International Journal of Food Science and Agriculture, 2026, 10(1), 31-39
https://www.hillpublisher.com/journals/jsfa/
ISSN Online: 2578-3475
ISSN Print: 2578-3467

Improving Agricultural Environmental Safety by Combining Novel Approaches with Insect Biology

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How to cite this paper: Muhammad Asim Qaisrani, Muhammad Akhtar. (2026). Improving Agricultural Environmental Safety by Combining Novel Approaches with Insect Biology. *International Journal of Food Science and Agriculture*, 10(1), 31-39.
DOI: 10.26855/ijfsa.2026.03.005

Received: January 23, 2026
Accepted: February 20, 2026
Published: March 18, 2026

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Abstract

The link between insect biology and modern farming practices is important for promoting environmental safety. Addressing the increasing pest challenges and ecological deterioration in agriculture demands a detailed understanding of insect physiology and behavior. The application of biocontrol agents also supports ecological balance, where some natural predators can be used to maintain pest populations within threshold levels. Precision agro-technology in remote sensing and data analytics can be used to provide farmers with much-improved support for crop protection. New genetic technologies, especially DNA editing, now offer opportunities to create pest-immune crops. What the new study reveals is that entomologists, agronomists, and policymakers are going to have to work on how this plan may be put into action. We emphasize the interaction of insect biology with agroecosystems and propose strategies by which environmental sustainability can be increased, and pest management maximized to enable a more resilient agricultural model in line with environmental stewardship. New genetic technologies, such as DNA editing, are creating possibilities for producing pest-immune crops. Recent work stresses cooperation between the entomologist, the agronomist, and the legislator in maximizing this method. This, by bringing forward the relationship between insect biology and agricultural systems, brings insight into better pest management and environmental sustainability in constructing a much stronger agricultural structure consistent with environmental stewardship.

Keywords

Insect biology; environmental safety; biocontrol; precision agriculture; genetic engineering; sustainable practices; ecosystem health; pest management

1. Introduction

Food availability and ecosystem conservation rely on new and sustainable pest control approaches [1]. Various pest control systems have depended on chemical pesticides, which lead to several threats to human health, contribute to biodiversity loss, and impair environmental safety [2]. The current research focuses on the technologies that employ our understanding of insect biology to promote environmental safety in agriculture. Recent innovations in precision agriculture, like sensors and drones, enable some new targeted pest management options that utilize fewer pesticides [3].

This is why the adoption of biological control initiatives, such as beneficial insects and microbiological agents, offers numerous avenues for effective control. Developments in genetic engineering also give a technique to produce crop types that are resistant to specific insects, which lessens the need for insecticides. Integrated pest management (IPM) offers a comprehensive approach based on multiple control methods with long-term effectiveness that delivers a comprehensive approach based on varied methods of control with durable outcomes [4, 5].

The engagement of education and awareness in promoting these practices cannot be neglected, since farmer input is important for their acceptance. By applying these approaches, the agricultural sector can enhance resistance to pests while safeguarding human health and environmental sustainability [6]. This research highlights these critical aspects and their potential use in promoting sustainable agriculture in the future.

2. Review Methodology

The study methodically collected, reviewed, and selected the literature to build a comprehensive and quality dataset. A structured search conducted in Google Scholar yielded 150 articles. In constructing and improving this dataset, an inspection for duplicate items was undertaken, and their removal led to the development of 135 unique entries. After that, each record was assessed for relevancy; based on that, 30 records were excluded because they were not relevant to the study topic. Then, 105 remaining records were verified for complete eligibility with pre-defined inclusion and exclusion criteria, where 40 records of less importance were given up due to out of scope, insufficient data, and an English language barrier. This stage ensured that only those papers with considerable relevance to the aims of the study were kept. In the end, 65 papers fulfilled the inclusion criteria for the final analysis, thus providing comprehensive data collection and acting as a useful platform for a detailed evaluation. All the phases of screening and eligibility evaluation were based on the formulation of precise criteria from the commencement of the study, so that the selection process would be without bias and would follow some regularity. These criteria have concentrated on the significance of each article related to the core concerns of the study and, at the same time, on the correctness and authenticity of the data presented. This far-reaching yet specific strategy tended to rule out bias and so allowed for the inclusion of numerous distinct but significant sources that, in turn, contributed to strengthening the robustness and reliability of the results produced.

