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Role of Insect Natural Enemies Integrated Pest Management of Citrus Insect Pests

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This study aimed to evaluate species diversity and population dynamics of citrus insect pests and their associated natural enemies in the Chiang Mai and Lamphang provinces. Additionally, it examined the biology and feeding potential of selected natural enemies to support the development of an Integrated Pest Management (IPM) programme. Analysis of population dynamics identified the lime butterfly (Papilio demoleus, Lepidoptera: Papilionidae), citrus leaf miner (Phyllocnistis citrella, Lepidoptera: Phyllocnistidae), yellow citrus aphid (Aphis citricola, Hemiptera: Aphididae), and thrips (Thrips spp., Thysanoptera: Thripidae) as major insect pests affecting citrus crops year-round. Among the 26 species of natural enemies observed, the stink bug Eocanthecona furcellata (Hemiptera: Pentatomidae), assassin bug Sycanus collaris (Hemiptera: Reduviidae), and green lacewing Mallada basalis (Neuroptera: Chrysopidae) emerged as potential predators for augmentative biological control of key pests. Species diversity was found to play a critical role in sustainable pest management strategies, as evidenced by a strong positive correlation (r = 0.82) between pest populations and their natural enemies. The feeding efficacy of the three selected predators was also assessed. Eocanthecona furcellata and Sycanus collaris demonstrated high potential in suppressing major lepidopterous pests, with feeding rates of 5.62±1.33 and 4.25±2.14 caterpillars per day, respectively. Conversely, Mallada basalis exhibited significant potential for controlling leaf-sucking pests, including aphids, whiteflies, scale insects, and thrips. The study thus underscores the biological and predatory potential of these natural enemies, advocating their use in IPM programmes to manage citrus pests effectively.

Keywords: Citrus Insect Pests, Natural Enemies, Biological Control, Pest Management, Species Diversity, Citrus Crops.

Introduction

Citrus crops globally are threatened by approximately 87 insect pest species (Riddick, 2022). In Thailand, the primary insect pests impacting citrus production include nine significant species: the lemon butterfly (Papilio spp.), the leaf miner (Phyllocnistis citrella), the citrus fruit borer (Citripestis sagittiferella), the Asian citrus psyllid (Diaphorina citri), the brown citrus aphid (Aphis citricola, Hemiptera: Aphididae), the citrus mealybug (Planococcus citri, Hemiptera: Pseudococcidae), the scale insect (Aonidiella aurantii, Hemiptera: Diaspididae), thrips (Scirtothrips dorsalis, Thysanoptera: Thripidae), and the citrus rust mite (Eutetranychus cendanai, Acari: Tetranychidae) (Bueno et al., 2023; Riddick, 2022; Vermelho et al., 2024; Ziaee & Babamir-Satehi, 2020).

Historically, citrus pests have been managed using chemical insecticides such as organophosphates, carbamates, and pyrethroids. However, the extensive application of these compounds has had significant adverse effects on biodiversity, ecological balance, and human health (Nadeem et al., 2022). Prolonged exposure to chemical pesticides has accelerated the development of resistance in pest populations, reducing the long-term efficacy of chemical control measures and leading to pest resurgence (Shaw, Nagy, & Fountain, 2021). Furthermore, the decline of natural enemy populations caused by these chemicals has exacerbated ecological imbalances, as the reduction of predators and parasites that naturally regulate pest numbers has disrupted ecosystem stability (Vermelho et al., 2024).

In recent years, the pursuit of sustainable pest management strategies has intensified interest in biological control, which employs natural enemies such as predators, parasitoids, and entomopathogens to suppress pest populations (Bouri, Arslan, & Şahin, 2023; Salem, Hamzah, & El-Taweelah, 2015). Biological control is regarded as an environmentally friendly alternative to chemical insecticides because it minimises harm to non-target organisms and reduces the risk of pesticide resistance (Owili et al., 2024). A notable example of successful biological control is the use of the vedalia beetle (Rodolia cardinalis) to manage cottony cushion scale (Icerya purchasi) in California's citrus orchards. This initiative significantly reduced pest populations and has since served as a model for subsequent biological control programmes (Fernando, Hale, & Shrestha, 2024; Nadeem et al., 2022).

Citrus cultivators in Thailand are increasingly adopting IPM programmes, which combine biological control with other pest management strategies to reduce reliance on chemical insecticides (Scrinis & Lyons, 2007; Sharma et al., 2010). IPM aims to maintain pest populations below economically damaging thresholds while promoting biodiversity and ecological balance. Recent research highlights the importance of utilising indigenous natural enemies to enhance biological control efforts, as local species are typically better adapted to the regional environment and pest dynamics (Mansour et al., 2018). This approach aligns with Good Agricultural Practices (GAP) and the principles of organic farming, which emphasise sustainable and environmentally friendly agricultural methods (Damavandian, 2007; George, Rao, & Rahangadale, 2019).

