International Journal of Environmental Sciences
ISSN: 2229-7359
Vol. 11 No. 7, 2025
https://www.theaspd.com/ijes.php

Review On Multi Class Classification Of Coconut Pests And The Corresponding Natural Enemies (Predators And Parasitoids)

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Abstract

Pests pose serious threats to the development of coconuts (Cocos nucifera L.) that impair both production volume and product quality. The sustainability of coconut farming relies on get- ting pest control right by performing exact pest identification as well as finding suitable natural enemies among diseases and parasitoids and predators. This review contains a detailed summary of multi-class identification techniques alongside an organized hierarchy connecting pests to their naturally occurring enemies. This paper examines recent developments in deep learning as well as machine learning through transfer learning and ensemble methods and vision trans- formers and CNNs and SVMs to accurately identify different pest species from visual images. The unbalanced distribution of pests within datasets creates difficulties because cost-sensitive learning suffers under sampling methodology. This work explores natural enemy ecological functions within pest management strategies for integrated pest control (IPC) planning purposes. The compilation of recent research findings through this review demonstrates the successful contribution of automated category systems to pest surveillance as well as control activities. The research presents a model to improve coconut pest management through biological control methods alongside advanced classification systems. The information acquired through this research will promote sustainable pest management practices which integrate natural enemies for efficient pest control systems to develop for improving coconut crop output and welfare.

Keywords: Natural enemies, Predators, Parasitoids, Integrated Pest Management (IPM)

1 INTRODUCTION

Farming is an integral part of life, especially for the farming community, as it occupies a central position in providing livelihood for their survival. It has been a way of life for the researcher's family for many generations. No other human endeavor provides food for humanity. The survival, growth, and development of humanity depend on its ability to provide food for billions of people around the world. Human behavior is influenced by the type and quality of food that people consume. For the last two centuries, inorganic manure or fertilizers have been in use to produce rich crops for feeding the growing number of populations in the world. However, the practice of using fertilizers has resulted in leaving the chemicals in the food that we consume. To meet the increasing demand for food with the rising population, and to provide food security for millions of people around the world, inorganic fertilizers and artificial chemicals were used. The consumption of such food began to show its effect on humans causing health issues and deterioration of organs in the body. The situation has become so alarming that people have started showing an inclination to consume organic food. With the growing awareness and demand for organic food, it is essential to find out different ways and means to produce healthy and organic food. Switching over to the organic ways of growing food from artificial ways of food production. However, such a sudden transition may lead to a shortage of food as the yield with the use of organic farming methods cannot produce food in large quantities like the artificial methods of food production.

In addition to fertilizers, potentially harmful agrochemicals were used to protect the yield from pests and weeds. Though these agrochemicals helped protect crops and produce optimum yields, they led to unexpected problems. The residues of such harmful pesticides and herbicides were found in the food, causing long-term health issues for people. Eventually, health issues like organ failures were traced to the consumption of food that had chemicals. Organic food is considered healthier than the food produced with the use of synthetic chemicals. As a result, there has been a growing interest in the organic ways of farming as it is healthier for people and there has been a rise in the demand for the same. However, switching over the to the organic methods is not easy after being accustomed to the use of fertilizers for over decades. The soil and the ecosystem have to regain its fertility and recover from the long abuse of chemicals [1]. The soil fertility remains depleted with the long use of fertilizers and synthetic chemicals. The transition towards organic methods poses many challenges to farmers like sudden drop in the yield of crops and financial losses. They need to find different ways and means and carefully plan their farming methods that include using compost, crop rotation and natural pest control methods. However, all the challenges can be addressed with careful planning, timely measures and applying the scientifically proven methods of farming. Organic farming methods are nature-friendly and healthy. Whereas, the use of fertilizers and synthetic chemicals causes loss of biodiversity in addition to harming humans and soil. In the ecosystem, every living organism has its role in keeping the ecosystem balanced.

In the ecosystem, every living organism has a role to play, and every species has natural enemies that help keep populations in check. For instance, predators act as natural controllers for pest popu- lations. Predators like ladybugs, spiders, and some birds survive on pests, which will have a negative impact on crops. It is essential to protect these natural enemies of pests by reducing the use of harm- ful agrochemicals, as these natural enemies play a significant role in sustainable organic farming. In addition, following best practices like companion planting, crop rotation and using organic compost can help strengthen the crops from pests and other diseases. Horticulture farming focuses on crops that have a longer growth cycle spanning several years. Many fruit trees like mango, avocado, and cashew, nut crops like areca nut, coconut, and almonds, and plantation crops like oil palm, cocoa, and cinnamon have life cycles for years. Horticulture crops need more time and investment before they yield produce. The long lifecycle is one of the reasons for their vulnerability to pests and other dis- eases over time. The pests that attack horticulture crops have longer life spans and require strategic management.

1.1 Pest Dynamics in Agriculture vs. Horticulture

Agricultural crops have shorter life spans, and the pests need to be controlled quickly within a short period of time to save the crop. Otherwise, the entire crop gets damaged and lost. Many farmers depend on chemical pesticides as an immediate solution for pest control. On the other hand, organic farming methods depend on natural pest control strategies like using bio-pesticides and predators. Horticultural crops, owing to their longer life cycle, experience chronic pest infestations. The pests get more time to establish firmly and adapt to the conditions of the horticulture crops. It requires integrated pest management (IPM) to introduce predator species and ensure biodiversity to control the pests in a natural way. Coconut is a popular commercial horticulture crop in the world, well- known for its versatile use around the world. It is grown in tropical and subtropical regions, often on the coastal seashores. Coconuts are consumed in multiple forms, such as fresh coconut water, copra (dried kernel), coconut oil, and other coconut-based products like milk, flour, and coir.

