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Comprehensive pest management techniques in fruit crops

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Abstract
The growing environmental and health concerns associated with pesticide residues, ecological imbalance, and insect resistance have intensified the demand for eco-friendly pest control strategies in fruit cultivation. Integrated Pest Management (IPM) provides a sustainable and science-based framework that combines biological, cultural, and behavior-oriented approaches to regulate pest populations effectively. This review discusses recent progress in developing non-toxic IPM models that rely on ecological processes and pest behavior rather than synthetic chemicals. Biological control, involving natural enemies such as predators, parasitoids, and entomo-pathogenic microorganisms, forms the cornerstone of sustainable pest regulation. When combined with cultural techniques like orchard hygiene, pruning, crop rotation, and intercropping, these practices disrupt pest habitats and limit their reproductive success. At the same time, semi-chemical tools, including pheromone traps, mating disruption devices, and attractant-based, play a crucial role in pest detection and targeted suppression. Recent advancements in precision agriculture, digital monitoring, and predictive pest modeling have further strengthened the integration of these IPM components, enabling more efficient and environmentally responsible pest management systems. This review emphasizes how harmonizing biological and behavioral strategies can minimize pesticide use, sustain fruit quality, and protect agroecosystems. Future directions focus on enhancing the adoption, economic feasibility, and climate resilience of non-toxic IPM practices across diverse fruit production systems.

Keywords: Integrated pest management (IPM), biological control, Semiochemical tools, eco-friendly pest regulation, sustainable fruit cultivation

Introduction

The intensifying reliance on chemical pesticides in fruit production has increasingly raised concerns regarding environmental degradation, human health risks, and the emergence of resistant pest populations, prompting the need for sustainable and non-toxic alternatives (Singh *et al.*, 2023) [9]. Integrated Pest Management (IPM) has emerged as a holistic strategy to address these challenges by combining biological, cultural, and semiochemical approaches to manage pest populations below economic thresholds while minimizing ecological disruption (Kumar *et al.*, 2022) [2]. Biological control, a key component of IPM, involves the use of natural enemies such as predators, parasitoids, and entomopathogenic microorganisms to suppress pest populations in a targeted manner. Recent studies have demonstrated that entomopathogenic fungi, such as *Beauveria bassiana*, and nematodes effectively control fruit fly and borers in citrus and apple orchards, reducing the need for synthetic pesticides (Garcia *et al.*, 2021) [1]. Similarly, the introduction of parasitoid wasps and predatory insects in pomegranate and mango orchards has contributed to significant reductions in pest infestations, highlighting the potential of biological agents in maintaining orchard ecosystem balance (Pobożniak *et al.*, 2025) [11]. Biological control not only directly suppresses pest populations but also enhances biodiversity in orchards, thereby promoting ecological resilience and long-term sustainability (Zhou *et al.*, 2024) [10].

Semiochemical strategies, which exploit insect communication and behavior through pheromones and kairomones, provide precise and environmentally safe means of pest suppression. Techniques such as mating disruption, pheromone-baited traps, and attract-and-kill approaches have shown efficacy in reducing populations of codling moth, oriental fruit moth, and fruit flies by interfering with mating and oviposition behaviors (Patel *et al.*, 2020) [6]. Integration of semiochemicals with biological control agents has been observed to enhance overall pest suppression, as behavioral manipulation facilitates greater exposure of pests to natural enemies (Harris *et al.*, 2025) [12]. Semiochemical tools are species-specific, minimizing risks to non-target organisms and supporting sustainable orchard management. However, their adoption is often constrained by the need for species-specific formulations and cost-effective deployment methods, which remain areas for further research (Mehta *et al.*, 2022) [5].

