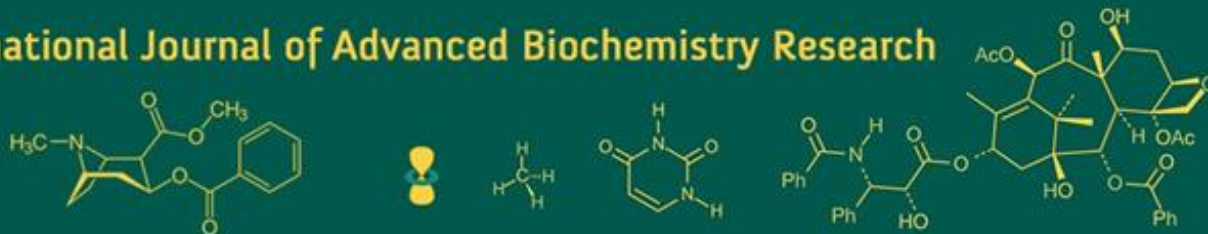


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Seasonal incidence of major insect pests and their association with weather parameters in watermelon (*Citrullus lanatus* L.)

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Abstract

Watermelon (*Citrullus lanatus* L.) is an economically important cucurbit crop whose productivity is severely constrained by a complex of sucking and chewing insect pests. Excessive dependence on synthetic insecticides has resulted in insecticide resistance, environmental contamination, destruction of beneficial arthropods and increased production costs, necessitating the development of sustainable pest management strategies. The present study aimed to develop and validate an integrated pest management (IPM) module for effective management of major insect pests in watermelon under field conditions in Tamil Nadu, India. The experiment was conducted using a randomized block design comprising different IPM modules integrating ecological engineering, neem oil, *Beauveria bassiana* and neem-based application of selective insecticides. The cluster bean-based IPM module comprising cluster bean (2:1) intercropping, neem oil (3%), *Beauveria bassiana* (1×10^{10} cfu g⁻¹ @ 8 g L⁻¹) and chlorantraniliprole 18.5 SC @ 0.6 ml L⁻¹ significantly reduced the populations of major insect pests, including aphids, thrips, whiteflies, leafhoppers, mites, leaf miners, leaf-eating caterpillars and melon fruit flies, compared with the conventional farmer's practice. The IPM module also conserved higher populations of natural enemies and pollinators, resulting in improved ecological stability. Although the cowpea-based module recorded the highest fruit yield (27.50 t ha⁻¹), the cluster bean-based module produced the highest Incremental Cost-Benefit Ratio (1:4.83), indicating superior economic viability. The validated IPM strategy effectively reduced pesticide dependence while enhancing pest suppression, crop productivity, biodiversity conservation and farm profitability. Therefore, the developed IPM module can be recommended as an environmentally sustainable and economically feasible approach for watermelon cultivation under tropical agro-ecosystems.

Keywords: *Citrullus lanatus*, Integrated pest management, Ecological engineering, *Beauveria bassiana*, Neem oil, Chlorantraniliprole, Natural enemies, Watermelon insect pests, Sustainable agriculture, Economic analysis

1. Introduction

Watermelon (*Citrullus lanatus* Thunb. Matsum. & Nakai), a member of the family Cucurbitaceae, is one of the most economically important fruit crops cultivated throughout tropical and subtropical regions of the world. Owing to its refreshing taste, high nutritional value and wide consumer acceptance, watermelon has become an indispensable component of horticultural production systems. The fruit contains more than 90% water and serves as an excellent source of vitamins A and C, potassium, magnesium, dietary fibre, citrulline, lycopene, carotenoids and several antioxidant compounds that contribute to human health by reducing oxidative stress and lowering the risk of cardiovascular diseases and certain cancers (Kyriacou *et al.*, 2021; Tlili *et al.*, 2022)^[17, 33]. The increasing awareness of healthy dietary habits, coupled with rising demand for fresh fruits, has significantly enhanced watermelon production worldwide. According to the Food and Agriculture Organization, global watermelon production has continued to increase over the last decade due to improved hybrids, modern cultivation technologies and expansion of irrigated agriculture (FAOSTAT, 2024)^[9]. Watermelon is susceptible to attack by numerous insect pests throughout its growth period, beginning from seedling emergence until fruit harvest. The succulent nature of vines, foliage, flowers and fruits provides favourable feeding and breeding conditions for several phytophagous insects. Both sucking and chewing pests inflict considerable damage either directly through feeding or indirectly by transmitting economically important viral pathogens. These infestations reduce plant vigour, interfere with normal physiological processes, impair flowering and fruit development and ultimately decrease marketable yield and fruit quality (Bharathi *et al.*, 2022).

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Yield losses attributable to insect pests vary depending on pest species, crop growth stage, climatic conditions, varietal susceptibility and management practices, but severe infestations may result in economic losses exceeding 40–70% under favourable environmental conditions (Patel *et al.*, 2023) ^[24].