Additionally, climate change and global trade have introduced new challenges to pest management in citrus cultivation. The spread of invasive species, such as the Asian citrus psyllid (Diaphorina citri), a vector of Huanglongbing (HLB) or citrus greening disease, has severely impacted citrus industries in regions including the United States and Asia (Gelaye & Negash, 2023; Ullah et al., 2018). Biological control, as part of IPM programmes, has proven effective in managing invasive pests and mitigating the effects of climate-induced shifts in pest behaviour and distribution (Franco et al., 2004; Itioka, Inoue, & Ishida, 1992).

Biological management is recognised as a fundamental component of sustainable agriculture (Bažok, 2022). In response to the growing demand for sustainable solutions, ongoing research continues to focus on improving the efficacy and adoption of biological control methods in citrus pest management (Deguine et al., 2021; Smaili, Boutaleb-Joutei, & Blenzar, 2020). The integration of biological control into IPM systems provides an effective approach to regulating insect populations while minimising the environmental and health risks associated with chemical pesticides, thereby contributing to global sustainability goals.

Material and Methods

Population Dynamic of Citrus Insect Pests and Associated Natural Enemies

Population data were collected from two provinces in northern Thailand, Chiang Mai and Lampang, representing organic and conventional farming systems. The sampling area size was 1,600 square metres per plot, with five subplots per plot across a total of 50 plots. The populations of citrus insect pests and their associated natural enemies were recorded following the methodology described by Dent and Walton (Singerman & Rogers, 2020). Plants were tapped to dislodge insect samples onto a 20 × 30 cm plastic plate, and the collected samples were used to identify key insect pests and their natural enemies, which were preserved in plastic tubes containing an alcohol-glycerine-acetic acid (AGA) solution. Data collection included location details, host plants, area photographs, and geographic coordinates recorded using a GPS device (Garmin-Oregon-450). Morphological identification was conducted in the laboratory under a stereo zoom microscope, with voucher specimens prepared on permanent slides using Canada balsam and Hoyer's solution. Additionally, fifty percent of infested plant parts, comprising 5–10 pieces per sample, were collected and placed in plastic tubes containing 10 ml of 70% alcohol solution. The solution was shaken to separate insect and plant debris, and key insect pests and their natural enemies were identified and processed into voucher specimens. Further samples were collected using an aspirator and processed with a cylinder extractor in the laboratory, where voucher specimens were prepared following the same procedure. The collected data were analysed to estimate population dynamics, track trends in population changes throughout the year, and identify key insect pests and their associated natural enemies.

Biology and Predatory Potential of Selected Natural Enemies

The biology of Eocanthecona furcellata and Sycanus collaris was documented in terms of their life cycle, life table, biological attributes, survival rate, fecundity, and fertility, following the methodology outlined by Dent and Walton (Singerman & Rogers, 2020). Predator eggs were placed in round plastic containers (25 × 10 cm) containing ten mealworms and soaked cotton bolls, which were replaced every 24 hours until the bugs reached the reproductive stage. Subsequently, 20 adult predators (sex ratio 1:1) were transferred to larger round plastic boxes (25 × 40 × 15 cm) equipped with artificial leaves to facilitate the reproductive stage. The duration of development and mortality at various developmental stages were recorded, enabling calculation of the mean duration of successive stages and subsequent life table analysis. The predatory potential of the insects was assessed by measuring daily prey consumption rates, providing insight into their efficacy as biological control agents.

Figure 1: Rearing of E. furcellata Equipment for Biology Study as Follow Tools for Mass Rearing, Egg Mass, Watering and Laying Equipment.

The biology of the green lacewing, Mallada basalis, was investigated by culturing citrus mealybugs on Thai pumpkin fruit one month prior to the biological study, following the methodology outlined by Dent and Walton. The life history and growth ratio of the lacewing were initiated by placing mealybug-infested pumpkin fruit in a cylindrical plastic box covered with a ventilated steel mesh layer. Under a light: dark cycle of 12:12 hours, lacewing adults were allowed to mate, and newly emerged adults were randomly paired and kept in a plastic box containing mealybug-infested pumpkin and cotton-soaked honey (Figure 2). The pumpkin was replaced every 24 hours, and the duration of development and mortality at certain developmental stages were recorded by counting the surviving individuals at each stage. This data was used to calculate the mean duration of successive stages and subjected to life table analysis. To assess daily prey consumption, the eggs laid by lacewings on the mealybug masses (comprising 75% of the pumpkin surface area) were kept and allowed to hatch in the cylindrical plastic box. This determination was carried out using five larvae per replicate, with five replicates. Additionally, to evaluate the reduction of mealybugs on the pumpkin surface area, control fruits with and without lacewing larvae were compared (Figure 2).