Cultural practices form another crucial component of IPM, involving agronomic interventions that modify the crop environment to reduce pest establishment and reproduction. Practices such as orchard sanitation, pruning, intercropping, crop rotation, and timing of irrigation have been shown to disrupt pest life cycles and enhance the effectiveness of biological and semiochemical control measures (Li *et al.*, 2021) [3]. For instance, intercropping fruit crops with aromatic plants has been reported to attract natural enemies, augmenting biological control and reducing pest pressure (Lamzira *et al.*, 2025) [4]. Similarly, the removal of fallen fruits and debris in orchards not only reduces breeding sites for pests but also complements pheromone-based interventions, demonstrating the synergistic potential of cultural practices in IPM programs (Rahman *et al.*, 2022) [7].

The integration of these biological, semi-chemical, and cultural strategies within a unified IPM framework is essential for achieving sustainable fruit pest suppression. Modern technological tools, including remote sensing, precision agriculture, and predictive pest modeling, have facilitated the real-time monitoring of pest populations and orchard health, enabling timely and targeted interventions (Santos *et al.*, 2023) [8]. The application of drones and IoT-based sensors allows for rapid detection of pest hotspots and evaluation of control measure efficacy, thereby enhancing decision-making and reducing unnecessary pesticide applications. Despite these advances, challenges persist in optimizing integrated approaches across diverse agroecosystems, assessing long-term impacts, and ensuring economic feasibility for both smallholder and commercial farmers (Mehta *et al.*, 2022) [5].

Biological Control in Fruit Pest Management

Biological control is a cornerstone of non-toxic Integrated Pest Management (IPM) in fruit crops, relying on natural enemies to regulate pest populations while preserving ecosystem balance (Garcia *et al.*, 2021) [1]. This strategy reduces dependence on chemical pesticides, mitigates environmental contamination, and supports long-term sustainability in orchards. Biological control can be classified into three main approaches: classical, augmentative, and conservation biological control, each offering unique benefits depending on the crop system and target pest.

Classical Biological Control

Classical biological control involves introducing natural enemies, often from a pest's native range, to control invasive or exotic pests in a new environment (Kumar *et al.*, 2022) [2]. For example, parasitoid wasps of the genus *Trichogramma* have been successfully released in mango and pomegranate orchards to control lepidopteran pests, including fruit borers. Similarly, the introduction of predatory beetles such as *Coccinella septempunctata* has effectively reduced aphid infestations in apple orchards. Classical biological control is particularly effective for long-term suppression of pests that lack native natural enemies, although careful ecological assessment is required to avoid unintended impacts on local biodiversity (Pobożniak *et al.*, 2025) [11].

Augmentative Biological Control

Augmentative biological control involves the periodic release of natural enemies to boost their population during critical pest infestation periods (Zhou *et al.*, 2024) [10]. This method is widely used in high-value fruit crops such as citrus, mango, and apple. For instance, the application of entomopathogenic fungi like *Beauveria bassiana* or *Metarhizium anisopliae* has been effective against fruit flies and borers, providing rapid suppression while minimizing pesticide use (Li *et al.*, 2021) [3]. Additionally, releases of predatory mites (*Phytoseiulus persimilis*) have been applied in orchards to manage spider mite outbreaks, demonstrating the versatility of augmentative control in different pest scenarios (Rahman *et al.*, 2022) [7]. Augmentative control is often integrated with cultural practices, such as pruning and sanitation, to enhance the effectiveness of natural enemies and maintain pest populations below economic thresholds.

Biological Control Conservation

Biological control emphasizes the protection and enhancement of existing natural enemy populations through habitat management and selective agronomic practices (Mehta *et al.*, 2022) [5]. For example, planting flowering cover crops and maintaining ground vegetation in orchards can provide alternative food sources, shelter, and mating sites for predators and parasitoids. In apple orchards, intercropping with aromatic herbs has been found to attract beneficial insects, improving predation rates on aphids and lepidopteran pests (Lamzira *et al.*, 2025) [4]. Similarly, avoiding broad-spectrum insecticides and adopting selective control measures helps conserve naturally occurring biocontrol agents, which can provide consistent suppression throughout the cropping season (Garcia *et al.*, 2021) [1].