Among the major sucking pests, the cotton aphid, *Aphis gossypii* Glover, is one of the most destructive species associated with watermelon cultivation. Aphids colonize tender shoots and young leaves, extracting plant sap and causing curling, chlorosis, reduced photosynthetic efficiency and stunted plant growth. Their feeding also results in the excretion of honeydew, which promotes the growth of sooty mould fungi and further interferes with photosynthesis. More importantly, *A. gossypii* functions as an efficient vector of several economically important viruses, including Cucumber mosaic virus, Watermelon mosaic virus, Papaya ringspot virus-W and Zucchini yellow mosaic virus, thereby substantially aggravating crop losses (Nyoike *et al.*, 2021; Zhao *et al.*, 2022) ^[22, 34]. Similarly, the melon thrips, *Thrips palmi* Karny, has emerged as a serious pest in cucurbit ecosystems because of its rapid reproductive potential, concealed feeding habit and ability to transmit orthotospoviruses. Feeding by thrips causes silencing, leaf distortion, flower abortion and reduced fruit set, significantly affecting both yield and fruit quality (Seal *et al.*, 2022) ^[29]. Whiteflies (*Bemisia tabaci* Gennadius) constitute another economically important pest complex in watermelon production. Both nymphs and adults feed on phloem sap, weakening plants and reducing photosynthetic activity. Furthermore, *B. tabaci* transmits numerous begomoviruses that induce severe viral diseases capable of causing devastating yield reductions. The polyphagous nature, insecticide resistance and remarkable adaptability of *B. tabaci* have transformed it into one of the most difficult pests to manage in cucurbit production systems (Navas-Castillo *et al.*, 2023) ^[20]. Other sucking pests such as leafhoppers (*Amrasca* spp.) and spider mites (*Tetranychus urticae* Koch) also contribute substantially to productivity losses by causing continuous sap depletion, chlorotic stippling, leaf bronzing, premature senescence and reduced photosynthetic efficiency, particularly under warm and dry environmental conditions (Xu *et al.*, 2021).

The economic consequences of these pest infestations extend beyond direct yield reduction. Damage to foliage, flowers and fruits lowers fruit size, sweetness, external appearance and overall market quality, thereby reducing consumer acceptance and market prices. Farmers often respond by increasing the frequency of insecticide applications, substantially increasing production costs and reducing profit margins. Excessive reliance on synthetic pesticides has also contributed to the development of insecticide resistance, pest resurgence, secondary pest outbreaks, elimination of natural enemies, environmental contamination and pesticide residues in harvested fruits, raising concerns regarding food safety and ecosystem sustainability (Sparks *et al.*, 2023; Bass *et al.*, 2024) ^[32, 1]. Effective management of insect pests depends largely on understanding their seasonal occurrence and population dynamics under prevailing agroclimatic conditions. Seasonal incidence studies provide valuable information regarding the time of pest appearance, peak population periods, duration of infestation and the influence of crop phenology on pest abundance. Such information forms the scientific basis for developing integrated pest management (IPM) programmes by enabling farmers to synchronize monitoring, cultural operations, biological control and need-based insecticide applications with periods of maximum pest vulnerability.

Instead of following calendar-based pesticide schedules, which often result in unnecessary applications, seasonal surveillance facilitates timely interventions based on actual pest incidence, thereby reducing production costs, minimizing pesticide residues and conserving beneficial arthropods (Pedigo & Rice, 2021; Furlong *et al.*, 2022) ^[25, 11]. Consequently, regular pest monitoring has become an indispensable component of sustainable crop protection strategies adopted worldwide.

Several studies have demonstrated significant associations between weather parameters and insect pest incidence in cucurbit crops. Positive correlations between maximum temperature and populations of thrips, mites and pumpkin beetles have been reported under tropical production systems, whereas aphid abundance has frequently shown significant relationships with moderate temperatures and relative humidity (Sharma *et al.*, 2022) ^[30]. Similarly, whitefly populations have been found to increase under warm, dry weather conditions characterized by low rainfall and extended sunshine hours, while prolonged precipitation often suppresses their multiplication (Kumar *et al.*, 2023) ^[16]. Seasonal fluctuations of *Spodoptera litura*, *Liriomyza* spp. and other chewing insects have also been associated with changes in temperature and humidity across different cropping seasons (Biondi *et al.*, 2021) ^[3]. Although these investigations have contributed significantly to understanding insect ecology, the strength and direction of weather–pest relationships vary considerably among geographical regions because of differences in climate, cropping practices, host cultivars, irrigation methods and local biodiversity. Consequently, region-specific studies are indispensable for generating reliable pest forecasting information suitable for local production systems. Tamil Nadu is one of the important horticultural states of India where watermelon cultivation has expanded rapidly due to increasing consumer demand and favourable environmental conditions. The crop is cultivated under diverse agro-ecological situations ranging from irrigated plains to riverbeds and semi-arid regions, exposing it to a wide spectrum of insect pests throughout the growing season. Farmers frequently rely on repeated applications of broad-spectrum insecticides to protect the crop from pest damage, often without considering actual pest population levels or economic threshold limits. Such indiscriminate pesticide use has resulted in increased production costs, accelerated development of insecticide resistance, disruption of natural enemy populations, environmental pollution and concerns regarding pesticide residues in fruits intended for fresh consumption (Bass *et al.*, 2024) ^[1]. Furthermore, repeated pesticide exposure may adversely affect pollinators, particularly honey bees, which are essential for successful pollination and fruit set in watermelon. These challenges underscore the need for ecologically sound pest management approaches based on scientific knowledge of pest population dynamics and environmental influences.