1.2 Pesticide Usage and Its Consequences

Coconut farmers often use heavy pesticides to protect the coconut trees from different types of pests as the coconut crop is vulnerable to several pests. The pests include rhinoceros beetles, red palm weevils, and eriophyid mites, which cause severe damage to coconut yield. Indiscriminate use of harmful chemical pesticides has become a normal practice among many coconut farmers. However, the use of high-power chemical pesticides causes many health issues as the residues and sediments of the chemicals still remain in the coconut food products. The consumption of contaminated coconut food products leads to serious health hazards for many people. In addition to causing health problems, they also harm the environment by polluting soil, water, and the surrounding ecosystems.

1.3 The Role of Natural Enemies

Natural pest control strategies are better and healthier than chemical pesticides. Nature has a perfect system to maintain equilibrium and every pest has a natural predator to feed on it. The commonly found predators on coconut trees are parasitic wasps, predatory beetles, and birds. Natural predators are not only effective but also eco-friendly for pest control.

1.4 Challenges in Identifying Predators

One of the major challenges is the lack of awareness among farmers about the natural pest control methods. Farmers are not able to distinguish between harmful and unharmful insects as they look very similar in appearance. For example, predatory beetles which feed on pest larvae look like harmful beetles. In the same way, parasitic wasps which lay eggs in pests are unharmful, but farmers may not be able to know this difference. During the farm visits and interactions with farmers, the researcher has understood that farmers are not aware of specific predators that can help the coconut crops.

1.5 The Need for Farmer Education

Educating farmers about the natural pest control methods like identifying natural predators plays a vital role in pest control. It also prevents dependence on chemical pesticides. Awareness among farm- ers can be created through different ways like visual guides, practical demonstrations and training. In addition to identification, awareness about how to attract natural predators and strengthen their presence is required. Planting flowering plants, installing bird perches can be helpful in attracting natural predators. Integrated Pest Management (IPM) that aims at adopting holistic and sustainable approach is vital. Promoting natural predators plays an important role in achieving the above goal. The effective management of pests in horticultural crops, especially coconut (Cocos nucifera L.), is a critical area of research, keeping the global demand for coconut products. Pests pose a significant threat to coconut crop yield and quality, causing problems of food security globally [2]. Identifica- tion and classification of pests are critically important for developing a sustainable pest management strategy. With the support of the latest machine learning techniques, the present paper focuses on the multi-class classification of coconut pests along with the hierarchical classification of their corre- sponding natural enemies for an efficient pest management strategy. Identification and classification of pests gain significance with the rise of invasive pest species, climate change, and the growing resis- tance of pests to conventional chemical control methods [2][3]. Producing high quality coconut yield while keeping environmental sustainability with innovative methods of technology occupies a crit- ically important place in the research. IPM strategies with biological control methods are gaining greater importance as they are environmentally friendly alternatives to chemical pesticides [4][5].

The scope of the paper is limited to a review of literature on the current status of pest classification methodologies, especially about coconut pests and their natural enemies, with a special focus on Machine Learning (ML) and Deep Learning (DL) applications. The objectives of this study are threefold: first, to explore the advances in multiclasssification techniques; second, to examine the hier- archical classification of natural enemies; and third, to assess the implications of these methodologies for improving pest control strategies in horticultural cropscrops, specifically coconut [2] [3].

This paper is structured as follows: it begins with a literature review that outlines the significance of pest classification in agriculture and the challenges associated with traditional methods. Next, we delve into the methodologies employed in recent studies, highlighting the usage of ML & DL techniques in enhancing classification accuracy. Next, the study presents illustrative examples for practical applications of these techniques in the ground level. The paper highlights the research gap and stresses the need for integrating the latest technologies into the current pest management strategies [2][3]. Finally, we conclude that addressing these important aspects occupies a significant position in the current discussion on sustainable agriculture and the role of the latest technologies in dealing with the effective pest classification and control especially with a special focus on coconut production.

2 BACKGROUND OR RELATED WORK

Over the year, pest management relied on the use of chemical pesticides which produced adverse effects like pest resistance, health issues to the consumers, ecological imbalances and harmful impact on the non-target organisms [6][7]. The growing awareness among people about the harmful effects of chemical pesticides is gradually shifting the focus on more sustainable methods with an emphasis on natural enemies, bio-pesticides and beneficial insects for effective pest control [8][9]. Research has shown that enhancing the variety of friendly insects can significantly reduce pest populations, thereby supporting sustainable agricultural practices [10][11]. Recent advancements in technology, particularly in ML and image processing, have revolutionized pest identification and classification. Automated systems utilizing deep learning techniques, such as transfer learning, ensemble techniques, vision transformers, CNNs and SVMs, have resulted high accuracy in identifying various pest species from images [12][13]. These technologies help in providing timely interventions and developing more effective Pest Management strategies with real time data on pest populations [14][15].

Interdisciplinary approach like combining Deep Learning methodologies combined with ecological principles offers new space for research on pest control. This approach will help in integrating the recent research findings on pests and the role of the natural predators. Research has highlighted the necessity of understanding the relations between harmful pests and their natural enemies and their natural dynamics [16][17]. There is extensive documentation on the role of habitat manipulation and the use of pheromones and allelochemicals in strengthening biological control agents [18][19]. On the technological front there has been growing research on the role of ML and DL in studying pest out- breaks and effective control methods. The predictive models developed by the recent algorithms help in identifying patterns and taking timely decisions for sustainable agricultural practices [20][21]. The field of pest control is shifting towards technology driven solutions from the use of heavy chemicals for pest control. Integrating biological control methods with advanced ML and DL techniques offers a promising solution for effective pest control on coconut crops leading to sustainable agricultural practices [22][23].

Classifying pests in agriculture, especially in coconut crops is a critical area for research. The focus on this area has been steadily growing over the years in search of better pest control methods. IPM is a promising approach that combines different methods for a holistic approach in pest control. This approach is particularly relevant for coconut cultivation for overcoming the substantial challenges posed by pests [24][25].

