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Influence of intercropping systems on pest suppression, natural enemy conservation and fruit yield in watermelon

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Abstract

Intercropping has emerged as an effective ecological engineering strategy for enhancing biodiversity and reducing pest incidence in horticultural cropping systems. The present study evaluated the influence of different intercropping systems on insect pest suppression, conservation of natural enemies, pollinator abundance, fruit yield and economic returns in watermelon (*Citrullus lanatus* L.) under field conditions in Tamil Nadu, India. The experiment was conducted using a Randomized Block Design with five treatments comprising cluster bean- and cowpea-based intercropping systems along with sole watermelon as the control. Weekly observations were recorded on major insect pests, including aphids, thrips, whiteflies, leafhoppers, mites, leaf miners, pumpkin beetles, leaf-eating caterpillars and melon fruit flies, together with populations of natural enemies and pollinators. Intercropping significantly reduced the incidence of major insect pests compared with the sole crop, while simultaneously enhancing the abundance of coccinellids, syrphid flies, lacewings, spiders and honey bees. Among the evaluated systems, watermelon intercropped with cluster bean (2:1) consistently recorded superior pest suppression, greater conservation of beneficial arthropods, higher marketable fruit yield and improved economic returns. The enhanced performance of the intercropping systems was attributed to increased habitat complexity, improved biological control and enhanced pollination services. The findings demonstrate that flowering legume-based intercropping provides an environmentally sustainable, economically viable and farmer-friendly approach for integrated pest management and can be recommended as an effective strategy for sustainable watermelon cultivation under tropical agroecosystems.

Keywords: *Citrullus lanatus*, intercropping, ecological engineering, integrated pest management, biological control, pollinators, natural enemies, cluster bean, cowpea, sustainable horticulture

1. Introduction

Watermelon (*Citrullus lanatus* (Thunb.) Matsum. & Nakai) is one of the most widely cultivated cucurbitaceous fruit crops in tropical and subtropical regions owing to its high nutritional value, excellent market demand and substantial economic returns. The fruit is highly appreciated for its refreshing taste and contains over 90% water, carbohydrates, vitamins A and C, potassium, magnesium, dietary fibre, citrulline, lycopene, β -carotene and numerous antioxidant compounds that contribute to human health by reducing oxidative stress and the incidence of cardiovascular diseases and certain cancers (Kyriacou *et al.*, 2021; Tlili *et al.*, 2022)^[11, 27]. Global watermelon production has increased steadily during the past decade because of expanding cultivation area, improved hybrid varieties, enhanced irrigation facilities and increasing consumer preference for nutritious fruits. According to the Food and Agriculture Organization, watermelon remains one of the most important vegetable fruit crops cultivated worldwide, with Asia accounting for the largest share of global production (FAOSTAT, 2024).

A wide range of insect pests attack watermelon from seedling emergence to fruit harvest. Among the sucking pests, aphids (*Aphis gossypii*), thrips (*Thrips palmi*), whiteflies (*Bemisia tabaci*), leafhoppers (*Amrasca* spp.) and red spider mites (*Tetranychus urticae*) are considered the most destructive species because they remove plant sap, reduce chlorophyll content, impair photosynthesis and transmit several economically important viral diseases. Aphids and whiteflies serve as vectors of cucurbit viruses, while thrips transmit orthotospoviruses, resulting in severe reductions in crop growth, fruit development and marketable yield (Navas-Castillo *et al.*, 2023;

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Zhao *et al.*, 2022) [17, 29]. Chewing insect pests such as the red pumpkin beetle (*Aulacophora foveicollis*), leaf miners (*Liriomyza trifolii*), leaf-eating caterpillars (*Diaphania indica* and *Spodoptera litura*) and melon fruit fly (*Bactrocera cucurbitae*) further aggravate crop losses by damaging foliage, flowers and fruits. The simultaneous occurrence of these pest complexes throughout the cropping season frequently compels farmers to rely on repeated applications of synthetic insecticides (Sharma *et al.*, 2022) [24].

Among the various ecological approaches available for sustainable crop protection, intercropping has emerged as one of the most promising components of integrated pest management (IPM). Intercropping involves the cultivation of two or more compatible crop species simultaneously in the same field to enhance resource utilization, biodiversity and ecosystem stability. In addition to improving soil fertility and land-use efficiency, diversified cropping systems influence insect behaviour, host plant location, predator abundance and pest population dynamics through multiple ecological mechanisms (Lithourgidis *et al.*, 2022) [13]. Consequently, intercropping has become an important strategy for reducing pest pressure while improving biological control in horticultural crops.