The integration of meteorological information with pest surveillance has become increasingly important in the era of precision agriculture and climate-smart crop protection. Advances in digital agriculture, remote sensing, automated weather stations and predictive analytics now enable researchers to develop decision-support systems capable of forecasting pest outbreaks before they reach economically damaging levels (FAO, 2023) ^[18]. Such forecasting systems reduce unnecessary pesticide applications, lower production costs, improve environmental sustainability and enhance farmers' decision-making capacity. However, the success of these systems depends fundamentally on reliable baseline data concerning

pest population dynamics and their relationships with local weather conditions. Therefore, generating region-specific ecological information remains a priority for developing effective forecasting models applicable to watermelon production systems in southern India.

In view of the economic importance of watermelon, the increasing challenges posed by insect pests and the limited ecological information available under Tamil Nadu conditions, the present investigation was undertaken to study the seasonal incidence of major insect pests and their association with prevailing weather parameters. The specific objectives were to monitor the population dynamics of major sucking and defoliating insect pests throughout the cropping season, identify the periods of peak infestation, determine the influence of meteorological variables on pest abundance through correlation and regression analyses and generate scientific information that could facilitate the development of weather-based pest forecasting models and integrated pest management strategies. The findings of this investigation are expected to contribute to a better understanding of insect pest ecology in watermelon and provide practical recommendations for timely, economically viable and environmentally sustainable pest management in the watermelon-growing regions of Tamil Nadu.

2. Materials and Methods

2.1 Experimental Site

The field experiment was conducted during the kharif season of 2021 at a farmer's field located in Akkarampalayam village (11° 08' 44" N, 78° 06' 05" E), Namakkal district, Tamil Nadu, India. The study area falls under the tropical agro-climatic zone characterized by warm temperatures and moderate rainfall, making it suitable for watermelon cultivation. The experiment was conducted under open-field conditions to evaluate an integrated pest management (IPM) module against major insect pests of watermelon.

2.2 Experimental Crop and Crop Establishment

The popular watermelon hybrid 'Melody' F₁ was used for the investigation. Seeds were sown in pro trays and 13-day-old healthy seedlings were transplanted to the main field at a spacing of 2.5×0.5 m. The crop was maintained by adopting the recommended package of practices for watermelon cultivation prescribed by the Tamil Nadu Agricultural University (TNAU, 2020), except for plant protection measures, which were imposed according to the experimental treatments. Uniform agronomic practices including irrigation, fertilizer application, intercultural operations and weed management were followed throughout the cropping season.

2.3 Experimental Design

The experiment was laid out in a Randomized Block Design (RBD) comprising six treatments with adequate replications. The experimental design and analysis followed the standard procedures described by Gomez and Gomez (1984). The treatments were formulated by integrating the best-performing eco-friendly crops, botanical pesticides, entomopathogenic fungi and selective insecticide molecules identified from earlier experiments.

2.4 Integrated Pest Management (IPM) Components

2.4.1 Ecological Engineering

Ecological engineering was achieved by growing cluster bean (*Cyamopsis tetragonoloba*) or cowpea (*Vigna unguiculata*) as intercrops in a 2:1 ratio with watermelon. These flowering

intercrops served as nectar and pollen sources for predators, parasitoids and pollinators, thereby improving biological control and enhancing ecosystem services. The ecological engineering approach was adopted according to the habitat management principles recommended by the National Institute of Plant Health Management (NIPHM, 2015).

2.4.2 Botanical Pesticide

Neem oil (3%) was applied as the first component of the IPM module immediately after pest populations approached the economic threshold level. The botanical spray was intended to suppress the initial build-up of sucking pests while minimizing adverse effects on natural enemies and pollinators.

2.4.3 Biological Control

The entomopathogenic fungus *Beauveria bassiana* (1×10⁸ cfu g⁻¹) was applied as a foliar spray at 8 g L⁻¹ following the botanical treatment. The fungal formulation was used to suppress major sucking and foliage-feeding insect pests as part of the biological control component of the IPM module.

2.4.4 Need-based Insecticide Application

Need-based application of selective insecticides was carried out only when pest populations exceeded the economic threshold level. The insecticides evaluated were Chlorantraniliprole 18.5 SC @ 0.6 ml L⁻¹ and Flubendiamide 39.35 SC @ 0.6 ml L⁻¹. Three rounds of foliar sprays were imposed at 15-day intervals. A treated check comprising Thiamethoxam 25 WG @ 0.4 g L⁻¹ and an untreated control receiving water spray alone were maintained for comparison.