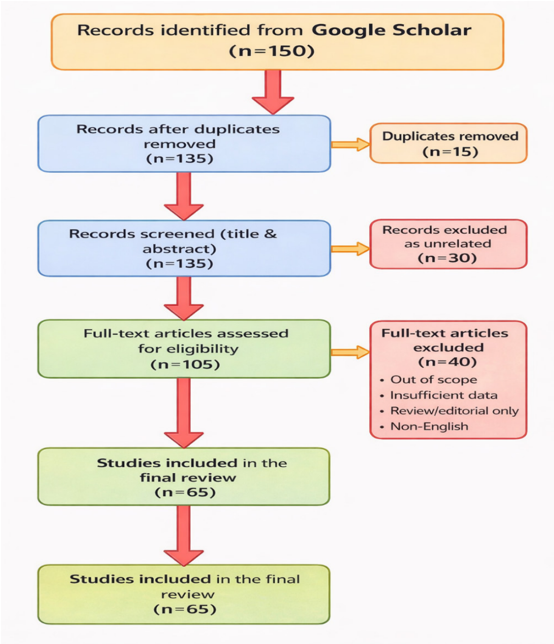

Figure 1. PRISMA chart of current review.

3. Understanding Insect Biology

Insect biology plays a key role in establishing sustainable pest control approaches. Key regions include:

3.1 Physiology and Behavior

The study of insect physiology, reproduction, metabolism, and sensory perception stimulates the creation of specific biopesticides and repellents [7]. In truth, designs of biopesticides have been developed to interfere with specific metabolic pathways during the life stages of pests, leaving non-target species undamaged. Furthermore, utilizing natural insect pheromones and other chemical signals might boost pest control tactics by efficiently attracting or repelling certain species, leading to more ecologically favorable agriculture methods [8].

3.2 Ecological Interactions

Understanding the ecological activities of insects, including pollination and nutrient cycling, reveals the necessity for techniques that conserve beneficial species while regulating invasive populations [9]. The emphasis should thus be on protecting such vital insects when it comes to creating sustainable strategies for pest management. In this sense, protecting ecosystem health and agricultural productivity will hinge on the depends on farmers creating conditions that support the conservation of beneficial insects through habitat restoration and promotion of varied agricultural systems [10]. Growing public knowledge of the benefits of insect biodiversity might potentially encourage efforts to limit pesticide usage and enhance integrated agricultural techniques [11].

3.3 Resistance Mechanisms

A deeper knowledge of the mechanisms of insecticide resistance may lead to the invention of newer and more ecologically suitable solutions for pest management [12]. Studies on the metabolic and genetic basis of resistance may suggest some techniques for postponing the development of resistance. Rotation or combination of the usage of drugs with diverse mechanisms of action may lead to a further delay of resistance and occasionally even to more effective management [13]. This also involves resistance management and monitoring approaches so that the farmer may have a chance to adjust strategies in case new information is available and to come up with more efficient ways of pest control [14].

Table 1. Key Aspects of Insect Biology in Sustainable Pest Control

Key Area	Details	References
Physiology and Behavior	Insect physiology, reproduction, metabolism, and sensory perception play a key role in designing biopesticides and repellents that target specific metabolic pathways of pests.	[15-16]
Ecological Interactions	Understanding insects' roles in pollination and nutrient cycling highlights the need for strategies that conserve beneficial species while regulating pests.	[17]
Resistance Mechanisms	Insights into the metabolic and genetic basis of resistance can help design better pest control methods and delay resistance development.	[18-19]
Insecticide Toxicity	Assessing the toxicity of different insecticides on pest species is essential for minimizing adverse effects on non-target organisms and promoting environmentally safe practices.	[20-21]
Behavioral Control	Taking advantage of insect behavior, including attraction for pheromones and avoidance of certain stimuli, could be helpful in the development of more focused and sustained management methods.	[22]
Biological Control	Integrating natural predators and parasitoids into pest management can enhance ecological balance and reduce dependence on chemical pesticides.	[23]