Figure 2: Mealybug-Rearing Tools Subject to the Biology of Green Lacewings

Data Analysis

Population dynamics of citrus insect pests and their natural enemies were analysed using the mean number of insects, which were transformed to log (n) + 1 and presented as a bar chart. To evaluate the association between the pests and their natural enemies, the collected data were subjected to a regression equation, where the log of insect pest populations was denoted as y and natural enemies as x. The correlation coefficient (r) was used to indicate the strength and trend of their relationship (Catling et al., 1977; Morse, 1995).The life cycle and biological life table were analysed using pivotal age (x), the day period, and the proportion of females alive at age x (lx). It was assumed that equal investment in males and females would result in a 1:1 sex ratio. Age-specific fecundity, or female eggs per female per day (mx), was calculated to generate an egg curve (lxmx), where the summation of all values provided the net reproductive rate of increase (Ro). Cohort generation time (Tc) and intrinsic rate of increase (rc) were determined using biological life table analysis parameters, following the methods outlined by Dent and Walton.

Results and Discussion

Population Dynamic and Correlation of Citrus Insect Pests and Associated Natural Enemies

Based on the survey and collection of plant hosts, citrus insect pests, and natural enemies from 33 districts in two provinces of northern Thailand, Chiang Mai and Lampang (Table 1 and Figure 3), the following citrus insect pests were identified: 1) caterpillars, including the lime butterfly

(Papilio demoleus, Lepidoptera: Papilionidae), citrus leaf miner (Phyllocnistis citrella, Lepidoptera: Phyllocnistidae), citrus fruit borer (Citripestis sagittiferella, Lepidoptera: Pyralidae), and citrus rind borer (Prays citri, Lepidoptera: Yponomeutidae); 2) aphids, including the Asian citrus psyllid (Diaphorina citri, Hemiptera: Psyllidae), yellow citrus aphid (Aphis citricola, Hemiptera: Aphididae), hard wax scale (Ceroplastes sinensis), black scale (Saissetia oleae), citrus mealybug (Planococcus citri, Hemiptera: Pseudococcidae), and thrips (Thysanoptera: Thripidae) (Figures 4-6).

Table 1: The Survey and Collection of Plant Host, Citrus Insect Pest and Natural Enemies from 33 Districts in 2 Provinces of Northern Thailand.

No.	Location	Plant	Insect Pest	Natural Enemies
1	Fang District, Chiang Mai	Orange and Pomelo	Citrus Yellow Mite	Green Lacewings
		Orange, Pomelo and Lime	Thrips	Green Lacewings
2	Chaiprakarn District, Chiang Mai	Orange, Kumquat and Lime	*D. Citri*	*E. Furcellata*
		Orange, Lime and Pomelo	*P. Demoleus*	*E. Furcellata*
		Pomelo	*Bactrocera* spp.	-
		Orange, Pomelo and Lime	Citrus Fruit Borer	*E. Furcellata*
		Kumquat and Lime	Citrus Mealybug	Mealybug Parasitoid and Green Lacewings
3	Chiang Dao District, Chiang Mai	Orange, Kumquat and Lime	*D. Citri*	Earwigs
		Orange, Lime and Kaffir Lime	*A. Citricola*	Mantis
		Pomelo and Lime	*P. Citrella*	*Trichogramma* spp.
		Orange, Lime and Pomelo	*P. Demoleus*	*Trichogramma* spp.
		Pomelo and Lime	*P. Citrella*	*E. Furcellata*
4	Phrao District, Chiang Mai	Orange and Pomelo	Citrus yellow Mite	Green Lacewings
		Orange, Pomelo and Lime	Thrips	Green Lacewings
		Orange, Pomelo and Lime	Citrus Rind Borer	*Sycanus* sp. (Coleoptera: Reduvidae)
		Orange, Kumquat and Lime	*D. Citri*	*Sycanus* sp.
5	San Sai District, Chiang Mai	Orange, Pomelo and Lime	*C. Saggittiferekka*	*Agriocnemis* sp.
		Lime	*P. Citri*	-
		Orange, Lime and Kaffir Lime	*A. Citricola*	Flower Flies
		Orange, Lime and Pomelo	*P. Demoleus*	*E. Furcellata*
6	Mueang Chiang Mai District, Chiang Mai	Orange and Pomelo	Citrus Yellow Mite	Green Lacewings
		Orange, Pomelo and Lime	Thrips	Green Lacewings
7	San Kamphaeng District, Chiang Mai	Orange and Pomelo	Citrus Yellow Mite	Green Lacewings
		Orange, Pomelo and Lime	Thrips	Green Lacewings
		Pomelo	Oriental Fruit Fly	-
8	Chom Thong District, Chiang Mai	Orange, Lime and Kaffir Lime	*A. Citricola*	Flower Flies
		Lime	*P. Citri*	Mantis
9	Wang Nuea District, Lampang, Ngao District,Lampang	Orange, Pomelo and Lime	*C. Saggittiferekka*	-
10		Orange and Pomelo	Citrus Yellow Mite	Green Lacewings
		Orange, Pomelo and Lime	Thrips	Green Lacewings
11	Mueang Pan District, Lampang	Orange and Pomelo	Citrus yellow Mite	Green Lacewings
		Orange, Pomelo and Lime	Thrips	Green Lacewings
		Orange, Pomelo and Lime	*C. Saggittiferekka*	*Neurothemis* sp.
		Orange, Lime Kaffir Lime and Pomelo	Citrus Leaf Miner	*E. Furcellata*
		Orange and Lime	Lamon Butterfly	*Eocanthecona furcellata* (Wolff)
12	Chae Hom District, Lampang	Orange, Kumquat and Lime	Asian Citrus Psyllid	*Sycanus* sp.
		Orange, Pomelo and Lime	*C. Saggittiferekka*	Earwigs
		Orange, Lime, Kaffir Lime and Kumquat	Yellow Citrus Aphid	Flower Flies
		Orange, Lime Kaffir Lime and Pomelo	Citrus Leaf Miner	*Argyrophylax Nigrotibialis* (Baranov) (Diptera: Tachinidae)
13	Mueang Lampang District, Lampang	Orange and Pomelo	Citrus Yellow Mite	Green Lacewings
		Orange, Pomelo and Lime	Thrips	Green Lacewings