2.1 Terminology and Concepts

Integrated Pest Management (IPM) is a sustainable approach to managing pests in different ways. It focuses on the use of multiple strategies to reduce the count of pests and excessive dependence on chemical pesticides. IPM uses different ways like incorporating biological control methods, supporting friendly insects and natural predators, parasitoids and bio-pesticides to control pest populations [24][25]. The effectiveness of IPM depends on understanding the life stages and behaviors of both pests and their natural enemies for taking decisions on pest control measures [25]. Biological Control is a vital approach in IPM as it involves natural enemies to manage pests. It also includes supporting the involvement of predators or parasitoids that specifically target pest species to reduce pests without harming non-target organisms [24][26]. For example, research has identified that baculoviruses are effective biological agents for controlling lepidopteran pests [27].

2.2 Machine and Deep Learning Techniques

Recent evaluations in ML and DL have shown promising results in pest detection and classification. These methodologies leverage large datasets and sophisticated techniques to automate the detection and classification of pests and their natural enemies. For example, the predefined architectures with transfer learning have been widely adopted for image classification tasks due to their ability to feature representations from raw pixel data [28][29]. CNNs have shown superior performance in identifying fine-grained features of pests, which is crucial for accurate classification [28][29]. SVMs, KNNs and Decision trees are popular ML techniques used for classification tasks. Particularly, these have proven highly useful in high-dimensional spaces where the number of dimensions are greater than the number of samples [29][30]. The integration of SVMs, KNNs and Decision trees with CNNs has been studied in detail to improve the accuracy levels of classification, especially in complex datasets.

2.3 Challenges in Pest Classification

The field of pest classification poses many challenges in spite of the developments in technology. The presence of imbalanced datasets is a significant problem with the underrepresentation of certain pest species causing biased classification results [2][31]. To overcome this challenge certain techniques like cost-sensitive learning and under-sampling were proposed to rectify the errors and train the mod- els on balanced datasets [2][31]. Integrating the latest machine learning technologies into practical agriculture needs to consider some vital factors. The factors include the adaptability of models to ground-level conditions, farmer-friendliness, and cost-effectiveness [25][32]. Efficient predator detec- tion and classification systems applying the latest technologies will have a significant impact on pest control, improving crop yields and environment protection [32][33].

Workers have made significant progress in integrated pest management (IPM) tactics throughout the years particularly for sustainable agricultural practices. A successful pest management system requires scientists to understand thoroughly all elements of their subjects including pests and friendly insects together with natural enemies such as parasitoids diseases and predators. Different research investigations have studied various IPM aspects by highlighting cultural methods together with bio- logical control practices and modern technology implementation. A significant survey investigates pest management methods that farmers use for growing beetroot. The article reviews multiple Inte- grated Pest Management methods including biological control and cultural approaches to evaluate their effectiveness in pest population management [34]. Afandhi (2020) studied IPM approach sus- tainability in rice farming through a study of Indonesian agricultural practices. The research studies demonstrate why farmers adopt IPM practices based on their socio-economic conditions [35].

Researchers recorded IPM methods together with agricultural understanding of vegetable growers residing in the Rupandehi District of Nepal. A training program demonstrates to farmers how they can learn better about integrated pest management (IPM) solutions for pest control [36]. AI- driven tools, which is useful for increasing farming systems, enhance predictive models for increase food demands and integration with enhanced IOT. The goal to optimize inputs (water, pesticides, fertilizer) and maximum sustainability an advanced method of farming Precision agriculture tech- niques are used [37]. The implementation of IPM approaches by vegetable farmers in West Sumatra received study from Sari et al. (2016) who documented both successful and challenging aspects of this practical application [38]. The implementation of AI-based pest management techniques has widened into a popular practice. Research on cotton pest control using AI methods exhibits how AI systems can enhance identification as well as classification of pests [39]. Modern ensemble techniques prove their effectiveness for accurate stored grain pest classification according to research findings [40].

Scientists have extensively studied the functionality of biological control agents that include parasitoids, predators, and infections. Evidence of sustainable pest management techniques exists through the difficulties that arise alongside the possibilities for using parasitoids as biocontrol agents in the Neotropical region [41]. The effectiveness of various biological control methods continues to be investigated because researchers understand these methods should form a crucial part of integrated pest management systems [42].

3 PROBLEM STATEMENT

For correct identification of pests, predators and parasitoids, farmers need to have basic knowledge.

3.1 Classification of Major Pests of Coconut

To address the challenge of pest identification, We need to focus on classifying 12 major pests that affect coconut crops. Effective pest identification requires classification of twelve major pests that affect coconut crops. The process includes creating datasets with clear images of diverse range of pests on coconut trees. It necessary to cover all the stages of growth of pests in the images. The next step in the process is the training of classification models like Convolutional Neural Network (CNN). It is found that frameworks like TensorFlow or PyTorch. Models like ResNet or InceptionV3 are best suited for capturing fine-grained features. At the same time, it is crucial to maintain high accuracy precision levels to avoid misclassification. The final step is creating a user-friendly application to enable farmers to upload an image of a pest and identify it and get immediate control methods.

3.2 Multi-Class Classification of Pests

Multi-class Classification requires advanced object detection. Creating a data set of images with labels and annotations using either LabelImg or Roboflow. It also includes training CNN's to recognize all 12 pests individually. Developing a systematic workflow starting from the collection of images, processing the images and training the model. An edge-deployable pest detection system based on convolutional neural networks (CNNs) and deep learning models for real-time monitoring and pest infestation early detection is the premise [43]. Finally sending alerts to farmers with all the required information through connected application.

3.3 Multi-Class Classification of Predators with a GUI Application

Identifying predators is vital for effective natural pest control. The researchers recommend the following steps: A) capturing images of all predators for the identified pests with all their variations in appearance and behavior. B) building a pest classification model specifically designed for accurate identification of predators without getting confused with pest which sometimes look alike. C) Creating a user-friendly interface for farmers to upload pest images and information. The GUI retrieves cor- responding predator details with images, descriptions, and guidelines for attracting them. It ensures that farmers get detailed information for effective pest management. Finally, embedding multimedia content in the application for easy education of farmers about each predator.