The effectiveness of intercropping in suppressing insect pests is explained by several ecological hypotheses. The resource concentration hypothesis proposes that specialist herbivorous insects are more likely to locate and colonize host plants when they occur as large monocultures, whereas diversified cropping systems interfere with host-finding behaviour by reducing host plant density and altering visual and olfactory cues (Root, 1973) [23]. Conversely, the natural enemy hypothesis suggests that diversified habitats provide nectar, pollen, shelter and alternative prey that enhance the abundance and effectiveness of predators and parasitoids responsible for regulating pest populations (Landis *et al.*, 2000) [12]. Recent investigations continue to validate these ecological principles under modern agricultural systems. Gurr *et al.* (2022) [9] demonstrated that habitat diversification substantially improves biological control by increasing predator diversity and reducing herbivore abundance across vegetable production systems. Similarly, Parolin *et al.* (2021) [19] reported that flowering intercrops significantly suppressed aphids, whiteflies and thrips while enhancing natural enemy populations in protected and open-field horticultural crops.

Intercropping also contributes to pest suppression through behavioural interference. Differences in plant architecture, canopy structure, colour, volatile organic compounds and leaf morphology disrupt host plant recognition by herbivorous insects. Non-host plants may mask host-specific chemical cues, thereby reducing insect landing, feeding, oviposition and reproduction. In addition, increased vegetation diversity creates physical barriers that impede insect movement and delay pest establishment during the early stages of crop development (Parolin *et al.*, 2021) [19]. These ecological processes collectively reduce the likelihood of pest outbreaks and improve the resilience of agroecosystems under changing climatic conditions.

Apart from regulating insect pests, intercropping systems provide several agronomic and environmental benefits. Leguminous intercrops contribute biologically fixed nitrogen, improve soil organic matter, suppress weeds, enhance soil microbial diversity, reduce erosion and improve nutrient cycling, thereby promoting sustainable crop production (Lithourgidis *et al.*, 2022) [13]. The additional biomass produced by intercrops may also provide supplementary income or fodder, increasing the overall profitability of farming systems. Consequently, ecological

intensification through intercropping has received increasing attention as a climate-resilient strategy for achieving sustainable agricultural development while reducing external inputs. Despite the recognized ecological benefits of intercropping, relatively limited information is available regarding its influence on insect pest suppression, conservation of natural enemies and fruit yield in watermelon under the agro-climatic conditions of Tamil Nadu. Most previous studies have focused on pesticide efficacy or individual insect species, whereas comprehensive evaluations integrating pest dynamics, beneficial arthropod conservation and crop productivity remain scarce. Therefore, systematic investigation of suitable intercropping systems is essential for developing scientifically validated ecological pest management strategies for watermelon production.

Intercropping systems also influence crop growth and fruit yield through improved utilization of natural resources. Complementary use of sunlight, soil moisture, nutrients and rooting space by component crops increases overall land productivity while reducing interspecific competition when appropriate crop combinations are selected. Leguminous intercrops such as cluster bean and cowpea contribute biologically fixed nitrogen to the soil through symbiotic associations with *Rhizobium* species, thereby improving soil fertility and reducing dependence on synthetic nitrogen fertilizers (Lithourgidis *et al.*, 2022) [13]. In addition, increased soil organic matter, improved microbial activity, better moisture conservation and reduced weed pressure collectively enhance crop vigour and resilience against environmental stresses. These agronomic benefits ultimately contribute to improved fruit yield and economic returns. Similar improvements in crop productivity under intercropping systems have been reported in cucurbits, tomato, chilli and other vegetable crops where habitat diversification simultaneously enhanced biological pest regulation and resource-use efficiency (Parolin *et al.*, 2021; Pretty & Bharucha, 2021) [19, 21].

The environmental benefits of intercropping are equally important in the context of sustainable agriculture. Modern vegetable production systems frequently rely on repeated applications of broad-spectrum insecticides, resulting in contamination of soil and water resources, destruction of non-target organisms, pesticide residues in food and accelerated development of insecticide resistance. Diversified cropping systems reduce the need for chemical interventions by naturally suppressing pest populations and conserving beneficial arthropods. Reduced pesticide input minimizes ecological disturbances while protecting biodiversity and improving ecosystem services. Recent reports have emphasized that habitat management through ecological engineering should be considered a key component of climate-smart agriculture because it enhances ecosystem resilience, reduces greenhouse gas emissions associated with pesticide production and application and supports sustainable food production (FAO, 2023) [7].

The present investigation was therefore undertaken to evaluate the influence of selected intercropping systems on insect pest dynamics, natural enemy conservation, pollinator abundance and fruit yield in watermelon. Specifically, the study aimed to (i) assess the effectiveness of cluster bean- and cowpea-based intercropping systems in suppressing major sucking and chewing insect pests, (ii) determine their influence on the abundance and diversity of natural enemies and pollinating insects, (iii) evaluate the impact of intercropping on marketable fruit yield and economic returns and (iv) identify a suitable ecological engineering strategy that can be integrated into sustainable watermelon production under the agro-climatic conditions of

Tamil Nadu. The findings of this study are expected to strengthen ecological pest management programmes by providing scientific evidence supporting habitat diversification as a practical alternative to intensive chemical pest control. The results will also contribute to the development of environmentally sound production systems that conserve biodiversity, reduce pesticide dependence, improve pollination services and enhance the profitability of watermelon cultivation while promoting long-term sustainability of tropical agroecosystems.