2.4.5 Field Sanitation

Regular field sanitation was maintained throughout the cropping period by removing weeds, alternate host plants, infested leaves, damaged vines and crop residues. Balanced fertilizer application and proper irrigation scheduling were followed to maintain healthy crop growth and reduce pest incidence.

2.5 Pest Monitoring and Data Collection

Ten plants were selected randomly from each replication and tagged for recording observations throughout the crop growth period. Pest observations were recorded before treatment application and subsequently at 1, 3, 7 and 14 days after each spray. Weekly observations were continued until harvest. Standard sampling methods described by Naik *et al.* (2019) and Udhayakumar (2020) were followed for recording insect populations.

2.5.1 Pest Population

The population of aphids (*Aphis gossypii*), thrips (*Thrips palmi*), whiteflies (*Bemisia tabaci*), leafhoppers and red spider mites (*Tetranychus urticae*) was recorded from the top three leaves (one unopened terminal leaf and two fully expanded leaves) of each observation plant. The incidence of leaf miners, red pumpkin beetles (*Aulacophora foveicollis*), leaf-eating caterpillars (*Spodoptera litura*) and fruit flies was assessed on a whole-plant basis at weekly intervals using standard field sampling procedures.

2.5.2 Natural Enemies and Pollinators

The abundance of natural enemies including coccinellid beetles, green lacewings (*Chrysoperla* spp.), spiders, predatory bugs and parasitoids was recorded simultaneously from the tagged

plants. Pollinator activity, particularly honey bees and other flower-visiting insects, was also recorded during the flowering period to assess the ecological compatibility of the IPM module.

2.5.3 Fruit Yield

Marketable fruits from each treatment were harvested at physiological maturity, weighed individually and converted into tonnes per hectare (tha^{-1}) for comparison among treatments.

2.5.4 Residue Analysis

Fruit samples collected from the most effective treatments were stored at -20°C until analysis. Pesticide residues were determined using the QuEChERS extraction method followed by High-Performance Liquid Chromatography (HPLC) according to the procedure described by Anastassiades *et al.* (2003).

2.6 Economic Analysis

Gross return, net return and the Incremental Cost–Benefit Ratio (ICBR) were calculated using the prevailing market price of watermelon fruits. The ICBR was determined following the procedure described by Akila and Sundara Babu (1994) by considering the total cost of cultivation and plant protection expenses.

2.7 Statistical Analysis

The experimental data on pest incidence, natural enemy abundance, fruit yield and economic returns were subjected to analysis of variance (ANOVA) appropriate for a Randomized Block Design following Gomez and Gomez (1984). Count data were transformed using $\sqrt{X+0.5}$ before analysis to stabilize variance. Treatment means were separated using Tukey's Honest Significant Difference (HSD) test at $P \leq 0.05$ (Tukey, 1949)^[35]. Statistical analyses were performed using IBM SPSS Statistics version 22.

3. Results

3.1 Effect of Integrated Pest Management Module on Major Insect Pest Suppression

The integrated pest management (IPM) modules significantly influenced the suppression of major insect pests infesting watermelon under field conditions. Among the evaluated treatments, the cluster bean-based IPM module [T_1 : Cluster bean (2:1) + Neem oil (3%) + *Beauveria bassiana* (1×10^8 cfu g^{-1} @ 8g L^{-1}) + Chlorantraniliprole 18.5 SC @ 0.6 ml L^{-1}] – consistently recorded the highest suppression of all major sucking and chewing insect pests throughout the cropping season. The aphid (*Aphis gossypii*) population was reduced by 65.61% in T_1 , followed by T_3 (60.57%), T_2 (54.97%), T_4 (47.42%), while the farmer's practice (T_5) recorded the lowest suppression (39.78%). Likewise, the highest reduction in thrips (*Thrips palmi*) population was recorded in T_1 (84.00%), followed by T_3 (80.85%), T_2 (76.95%), T_4 (70.22%) and T_5 (68.00%). A similar trend was observed for whitefly (*Bemisia tabaci*), wherein T_1 recorded the highest suppression (78.38%), followed by T_3 (73.96%), T_2 (70.22%), T_4 (64.72%), whereas the lowest suppression was recorded under farmer's practice (56.92%). Leafhopper (*Amrasca biguttula*) incidence was reduced by 73.90% in T_1 , followed by 69.71% in T_3 , 64.24% in T_2 , 59.51% in T_4 and 57.35% in T_5 .