3.4 Hierarchical Classification of Predators, Parasitoids and pathogens

This phase deals with differentiating between the key categories of natural pest con- trollers—predators, parasitoids and pathogens. Using a hierarchical classification approach is best suited for this task. The process has two levels: 1: Classifying predators (organisms that directly con- sume pests) and parasitoids (organisms that lay eggs in or on pests, leading to their destruction), 2: subcategorizing predators and parasitoids based on species, behavior, and target pests. Designing a model using hierarchical method to record loss functions like combination of CNNs or decision- tree- based classifiers, to deal with layered classification tasks. Data Annotation: Building a dataset where labels reflect the hierarchy (e.g., Predator ¿ Beetle ¿ Ladybird or Parasitoid ¿ Wasp ¿ Trichogramma). System Output: Providing structured information to farmers, showing the pest, its natural enemies, and their specific category (predator or parasitoid), with practical advice for field application. The entire process flow chart is shown in figure no. 1.

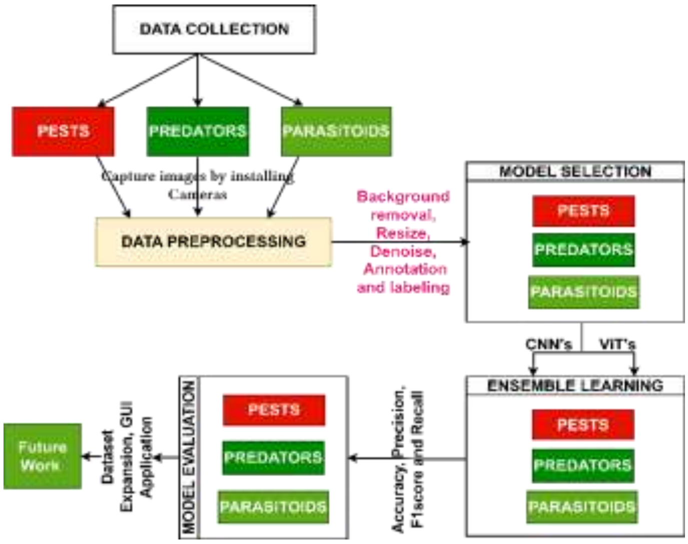

Figure no. 1 Overview of the research methodology

3.5 Methodologies

Recent advancements in methodologies for pest detection and classification have been significantly influenced by ML and DL. These methodologies leverage large datasets and sophisticated techniques to automate the detection and classification of pests and their natural enemies. The predefined archi- tectures with transfer learning have been widely adopted for image classification. Recent technologies like transfer learning, ensemble techniques and vision transformers have been employed to enhance the accuracy of pest and predator identification and classification [44]. With increasing agricultural demands worldwide, the capacity for the implementation of good pest management practices becomes even more essential. Pests reduce the yield, compromise the quality and possible total failure of these long term plants like coconut, inducing substantial economic loss for farmers and affecting food supply chain globally [32][45].

Table 1: Natural enemies of coconut pests across life stages

Pest Name	Life Stage	Predators	Parasitoids
1.Rhinoceros beetle	Egg	Scolia oryctophaga (Scarabid wasp)	Scolia oryctophaga (Scarabid wasp)
		Tiphia spp. (Tiphiid wasp)	Tiphia spp. (Tiphiid wasp)
	Larva	Scolia oryctophaga (Scarabid wasp)	Scolia oryctophaga (Scarabid wasp)
		Tiphia spp. (Tiphiid wasp)	Tiphia spp. (Tiphiid wasp)
	Adult	Scolia oryctophaga (Scarabid wasp)	Scolia oryctophaga (Scarabid wasp)
		Tiphia spp. (Tiphiid wasp)	Tiphia spp. (Tiphiid wasp)
2. Red palm weevil	Egg	Paratheresia claripalpis (Tachinid fly)	Paratheresia claripalpis (Tachinid fly)
		Dirhinus giffardii (Braconid wasp)	Dirhinus giffardii (Braconid wasp)
	Larva	Dirhinus giffardii (Braconid wasp)	Dirhinus giffardii (Braconid wasp)
		Paratheresia claripalpis (Tachinid fly)	Paratheresia claripalpis (Tachinid fly)
	Adult	Paratheresia claripalpis (Tachinid fly)	Paratheresia claripalpis (Tachinid fly)
		Dirhinus giffardii (Braconid wasp)	Dirhinus giffardii (Braconid wasp)
3. Bark weevil	Egg	Theocolax elegans (Eulophid wasp)	Theocolax elegans (Eulophid wasp)
		Anisopteromalus calandrae (Pteromalid wasp)	Anisopteromalus calandrae (Pteromalid wasp)
	Larva	Theocolax elegans (Eulophid wasp)	Theocolax elegans (Eulophid wasp)
		Anisopteromalus calandrae (Pteromalid wasp)	Anisopteromalus calandrae (Pteromalid wasp)
	Adult	Theocolax elegans (Eulophid wasp)	Theocolax elegans (Eulophid wasp)
		Anisopteromalus calandrae (Pteromalid wasp)	Anisopteromalus calandrae (Pteromalid wasp)
4. Shot hole borer	Egg	Eupelmus spp. (Eulophid wasp)	Eupelmus spp. (Eulophid wasp)
		Spathius spp. (Braconid wasp)	Spathius spp. (Braconid wasp)
	Larva	Eupelmus spp. (Eulophid	Eupelmus spp.