Synergy with Other IPM Components

Biological control is most effective when integrated with semiochemical strategies and cultural practices. For example, combining parasitoid releases with pheromone traps for fruit flies can target both adult and immature stages of the pest, enhancing overall suppression (Patel *et al.*, 2020) [6]. Similarly, cultural practices such as orchard sanitation and canopy management enhance habitat suitability for natural enemies while simultaneously reducing pest populations, creating a synergistic effect that improves the sustainability and efficiency of IPM programs (Santos *et al.*, 2023) [8].

Semiochemical Strategies in Fruit Pest Management

Semiochemicals, which include pheromones, allomones, and kairomones, are chemical signals used to manipulate insect behavior and reduce pest populations in fruit crops. Unlike broad-spectrum insecticides, semiochemicals are highly specific, targeting particular species and life stages, making them environmentally safe and compatible with sustainable agriculture practices (Thakur *et al.*, 2021) [18]. These compounds can be deployed to interfere with pest mating, feeding, aggregation, or oviposition, thereby reducing reproductive success and infestation levels.

Semiochemical strategies have gained considerable attention as a key component of non-toxic Integrated Pest Management (IPM) programs for fruit crops worldwide.

Pheromone-Based Mating Disruption

One of the most widely used semiochemical approaches is mating disruption, which employs synthetic sex pheromones to confuse or overwhelm male insects, preventing them from locating females. This technique has been successfully applied to pests such as the codling moth (*Cydia pomonella*) in apple orchards and the oriental fruit moth (*Grapholita molesta*) in stone fruits (Rani *et al.*, 2022) [27]. Mating disruption reduces pest reproduction without harming beneficial insects and is often integrated with biological control for enhanced effectiveness. Studies have demonstrated that sustained-release pheromone dispensers can maintain effective disruption over the entire growing season, leading to a significant reduction in larval infestation (Verma *et al.*, 2023) [20]. The technique also allows for reduced pesticide use, lowering production costs and environmental risks.

Attract-and-Kill Strategies

Attract-and-kill methods combine semiochemicals with toxic baits, luring pests to a point of control while minimizing exposure to non-target species. In mango orchards, protein hydrolysate-based lures combined with male-targeted pheromones have effectively controlled populations of *Bactrocera dorsalis*, a major fruit fly species (Sharma *et al.*, 2021) [17]. Similarly, kairomone-based traps using fruit volatiles have been deployed in citrus orchards to attract and capture adults of *Carpophilus* spp., significantly reducing crop damage. Attract-and-kill strategies are particularly useful in high-density orchards where conventional spraying is difficult or environmentally undesirable.

Integration with Biological and Cultural Controls

Semiochemical strategies are most effective when integrated with other IPM components. For example, combining pheromone traps with the release of parasitoid wasps targeting fruit fly larvae has been shown to provide better suppression than either method alone (Bhosale *et al.*, 2022) [13]. Likewise, cultural practices such as sanitation and pruning improve the effectiveness of semiochemical interventions by reducing pest breeding sites and facilitating better trap placement. This integration ensures a multi-pronged approach, addressing multiple life stages of pests simultaneously and increasing overall IPM efficiency (Tripathi *et al.*, 2023) [19].

Advantages and Limitations

Semiochemical methods offer several advantages over conventional pest control. They are species-specific, environmentally benign, and compatible with organic farming practices. Additionally, semiochemicals can be used to monitor pest populations, providing early warnings and informing timely interventions. However, limitations include the high cost of pheromone synthesis and the need for species-specific formulations. Environmental factors such as temperature, wind, and rainfall can also affect pheromone dispersion and efficacy, requiring careful deployment and monitoring (Chauhan *et al.*, 2022) [25]. Research continues to optimize formulation, delivery, and release mechanisms to enhance field performance.

Cultural Practices in Fruit Pest Management

Cultural practices are agronomic interventions designed to modify the crop environment, making it less favorable for pest establishment and proliferation. These methods are an integral component of Integrated Pest Management (IPM) because they are non-toxic, cost-effective, and environmentally sustainable (Alam *et al.*, 2021) [21]. Cultural practices aim to reduce pest populations directly or indirectly by disrupting their life cycles, enhancing the effectiveness of natural enemies, and improving crop resilience.