The IPM modules were equally effective against chewing pests. The maximum reduction in red spider mite (*Tetranychus urticae*) was observed in T_1 (71.29%), followed by T_2 (66.02%), T_3 (60.67%), T_4 (57.35%) and T_5 (55.64%). Leaf miner infestation was reduced by 73.80% in T_1 , followed by 68.00% in T_3 and 62.71% in T_2 . Likewise, the highest reduction in leaf-eating caterpillar (*Diaphania indica*) was recorded in T_1 (76.14%), followed by T_3 (70.04%), T_2 (67.18%), T_4 (63.61%) and T_5 (61.97%). Melon fruit fly (*Bactrocera cucurbitae*) infestation was also effectively suppressed, with the highest reduction recorded in T_1 (80.04%), followed by T_3 (79.82%), T_2 (79.02%), T_4 (72.72%), while the lowest reduction was observed in T_5 (68.01%). Overall, the cluster bean-based IPM module demonstrated superior efficacy by maintaining pest populations below the economic threshold level throughout the crop growth period.

Table 1: Effect of integrated pest management modules on suppression of major insect pests of watermelon

Treatment	Aphids(%)	Thrips(%)	Whiteflies(%)	Leafhoppers(%)	Mites(%)	Leafminers(%)	Caterpillars(%)	Fruitflies(%)
T_1	65.61	84.00	78.38	73.90	71.29	73.80	76.14	80.04
T_2	54.97	76.95	70.22	64.24	66.02	62.71	67.18	79.02
T_3	60.57	80.85	73.96	69.71	60.67	68.00	70.04	79.82
T_4	47.42	70.22	64.72	59.51	57.35	-	63.61	72.72
T_5 (Farmer's practice)	39.78	68.00	56.92	57.35	55.64	-	61.97	68.01

3.2 Reduction in Pest Population over Farmer's Practice

The integrated pest management modules outperformed the conventional farmer's practice in suppressing insect pest populations. Compared with T_5 , the cluster bean-based IPM module (T_1) achieved substantially greater reductions across all major pest groups. Aphid suppression under T_1 was 25.83 percentage points higher than the farmer's practice, while reductions of 16.00, 21.46, 16.55, 15.65, 18.10, 14.17 and 12.03 percentage points were recorded for thrips, whiteflies, leafhoppers, red spider mites, leaf miners, leaf-eating caterpillars and fruit flies, respectively. The cowpea-based IPM module (T_3) also showed superior performance over farmer's practice, indicating that ecological engineering coupled with botanicals, entomopathogenic fungi and selective insecticides

provides more sustainable and effective pest management than repeated insecticide application alone.

The enhanced suppression observed under the IPM modules may be attributed to the complementary action of flowering intercrops, which reduced pest colonization while simultaneously promoting biological control through increased abundance of natural enemies. Neem oil effectively suppressed early pest establishment, whereas *Beauveria bassiana* provided biological regulation of insect populations. The selective application of chlorantraniliprole only after the pest population exceeded the economic threshold level ensured effective control of remaining infestations while minimizing disruption to beneficial arthropods. In contrast, reliance solely on insecticide application in the farmer's practice resulted in comparatively

lower pest suppression and greater fluctuations in pest populations during the cropping season.

Table 2: Improvement in pest suppression over farmer's practice

Pest	T ₁ over T _s (%)	T ₃ over T _s (%)
Aphids	25.83	20.79
Thrips	16.00	12.85
Whiteflies	21.46	17.04
Leafhoppers	16.55	12.36
Red spider mites	15.65	5.03
Leaf miners	18.10	-
Leaf-eating caterpillars	14.17	8.07
Melon fruit flies	12.03	11.81

3.3 Conservation of Natural Enemies and Pollinators

The integrated pest management modules significantly enhanced the conservation of beneficial arthropods compared with the insecticide-based farmer's practice. Among the treated plots, T₁ supported the highest abundance of coccinellid beetles (2.12 adults plant⁻¹), followed by T₃ (2.04), T₄ (1.96), T₂ (1.89) and T₅ (1.51 adults plant⁻¹). Syrphid fly populations exhibited a similar trend, with 2.11 adults plant⁻¹ in T₁, followed by 2.01 in T₃, 1.94 in T₄, 1.82 in T₂ and only 1.15 adults plant⁻¹ in

the farmer's practice. Green lacewings and predatory spiders were also more abundant in the IPM treatments than in the conventional insecticide treatment, indicating that ecological engineering and biological control measures effectively conserved beneficial insects.

The abundance of pollinators was significantly influenced by the IPM modules. The highest number of *Apis dorsata* (3.11 bees plant⁻¹) was recorded in T₁, followed by T₄ (2.39), T₃ (1.82), T₂ (1.79) and T₅ (1.41 bees plant⁻¹). Likewise, *Apis florea* populations were highest in T₁ (3.23 bees plant⁻¹) followed by T₄ (3.07), T₃ (2.24), T₂ (1.93) and T₅ (1.39). Similar observations were recorded for *Apis cerana indica*, where 3.40 bees plant⁻¹ were observed in T₁ compared with only 1.44 bees plant⁻¹ under the farmer's practice. Although the untreated control maintained the highest overall beneficial insect population because no pesticides were applied, among the protected treatments, the cluster bean-based IPM module provided the greatest conservation of natural enemies and pollinators while simultaneously maintaining effective pest suppression. These findings demonstrate the ecological compatibility of the developed IPM strategy.