		wasp)	(Eulophid wasp)
		Spathius spp. (Braconid wasp)	Spathius spp. (Braconid wasp)
	Adult	Eupelmus spp. (Eulophid wasp)	Eupelmus spp. (Eulophid wasp)
		Spathius spp. (Braconid wasp)	Spathius spp. (Braconid wasp)
5. Black-headed caterpillar	Egg	Trichogramma chilonis (Egg parasitoid)	Trichogramma chilonis (Egg parasitoid)
		Goniozus nephantidis (Bethylid wasp)	Goniozus nephantidis (Bethylid wasp)
	Larva	Bracon brevicornis (Braconid wasp)	Bracon brevicornis (Braconid wasp)
		Goniozus nephantidis (Bethylid wasp)	Goniozus nephantidis (Bethylid wasp)
	Adult	Bracon brevicornis (Braconid wasp)	Bracon brevicornis (Braconid wasp)
		Goniozus nephantidis (Bethylid wasp)	Goniozus nephantidis (Bethylid wasp)
6. Slug caterpillar	Egg	Chelonus spp. (Chelonid wasp)	Chelonus spp. (Chelonid wasp)
		Bracon hebetor (Braconid wasp)	Bracon hebetor (Braconid wasp)
	Larva	Chelonus spp. (Chelonid wasp)	Chelonus spp. (Chelonid wasp)
		Bracon hebetor (Braconid wasp)	Bracon hebetor (Braconid wasp)
	Adult	Chelonus spp. (Chelonid wasp)	Chelonus spp. (Chelonid wasp)
		Bracon hebetor (Braconid wasp)	Bracon hebetor (Braconid wasp)
7. Bag worm	Egg	Tachinid flies (e.g., Apolysis albicollis)	Brachymeria spp. (Chalcid wasp)
		Parasitic wasps (e.g., Tachinae spp.)	Hymenoptera (various species)
	Larva	Birds (e.g., crows, blackbirds)	Brachymeria spp. (Chalcid wasp)
		Predatory beetles (e.g., Calosoma spp.)	Tachinid flies (e.g., Apolysis albicollis)
	Adult	Birds (e.g., crows, blackbirds)	Brachymeria spp. (Chalcid wasp)
		Predatory beetles (e.g., Calosoma spp.)	Tachinid flies (e.g., Apolysis albicollis)
8. White grub	Egg	Ants (e.g., Formicidae)	Hymenoptera (various species)
		Nematodes (e.g., Heterorhabditis bacteriophora)	Hymenoptera (various species)
	Larva	Nematodes (e.g.,	Hymenoptera (various

		Heterorhabditis bacteriophora)	species)
		Predatory beetles (e.g., Calosoma spp.)	Hymenoptera (various species)
	Adult	Ants (e.g., Formicidae)	Hymenoptera (various species)
		Nematodes (e.g., Heterorhabditis bacteriophora)	Hymenoptera (various species)
9. Coconut skipper	Egg	Tachinid flies (e.g., Apolysis albicollis)	Tachinid flies (e.g., Apolysis albicollis)
		Predatory wasps (e.g., Trichogramma spp.)	Trichogramma spp. (Egg parasitoid)
	Larva	Predatory wasps (e.g., Trichogramma spp.)	Tachinid flies (e.g., Apolysis albicollis)
		Tachinid flies (e.g., Apolysis albicollis)	Trichogramma spp. (Egg parasitoid)
	Adult	Birds (e.g., crows, blackbirds)	Tachinid flies (e.g., Apolysis albicollis)
		Predatory wasps (e.g., Trichogramma spp.)	Trichogramma spp. (Egg parasitoid)
10. Lacewing bug	Egg	Ladybugs (e.g., Coccinella septempunctata)	Trichogramma spp. (Egg parasitoid)
		Predatory beetles (e.g., Calybites spp.)	Tachinid flies (e.g., Apolysis albicollis)
	Larva	Ladybugs (e.g., Coccinella septempunctata)	Tachinid flies (e.g., Apolysis albicollis)
		Predatory beetles (e.g., Calybites spp.)	Trichogramma spp. (Egg parasitoid)
	Adult	Birds (e.g., crows, blackbirds)	Tachinid flies (e.g., Apolysis albicollis)
		Ladybugs (e.g., Coccinella septempunctata)	Trichogramma spp. (Egg parasitoid)
11. Scale insect	Egg	Lacewing larvae (e.g., Chrysopa spp.)	Encarsia spp. (Encyrtid wasp)
		Predatory beetles (e.g., Scymnus spp.)	Aphytis spp. (Encyrtid wasp)
	Larva	Lacewing larvae (e.g., Chrysopa spp.)	Encarsia spp. (Encyrtid wasp)
		Predatory beetles (e.g., Scymnus spp.)	Aphytis spp. (Encyrtid wasp)
	Adult	Lacewing larvae (e.g., Chrysopa spp.)	Encarsia spp. (Encyrtid wasp)
		Predatory beetles (e.g., Scymnus spp.)	Aphytis spp. (Encyrtid wasp)
12. Coreid bug	Egg	Erythmelus spp.	Erythmelus spp. (Hymenopteran egg)
	Larva	Spider predators	-
		Reduviid bugs (Assassin	-

		bugs)	
	Adult	Ophionea spp. (Ground beetle)	-

The effectiveness of chemical pesticides in short-term pest control creates environmental side effects that include pest resistance along with damage to other organisms and soil and water con- tamination [46][47]. People have raised questions about sustainability because of overuse of select substances. The urgent requirement for IPM strategies requires pairing modern AI and ML with DL technologies with biological control practices [48][49].

The advent Vision transformers offers promising avenues for improving pest detection and classi- fication. However, the implementation of these technologies in real-world agricultural settings faces several challenges. For instance, many existing pest detection systems struggle with issues related to data quality, model interpretability, and the ability to generalize across diverse agricultural environments [50][51]. Additionally, the integration of these advanced technologies into traditional farming practices requires significant changes in farmer behavior and training, which can be met with resistance [52][53].

Effective management plan development requires superior understanding of these dynamics because pest ecosystems along with their pest-natural enemy relationships prove complex [54][55]. Machine learning model training faces an obstacle because research databases for pests and their natural enemies are limited in size [56][57]. In light of these challenges, this research aims to address the following key questions:

How effectively these DL can be utilized to enhance the classification and identification of coconut pests and their natural enemies?

What are the ecological implications of integrating biological control methods with advanced technological solutions in pest management?