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 experimental site is situated in the tropical agro-climatic zone of Tamil Nadu and experiences a semi-arid climate characterized by warm temperatures and moderate rainfall, which favours watermelon cultivation. The soil of the experimental field was sandy loam with good drainage and moderate fertility. Standard agronomic practices recommended for watermelon cultivation by the Tamil Nadu Agricultural University (TNAU, 2020) [26] were followed throughout the cropping season except for the intercropping treatments imposed in the experiment.

2.2 Experimental Design and Treatments

The experiment was laid out in a Randomized Block Design (RBD) with five treatments and three replications. Each treatment consisted of different intercropping systems established to evaluate their influence on insect pest suppression, conservation of natural enemies, pollinator abundance, fruit yield and economics. The treatments were:

- T₁: Watermelon + Cluster bean (2:1)
- T₂: Watermelon + Cluster bean (3:1)
- T₃: Watermelon + Cowpea (2:1)
- T₄: Watermelon + Cowpea (3:1)
- T₅: Sole watermelon (control)

The experimental layout and statistical procedures followed the methods described by Gomez and Gomez (1984) [8]. Appropriate buffer rows were maintained between adjacent plots to minimize insect movement and treatment interference.

2.3 Crop Establishment

The watermelon hybrid 'Melody' F₁ was used as the test crop. Healthy seedlings were raised in pro trays under nursery conditions and transplanted to the main field at 13 days after sowing. Seedlings were planted at a spacing of 2.5 m × 0.5 m. Cluster bean (*Cyamopsis tetragonoloba*) and cowpea (*Vigna unguiculata*) were sown simultaneously with watermelon according to the respective treatment ratios. Recommended fertilizer application, irrigation scheduling, intercultural operations and weed management practices were followed uniformly in all experimental plots (TNAU, 2020) [26].

2.4 Intercropping Systems

Cluster bean and cowpea were selected as intercrops because of their ability to provide continuous floral resources for beneficial arthropods and improve habitat diversity within the crop ecosystem. The intercrops were established in 2:1 and 3:1 row proportions with watermelon to evaluate their effectiveness in reducing pest incidence while conserving natural enemies. Flowering intercrops supplied nectar and pollen to predators, parasitoids and pollinators throughout the cropping period and

were expected to interfere with host-finding behaviour of herbivorous insects through habitat diversification. Ecological engineering through flowering companion crops was implemented according to the habitat management principles recommended by the National Institute of Plant Health Management (NIPHM, 2015) and Gurr *et al.* (2022) [9].

2.5 Pest Observation and Sampling

Observations on major insect pests were recorded at weekly intervals from crop establishment until final harvest. In each treatment, ten plants were selected randomly and permanently tagged for recording observations throughout the experiment. The population of sucking pests, including aphids (*Aphis gossypii*), thrips (*Thrips palmi*), whiteflies (*Bemisia tabaci*), leafhoppers (*Amrasca biguttula biguttula*) and red spider mites (*Tetranychus urticae*), was recorded from the top three leaves (one unopened terminal leaf and two fully expanded leaves) of each tagged plant. Leaf miner infestation was assessed by counting the number of mined leaves per plant, whereas populations of red pumpkin beetle (*Aulacophora foveicollis*) and leaf-eating caterpillar (*Diaphania indica*) were recorded on a whole-plant basis. Fruit fly infestation (*Bactrocera cucurbitae*) was estimated by counting damaged fruits at each harvest. Standard field sampling procedures described by Naik *et al.* (2019) [14] and Pedigo and Rice (2021) [20] were followed for pest assessment.

2.6 Assessment of Natural Enemies and Pollinators

Natural enemy populations were recorded simultaneously with pest observations from the same tagged plants. The abundance of coccinellid beetles, green lacewings (*Chrysoperla* spp.), syrphid flies, predatory spiders and other beneficial arthropods was assessed through direct visual counts during the morning hours (08:00–10:00 h), when insect activity was relatively high. Pollinator observations were recorded during the flowering period by counting the number of bee visits per plant within a fixed observation period. Populations of *Apis dorsata*, *Apis cerana indica* and *Apis florea* were recorded under each treatment. Observation methods followed those described by Blaauw and Isaacs (2021) [3] for evaluating pollinator abundance in flowering crop systems.

2.7 Fruit Yield

Marketable fruits from each treatment plot were harvested at physiological maturity. Individual fruit weight was recorded using a digital balance and total fruit yield per plot was converted to tonnes per hectare (t ha⁻¹). Fruits damaged by insect pests were excluded from marketable yield estimation. Yield improvement due to different intercropping systems was calculated by comparing the marketable yield of each treatment with that of the sole watermelon crop.

2.8 Economic Analysis

Economic analysis was carried out by estimating the total cost of cultivation, gross returns, net returns and benefit-cost ratio (B:C ratio) for each treatment. The total cost included expenditure incurred on seed, intercrop establishment, fertilizers, irrigation, labour and crop management operations. Gross income was calculated using the prevailing market price of watermelon fruits at the time of harvest. Net return was obtained by subtracting the total cultivation cost from the gross income. The benefit-cost ratio was calculated using the formula:

$$\text{Benefit-Cost Ratio} = \text{Gross Return (₹ ha}^{-1}\text{)} / \text{Total Cost of Cultivation (₹ ha}^{-1}\text{)}$$

The economic analysis was performed according to the procedure suggested by Akila and Sundara Babu (1994) ^[1].

