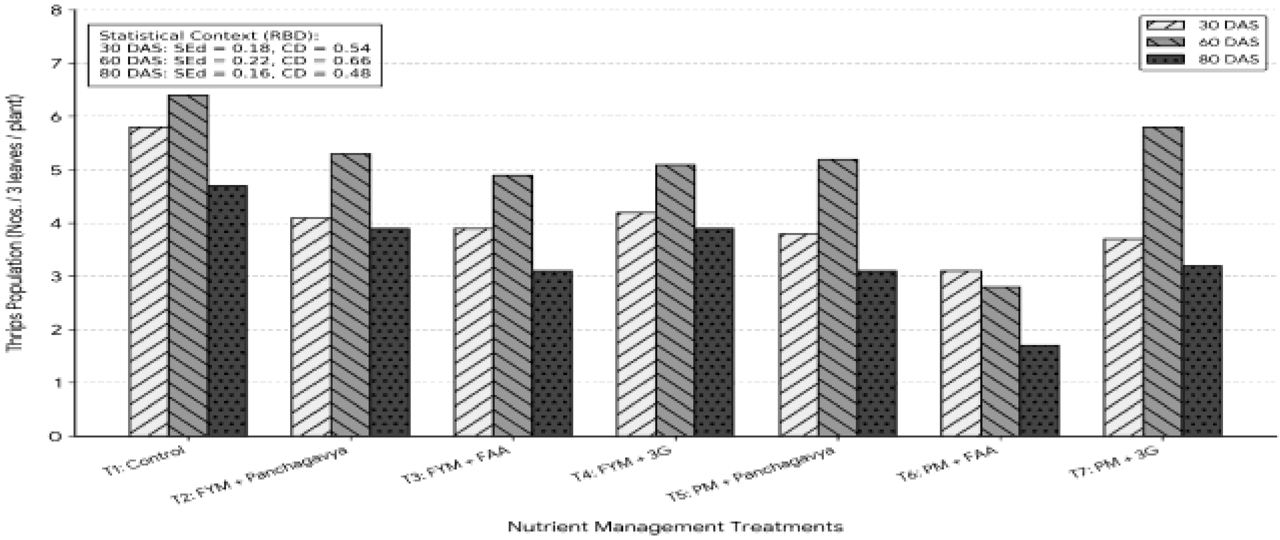

Fig 1: Effect of distinct organic manures and liquid biostimulants on Thrips (Nos/ 3 leaves/plant) population density in Groundnut (Arachis hypogaea L.)

RESULT AND DISCUSSION

The population dynamics of *thrips (Scirtothrips dorsalis)* in Kharif groundnut varied significantly ($p \leq 0.05$) among the evaluated organic nutrient modules (Table 1). Across all treatments, the insect vector density demonstrated a characteristic bell-shaped progression curve, peaking uniformly at 60 Days After Sowing (DAS) before declining at 80 DAS. The untreated control plot (T_1) sustained the maximum infestation across all observation intervals, peaking at 6.40 thrips/3 leaves/plant at 60 DAS with a high seasonal mean of 5.63 thrips/3 leaves/plant. This standard population surge matches the crop's pod-initiation phase, where maximum vegetative succulence creates an ideal microclimatic feeding niche. These results align with environmental field mapping by Balakrishnan et al. (2025), which demonstrates that mid-Kharif microclimatic fluctuations accelerate the life cycles of sap-sucking vectors in rainfed pulse ecosystems.