How can the adoption of these integrated approaches be facilitated among farmers to ensure sustainable agricultural practices?

By exploring these questions, this study seeks to the development of more effective and sustain- able pest management strategies that leverage both biological control and advanced technological solutions, ultimately enhancing the resilience of coconut and horticultural crop production systems [58][59].

4 SURVEY OF LITERATURE

4.1 Classification

Basic IPM operations require proper identification of pests as well as their natural enemies to guaran- tee effective pest control methods. The study of pest taxonomy has centered on insects which attack horticulture plants as well as agricultural crops including coconuts. It demonstrates that molecular techniques are better than traditional morphological methods for identifying pests [4]. The taxonomy of pests includes their natural enemies such as parasitoids and predators since these enemies are vital for biological pest control methods. AI approaches help manage diseases together with insect pests while pushing the integration of pest and natural enemy taxonomic information into IPM practices [39]. For effective pest management, it is essential to combine both biological and chemical control methods for classification of pests.

DNA barcoding as a diagnostic tool has gained importance for effective pest management to identify pest specifies [60]. AI-driven mobile applications for immediate pest monitoring have immense potential for pest management in viticulture [61]. Furthermore, the use of molecular techniques such as DNA barcoding and metagenomic sequencing plays a significant role in understanding pests and their interactions with natural enemies. For example, on the gut microbiome of the diamondback moth indicates how molecular insights can prove to be useful for pest management strategies [62].

4.2 Trends and Advances

The current trends in pest management research are more inclined towards sustainable and integrated approaches combining both traditional methods and advanced technologies. The increasing use of AI and machine learning in the classification of pests suggests the introduction of precision agriculture with data-driven decisions. The systematic review indicates the growing use of AI technologies for pest detection and management. It also indicates the need for more research for continuous innovation and development in this field [39]. However, there are potential challenges like obtaining accurate datasets for interpreting models. Dependence on inaccurate and imbalanced datasets for training advanced DL models can lead to biased results [44]. Additionally, the integration of these technologies into traditional farming practices meets with challenges like resistance to change, and lack of awareness in farmers.

In conclusion, the literature indicates that the field of pest research is dynamic and rapidly evolving field with research focused on the detection, classification, methodologies, and trends in pest control. The advanced use of technologies with traditional practices presents a promising pathway for addressing the challenges faced in agricultural pest management.

4.3 Synopsis of Comparative Research

General and specific topics related to pest management and natural farming education and IPM education together with research on beetroot, rice, tomato, maize and citrus crops are covered in the papers.

Multiple research methods used by scientists in this discipline include systematic reviews together with field experiments and surveys and genomic analyses and other research techniques.

AIML and DL systems should be employed for the complementarity of biological control approaches using improved extension services which is critical for sustainable and long-term management of pests.

Approaches to pest management in agriculture is an inherently complex issue, and research into it is necessarily about complexity with agricultural minds trying to spread [conveniently], sustainable efficient plans

5 CRITICAL DISCUSSION OR ANALYSIS

The survey of literature on Integrated Pest Management (IPM) indicates that there are different approaches and methodologies to address the problem of pests. The present study presents a critical analysis of the strengths and weaknesses of different approaches and highlights their implications for sustainable agricultural practice. Strengths of Different Approaches

5.1 IPM Modules

The research studies of Priyanka et al. (2023) and Reddy et al. (2023) demonstrate the effectiveness of various IPM modules in managing specific pests. The pests included in the study were sucking insects in groundnut and fall armyworm in maize. The literature indicates that localized solutions for farmers are essential for understanding pests and their control as a part of IPM strategies. The localized strategies have shown a remarkable reduction in pest control and an increase in yield [73][74]. As part of Integrated Pest Management, Farmer Field Schools (FFS) have positively impacted farmers' awareness of pests and their control. It has led to sustainable practices, as stated by Hassanpour and Saeidi (2020) [75]. The FFS approach has proved useful in creating awareness among the farming community for making effective decisions in pest control.

5.2 Vulnerability and difficulties

Resistance to change is one of the significant challenges to introducing new ways to deal with pest management. Transitioning to sustainable practices from traditional methods faces resistance from farmers. There are several factors for resistance from farmers due to their lack of awareness, doubtfulness about new methods, and habitual dependence on chemical pesticides. Understanding the local problems and practices is essential for the effective implementation of innovative pest management methods [76].

Economic viability is another critical challenge when introducing new methods of pest management. Though IPM strategies have promising environmental benefits, they prove costly to farmers, especially for smallholders with limited resources [74][77]. Hence, it is essential to ensure that the new IPM practices are not costly and within the reach of smallholders.

Regulatory frameworks and policies often guide the farming community. Hence, it is necessary to make the required changes to the policies for the effective implementation of IPM. Supportive policies that encourage natural methods are necessary to avoid synthetic pesticides [78]. The lack of clear policies has reduced the impact of IPM, as revealed in the literature. An integrated approach combining traditional methods and modern technologies should be considered when designing sup- port policies. Hence, challenges like suitable data quality, farmer adoption, economic viability, and regulatory frameworks must be addressed for effective IPM.

5.3 Finding Literary Gaps

The research literature on Integrated Pest Management (IPM) records progress in pest control strate- gies over the years, though there are some gaps. These gaps hinder the effectiveness of IPM practices and the development of sustainable agricultural systems. This section identifies areas for further research for effective implementation of IPM.

Table 2: Recent studies on pest management practices and innovations

Citation	Title	Authors	Year	Focus Area	Methods	Key Findings
[34]	Integrated pest Management in beetroot cultiva- tion: A systematic review	Singh et al.	2024	IPM in Beetroot	Systematic review Of IPM strategies	Evaluates biological control, cultural practices, and chemical interven- tions tailored for beetroot farming.
[63] Sheikh Gouse et al., 2025	CNN-Driven Ensemble Model for Rice Pests, Dis- eases and Weeds classification and detection from whole rice plant images.	Sheikh Gouse et al.,	2025	Rice dis- eases, pests, and weeds	Hybrid deep learning framework	Proposed system achieves a classifi- cation accuracy of up to 98.50%. It incorporates deci- sion support based on integrated pest management and economic thresh- olds.