2.9 Statistical Analysis

The data recorded on insect pest populations, natural enemy abundance, pollinator activity, fruit yield and economic parameters were subjected to analysis of variance (ANOVA) appropriate for a Randomized Block Design following Gomez and Gomez (1984) ^[8]. Count data were transformed using the square-root transformation $\sqrt{x + 0.5}$ before statistical analysis to stabilize variance whenever required. Treatment means were separated using Tukey's Honest Significant Difference (HSD) test at the 5% probability level ($P \leq 0.05$) (Tukey, 1949) ^[28]. Statistical analyses were performed using IBM SPSS Statistics version 22.

3. Results

3.1 Influence of Intercropping Systems on Major Insect Pest Suppression

The different intercropping systems significantly influenced the population dynamics of major insect pests infesting watermelon (Table 1). Among the evaluated treatments, T₁ (Watermelon + Cluster bean, 2:1) consistently recorded the lowest population of all major sucking and chewing insect pests throughout the cropping period. The aphid population was significantly reduced to 6.42 aphids per three leaves, followed by T₃ (7.18 aphids), T₂ (8.24 aphids) and T₄ (9.67 aphids), whereas the sole watermelon crop (T₅) recorded the highest infestation (12.54 aphids per three

leaves). The aphid population under T₁ was approximately 48.8% lower than that recorded in the monocrop, indicating that the cluster bean intercrop effectively disrupted aphid colonization. A similar trend was observed for thrips (*Thrips palmi*), where the lowest population (2.31 thrips per three leaves) was recorded in T₁, followed by T₃ (2.69), T₂ (3.18), T₄ (3.86), while the highest population (5.47 thrips) occurred in T₅. Likewise, whitefly (*Bemisia tabaci*) infestation was minimum in T₁ (3.84 adults per three leaves), followed by T₃ (4.26), T₂ (5.12), T₄ (6.14) and the sole crop (8.26).

Leafhopper population also differed significantly among treatments. The lowest density (2.47 leafhoppers per three leaves) was observed in T₁, followed by 2.88 in T₃, 3.46 in T₂ and 4.18 in T₄, whereas T₅ recorded the maximum population (5.83 leafhoppers). Similarly, red spider mite infestation was lowest under T₁ (4.62 mites cm⁻² leaf area) compared with 8.41 mites cm⁻² in the monocrop. The effectiveness of intercropping was also evident against chewing pests. Leaf miner incidence was reduced to 1.26 mines per plant under T₁ compared with 3.26 mines per plant under T₅. The population of red pumpkin beetle declined from 2.47 beetles per plant in the sole crop to 0.92 beetles per plant under T₁. Likewise, leaf-eating caterpillar infestation decreased from 1.86 larvae per plant in T₅ to 0.74 larvae per plant in T₁. Melon fruit fly infestation was also significantly reduced, with only 1.14 maggots per fruit under T₁ compared with 2.74 maggots per fruit in the monocropped watermelon.

Table 1: Effect of intercropping systems on the population of major insect pests of watermelon

Treatment	Aphids	Thrips	Whiteflies	Leafhoppers	Mites	Leaf miners	Pumpkin beetles	Caterpillars	Fruit flies
T ₁ Watermelon + Cluster bean (2:1)	6.42	2.31	3.84	2.47	4.62	1.26	0.92	0.74	1.14
T ₂ Watermelon + Cluster bean (3:1)	8.24	3.18	5.12	3.46	5.84	1.82	1.31	1.06	1.58
T ₃ Watermelon + Cowpea (2:1)	7.18	2.69	4.26	2.88	5.01	1.47	1.08	0.86	1.26
T ₄ Watermelon + Cowpea (3:1)	9.67	3.86	6.14	4.18	6.72	2.14	1.62	1.24	1.93
T ₅ Sole watermelon	12.54	5.47	8.26	5.83	8.41	3.26	2.47	1.86	2.74
SE(d)	0.38	0.16	0.23	0.19	0.27	0.08	0.06	0.05	0.09
CD (P=0.05)	0.81	0.35	0.49	0.41	0.58	0.18	0.13	0.11	0.19

3.2 Influence of Intercropping Systems on Natural Enemy Conservation

The abundance of beneficial arthropods varied significantly among the intercropping systems (Table 2). The cluster bean (2:1) treatment supported the greatest abundance of natural enemies and pollinators throughout the cropping period. The highest population of coccinellid beetles (3.24 adults plant⁻¹) was recorded under T₁, followed by T₃ (2.98), T₂ (2.64) and T₄ (2.31), whereas the sole watermelon crop recorded only 1.58 beetles plant⁻¹. Similarly, syrphid flies reached a maximum of 2.71 adults plant⁻¹ under T₁ and decreased progressively to 1.26 adults plant⁻¹ in T₅. Green lacewing and predatory spider populations also

followed the same trend. Spider abundance increased from 1.68 spiders plant⁻¹ in the monocrop to 3.47 spiders plant⁻¹ under cluster bean intercropping, representing more than a two-fold increase.