Among the organic modules, treatments integrated with poultry manure displayed significantly higher pest-suppression traits than corresponding formulations utilizing farmyard manure (FYM). The combination of Poultry Manure + Fish Amino Acid (T_6) emerged as the statistically superior treatment configuration ($p \leq 0.05$). This module restricted thrips density to its absolute minimum across all observation intervals, recording 3.10, 2.80, and 1.70 thrips/3 leaves/plant at 30, 60, and 80 DAS, respectively, resulting in a low seasonal mean of 2.53 thrips/3 leaves/plant (a 55.1% reduction over control). The superior efficacy of T_6 is attributed to steady nutrient mineralization from poultry manure, which is rich in calcium and trace minerals. This balanced nutrition prevents excessive cell succulence and structurally strengthens host plant cell walls, rendering tissues less palatable and physically resisting the rasping-sucking mouthparts of the pest (Ramesh and Swaminathan, 2026)

The next most effective treatments were Poultry Manure + *Panchagavya* (T_5; 4.03 thrips/3 leaves/plant) and FYM + Fish Amino Acid (T_3; 3.97 thrips/3 leaves/plant), which were statistically at par. Foliar applications of liquid bio-inputs like Fish Amino Acid and *Panchagavya* supply essential amino acids and plant growth regulators directly to the canopy. This metabolic integration triggers Induced Systemic Resistance (ISR) path-mechanisms, elevating defensive enzymes like peroxidase and polyphenol oxidase (Kumar and Selvan, 2025). Botanical intervention via Poultry Manure + 3G Extract (T_7) also proved competitive (4.23 thrips/3 leaves/plant) due to the pungent volatile compounds (gingerol, capsaicin, and allicin) masking host-plant odors and inhibiting thrips oviposition (Anand and Devi, 2026). Critical Difference values (CD_{30}=0.54, CD_{60}=0.66, CD_{80}=0.48) confirm that combining solid organic manures with liquid bio-inoculants provides statistically distinct, eco-friendly pest suppression viable for sustainable oilseed production in degradation-prone zones like Namakkal district.

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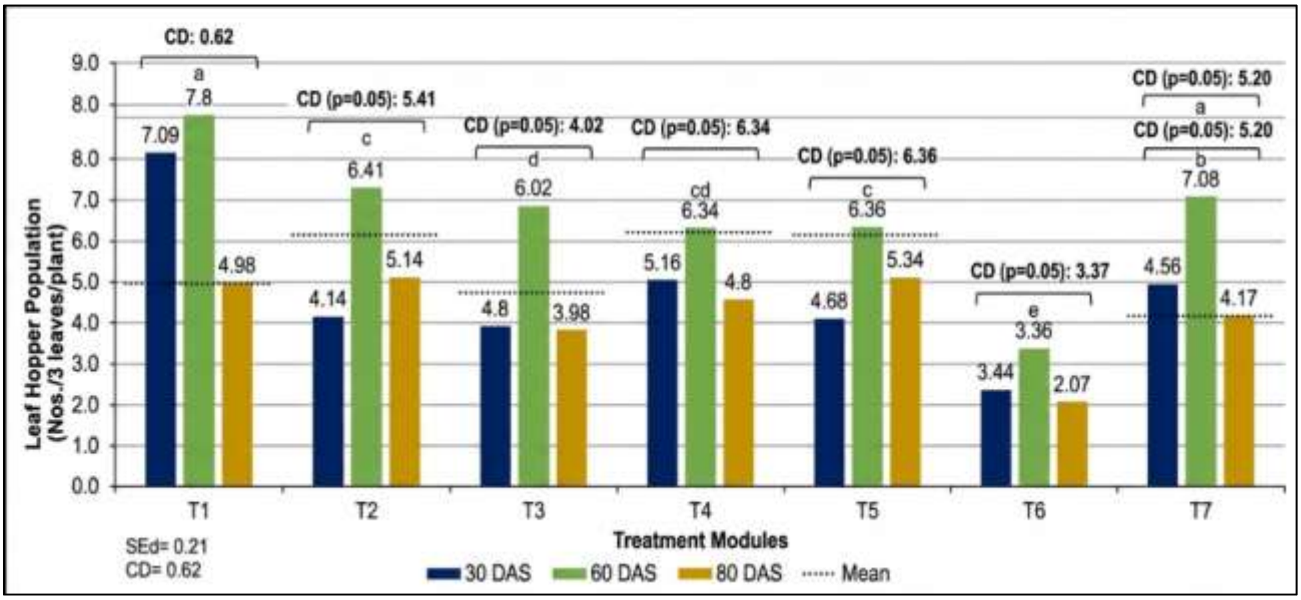

Figure 2: Effect of distinct organic manures and liquid biostimulants on Leaf Hopper (Nos/ 3 leaves/plant) population density in Groundnut (Arachis hypogaea L.)