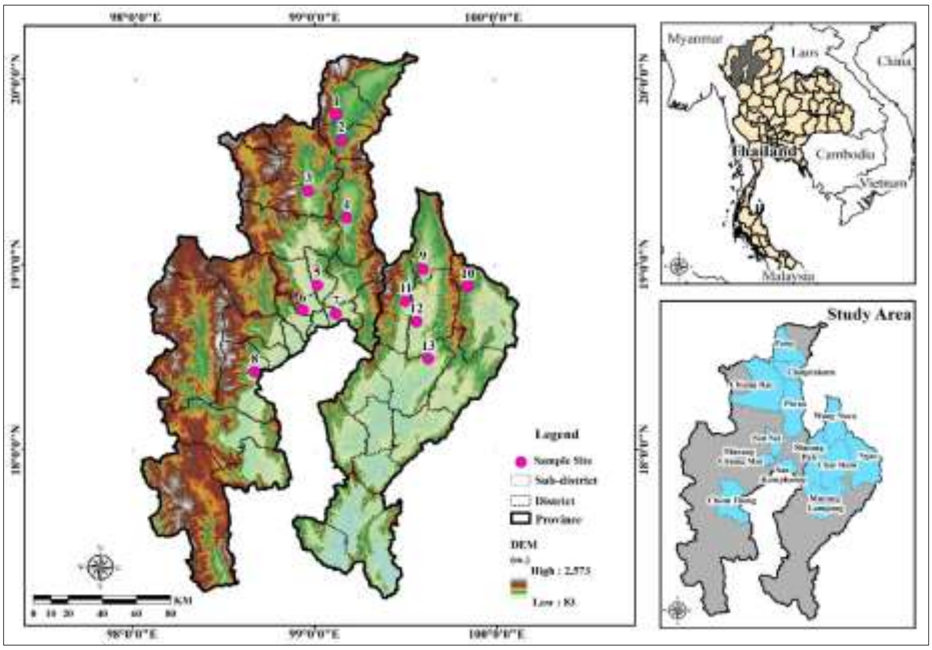

Figure: Survey and Collection Site of Citrus Insect Pests and their Natural Enemies in 13 Districts of Two Provinces of Northern Thailand: Chiang Mai and Lampang.

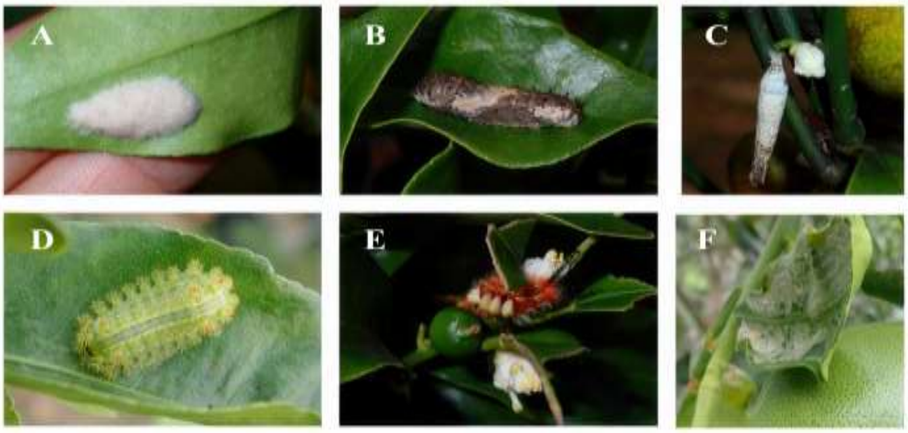

Figure 4: Lepidopterous Citrus Insect Pests Collected from Chiang Mai and Lampang Province, Including Egg Mass of Fall Armyworm (A), Lemon Butterfly Larva (B), Clothes Moth Larva (C), Stinging Nettle Caterpillar (D), Hairy Caterpillar (E), and Citrus Leaf Miner (F).