Table 3: Effect of integrated pest management modules on natural enemies and pollinators

Treatment	Coccinellids (No. plant ⁻¹)	Syrphids (No. plant ⁻¹)	Lacewings (No. plant ⁻¹)	Spiders (No. plant ⁻¹)	Apis dorsata	Apis florea	Apis cerana indica
T ₁	2.12	2.11	3.47	2.65	3.11	3.23	3.40
T ₂	1.89	1.82	2.94	2.16	1.79	1.93	1.87
T ₃	2.04	2.01	3.16	2.41	1.82	2.24	1.98
T ₄	1.96	1.94	3.01	2.32	2.39	3.07	2.98
T ₅ (Farmer's practice)	1.51	1.15	2.08	1.09	1.41	1.39	1.44
Untreated control	3.53	3.48	3.47	3.87	4.96	5.21	5.77

3.4 Effect of Integrated Pest Management Modules on Fruit Yield

The integrated pest management (IPM) modules significantly influenced marketable fruit yield of watermelon (Table 4). Among the different treatments, the cowpea-based IPM module [T₃: Cowpea (2:1) + Neem oil (3%) + *Beauveria bassiana* + Chlorantraniliprole 18.5 SC @ 0.6 ml L⁻¹] recorded the highest fruit yield of 27.50tha⁻¹, which was closely followed by the cluster bean-based IPM module (T₁) with 26.50tha⁻¹. The cluster bean module integrated with flubendiamide (T₂) produced 25.50tha⁻¹, whereas the cowpea module integrated with flubendiamide (T₄) recorded 23.30tha⁻¹. The conventional farmer's practice (T₅) resulted in the lowest marketable fruit yield of 20.30tha⁻¹ among all protected treatments.

The higher fruit yield observed in T₃ and T₁ could be attributed to effective suppression of sucking and chewing insect pests during the critical vegetative, flowering and fruit development stages, resulting in improved photosynthetic activity, better fruit set and reduced fruit damage. Moreover, ecological engineering through flowering intercrops promoted the abundance of pollinators and natural enemies, which contributed to enhanced pollination efficiency and sustainable pest regulation. In contrast, repeated reliance on insecticides under the farmer's practice adversely affected beneficial arthropods and provided comparatively lower seasonlong pest suppression, ultimately resulting in reduced fruit yield. The untreated control recorded the lowest yield owing to severe pest infestation and extensive crop damage throughout the growing period.

Table 4: Effect of integrated pest management modules on marketable fruit yield of watermelon

Treatment	Description	Fruit yield (t ha ⁻¹)
T ₃	Cowpea + Neem oil + B. bassiana + Chlorantraniliprole	27.50
T ₁	Cluster bean + Neem oil + B. bassiana + Chlorantraniliprole	26.50
T ₂	Cluster bean + Neem oil + B. bassiana + Flubendiamide	25.50
T ₄	Cowpea + Neem oil + B. bassiana + Flubendiamide	23.30
T ₅	Farmer's practice (Thiamethoxam)	20.30
Control	Untreated	Lowest

3.5 Economic Analysis

The economic analysis clearly demonstrated the superiority of the integrated pest management modules over the conventional farmer's practice (Table 5). Among the evaluated treatments, the cluster bean-based IPM module (T₁) recorded the highest Incremental Cost-Benefit Ratio (ICBR) of 1:4.83, indicating the greatest economic return per unit investment. This was closely followed by the cowpea-based IPM module (T₃) with an ICBR of 1:4.71, whereas T₂ and T₄ recorded ICBRs of 1:4.39 and 1:4.14, respectively. The lowest economic return among the treated plots was obtained under the farmer's practice (T₅), which recorded an ICBR of 1:3.57.

Although the establishment of flowering intercrops and application of biological control agents slightly increased the initial cultivation cost, the investment was compensated by

substantial reductions in pest incidence, lower crop losses, higher marketable yield and reduced dependence on repeated insecticide applications. The combination of ecological engineering, botanical pesticides, entomopathogenic fungi and need-based insecticides proved to be economically viable by improving productivity while minimizing unnecessary pesticide expenditure. Consequently, the integrated modules generated greater net returns than the insecticide-based conventional practice, confirming their suitability for commercial watermelon production.

Table 5: Economic performance of integrated pest management modules

Treatment	Fruit yield (t ha ⁻¹)	ICBR
T ₁	26.50	1:4.83
T ₃	27.50	1:4.71
T ₂	25.50	1:4.39
T ₄	23.30	1:4.14
T ₅	20.30	1:3.57

3.6 Validation of the Integrated Pest Management Module

The field validation experiment confirmed the effectiveness of the developed integrated pest management module under farmers' field conditions. Among all treatments, the cluster bean-based IPM module (T₁) emerged as the most balanced and sustainable pest management strategy. The module reduced aphid, thrips, whitefly, leafhopper, mite, leaf miner, leaf-eating caterpillar and melon fruit fly populations by 65.61–84.00%, while simultaneously conserving higher populations of coccinellids, lacewings, syrphid flies, spiders and bee pollinators compared with the farmer's practice. Furthermore, the module produced a marketable fruit yield of 26.50 t ha⁻¹ and generated the highest Incremental Cost–Benefit Ratio (1:4.83) among all evaluated treatments.