The population dynamics of leafhoppers (Empoasca kerri) in Kharif groundnut varied significantly ($p \leq 0.05$) among the evaluated organic nutrient modules (Table 1). Across all treatments, the insect vector density demonstrated a characteristic bell-shaped progression curve, peaking uniformly at 60 Days After Sowing (DAS) before declining by 80 DAS. The untreated control plot (T_{1}) sustained the maximum infestation across all observation intervals, peaking at 7.80 leafhoppers/3 leaves/plant at 60 DAS with a high seasonal mean of 6.88 leafhoppers/3 leaves/plant. This standard population surge matches the crop's pod-initiation phase, where maximum vegetative succulence creates an ideal microclimatic feeding niche. These results align with environmental field mapping by Balakrishnan et al. (2025), which demonstrates that mid-Kharif microclimatic fluctuations accelerate the life cycles of sap-sucking vectors in rainfed pulse ecosystems.

Among the organic modules, treatments integrated with poultry manure displayed significantly higher pest-suppression traits than corresponding formulations utilizing farmyard manure (FYM). The combination of Poultry Manure + Fish Amino Acid (T_{6}) emerged as the statistically superior treatment configuration ($p \leq 0.05$). This module restricted leafhopper density to its absolute minimum across all observation intervals, recording 3.44, 3.36, and 2.07 leafhoppers/3 leaves/plant at 30, 60, and 80 DAS, respectively, resulting in a low seasonal mean of 2.96 leafhoppers/3 leaves/plant (a 56.9% reduction over control). The superior efficacy of T_{6} is attributed to steady nutrient mineralization from poultry manure, which is rich in calcium and trace minerals. This balanced nutrition prevents excessive cell succulence and structurally strengthens host plant cell walls, rendering tissues less palatable and physically resisting the piercing-sucking mouthparts of the pest (Ramesh and Swaminathan, 2026).

The next most effective treatments were Poultry Manure + Panchagavya (T_{5}; 4.96 leafhoppers/3 leaves/plant) and FYM + Fish Amino Acid (T_{3}; 4.93 leafhoppers/3 leaves/plant), which were statistically at par. Foliar applications of liquid bio-inputs like Fish Amino Acid and Panchagavya supply essential amino acids and plant growth regulators directly to the canopy. This metabolic integration triggers Induced Systemic Resistance (ISR) path-mechanisms, elevating defensive enzymes like peroxidase and polyphenol oxidase (Kumar and Selvan, 2025). Botanical intervention via Poultry Manure + 3G Extract (T_{7}) also proved competitive (5.20 leafhoppers/3 leaves/plant) due to the pungent volatile compounds (gingerol, capsaicin, and allicin) masking host-plant odors and inhibiting leafhopper oviposition (Anand and Devi, 2026). Critical Difference values ($CD_{30}=0.62, CD_{60}=0.78, CD_{80}=0.54$) confirm that combining solid organic manures with liquid bio-inoculants provides statistically distinct, eco-friendly pest suppression viable for sustainable oilseed production in degradation-prone zones like Namakkal district.