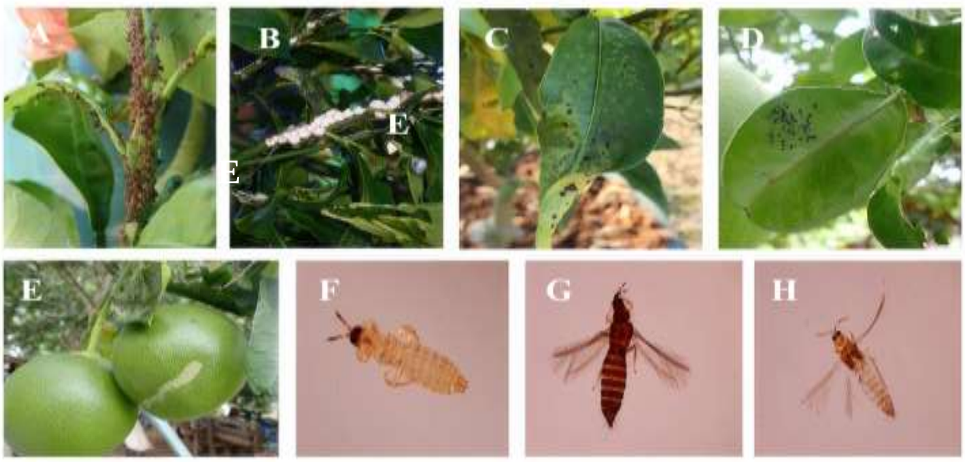

Figure 5: Leaf Sucking Citrus Insect Pests Found in Chiang Mai and Lampang Province, Including Yellow Citrus Aphid (A), Citrus Scale Mealybug (B), Citricola Scale (C), Citrus Blackfly (D), Thrips Infestation Fruit (E), and Types of Thrips (F-H).

The natural enemies found were categorised into three groups: 1) generalist predators, including Neurothemis sp., Agriocnemis sp., Micraspis discolor (F.), and Micraspis vincta (Gorham); 2) spiders, such as Neoscona jinghongensis, Argiope catenulata, Tetragnatha maxillosa, Thomisus stoliczka, and Runcinia albostriata; and 3) parasites, including Aphelinus sp., Anagyrus lopezi, Trichogramma, and Argyrophylax nigrotibialis (Baranov) (Diptera: Tachinidae). Analysis of the population ecology of citrus insect pests and their associated natural enemies revealed a Shannon-Weiner Index diversity of 1.11 at the study sites. The pest population and certain natural enemies were positively correlated (R = 0.82). The associations were divided into two groups: caterpillars and their natural enemies, which included 1) egg parasitoids (Trichogramma), predatory bugs (E. furcellata and S. collaris), and 2) leaf-feeding insect pests and their effective natural enemies, which comprised various species of predatory beetles, flower fly larvae, and aphid flies (Figures 7-8). The population dynamics were found to be influenced by timing and season. The population ratio study showed that insect pests and natural enemies were related by density-dependent factors (DD factors) (Figure 9), which indicated a high density of effective predators during months 9-11.