Orchard Sanitation

Orchard sanitation involves the removal of pest breeding and overwintering sites, including fallen fruits, pruned branches, and debris. This practice is particularly effective against pests such as fruit flies (*Bactrocera* spp.) and borers (*Grapholita* spp.), which utilize fallen fruits or crop residues for reproduction (Khan *et al.*, 2022) [22]. Regular collection and destruction of infested material can significantly reduce initial pest populations, thereby lowering the need for chemical interventions. Studies have shown that combining sanitation with trapping methods increases overall pest suppression and enhances orchard productivity (Rai *et al.*, 2023) [15].

Pruning and Canopy Management

Pruning and proper canopy management improve air circulation and light penetration within the orchard, reducing humidity levels that favor pest and pathogen development. In apple and peach orchards, strategic pruning has been found to decrease infestation by leaf rollers and scale insects (Singh *et al.*, 2021) [24]. Canopy management also facilitates the movement and efficiency of natural enemies such as predatory mites and parasitoids, supporting biological control efforts. Additionally, pruning residues can be collected and processed as compost, further integrating sustainable practices into orchard management.

Intercropping and Crop Rotation

Intercropping and crop rotation are valuable cultural strategies that reduce pest colonization and reproduction. Intercropping fruit trees with aromatic or trap crops can attract beneficial insects, acting as a reservoir for natural enemies while diverting pests away from the main crop (Patel *et al.*, 2022) [23]. Crop rotation disrupts pest life cycles by alternating susceptible crops with non-host species, particularly effective against soil-borne pests and borers. Studies in citrus and mango orchards demonstrate that strategic intercropping with legumes or flowering plants increases predation on pests and reduces infestation rates without chemical inputs (Chauhan *et al.*, 2022) [25].

Soil and Irrigation Management

Proper soil and irrigation practices can influence pest populations by modifying microclimate and soil health. Over-irrigation can create favorable conditions for pests such as root weevils and fungal pathogens, while regulated deficit irrigation reduces pest survival and enhances plant resistance (Mehta *et al.*, 2022) [5]. Additionally, soil amendments, including organic mulches and compost, promote beneficial microbial communities and natural enemies, contributing to integrated pest suppression.

Integration with Biological and Semiochemical Approaches

Cultural practices are most effective when combined with biological control and semiochemical strategies. For instance, pruning and sanitation reduces pest refuges, increasing the exposure of pests to parasitoids and predators (Bhosale *et al.*, 2022) [13]. Similarly, intercropping with flowering plants complements pheromone-based monitoring or mating disruption by attracting natural enemies that further suppress pest populations. This multi-layered approach enhances overall IPM efficiency, reduces reliance on chemical pesticides, and supports sustainable fruit production.

Integration of Biological, Semiochemical, and Cultural Strategies in Fruit Pest Management

The integration of biological, semiochemical, and cultural strategies represents the core of sustainable, non-toxic Integrated Pest Management (IPM) for fruit crops. While each approach individually contributes to pest suppression, their synergistic application maximizes effectiveness, reduces reliance on chemical pesticides, and supports ecosystem resilience (Rathore *et al.*, 2021) [28]. Integration is not merely additive; it allows for complementary mechanisms where biological control agents, behavioral interventions, and agronomic practices reinforce one another, addressing multiple pest life stages simultaneously.

Synergistic Interactions

One of the primary benefits of integrated strategies is the synergy between control methods. Biological control agents such as parasitoids or predatory insects are more effective when cultural practices reduce pest refuges and enhance habitat conditions (Sharma *et al.*, 2022) [29]. For instance, pruning and sanitation in mango orchards reduce larval hiding sites, increasing the predation efficiency of released *Trichogramma* wasps against fruit borers. Similarly, semiochemical-based mating disruption can reduce adult populations, making parasitoid releases more impactful on the remaining immature stages (Verma *et al.*, 2023) [20]. This multi-layered suppression reduces pest density below economic thresholds while minimizing environmental impact.