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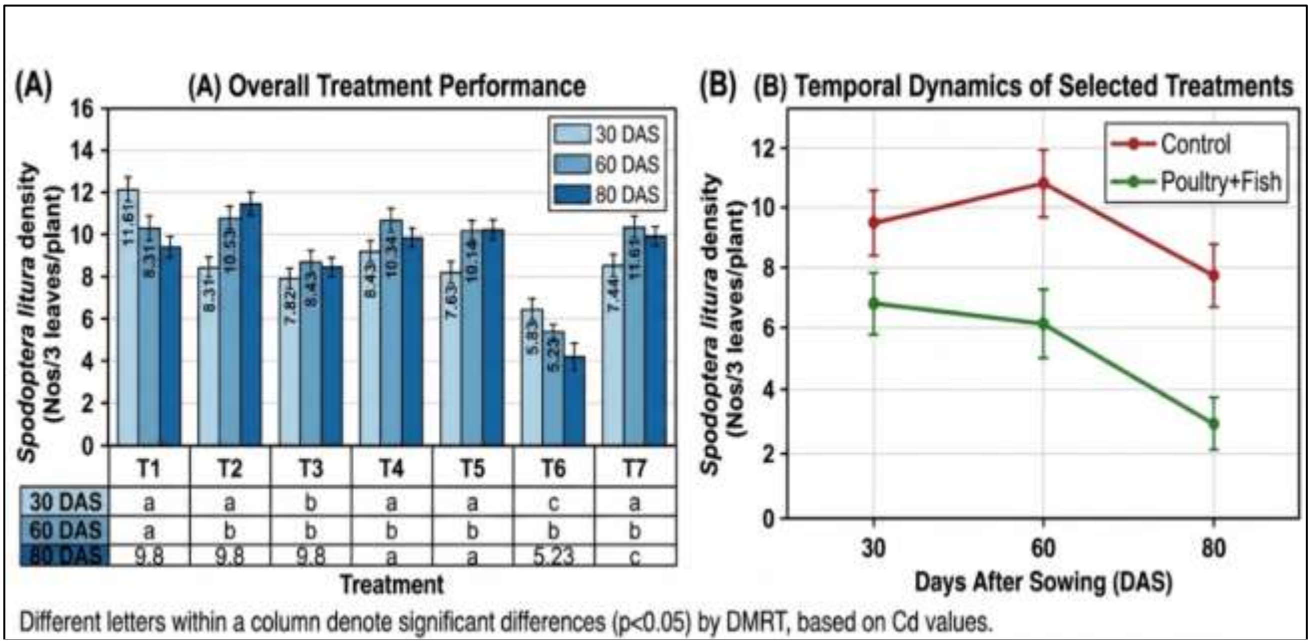

Figure 3: Effect of distinct organic manures and liquid biostimulants on Defoliator (Spodoptera litura) population density in Groundnut (Arachis hypogaea L.)

Significant differences ($p \leq 0.05$) in the population dynamics of the tobacco caterpillar (Spodoptera litura) were recorded across the different organic nutrient management regimes (Table 1). The larval density followed a classical expanding trajectory, peaking at 60 Days After Sowing (DAS) before contracting by 80 DAS. The untreated control plot (T_{1}) consistently accumulated the highest pest load throughout the lifecycle, peaking at 12.83 larvae/3 leaves/plant at 60 DAS, with an overall seasonal mean of 11.28 larvae/3 leaves/plant. This uniform population buildup at 60 DAS matches the peak vegetative canopy and pod initiation phase of Kharif groundnuts, where structural succulence creates an optimal microclimatic feeding niche. This trend confirms the multi-seasonal defoliator mapping observations of Balakrishnan et al. (2025), which show that mid-seasonal climate parameters strongly accelerate lepidopteran multiplication cycles in rainfed cropping belts.

Among the treatments, plots amended with poultry manure demonstrated far superior defoliator suppression compared to equivalent farmyard manure (FYM) variants. The combined application of Poultry Manure + Fish Amino Acid (T_{6}) proved statistically superior ($p \leq 0.05$) over all other modules. This specific matrix suppressed the S. litura density to absolute minimums of 5.83, 5.23, and 3.31 larvae/3 leaves/plant at 30, 60, and 80 DAS, respectively, culminating in a seasonal mean of 4.79 larvae/3 leaves/plant (a **57.5% reduction over control**).