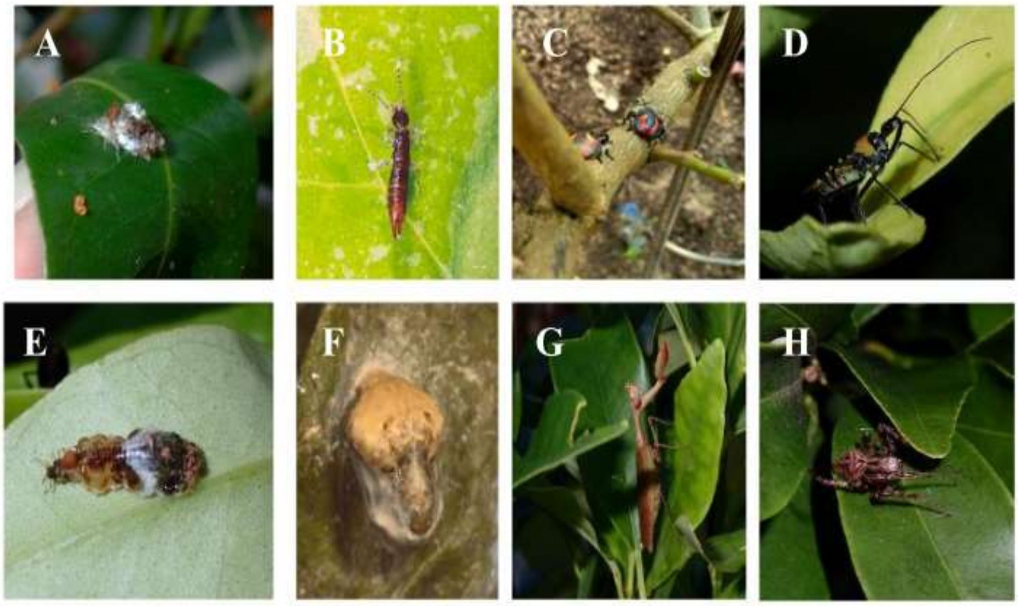

Figure 6: Insect Natural Enemies of Citrus Insect Pests Found in Citrus Orchards in Chiang Mai and Lampang Province, Such as Green Lacewing Larvae (A), Ring-Legged Earwigs (B), Predatory Stink Bug (C), Assassin Bug (D), Flower Fly Larva (E), Apefly (F), Mantis (G), and Spider (H).

Figure 7: Predatory Beetles Found in Citrus Orchards in Chiang Mai and Lampang Provinces as Subfamily Scymninae (A-C), Subfamily Coccinellinae (D-F).

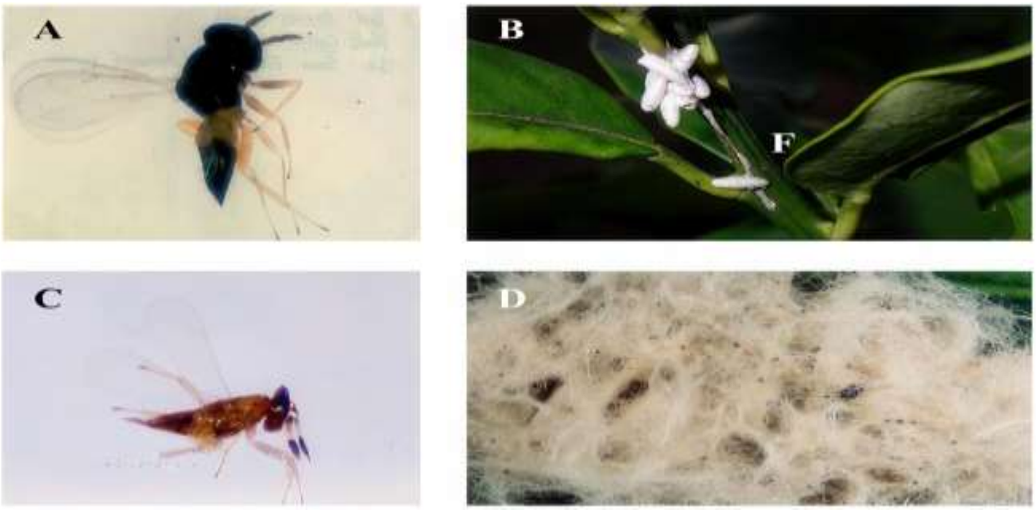

Figure 8: Some Parasitoids Found in Citrus Orchards in Chiang Mai and Lampang Province as Adults of Scale Insect Parasite (A), Cocoon of Bracon Hebetor (B) Adult Black Scale Parasite (C), Egg Parasitoid (D).