4. Biocontrol Strategies

Diseases, parasitoids, and natural predators are all utilized in biological management to reduce the number of parasites. Recent advancements include

4.1 Microbial Biopesticides

The scientific use of pathogenic bacteria, fungi, and viruses that selectively target pest species while avoiding harm to non-target organisms is a promising technique for sustainable pest control [24]. These biological control compounds may impact insect populations by several processes, such as infection, competition, or the production of inhibitory compounds. By effectively identifying and distributing these microbial biocontrol agents, growers can achieve effective pest control without harmful impacts on the environment [25]. Using these biological control strategies in present management systems may enhance resistance against pests, increasing crop health as well as ecological equilibrium.

4.2 Biological Control Conservation

Naturally occurring pest adversaries, ladybugs and lacewings, flourish under better living circumstances that reduce the pressure from pests [26]. Maintaining hedgerows encircling the area or planting enough flowering plants would help create favorable habitat conditions. Enhancing the natural predator habitat of pests is one method that farmers may use for biological management of their crops [27]. This would enhance the balance of nature and minimize the need for chemical pest control measures.

4.3 Integrated Pest Management (IPM)

Integrating biocontrol with other cultural practices and monitoring may boost an agricultural system's sustainability while minimizing environmental concerns [28]. The adoption of management methods, including crop rotation, intercropping, and sanitation, minimizes the size of the insect populations, boosting the efficacy of the biocontrol agent. All beneficial and pest species must be regularly monitored to intervene at a suitable moment and thereby make the management methods dynamic depending on changing conditions [29]. This integrated strategy enables sustained management of pests, an increase in soil health and biodiversity, increased crop productivity, and ecosystem resilience.

Table 2. Biocontrol Strategies for Sustainable Pest Management

Biocontrol Strategy	Description	References
Microbial Biopesticides	Utilization of bacteria, fungi, and viruses that selectively target pest species without adversely affecting non-target organisms, acting through infection, competition, or the production of inhibitory metabolites.	[24-25]
Conservation Biological Control	Enhancement of habitats for natural enemies, such as lady beetles and lacewings, through practices including hedgerow maintenance and the establishment of flowering plants, thereby reducing pest pressure.	[30-31]
Integrated Pest Management (IPM)	Integration of biological control with cultural practices, including crop rotation, intercropping, and field sanitation, to suppress pest populations, monitor pest dynamics, and improve long-term sustainability.	[32]
Augmentative Biological Control	Release of mass-reared natural enemies to supplement existing predator and parasitoid populations, enhancing pest regulation when native natural enemies are insufficient.	[33]
Biopesticide Resistance Management	Implementation of resistance-management strategies, such as rotation or a combination of biocontrol agents with complementary control measures, to maintain the effectiveness and longevity of biocontrol interventions.	[34]

5. Precision Farming Technologies

The application of the following improved technologies in precision agriculture will lead to enhanced environmental sustainability by managing pests:

5.1 Remote Sensing and Drones

This would enable the usage of drones and satellite imagery for monitoring insect populations and crop health to support management decisions, thereby decreasing the administration of pesticides in a blanket way [35]. They provide real-time insight into the state of the crops and the distribution of pests; they help farmers make educated decisions on where and when treatments are essential or should be carried out [36]. Farmers are free to designate areas of concern where resource utilization may be maximized, combined with lowering environmental effects and boosting total crop production, promoting sustainable farming approaches [37].

5.2 Data Analytics and AI

Analytics of pest dynamics and environmental variables can enable faster, more informed decisions with reduced chemical use in pest management [38]. By applying modern analytics to predictive models, farmers will be able to find trends in and predict insect outbreaks before they take a turn for the worse. It is also connected with weather forecasts and ecological information for decision-making on monitoring scheduled management operations against changes in environmental conditions [39]. It guarantees that the control methods become much more successful through correct data driving the plan, aiming towards sustainable agriculture by reducing pesticide application and keeping ecological balance [40].