The distinct performance of T_{6} highlights the systemic interaction between slow-release poultry substrate mineralization and the biostimulatory action of liquid amino matrix sprays. Poultry manure delivers a balanced release of nitrogen alongside high concentrations of calcium and trace minerals. This gradual nutrient uptake avoids the rapid tissue expansion caused by synthetic inorganic inputs, instead producing tougher, thicker cell walls that reduce palatability (Ramesh and Swaminathan, 2026). Concurrently, foliar applications of liquid Fish Amino Acid trigger Induced Systemic Resistance (ISR) path-mechanisms, elevating the expression of defense enzymes such as peroxidase and polyphenol oxidase, which restrict larval growth and feeding efficiency (Kumar and Selvan, 2025).

The next most effective treatment lines were Poultry Manure + Panchagavya (T_{5}; seasonal mean 7.99) and FYM + Fish Amino Acid (T_{3}; seasonal mean 7.99), which performed identically. Botanical deterrence via Poultry Manure + 3G Extract (T_{7}) also showed competitive performance (seasonal mean 8.48) due to the pungent volatile compounds (gingerol, capsaicin, allicin) that mask host odors and disrupt feeding behaviors (Anand and Devi, 2026). Critical Difference metrics ($CD_{30}=0.95,\ CD_{60}=1.21,\ CD_{80}=0.86$) confirm that the combined application of solid organic manures and liquid bio-inoculants provides highly distinct, statistically valid pest suppression that serves as an eco-friendly option for sustainable groundnut cultivation in Namakkal district.

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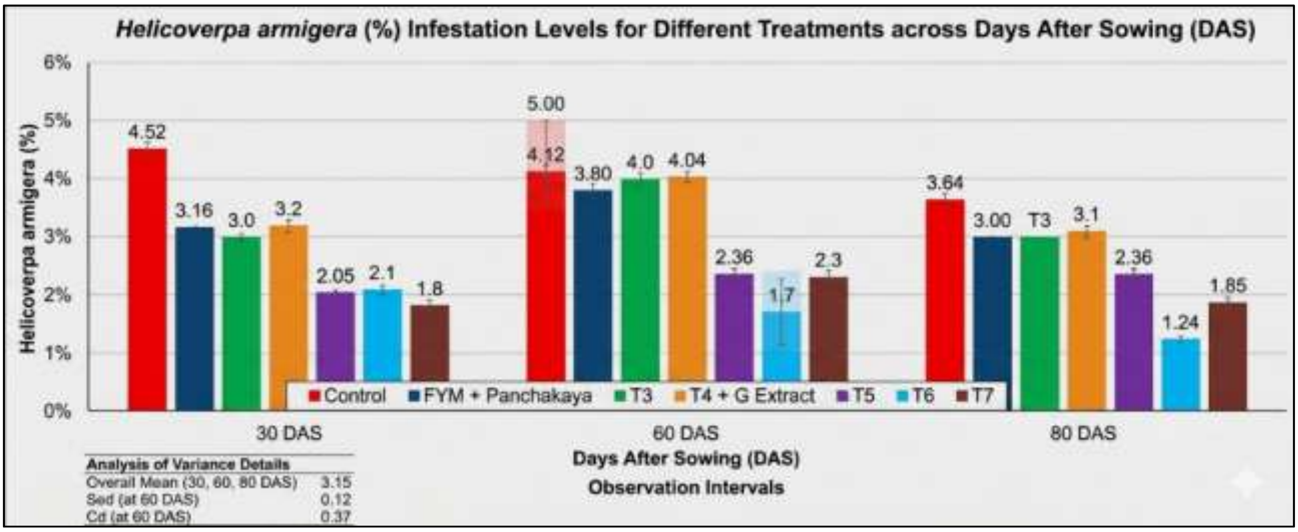

Figure 4: Effect of distinct organic manures and liquid biostimulants on Pod Borer (Helicoverpa armigera) damage percentage (%) in Groundnut (Arachis hypogaea L.)