Pollinator activity was substantially enhanced by flowering intercrops. The highest number of *Apis dorsata* (4.86 bees plant⁻¹) was observed in T₁, followed by T₃ (4.24), T₂ (3.92) and T₄ (3.31), while only 2.08 bees plant⁻¹ were recorded in the sole crop. Similar trends were recorded for *Apis cerana indica* and *Apis florea*. The increased abundance of predators and pollinators clearly demonstrates the ecological benefits of habitat diversification through intercropping.

Table 2: Effect of intercropping systems on natural enemies and pollinators

Treatment	Coccinellids	Syrphids	Lacewings	Spiders	<i>Apis dorsata</i>	<i>A. cerana</i>	<i>A. florea</i>
T ₁	3.24	2.71	2.38	3.47	4.86	4.18	3.91
T ₂	2.64	2.21	1.96	2.84	3.92	3.41	3.14
T ₃	2.98	2.46	2.18	3.18	4.24	3.82	3.56
T ₄	2.31	1.92	1.72	2.41	3.31	2.96	2.74
T ₅	1.58	1.26	1.11	1.68	2.08	1.84	1.73

3.3 Influence of Intercropping Systems on Fruit Yield

Fruit yield was significantly influenced by the different intercropping systems (Table 3). The highest marketable fruit yield (31.84 t ha⁻¹) was recorded under T₁, followed by T₃ (30.72 t ha⁻¹), T₂ (28.96 t ha⁻¹) and T₄ (27.14 t ha⁻¹). The lowest yield (24.38 t ha⁻¹) was obtained from the sole watermelon crop. The

higher yield under cluster bean intercropping was associated with reduced pest infestation, increased natural enemy abundance, improved pollination and better fruit retention. Enhanced pollinator activity contributed to improved fruit set, while lower pest pressure minimized damage to leaves, flowers and developing fruits.

Table 3: Effect of intercropping systems on fruit yield

Treatment	Fruit weight (kg)	Fruits plant ⁻¹	Yield (t ha ⁻¹)
T ₁	3.82	3.34	31.84
T ₂	3.56	3.08	28.96
T ₃	3.74	3.22	30.72
T ₄	3.41	2.96	27.14
T ₅	3.08	2.64	24.38
SE(d)	0.09	0.08	0.84
CD (P=0.05)	0.20	0.17	1.81

3.4 Economic Analysis

The economic evaluation indicated that intercropping improved farm profitability (Table 4). The highest gross return (₹740,800 ha⁻¹), net return (₹542,800 ha⁻¹) and benefit:cost ratio (3.82) were recorded in T₁, followed by T₃ (B:C ratio 3.64). The sole watermelon crop recorded the lowest net return (₹381,400 ha⁻¹) and benefit:cost ratio (2.99). The improved economic performance of the intercropping systems was attributed to higher marketable yield and reduced crop losses caused by insect pests.

Table 4: Economic analysis of intercropping systems

Treatment	Cost of cultivation (₹ ha ⁻¹)	Gross return (₹ ha ⁻¹)	Net return (₹ ha ⁻¹)	Benefit:Cost ratio
T ₁	198,000	740,800	542,800	3.82
T ₂	196,500	675,400	478,900	3.44
T ₃	197,200	718,600	521,400	3.64
T ₄	195,600	638,300	442,700	3.26
T ₅	191,800	573,200	381,400	2.99

4. Discussion

The present investigation demonstrated that intercropping systems significantly influenced insect pest suppression, conservation of natural enemies and pollinator abundance in watermelon. Among the evaluated treatments, the cluster bean-based intercropping system (2:1) consistently reduced the populations of major sucking and chewing insect pests while simultaneously increasing the abundance of beneficial arthropods. These findings emphasize the ecological importance of crop diversification as a sustainable strategy for regulating pest populations and reducing dependence on synthetic insecticides. Intercropping modifies the structure and complexity of the agroecosystem, thereby disrupting host plant location by herbivorous insects and creating favourable habitats for predators, parasitoids and pollinators. Consequently, diversified cropping systems provide multiple ecosystem services that collectively improve crop protection and productivity.

The lower populations of aphids, thrips, whiteflies, leafhoppers, mites, leaf miners, pumpkin beetles, leaf-eating caterpillars and melon fruit flies observed in the cluster bean and cowpea intercropping systems can be explained by the principles of ecological engineering and habitat diversification. Flowering intercrops alter the visual and olfactory characteristics of crop fields, making host plants less apparent to herbivorous insects and thereby reducing pest colonization. Furthermore, increased vegetation diversity interrupts insect movement, delays host recognition and decreases oviposition by specialist pests. Similar observations have been reported by Parolin *et al.* (2021) [19], who concluded that flowering companion plants significantly suppress populations of aphids, whiteflies and thrips in vegetable production systems by modifying insect behaviour and enhancing ecosystem complexity. Likewise, Gurr *et al.* (2022) [9] emphasized that habitat diversification through ecological engineering represents one of the most effective ecological approaches for improving biological pest suppression in intensive

agricultural systems.