5.3 Automated insect identification

Automation of early insect detection systems will decrease dependency on broad-spectrum pesticides by producing rapid and correct responses [41]. These include smart traps, sensors, and AI-enabled analytics to identify the presence of insects and their population levels in near real-time to allow targeted applications. By recognizing pests at their early stages, farmers may adopt limited control approaches, limiting the effect on beneficial species and the environment [42]. This revolutionary technology not only boosts pest control efficacy but also contributes to the general sustainability of agricultural operations [43].

6. Genetic Technologies

Developments in genetic technology provide exciting opportunities to increase environmental safety.

6.1 Genome Editing

With the help of technologies like CRISPR, crops will be able to withstand pests, which will minimize the need for chemical treatments [44]. Through genetic alteration, scientists change the crops' innate hardiness that causes insect sensitivity. This normally suggests that there will be large yields with less loss, as they grow less vulnerable [45]. CRISPR achieves this more rapidly than traditional breeding and has created new paths in accomplishing the work of producing resilient variations at a rate substantially unmatched by conventional ways [46]. This will also contribute to enhanced biodiversity since one will require less reliance on chemical pesticides, hence enabling better environments and more sustainable means of farming.

6.2 Transgenic Approaches

Some of the major problems linked with their application to agricultural operations include public acceptability and regulatory limits [47]. All this will need good communication regarding the safety and advantages of GMOs to earn customer trust and relieve apprehensions associated with their usage. Furthermore, interaction with regulatory organizations ensures that GMOs are examined for environmental impact and food safety, supporting responsible adoption [48]. The agriculture sector may maximize its capacity for enhancing sustainable pest management while resolving the challenges related to GMO incorporation by including stakeholders, particularly consumers, farmers, and legislators [49].

6.3 Gene Drives

Better gene drives impact insects' capacity for reproduction, therefore lowering populations and opening novel possibilities for controlling pests [50]. These variables enhance the transmission of genetic characteristics that limit reproduction or induce death within species of pest, which may lead to population decline or disruption of populations. This may be of use in the control of invasive insects and vectors of diseases that have devastating impacts on public health and agricultural production. While these new technologies should go a long way in supporting sustainability, their implications on ecology must be examined with ethical concern to ensure that development and deployment do not interact negatively with natural ecosystems [51].

Table 3. Genetic Technologies for Sustainable Pest Management

Genetic Technology	Description	References
Genome Editing	Genome-editing tools, such as CRISPR-based systems, enable the development of crop varieties with enhanced resistance to insect pests, reducing dependence on chemical pesticides by improving plant resilience.	[52]
Transgenic Approaches	Transgenic crops can be engineered to express pest-resistant traits; however, their adoption is influenced by public perception, regulatory frameworks, and the need for effective stakeholder communication.	[53]
Gene Drives	Gene drive technologies can suppress or modify pest populations by altering reproductive capabilities, offering novel tools for managing invasive species and disease vectors, while requiring careful ecological risk assessment.	[54]
Marker-Assisted Selection	Marker-assisted selection accelerates crop breeding programs by employing molecular markers to identify and incorporate desirable traits, including enhanced resistance to insect pests.	[55]
Synthetic Biology	Synthetic biology enables the design of novel biological systems or the modification of existing organisms to enhance pest resistance and introduce other agriculturally beneficial traits.	[56]

7. Challenges and Future Directions

While the integration of insect biology with contemporary technology has tremendous potential, numerous challenges have yet to be overcome:

7.1 Regulatory Hurdles

Laws controlling GMOs and biocontrol agents are a barrier to the adoption rates of novel techniques due to the slow implementation of such laws [57]. Excessive and extensive procedures for licensing, with rigorous inspection to ensure safety, might impede timely access to such useful technology and, thus, the farmers' capacity to control the pests successfully [58]. Further fine-tuning of the regulatory procedures and communication between the scientists, the industry players, and the numerous regulatory authorities will bring forward speedier adoption of best practices. Besides the foregoing, public knowledge and education on the safety and efficacy of biocontrol agents and GMOs would also be improved and may enable better public support for their deployment, thus helping toward agricultural resilience and sustainability [59].