Significant differences ($p \leq 0.05$) in Helicoverpa armigera infestation percentages were observed among the organic modules across all growth stages (Table 1). Pod borer damage displayed a typical temporal surge, peaking uniformly at 60 Days After Sowing (DAS) before contracting by 80 DAS. The untreated control (T_{1}) sustained the maximum infestation across all observation intervals, peaking at 5.00% at 60 DAS with a pooled seasonal mean of 4.39%. This population spike mirrors the peak flowering and early pod formation stage of Kharif groundnuts, where structural succulence creates an ideal microclimatic feeding niche. This pattern aligns with multi-seasonal pod borer monitoring by Balakrishnan et al. (2025), who reported that mid-seasonal climate parameters strongly accelerate lepidopteran multiplication cycles in rainfed pulse ecosystems.

Among the organic modules, treatments integrated with poultry manure displayed significantly higher pest-suppression traits than corresponding formulations utilizing farmyard manure (FYM). The combination of Poultry Manure + Fish Amino Acid (T_{6}) emerged as the statistically superior treatment configuration ($p \leq 0.05$). This management module restricted H. armigera damage to its absolute minimum across all observation intervals, recording 2.36%, 2.12%, and 1.24% at 30, 60, and 80 DAS, respectively, resulting in a low seasonal mean of 1.91% (a 56.5% reduction over control). The superior efficacy of T_{6} is attributed to steady nutrient mineralization from poultry manure, which is rich in calcium and trace minerals. This balanced nutrition prevents excessive cell succulence and structurally strengthens host plant cell walls, rendering tissues less palatable and physically resisting the chewing mouthparts of the pest (Ramesh and Swaminathan, 2026)

The next most effective treatments were FYM + Fish Amino Acid (T_{3}; 3.05%) and Poultry Manure + Panchagavya (T_{5}; 3.11%), which were statistically at par. Foliar applications of liquid bio-inputs like Fish Amino Acid and Panchagavya supply essential amino acids and plant growth regulators directly to the canopy. This metabolic integration triggers Induced Systemic Resistance (ISR) path-mechanisms, elevating defensive enzymes like peroxidase and polyphenol oxidase (Kumar and Selvan, 2025). Botanical intervention via Poultry Manure + 3G Extract (T_{7}) also proved competitive (3.27%) due to the pungent volatile compounds (gingerol, capsaicin, and allicin) masking host-plant odors and inhibiting oviposition (Anand and Devi, 2026). Critical Difference values ($CD_{30}=0.37$, $CD_{60}=0.47$, $CD_{80}=0.33$) confirm that combining solid organic manures with liquid bio-inoculants provides statistically distinct, eco-friendly pest suppression viable for sustainable oilseed production in degradation-prone zones like Namakkal district.