[64] Chowd- hurry et al., 2023	Natural Farming Boosts Coccinelid Abundance and Suppressing Rice Leaf Folder	S. Chowd- hurry et al.	2023	Natural Farming	Field experi- ments, ecological engineer- ing	Highlights effec- tiveness of natural farming in enhanc- ing predator abundance and reducing pest popu- lations.
[65] (Kumar et al., 2021)	Characterization of Organic, Inorganic and Integrated Farming Prac- tices for Livelihood Assessment	S. Kumar et al.	2021	Farming Practices	Descriptive statistics	Assesses impact of farming practices on livelihoods in Jammu region.
[36] (Thapa, 2017)	Survey of Inte- grated Pest Management (IPM) Practice in Veg- etable Crops	C. Thapa	2017	IPM in Vegeta- bles	Semi- structured interviews	Documents farm- ers' knowledge and practices on veg- etable IPM.
[66] (Kafle et al., 2024)	Farmers' percep- tion and adoption of management practices against tomato damage by tomato leaf miner	Santosh Kafle et al.	2024	Tomato Pest Man- agement	Survey	Investigates farm- ers' practices and perceptions on Tuta absoluta.
[67] (Rijal et al., 2018)	Farmers' Knowl- edge on Pesticide Safety and Pest Management Prac- tices	J. Rijal et al.	2018	Pesticide Safety	Household survey	Highlights edu- cation needs on pesticide safety and IPM.
[68] (Bas- Takoti et al., 2024)	Comparative analy- sis of knowledge and management prac- tices of insect pests of maize	Bipin Bastakoti et al.	2024	Maize Pest Man- agement	Primary and sec- ondary data col- lection	Compares IPM adopters and non- adopters.
[69] (Bhattarai et al., 2022)	Perception of Farm- ers on Handling Pesticide and Adop- tion of IPM	Bhattarai et al.,	2022	Pesticide Handling	Focus Group Discussion	Examines percep- tions and IPM adoption.

[70] (Magar et al., 2024)	Farmer knowledge on insect pests of Citrus and their management	Sudip Bhujel Magar et al.	2024	Citrus Pest Management	Semi-structured interviews	Assesses farmers' knowledge of citrus pests and management.
[39] (Toscano-Miranda et al., 2022)	AI and sensing techniques for pest and disease management in cotton	R. Toscano-Miranda et al.	2022	AI in Pest Management	Systematic literature review	Focuses on AI-based classification and feature extraction.
[71] (Xin Et al., 2020)	Exploratory Survey of Spotted Lantern- fly and Its Natural Enemies in China	Bei Xin et al.	2020	Lanternfly Management	Field surveys	Identifies natural enemies with biocontrol potential.
[72] (Yang et al., 2020)	Immune signaling pathways in the endoparasitoid, Pteromalus puparum	Lei Yang et al.	2020	Biological Control	Genomic analysis	Identifies immune-related genes in parasitoids enhancing biocontrol.
[63] Sheikh Gouse et al., 2025	Hybrid CNN-Attention Framework with Texture Feature Fusion for Multi-Label Detection of Co-Infections in Rice Leaves.	Sheikh Gouse et al.,	2025	Co-Infections In Rice Leaves	Hybrid CNN attention	The model is Trained on a dataset of rice leaf images categorized into diseases and pests, with multi- label annotations representing potential co-infections.

The survey reveals that farmers lack a proper understanding of ecological interactions. Comprehensive knowledge of the biology and ecology of invertebrate pests and their natural enemies, is found lacking [79]. This gap in knowledge reduces the impact of IPM strategies. Further research is necessary to understand the factors leading to pest outbreaks and the role of natural enemies in pest control.

The economic viability of these IPMs needs to be studied further to determine economically feasible practices for effective pest management. The initial cost of implementing IPM is hindering many smallholders [80]. Further research on comprehensive economic analysis and viability proves helpful in finding the best economic ways to implement IPM. In addition, socio-economic factors that influence IPM must be explored further from the effective implementation and sustainable practices. Another vital area for future research is the development of resistance among pest populations to chemical control methods. The literature indicates a lack of a comprehensive framework to integrate resistance of pest population into IPM strategies. In addition, there is a need for public-supported financial incentives to encourage the adoption of IPM practices to reduce resistance development [81]. Further research is required to develop effective resistance management strategies in the IPM framework.

Future research should also focus on emerging technologies, such as CRISPR and precision agri- culture, for effective pest management strategies. The CRISPR-Cas-based population replacement strategies for insect pest management and their practical applications should be further studied [82]. In addition, the safety aspect of the new technologies when they are applied to in real-world agricultural settings.

Another vital area for further research should focus on finding innovative methods to educate farmers and create awareness about the new methods of IPM as many research studies indicate that many farmers lack adequate knowledge about IPM practices and their benefits [67]. Exploring innovative knowledge transfer methods using digital platforms and community-based training programs is essential to improve farmers' understanding of the impact of climate change on pest dynamics. It will lead to the successful implementation of IPM in diverse agricultural systems.

6 CHALLENGES AND OPEN ISSUES

The ongoing issues and unresolved matters within integrated pest management (IPM) prevent its effectiveness as well as its broad acceptance by the scientific community. These subsequent sections detail both problems currently affecting IPM practice together with research directions and development areas requiring proper evaluation. Multiple kinds of obstacles continue to affect the implementation of IPM systems. The following section details several implementation problems after explaining them separately.

Because IPM is complex, it is the most significant impediment to implementation. Farmers have implementation problems with multicomponent IPM methodologies, since they require in-depth knowledge of insect and ecological studies and their interactions with the management practices. Small-farm operators in both groups are usually unskilled in technical IPM tasks which has resulted in haphazard applications yielding insignificant results [83].