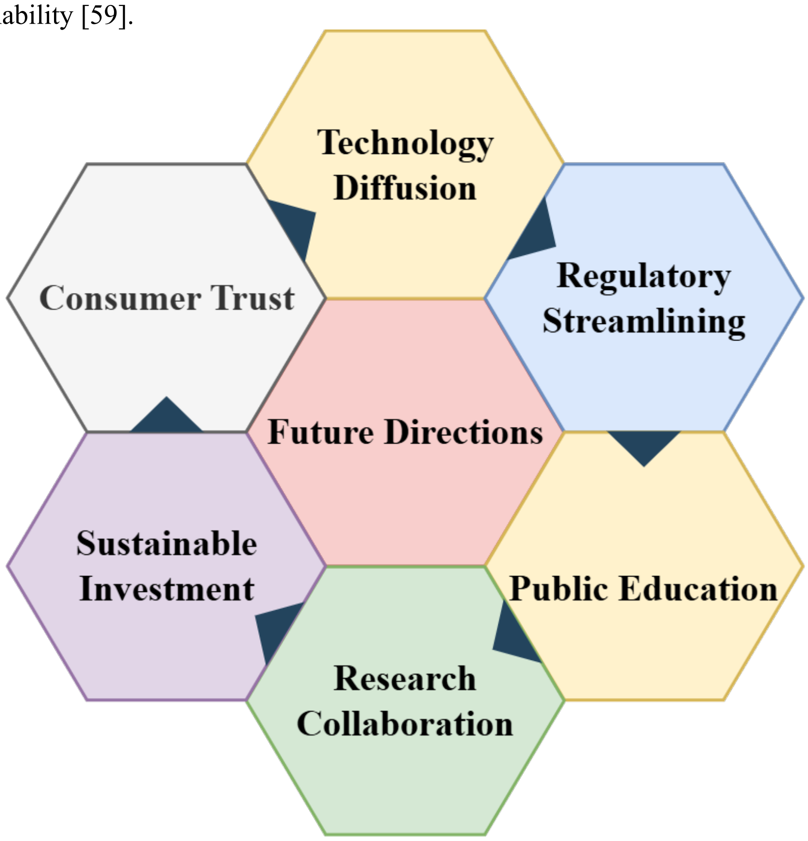

Figure 2. Future Directions for Sustainable Agricultural Development.

7.2 Public Perception

Consumer concerns must be addressed if genetic advances and biopesticides are to be effectively incorporated into traditional agriculture [60]. Proper education about the benefits, safety, and environmental impacts of these things can overcome public ignorance and fears. Active educational outreach programs and community-based activities foster engagement and understanding among stakeholders. Additionally, information on the legislative norm should be more readily available, and involving users in decision-making can help build consumer trust in the ethical use of such technologies, thereby facilitating greater diffusion into environmentally friendly farming [61, 62].

7.3 Research & Development

The complete potential of insect biology in contributing to this effort necessitates continued investment in R&D linked to sustainable agricultural solutions [63]. This may be developed via resistant cultivars, expanding biological control technologies, and increasing the adoption of ecologically friendly activities through sponsorship for creative research. Collaborative initiatives involving educational organizations, industry, and regulatory bodies may hasten the translation of research results into practical implementations, ultimately promoting the trend towards more sustainable agricultural systems [64, 65].

8. Conclusion

The merging of insect biology and modern agricultural technology allows environmental conservation in agriculture. Adoption of more environmentally friendly pest control strategies that seek a healthy environment decreases the heavy dependence on chemical pesticides and enables the cultivation of healthier ecosystems. Collaboration among academics, policymakers, and practitioners is essential in achieving the realization of the promise these advancements hold for an ecologically sustainable future for agriculture. Additionally, the investment in education and training programs will further allow farmers to put in place strategic measures that improve resilience against pest threats. In this attitude, as we move forward, continuing to learn and adapting, we can make sure agriculture serves current food needs but is supportive of the environment in the future.

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