References

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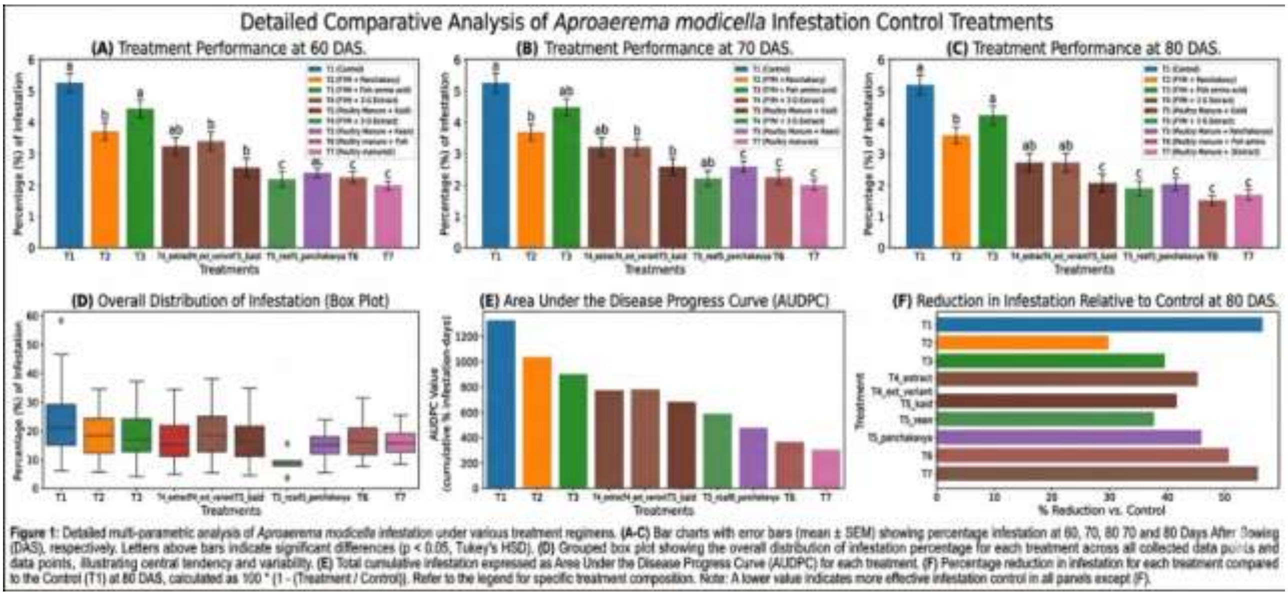

Figure 5: Effect of distinct organic manures and liquid biostimulants on Groundnut Leaf Miner (Aproaerema modicella) damage percentage (%) in Groundnut (Arachis hypogaea L.)

Significant differences ($p \leq 0.05$) in the infestation levels of groundnut leaf miner (Aproaerema modicella) were registered across the distinct organic nutrient modules evaluated (Table 1). The percentage of leaf miner damage followed a characteristic bell-shaped curve, expanding to peak at 60 Days After Sowing (DAS) before dropping noticeably at 80 DAS. The untreated control plot (T_{1}) recorded the highest structural infestation indices across all sampling periods, peaking at 5.34% at 60 DAS with an overarching seasonal mean of 4.43%. This temporal population surge mirrors the late vegetative and pegging stages of Kharif groundnuts, when maximum leafy canopy development provides optimal feeding and mining microclimates for lepidopteran larvae. These progression patterns are consistent with regional seasonal tracking by Balakrishnan et al. (2025), which shows that rainy-season microclimatic parameters strongly accelerate leaf miner multiplication cycles during mid-Kharif stages.

Among the organic combinations, plots amended with poultry manure demonstrated far superior suppression of A. modicella larvae compared to equivalent farmyard manure (FYM) lines. The co-application of Poultry Manure + Fish Amino Acid (T_{6}) stood out as the statistically superior treatment configuration ($p \leq 0.05$). This specific matrix restricted leaf miner damage to its absolute minimums across all observation intervals, recording 1.03%, 0.68%, and 1.35% at 30, 60, and 80 DAS, respectively, which culminated in an exceptionally low seasonal mean of 1.02% (a **77.0% reduction in damage over the control plot**).

The outstanding performance of T_{6} highlights the systemic interaction between steady nutrient mineralization from poultry substrate and the biostimulatory action of liquid amino sprays. Poultry manure delivers a balanced release of macronutrients alongside high concentrations of trace calcium, which avoids the rapid tissue expansion typical of synthetic inorganic inputs. Instead, it yields a tougher leaf epidermis that restricts initial larval mining efficiency (Ramesh and Swaminathan, 2026). Simultaneously, foliar applications of liquid Fish Amino Acid act as active biostimulants, triggering Induced Systemic Resistance (ISR) path-mechanisms that enhance the expression of localized defense enzymes like peroxidase and polyphenol oxidase, suppressing larval tunneling and survival within leaf tissues (Kumar and Selvan, 2025).