Although the cowpea-based IPM module (T₃) produced the highest fruit yield (27.50 t ha⁻¹) its economic return (ICBR 1:4.71) was marginally lower than that of T₁. Therefore, considering pest suppression efficiency, conservation of beneficial arthropods, economic profitability, environmental safety and ease of adoption by farmers, T₁ was identified as the most suitable integrated pest management module for sustainable watermelon cultivation. The validation study further demonstrated that integration of ecological engineering, neem oil, *Beauveria bassiana* and need-based application of chlorantraniliprole effectively maintained pest populations below the economic threshold level, reduced reliance on synthetic insecticides, improved biodiversity and enhanced crop productivity. Hence, the validated IPM module can be recommended for large-scale adoption in watermelon-growing regions of Tamil Nadu and similar agro-ecological conditions.

4. Discussion

The present investigation clearly demonstrated that integrating ecological engineering, botanical pesticides, entomopathogenic fungi and selective insecticides provided significantly better suppression of major insect pests than the conventional insecticide-based management practice. The superior performance of the cluster bean- and cowpea-based IPM modules highlights the importance of combining multiple compatible pest management tactics that act through different ecological and biological mechanisms. Rather than relying solely on chemical insecticides, the integration of flowering intercrops, neem oil, *Beauveria bassiana* and need-based application of chlorantraniliprole effectively disrupted pest

colonization, reduced population build-up, enhanced natural biological control and maintained pest populations below the economic threshold level throughout the crop season. Neem oil served as an effective botanical component of the IPM module by suppressing early infestations of sucking pests without adversely affecting beneficial arthropods. The bioactive compound azadirachtin interferes with insect feeding, moulting, oviposition and reproduction, thereby reducing pest populations through multiple physiological pathways. Unlike broad-spectrum synthetic insecticides, neem-based products exhibit comparatively lower toxicity toward predators, parasitoids and pollinators, making them highly compatible with biological control programmes. The successful integration of neem oil with ecological engineering observed in the present study corroborates the findings of Isman (2020) [14] and Benelli *et al.* (2023) [2], who reported that botanical pesticides represent valuable components of sustainable integrated pest management because of their selective toxicity, biodegradability and reduced environmental persistence.

The entomopathogenic fungus *Beauveria bassiana* further enhanced the effectiveness of the IPM module by providing biological suppression of both sucking and foliage-feeding insect pests. Once the fungal spores contacted susceptible insects, they germinated on the insect cuticle, penetrated the integument, proliferated within the haemocoel and eventually caused insect mortality. Besides direct pathogenicity, fungal infection reduces feeding activity and reproductive capacity before insect death, thereby contributing to long-term population suppression. The compatibility of *B. bassiana* with neem oil and ecological engineering allowed the conservation of beneficial insects while reducing dependence on repeated chemical insecticide applications. Similar synergistic interactions between entomopathogenic fungi and botanical pesticides have been reported by Mascarín and Jaronski (2022) [18] and Ruiu (2023) [28], who concluded that microbial biopesticides provide environmentally safe alternatives for managing insect pests within integrated pest management programmes.

The final component of the IPM module involved the need-based application of chlorantraniliprole only after pest populations exceeded the economic threshold level. Unlike calendar-based insecticide applications commonly adopted by farmers, threshold-based intervention minimized unnecessary pesticide use while maintaining effective pest suppression. Chlorantraniliprole, belonging to the anthranilic diamide group, possesses a unique mode of action by activating insect ryanodine receptors, leading to muscle paralysis and rapid cessation of feeding. Its high selectivity toward target pests and relatively lower toxicity to beneficial arthropods make it particularly suitable for integration into IPM programmes. The superior performance of chlorantraniliprole-based modules observed in the present study agrees with reports by Sparks *et al.* (2023) [32] and Cordova *et al.* (2021) [5], who demonstrated that selective insecticides can effectively complement biological control and ecological engineering while minimizing disruption of natural enemy populations.

An important outcome of the present investigation was the conservation of pollinator diversity under the integrated modules. Watermelon is highly dependent on insect-mediated cross-pollination for optimum fruit set, fruit size and seed development. The higher abundance of *Apis dorsata*, *Apis cerana indica* and *Apis florea* recorded in the IPM plots indicates that the integrated approach created a pollinator-friendly environment by reducing exposure to broad-spectrum

insecticides and increasing the availability of floral resources. Similar improvements in pollinator abundance following habitat diversification have been documented by Blaauw and Isaacs (2021) ^[4] and Nicholson *et al.* (2022) ^[21], who demonstrated that flowering strips surrounding crop fields substantially improve pollination services while simultaneously supporting natural enemy communities.