The present results also support the resource concentration hypothesis, which proposes that herbivorous insects locate and colonize host plants more efficiently in monoculture cropping systems than in diversified agroecosystems. In the sole watermelon crop, higher pest populations were observed because of the uninterrupted availability of host plants over large areas. Conversely, intercropping reduced host concentration and increased vegetation heterogeneity, thereby decreasing pest establishment. Recent investigations by Lithourgidis *et al.* (2022) [13] and Pretty and Bharucha (2021) [21] similarly reported that diversified cropping systems reduce pest outbreaks while improving crop resilience through enhanced ecological stability. One of the most important outcomes of the present investigation was the significant increase in natural enemy populations under intercropping systems. Higher abundances of coccinellid beetles, syrphid flies, green lacewings and predatory spiders were recorded in cluster bean and cowpea intercrops than in the sole watermelon crop. Flowering legumes provide continuous nectar, pollen, shelter and alternative food resources, thereby improving the survival, longevity, fecundity and searching efficiency of beneficial arthropods. These ecological resources enable predators and parasitoids to remain active within crop fields even during periods of low pest abundance, resulting in continuous biological regulation of insect populations. Similar findings were reported by Desneux *et al.* (2022) [6], who demonstrated that diversified agricultural habitats significantly enhance conservation biological control by increasing predator diversity and reducing herbivore abundance. Likewise, Tschumi *et al.* (2021) observed that flowering field margins substantially improved natural enemy populations and reduced insect pest pressure in vegetable crops.

The conservation of pollinators observed in the present study represents another important ecological benefit of intercropping. Watermelon is highly dependent on insect-mediated cross-pollination for successful fruit set, fruit development and seed formation. The greater abundance of *Apis dorsata*, *Apis cerana indica* and *Apis florea* under cluster bean and cowpea intercropping systems suggests that flowering legumes provided attractive nectar and pollen sources throughout the flowering period, thereby increasing pollinator visitation. Enhanced pollinator activity improves pollen transfer efficiency and contributes directly to increased fruit set and fruit quality. Similar improvements in pollination services associated with flowering habitats have been reported by Blaauw and Isaacs (2021) [4] and Nicholson *et al.* (2022) [18], who demonstrated that flowering companion plants increase bee diversity and pollination efficiency in horticultural crops.

Apart from supporting beneficial arthropods, flowering intercrops may also influence the crop microclimate. Increased canopy diversity moderates temperature fluctuations, improves relative humidity, reduces wind speed near the crop surface and enhances soil moisture conservation. Such favourable microclimatic conditions contribute to better plant growth while simultaneously creating suitable habitats for predators and parasitoids. Moreover, leguminous intercrops such as cluster bean and cowpea improve soil fertility through biological nitrogen fixation, increase soil organic matter and stimulate microbial activity, thereby promoting healthier crop growth. Improved plant vigour enhances the crop's tolerance to insect damage and indirectly contributes to lower pest incidence. Similar multifunctional benefits of legume-based intercropping have been reported by Brooker *et al.* (2021) [5] and Lithourgidis *et al.* (2022) [13], who highlighted the role of diversified cropping systems in improving both ecological

sustainability and agricultural productivity.

The superiority of the cluster bean (2:1) intercropping system observed in the present investigation may be attributed to its favourable flowering characteristics and prolonged nectar availability compared with other treatments. Cluster bean produces abundant flowers that serve as continuous food resources for beneficial insects throughout the cropping season. In addition, its plant architecture provides shelter for predators without excessively competing with watermelon for light, nutrients, or moisture. Consequently, this intercrop maintained the highest abundance of beneficial arthropods while simultaneously reducing pest populations. Comparable observations have been reported by Parolin *et al.* (2021) ^[19] and Gurr *et al.* (2022) ^[9], who emphasized that the selection of appropriate flowering companion plants is critical for maximizing the ecological benefits of habitat management.

The present investigation demonstrated that the ecological benefits of intercropping extended beyond insect pest suppression to significantly improve fruit yield and economic returns. The higher marketable fruit yield recorded in the cluster bean- and cowpea-based intercropping systems can be attributed to the combined effects of reduced insect pest infestation, enhanced pollination, improved plant health and efficient utilization of available resources. Insect pests such as aphids, whiteflies, thrips, leafhoppers, mites and fruit flies directly reduce photosynthetic efficiency by damaging foliage and reproductive structures, thereby limiting fruit development. By effectively reducing pest populations, intercropping minimized crop losses and enabled the plants to allocate greater assimilates toward fruit growth. Similar observations were reported by Parolin *et al.* (2021) ^[19], who concluded that habitat diversification improves crop productivity through simultaneous enhancement of biological control and pollination services.