Insect populations are currently developing resistance against chemical control methods which stands as one of the main issues. Pest management has become more difficult as pest species develop resistance due to the increasing use of chemical insecticides according to Craig et al. (2022) [84]. The resistance issue creates two serious problems by disabling previously effective pest control strategies and demanding expensive constant developments of new methods.

The adoption of Integrated Pest Management methods faces economic practicality challenges at the implementation level for various economic decision-making agents. Most farmers consider the upfront expenses for IPM training combined with environmental monitoring and multiple pest con- trol choices to be overly expensive because of small farming units. Advanced pest control methods require financial motivation [85]. The current literature shows a serious deficit in complete training programs which teach farmers effective IPM practices. Farmers continue to depend on synthetic pes- ticides because they have not learned pest recognition methods and IPM benefits. Increased extended services and purposeful educational efforts will lead to better farmer knowledge and acceptance of IPM methods [86].

6.1 Areas Possessed of Major Room for Development

This reflects an important gap in research quality that can influence improper research conclusions and recommendations. Building pest dynamics when appropriate amount of pest population informa- tion is supplied [85]. Improved methods for both data collection and analytical processes are needed in creating successful IPM initiatives.

The use of remote sensing and machine learning technology on IPM implementations are on the rise, but their actual applications are still unclear to the majority of users. Research initiatives need to explore optimal technology use in the agricultural field [85].

Current legal systems and policy frameworks control the effectiveness outcomes of IPM prac- tice implementations. Some policy-makers need to step in to enable the adoption of innovative pest management techniques especially those with biological principles that reduce dependency on chem- ical pesticides (for further information on IPM sign up here to receive IPM information release). Widespread implementation of IPM depends heavily on the development of precise regulatory frameworks that would create a fair market environment [87].

6.2 Future Orientation

The establishment of future research direction requires improved comprehension of pest life systems in addition to better understanding of how pests coordinate with their natural predator-base. Scientists should analyze how environmental conditions affect the functioning of biological control agents together with their influence on insect outbreaks patterns. Over time what influence do various Integrated Pest Management techniques have on pests as well as their native enemy species? Cost-effective tests should be developed to determine the sustainable benefits of IPM methodologies because they are vital for assessment purposes. The costly comparison between integrated pest man- agement and conventional pest control systems in most pest infestations and /or pest-invaded crops proves extremely difficult to accomplish. What are possible economic benefits which farmers should receive for implementing IPM methods? The evaluation of multiple current educational approaches about IPM practice relations with farming activities must be performed by researchers. An extensive research study needs to probe which training programs offer the best results for farmer improvement in agricultural IPM knowledge.

Digital technology presents opportunities for remote farmers to get better knowledge access and training opportunities. Future research into IPM systems requires building effective resistance management strategies as its most important priority. What would be the optimal approach to develop resistance prevention methods that protect insect populations from developing resistance? Which methods will allow us to utilize biocontrol agents at their best for resistance management purposes? The many innovative achievements of IPM have been made to try and solve the agricultural pest problem and are no one-size fits all solution to all pest problems. In addition to the above integrated pest management, research will be an application of sustainable pest management systems, to be necessarily based on better implementation and educational methods and technological advancements.

7 CONCLUSION

The reviewed literature shows that IPM is both a comprehensive and one-form solution for agricul- tural pest management. Scientific studies have confirmed that the use of high technologies in pest management in combination with biological control methods and farmer educational programs will facilitate pest control research.

7.1 Essential Discoveries and Learnings

1. Diversity of IPM Strategies: The study of literature emphasizes the diversity of IPM strategies used for different crops in different regions. Its effectiveness was due to the combination of chemical, biological and cultural practices for specific pest problems. Diversity plays a crucial role while dealing in different local conditions and pests.

2. Role of Technology: The use of machine learning with data-driven methods has proved immensely useful in managing pests effectively. Research studies have emphasized the usefulness of the latest technologies in pest detection, classification and management.

3. Farmer Engagement and Education: A recurrent theme in literature is the need for creating awareness among farmers about effective and natural methods of pest detection, management and IPM practices. Research has revealed that resistance to change and lack of awareness among farmers as the main barriers for adopting the latest scientific methods for effective IPM methods.

4. Economic Viability: The economic dimension of IPM plays a critical role. Research has indicated that though IPM methods are effective with long-term benefits, the initial investment and the anticipated risks have a discouraging trend among farmers. When farmers are supported financially and with the required awareness, IPM adoption will be successful. Environmental and Ecological Considerations: The literature also revealed that environmental benefits of IPM like protecting the biodiversity and reducing the use of chemical pesticides. It has also revealed that IPM can effectively contribute to sustainable agricultural practices that can lead to environmental conservation.

7.2 Suggestions and final notes for scholars

Integrated pest management research will benefit from these following recommendations: Interdisciplinary approach for pest management has immense potential for solving many prob- lems of farmers. Research studies that can integrate economic, ecological and social aspects of pest management can lead to a holistic approach for finding economically sustainable solutions.

There is a huge requirement for quality data and easy accessibility to the same for effective research on pest management. Building unbiased and comprehensive databases can help in taking informed decisions and sharing the same in different regions for developing effective strategies.

Further research can also undertake in developing highly effective resistance management strate- gies within the IPM framework. Understanding resistance and finding other methods of pest management play a significant role for maintaining the effective pest management.

Farmer-centric research can lead to effective and farmer-friendly methods of pest management. Engaging farmers in the research process will be beneficial as they share their firsthand experiences adding to the depth of research. The collaborative approach making farmers as active participants will be highly effective in identifying, analyzing and finding solutions for the pest management.

The continuous investigation of developing technologies including precision agriculture as well as artificial intelligence in horticulture and agricultural crops can generate novel pest control methods.

Research should focus entirely on both practical applications and legal structures of these technolo- gies used in horticultural and agricultural settings.

Conflict of interest: Not applicable.

Data availability: No data was used in this work.

Funding: Not applicable.

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