One of the major strengths of the developed integrated pest management module is its contribution to sustainable watermelon production. Conventional watermelon cultivation in many parts of India largely depends on repeated applications of broad-spectrum insecticides, often applied prophylactically without monitoring pest populations or considering economic threshold levels. Such indiscriminate pesticide use has resulted in insecticide resistance, resurgence of secondary pests, contamination of soil and water resources, pesticide residues in fruits and adverse impacts on biodiversity and human health. In contrast, the present investigation demonstrated that integrating ecological engineering, biological control, botanicals and selective insecticides substantially reduced reliance on chemical pesticides while maintaining effective pest suppression.

The sequential application strategy adopted in the present study ensured that chemical insecticides were used only when absolutely necessary. Early-season pest suppression was primarily achieved through habitat manipulation, neem oil and *Beauveria bassiana*, thereby avoiding multiple insecticide sprays during the initial stages of crop growth. Consequently, the total pesticide load imposed on the cropping system was considerably lower than that under the conventional farmer's practice. Similar reductions in insecticide usage have been reported by Pretty and Bharucha (2021) ^[26], Desneux *et al.* (2022) ^[6] and FAO (2023), who emphasized that integrated pest management can reduce pesticide use by 30–70% without compromising crop productivity.

The success of any integrated pest management (IPM) programme depends not only on its biological effectiveness but also on its technical feasibility, economic viability and ease of adoption by farmers. The present investigation demonstrated that the developed IPM modules satisfy all these requirements by integrating readily available cultural, biological, botanical and chemical control measures into a practical management strategy. The cluster bean-based IPM module effectively reduced the populations of major sucking and chewing insect pests, conserved beneficial arthropods, increased marketable fruit yield and generated the highest economic return. These advantages make the validated IPM module highly suitable for adoption by watermelon growers under Tamil Nadu conditions. Economic profitability remains the primary factor influencing farmers' decisions regarding pest management technologies. Although the integrated modules involved slightly higher initial investment for establishing flowering intercrops and biological control agents, the additional expenditure was compensated by lower crop losses, higher marketable fruit yield, improved fruit quality and reduced pesticide consumption. The highest Incremental Cost–Benefit Ratio (ICBR) recorded by the cluster bean-based IPM module clearly indicates that integrated pest management is economically more profitable than repeated insecticide applications. Similar economic advantages of integrated pest management have been reported in cucurbit crops by Pretty and Bharucha (2021) ^[26], FAO (2023) and Parolin *et al.* (2021) ^[23], who concluded that ecological approaches increase farm profitability by reducing pesticide expenditure while maintaining or improving crop productivity.

Another important factor supporting farmer adoption is the reduced risk of insecticide resistance. Repeated application of insecticides having similar modes of action has resulted in widespread resistance among aphids, whiteflies, thrips and other economically important vegetable pests. The integrated approach developed in the present study combines multiple control tactics with different mechanisms of action, thereby reducing selection pressure on pest populations and delaying the development of resistance. Furthermore, the use of threshold-based insecticide application minimizes unnecessary pesticide exposure, which is one of the principal drivers of resistance evolution (Bass *et al.*, 2024; Sparks *et al.*, 2023) ^[1, 32].

The conservation of pollinators and natural enemies observed in the present study further enhances the practical value of the validated IPM module. Flower-visiting bees are essential for optimum fruit set and fruit quality in watermelon, whereas predators and parasitoids provide continuous natural suppression of insect pests. Conservation of these beneficial organisms reduces future pest outbreaks and strengthens ecosystem resilience, thereby providing long-term benefits beyond a single cropping season. Such ecological services reduce production risks and improve system stability, making the IPM module particularly attractive for resource-poor farmers who cannot afford repeated pesticide applications.

The widespread adoption of the developed IPM strategy can be further strengthened through farmer training programmes, front-line demonstrations, farmer field schools and extension campaigns emphasizing pest monitoring and economic threshold-based decision making. Digital advisory services, mobile applications and weather-based pest forecasting systems can also facilitate timely implementation of IPM components. Collaboration among research institutions, extension agencies, input suppliers and farmer producer organizations will be essential for scaling up adoption across major watermelon-growing regions.

5. Conclusion

The present investigation demonstrated that integrating ecological engineering, botanical pesticides, microbial biocontrol agents and selective need-based insecticides provides a robust and sustainable strategy for watermelon pest management. The validated IPM module effectively suppressed major insect pests, conserved natural enemies and pollinators, reduced dependence on synthetic pesticides, increased fruit yield and generated superior economic returns compared with the conventional farmer's practice. The findings strongly support the adoption of ecological intensification approaches for sustainable watermelon production and contribute to national efforts aimed at promoting environmentally responsible crop protection, improving farmer profitability and ensuring safe, residue-minimized food production.

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