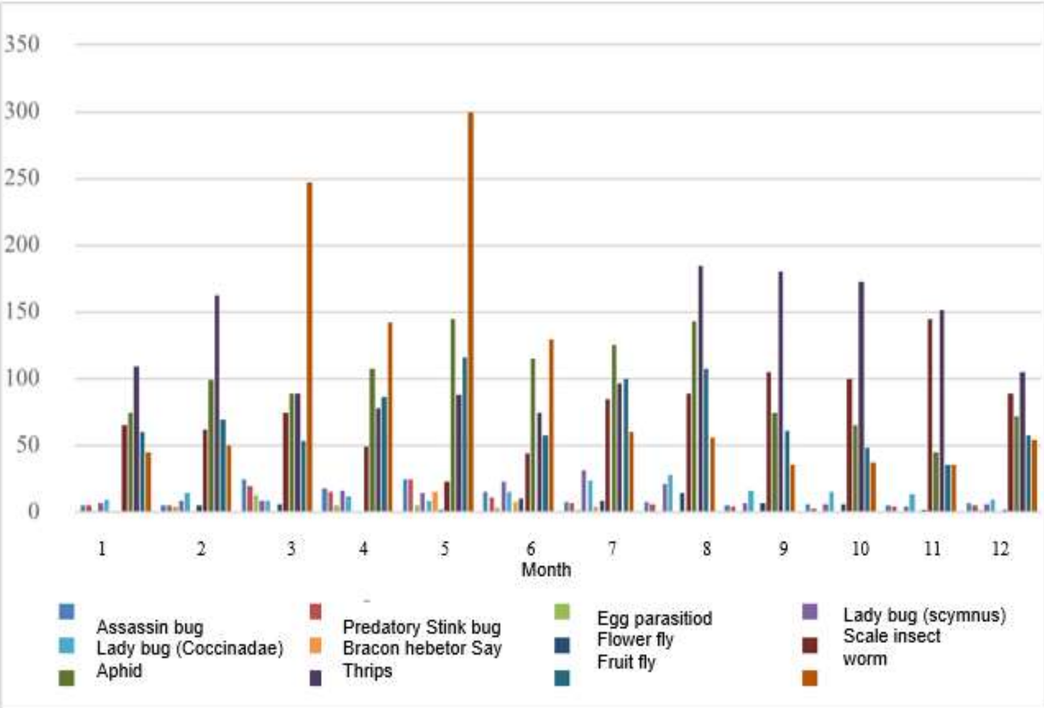

Figure 9: Population Dynamics of Insect Pests and Natural Enemies at 12 Months of Year.

Biology and Predatory Potential of Selected Natural Enemies

The results of the population dynamics and correlation studies indicate that certain natural enemies effectively suppress citrus insect pests in orchards. Predatory bugs and lacewings were identified as key control agents for caterpillars and leaf-sucking insects, respectively. Consequently, the biology of these efficient natural enemies was evaluated to support and enhance IPM programs.

Biology and Feeding Efficiency of Eocanthecona Furcellata

The predator Stink Bug (E. furcellata), from the Pentatomidae family, is effective against pests like the citrus worm. It feeds on 5.62 ±1.33 worms/day and is released at 200 predators/rai to control pests. E. furcellata reproduces sexually, with females laying 10-70 eggs per group and producing 300-500 eggs in 30-40 days. Both larval and adult stages are predatory. Optimal conditions for activation are 25-30°C and 70-80% humidity. Its net reproductive rate (Ro) is 12.17 for orange worms and 8.34 for silkworms, with a generation time of 29.35 ±1.49 days, making it suitable for mass production to control citrus caterpillar pests.

Biology and Feeding Efficiency of Sycanus Collaris

The Assassin bug (S. collaris) from the Reduviidae family is a predator of flower fly caterpillars and shows cannibalistic behaviour. It feeds on 4.25 ±2.14 worms/day and has resistance to insecticides like NPV, spinosad, and indoxacarb. Adults are 10-30 mm long with a slender body and swollen belly, while larvae resemble adults but lack wings. They live singly or in groups on plants and reproduce sexually. Females lay 30-60 eggs/group, producing 150-300 eggs over 6-10 months, hatching in 2 weeks. The biological life table showed a net reproductive rate (Ro) of 15.20 for orange worms and 7.88 for silkworms, with a generation time of 40.35 ±3.49 days, making it suitable for mass production to control citrus worm pests.

Biology and Feeding Efficiency of Mallada Basalis

Green Lacewings (M. basalis, Chrysopidae) larvae are natural predators of citrus pests like aphids, thrips, and citrus rust mites. Adult females lay oval, light green eggs, which hatch in an average of 3.5 days, changing to brown. Larvae have pointed bodies, long, curved jaws, and a white waxy powder coating. The larval stage lasts 10.5 days before transforming into a chrysalis, covered in white fibers. Adults are light green, with red compound eyes, clear wings, and body lengths of 1.55-10 mm for females and 1.20-7.50 mm for males. Females produce 12.5 eggs per time, averaging 125.50 eggs during their life. The life cycle lasts 12.5 days for males and 17.5 days for females. The net Ro is 17.30 for papaya mealybug bait within 40.35 ±3.49 days, making them suitable for mass production to control citrus aphids.

This study examines the distribution of citrus insect pests and natural enemies in Chiang Mai and Lampang provinces, focusing on Integrated Pest Management (IPM). It identifies four main pests: lime butterfly (Papilio demoleus), citrus leaf miner (Phyllocnistis citrella), yellow citrus aphid (Aphis citricola), and thrips (Thrips spp.), which are present year-round and pose a constant threat to citrus crops. The study found 26 species of natural enemies, including Eocanthecona furcellata, Sycanus collaris, and Mallada basalis, that are effective for augmentative biological control. E. furcellata and S. collaris consume 5.62 ± 1.33 and 4.25 ± 2.14 caterpillars per day, respectively, making them valuable for biocontrol in citrus production.