Case Studies in Fruit Crops

In apple orchards, combining entomopathogenic fungi with pheromone traps and strategic pruning has been shown to suppress codling moth populations more effectively than any single strategy (Rani *et al.*, 2022) [27]. Likewise, in citrus and mango orchards, intercropping with flowering plants, releasing predatory mites, and deploying kairomone-baited traps significantly decreased pest infestation and increased fruit yield (Patel *et al.*, 2022) [23]. These examples illustrate how well-planned integration leverages ecological, behavioral, and agronomic knowledge for sustainable pest control.

Benefits of Integrated Approaches

Integrated strategies offer multiple advantages over conventional pesticide-based control. They are environmentally safe, reducing non-target impacts and chemical residues on fruits (Tripathi *et al.*, 2023) [19]. They also enhance biodiversity within orchards, supporting natural pest suppression and ecological resilience. Additionally, integrated approaches improve economic sustainability by lowering pesticide costs, reducing crop losses, and promoting higher-quality produce. Moreover, they align with organic and sustainable certification standards, increasing market value for fruit crops.

Challenges and Limitations

Despite the advantages, integrating multiple IPM strategies presents challenges. Effective integration requires knowledge of pest biology, natural enemy interactions, and local environmental conditions (Chauhan *et al.*, 2022) [25]. The timing and synchronization of biological releases, pheromone deployment, and cultural interventions are critical for success, demanding careful planning and monitoring. Additionally, variability in pest pressure, climate, and orchard design can influence outcomes, making site-specific adaptations necessary. Research and extension services are essential to train farmers in adopting integrated practices effectively.

Future Directions and Technological Innovations

Emerging technologies provide opportunities to optimize integrated pest management. Precision agriculture tools such as remote sensing, drones, and IoT-based monitoring can track pest populations, orchard health, and the activity of natural enemies in real time (Rai *et al.*, 2023) [15]. This data-driven approach allows targeted deployment of biological agents, pheromone traps, and cultural interventions, enhancing efficiency while minimizing labor and resource use. Additionally, modeling pest dynamics and predicting outbreaks can guide integration strategies, ensuring timely and coordinated interventions. Future research should focus on long-term field trials, economic analysis, and ecosystem-level impacts to refine integrated approaches across diverse fruit production systems.

Conclusion

Sustainable fruit production increasingly relies on pest management strategies that are effective, environmentally safe, and economically viable. Excessive use of chemical pesticides has caused negative effects on human health, ecological balance, and has led to the development of resistant pest populations. Non-toxic Integrated Pest Management (IPM) offers a viable solution by combining biological control, semiochemical methods, and cultural practices into a unified system. Biological control utilizes natural enemies such as predators, parasitoids, and microbial agents to suppress pest populations while maintaining biodiversity within orchards. Semiochemical techniques, including pheromone-mediated mating disruption and attract-and-kill approaches, manipulate pest behavior to reduce reproduction and crop damage. Cultural practices, such as orchard sanitation, pruning, intercropping, and proper soil management, make the environment less favorable for pests and enhance the effectiveness of natural control agents.

Integrating these approaches strengthens their overall impact, targeting multiple pest stages simultaneously while reducing the need for chemical inputs. This comprehensive strategy helps lower pest pressure, improves fruit quality and yield, and supports long-term ecological stability. Furthermore, advances in precision agriculture, drone monitoring, and IoT-based pest surveillance can optimize the timing and application of these interventions, improve efficiency, and reduce labor and cost requirements.

In summary, a well-coordinated, non-toxic IPM framework provides a sustainable path for controlling fruit pests. By combining complementary methods, growers can minimize pesticide use, conserve beneficial organisms, enhance ecosystem health, and ensure high-quality fruit production. Adoption of integrated and environmentally friendly strategies is crucial for achieving a balance between agricultural productivity and ecological sustainability.

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