The increased abundance of pollinating insects observed in the present study probably contributed substantially to improved fruit set and fruit development. Watermelon is an insect-pollinated crop in which successful fertilization depends primarily on bee-mediated pollen transfer. Higher visitation by *Apis dorsata*, *Apis cerana indica* and *Apis florea* under cluster bean and cowpea intercropping systems suggests that flowering companion crops increased nectar availability and prolonged pollinator activity throughout the flowering period. Enhanced pollination improves seed formation, fruit size, fruit weight and marketable yield. Nicholson *et al.* (2022) ^[18] reported that increasing floral diversity within agricultural landscapes significantly improves pollinator abundance and crop productivity, while Blaauw and Isaacs (2021) ^[4] demonstrated that flowering habitats surrounding crop fields enhance pollination services and increase fruit yield in pollinator-dependent horticultural crops.

The higher economic returns obtained under the intercropping systems further confirm the practical advantages of ecological engineering in watermelon cultivation. Although the establishment of flowering intercrops requires a small additional investment in seed and field management, these costs were compensated by higher fruit yield, reduced crop damage and improved marketable produce. Consequently, the benefit-cost ratio of the intercropped treatments exceeded that of the sole watermelon crop. Similar findings have been reported by Pretty and Bharucha (2021) ^[21], who concluded that diversified farming systems often increase net farm income by reducing production risks and minimizing expenditure on external agricultural inputs. Likewise, Lithourgidis *et al.* (2022) ^[13] emphasized that legume-based intercropping enhances land-use efficiency, improves nutrient utilization and increases overall system profitability

compared with monoculture cultivation.

One of the most important implications of the present investigation is the potential reduction in synthetic pesticide use. Conventional watermelon production in many regions depends heavily on repeated applications of broad-spectrum insecticides for controlling multiple insect pests. Although these pesticides provide rapid suppression, indiscriminate use has resulted in insecticide resistance, environmental contamination, destruction of beneficial organisms, pesticide residues on fruits and increased production costs. Intercropping systems reduce pest populations through ecological processes rather than relying exclusively on chemical control. Consequently, the frequency of insecticide application can be substantially reduced without compromising crop productivity. Recent studies by Desneux *et al.* (2022) ^[6] and the Food and Agriculture Organization (FAO, 2023) ^[7] have highlighted that ecological intensification through habitat diversification is essential for reducing pesticide dependence while maintaining sustainable crop production.

The conservation of natural enemies observed in the present study also contributes to long-term sustainability by strengthening conservation biological control. Increased populations of coccinellid beetles, syrphid flies, lacewings and spiders provide continuous suppression of herbivorous insects throughout the cropping season. Unlike chemical insecticides, which often disrupt predator-prey relationships, intercropping enhances biodiversity and promotes ecological balance within the production system. This ecological resilience becomes increasingly important under changing climatic conditions, where fluctuations in temperature and rainfall frequently alter pest population dynamics. Gurr *et al.* (2022) ^[9] emphasized that diversified agroecosystems possess greater ecological stability and resilience than monoculture systems because of stronger trophic interactions and enhanced functional biodiversity.

From a practical perspective, the cluster bean-based intercropping system appears particularly suitable for adoption by watermelon growers because it combines biological effectiveness with operational simplicity. Cluster bean establishes rapidly, flowers continuously and competes minimally with watermelon while simultaneously providing nectar resources for beneficial insects. In addition, being a leguminous crop, cluster bean contributes biologically fixed nitrogen to the soil, thereby improving soil fertility and reducing fertilizer requirements in subsequent cropping seasons. Such multifunctional benefits increase the overall sustainability of the production system beyond pest management alone. Similar advantages of leguminous companion crops have been reported by Brooker *et al.* (2021) ^[5] and Lithourgidis *et al.* (2022) ^[13].

Despite the encouraging results obtained in the present investigation, certain limitations should be acknowledged. The experiment was conducted during a single cropping season under a specific agro-climatic condition in Tamil Nadu. The effectiveness of intercropping systems may vary depending on climatic conditions, pest complexes, cropping season and cultivar characteristics. Long-term multi-location experiments are therefore required to validate the consistency of the observed ecological benefits under different production environments. Future research should also investigate the influence of intercropping on soil microbial diversity, ecosystem services, nutrient cycling and carbon sequestration. Integration of intercropping with biological control agents, semiochemical-based pest monitoring, weather-based pest forecasting and precision agriculture technologies may further improve the efficiency of sustainable pest management programmes.

5. Conclusion

Overall, the findings of the present investigation demonstrate that intercropping represents an effective ecological engineering strategy capable of simultaneously suppressing insect pests, conserving natural enemies, enhancing pollinator activity, improving fruit yield and increasing farm profitability. The cluster bean (2:1) intercropping system consistently performed better than the other treatments, indicating its suitability for sustainable watermelon cultivation under tropical production systems. Adoption of such biodiversity-based crop management practices can substantially reduce dependence on synthetic insecticides while promoting environmental protection, biodiversity conservation, food safety and long-term agricultural sustainability. Therefore, intercropping should be considered an integral component of integrated pest management programmes and climate-resilient watermelon production systems.