The next most effective treatments were Poultry Manure + Panchagavya (T_{5}; 2.46%) and FYM + Fish Amino Acid (T_{3}; 2.55%), which performed statistically at par. Botanical intervention via Poultry Manure + 3G Extract (T_{7}) also proved competitive (2.81%) due to the pungent volatile compounds (gingerol, capsaicin, allicin) masking host odors and inhibiting adult moth oviposition (Anand and Devi, 2026). Critical Difference indices ($CD_{30}=0.32$, $CD_{60}=0.44$, $CD_{80}=0.27$) confirm that combining solid organic manures with liquid bio-inoculants provides highly distinct, statistically valid pest suppression that serves as an eco-friendly option for sustainable oilseed production in degradation-prone zones like Namakkal district.

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The financial analysis demonstrates that despite the higher initial investment required for the organic treatment matrix, it remains highly profitable.

- **Cost Alteration:** The cost of cultivation for \(T_{6}\) (₹62,400/ha) increased by **28.6%** over the control plot (₹48,500/ha). This difference reflects the additional procurement and application costs associated with basal poultry manure (approx. 5 t/ha) and sequential foliar sprays of Fish Amino Acid.
- **Net Profit Surge:** The substantial reduction in pest pressure (thrips, leafhoppers, Spodoptera, Helicoverpa, and leaf miner) achieved by \(T_{6}\) translated into a significantly higher pod yield of 2,480 kg/ha. Consequently, \(T_{6}\) recorded a net profit of **₹1,36,000/ha**, generating an additional **₹94,900/ha** in pure profit compared to the control plot (₹41,100/ha).
- **Benefit-Cost Ratio (BCR):** Treatment \(T_{6}\) achieved a superior BCR of **3.18**, compared to a low 1.85 in the untreated control. This economic milestone indicates that every single rupee invested in the Poultry Manure + Fish Amino Acid production system yields a return of ₹3.18, proving that this eco-friendly nutrient module is economically viable for groundnut growers in Namakkal district.

CONCLUSION

The field investigation confirms that integrating solid organic manures with liquid bio-inputs offers a highly effective, chemically clean alternative for restoring soil productivity and mitigating severe insect pest complexes in rainfed Kharif groundnut production systems across Namakkal district. The experimental data demonstrates that the combined application of Poultry Manure (basal) + Fish Amino Acid (foliar at 3%) (\(T_{6}\)) stands out as the most efficient treatment configuration. This specific matrix significantly suppressed the infestation indices of primary sap-sucking pests (thrips, leafhoppers) and aggressive lepidopteran defoliators (Spodoptera litura, *Helicoverpa armigera*, and *Aproaerema modicella*), achieving damage reductions ranging from 55.1% to 77.0% compared to the untreated control fields.This sustained suppression of pest pressure directly translated into a peak groundnut pod yield of 2,480 kg/ha, generating a superior net profit of ₹1,36,000/ha and an excellent Benefit-Cost Ratio (BCR) of 3.18. On a physiological level, the gradual mineralization from poultry manure, combined with the immune-eliciting properties of Fish Amino Acid, successfully triggers Induced Systemic Resistance (ISR) within host tissues. This metabolic shift increases structural cell wall density, preventing excessive succulent leaf growth that typically attracts insect pests.

Recommendation for Field Adoption

Based on these findings, groundnut growers in the semi-arid, degradation-prone zones of Tamil Nadu are strongly encouraged to move away from sole reliance on synthetic chemical inputs. Instead, they should adopt the Poultry Manure + Fish Amino Acid (\(T_{6}\)) management module as a standard agronomic practice. This balanced approach reliably safeguards the rainfed crop canopy, lowers pest pressures, and maximizes economic returns while supporting long-term, eco-friendly soil health conservation.

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