M. basalis proved effective in controlling leaf-sucking pests like aphids and whiteflies, with E. furcellata being the most effective predator overall. The study's data, including a bar graph on predation rates and species diversity using the Shannon-Weiner index, revealed a positive correlation (+0.82) between pests and their natural enemies, highlighting the importance of ecological interactions in pest management. Seasonal pest and natural enemy data confirmed the complexity of effective control, emphasising the value of native natural enemies. This research promotes IPM by reducing chemical pesticide use and supports a sustainable agricultural ecosystem. The IPM framework developed could inform pest control strategies in similar agricultural landscapes globally, supporting biological pest control for sustainable citrus farming in Thailand and beyond.

The study underscores the importance of natural enemies in managing citrus insect pest infestations under an IPM plan. It highlights the role of species diversity, population trends, and the feeding capacity of natural enemies in shaping pest control strategies. Major pests, including the lime butterfly (Papilio demoleus), citrus leaf miner (Phyllocnistis citrella), yellow citrus aphid (Aphis citricola), and various thrips, cause year-round damage to citrus crops. The study confirms that citrus crops are vulnerable to a variety of pests, which have developed resistance to chemical treatments. To address this, IPM strategies, focusing on pest life cycles and behaviours, are essential. The study identified eight genera and 26 species of natural enemies, including Eocanthecona furcellata, Sycanus collaris, and Mallada basalis, which demonstrated high biocontrol efficacy. These predators, particularly E. furcellata and S. collaris, effectively suppress lepidopterous pests, confirming their significant role in regulating citrus pest populations in agro-ecosystems.

The Shannon-Wiener index revealed a direct relationship between many insect pests and their natural enemies, indicating that an increase in pest populations corresponds with a rise in the populations of their natural enemies. This discovery holds significant implications for pest control practices, emphasising the importance of preserving and promoting existing populations of natural enemies in citrus production regions. Measures such as habitat manipulation and reduced pesticide use can enhance these species, thereby helping achieve pest control objectives. Sustainable pest management has become increasingly critical due to the negative consequences associated with chemical pesticide use, including biodiversity loss, pest resistance, and ecological imbalance. This study highlights the potential benefits of promoting IPM approaches that prioritise the use of biocontrol agents.

Citrus farmers can encourage the self-regulation of pests by fostering the natural enemies present in their local environments, thereby reducing reliance on chemicals and promoting ecosystem conservation. Furthermore, as noted in the introduction, IPM programs integrate pest management with GAP and organic farming systems, which also support the preservation of beneficial insects and stress the importance of diversity in permaculture farming systems. With education and training on natural enemies, local farmers can adopt these practices, staying within the recommended conservation techniques for IPM. This study highlights the advantages of using natural enemies while acknowledging the challenges, such as the timing of their release, their ability to establish in fluctuating environments, and the compatibility of biological control with conventional pest management methods. Relying solely on biological control can create imbalances, such as when a natural enemy surpasses its host pest population, potentially leading to new pest issues or the collapse of the natural enemy due to a lack of food. Farmers should also be cautious about the ecological disturbances caused by introducing non-native species. Therefore, the focus should be on enhancing and conserving local natural enemy populations through practices like planting cover crops, creating refuge habitats, and minimising ecosystem disturbance, enabling natural enemies to thrive and manage pest populations effectively.

Suggestions and Scope for Future Research

This study provides a foundation for future research into the interactions between citrus pests and their natural predators. It suggests the need to explore favourable environmental conditions that support the population and diversity of beneficial species in citrus orchards. Further research incorporating climate factors into risk models could help predict pest and predator behaviour, allowing farmers to take preventive actions. Long-term studies are also essential to assess the environmental impact of insect growth and IPM practices. Interdisciplinary collaboration among ecologists, agricultural scientists, and entomologists will lead to comprehensive, sustainable solutions for citrus production. The study highlights the importance of natural enemies in pest control and advocates for increased use of IPM. It also calls for improved communication between researchers, farmers, and policymakers, as well as educational efforts and supportive policies to encourage sustainable citrus farming practices.

Conclusion

A survey of citrus insect pests, conducted alongside an investigation into their natural enemies, revealed a total of 11 pest species: caterpillars from four species, aphids from five species, and one species each of fruit flies and mites. Additionally, 26 species of insect natural enemies were identified, comprising 15 predator species and 11 parasitoid species. Among the natural enemies, the predatory bugs E. furcellata and S. collaris were found to suppress caterpillars, while the lacewing larva, M. basalis, was effective in controlling numerous leaf-sucking insect pests. These species are considered the most promising natural enemies for augmentative biological control in pest management programs. Furthermore, the study highlighted that the diversity and stability of population dynamics were higher in organic citrus orchards compared to those treated with chemicals. This underscores the importance of biodiversity, which plays a central role in the success of various IPM approaches.

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