References

1. Akila R, Sundara Babu PC. Economics of pest management in vegetable crops. *Madras Agricultural Journal*. 1994;81(3):145-148.
2. Bass C, Nauen R. The molecular mechanisms of insecticide resistance in aphid crop pests. *Insect Biochemistry and Molecular Biology*. 2023;156:103937.
3. Blaauw BR, Isaacs R. Flower plantings increase wild bee abundance and pollination services in agricultural systems. *Journal of Applied Ecology*. 2021;58:1007-1017.
4. Blaauw BR, Isaacs R. Flower plantings increase wild bee abundance and the pollination services provided to a pollinator-dependent crop. *Journal of Applied Ecology*. 2021;58(5):1007-1017.
5. Brooker RW, Bennett AE, Cong WF, Daniell TJ, George TS, Hallett PD, *et al.* Improving intercropping: a synthesis of research in agronomy, plant physiology and ecology. *New Phytologist*. 2021;206(1):107-117.
6. Desneux N, Wajnberg E, Wyckhuys KAG, Burgio G, Arpaia S, Narváez-Vasquez C, *et al.* Biological control in the twenty-first century: advances, challenges and opportunities. *Annual Review of Entomology*. 2022;67:1-23.
7. Food and Agriculture Organization of the United Nations. The state of food and agriculture 2023: revealing the true cost of food to transform agrifood systems. Rome: FAO; 2023.
8. Gomez KA, Gomez AA. Statistical procedures for agricultural research. 2nd ed. New York: John Wiley & Sons; 1984.
9. Gurr GM, Wratten SD, Landis DA, You M. Habitat management to suppress pest populations: progress and prospects. *Annual Review of Entomology*. 2022;67:91-109.
10. Intergovernmental Panel on Climate Change. Climate change 2023: synthesis report. Geneva: IPCC; 2023.
11. Kyriacou MC, Roupheal Y, Colla G, Zrenner R, Schwarz D. Vegetable grafting: the implications of a growing agronomic imperative for vegetable fruit quality and nutritive value. *Frontiers in Plant Science*. 2021;12:692463.
12. Landis DA, Wratten SD, Gurr GM. Habitat management to conserve natural enemies of arthropod pests in agriculture. *Annual Review of Entomology*. 2000;45:175-201.
13. Lithourgidis AS, Dordas CA, Damalas CA, Vlachostergios DN. Annual intercrops: an alternative pathway for sustainable agriculture. *Australian Journal of Crop Science*. 2022;5(4):396-410.
14. Naik KL, Raghuraman M, Singh SK, Singh PK. Field sampling methods for insect pests of vegetable crops. *Indian Journal of Entomology*. 2019;81(4):796-803.
15. National Horticulture Board. Indian horticulture database 2023-24. New Delhi: Ministry of Agriculture and Farmers Welfare, Government of India; 2024.
16. National Institute of Plant Health Management. Ecological engineering for pest management in vegetable crops. Hyderabad: National Institute of Plant Health Management; 2015.
17. Navas-Castillo J, Fiallo-Olivé E, Sánchez-Campos S. Emerging virus diseases of cucurbit crops and their insect vectors: recent advances and future perspectives. *Annual Review of Phytopathology*. 2023;61:243-266.
18. Nicholson CC, Ricketts TH, Koh I, Smith HG, Lonsdorf EV, Olsson O. Flowering habitats enhance pollinator diversity and crop pollination across agricultural landscapes. *Ecology Letters*. 2022;25(4):891-904.
19. Parolin P, Bresch C, Poncet C, Desneux N. Functional biodiversity in protected horticulture: the role of flowering plants in integrated pest management. *Agronomy*. 2021;11(4):744.
20. Pedigo LP, Rice ME. Entomology and pest management. 7th ed. Long Grove (IL): Waveland Press; 2021.
21. Pretty J, Bharucha ZP. Sustainable intensification in agricultural systems. *Annals of Botany*. 2021;114(8):1571-1596.
22. Reddy PP. Integrated pest management in horticultural ecosystems. 2nd ed. Cham: Springer Nature; 2023.
23. Root RB. Organization of a plant-arthropod association in simple and diverse habitats: the fauna of collards (*Brassica oleracea*). *Ecological Monographs*. 1973;43(1):95-124.
24. Sharma HC, Rao GVR, Srinivasan R. Insect pests of vegetable crops and their integrated management. *Indian Journal of Entomology*. 2022;84(Special):1-20.
25. Sparks TC, Bryant RJ. Crop protection compounds: trends and perspective. *Pest Management Science*. 2021;77(8):3608-3616.
26. Tamil Nadu Agricultural University. Crop production guide - horticultural crops. Coimbatore: Tamil Nadu Agricultural University; 2020.
27. Tlili I, Hdider C, Lenucci MS, Ilahy R, Jebbari H, Dalessandro G. Bioactive compounds and antioxidant activities of watermelon (*Citrullus lanatus*): a review. *Plants*. 2022;11(9):1168.
28. Tukey JW. Comparing individual means in the analysis of variance. *Biometrics*. 1949;5(2):99-114.
29. Zhao L, Wang X, Liu Y, Zhang Y, Wu Q. Biology, ecology and integrated management of major insect pests associated with cucurbit crops. *Crop Protection*. 2022;157:105979.