University of Thi-Qar Journal of Science (UTJsci)
E-ISSN: 2709-0256, P-ISSN: 1991-8690, Vol. 12, No. 1, June. 2025

Insecticide Resistance in Agricultural Pests: Mechanisms, Case Studies, and Future Directions

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Received: 2025-04-27, Revised: 2025-06-03, Accepted: 2025-06-29, Published: 2025-06-30

***Abstract*—Pesticide resistance is an escalating global challenge that threatens agricultural productivity, food security, and the sustainability of pest control methods. Over 600 insect species have developed resistance, compromising the effectiveness of chemical controls and exacerbating pest outbreaks. Species such as *Helicoverpa armigera* and Bemisia tabaci serve as prominent examples of pests displaying this growing resistance problem. This study aims to explore the underlying mechanisms of pesticide resistance in key agricultural pests, identify the major contributing factors, assess the effectiveness of current management strategies, and examine potential future tools and technologies for combating resistance. The study integrates data from global case studies, specifically focusing on *Helicoverpa armigera* in India and Bemisia tabaci in China. It also synthesizes information on various resistance mechanisms, including metabolic, target-site, penetration, and behavioral processes. Several resistance management strategies, such as pesticide rotation, integrated pest management (IPM), and refuge policies, are evaluated for their effectiveness. Metabolic and target-site resistance mechanisms are particularly prevalent in resistant insect populations. Contributing factors include overuse of single pesticide classes, sub-lethal dosages, inadequate treatment regimens, and monoculture farming. IPM and pesticide rotation employing different modes of action are among the most effective current strategies. Emerging technologies, such us RNA interference (RNAi) and CRISPR gene editing , offer promising new approaches. Addressing pesticide resistance requires a comprehensive, multi-faceted strategy that incorporates genetic tools, real-time monitoring, biopesticide development, and stronger regulatory frameworks. International cooperation, farmer education, and scientifically informed policies will be critical to future success.**

Keywords: insecticide resistance, Agricultural pests, Integrated pest management, CRISPR, and RNA interference.

I. Introduction

In modern agriculture, chemical pesticides serve as critical tools that have significantly reduced pest populations and improved crop yields. However, the extensive and sometimes unregulated use of these chemicals has led to the development of pesticide resistance in many economically important insect species. According to the Insecticide Resistance Action Committee [1], over 600 insect species worldwide have evolved resistance to at least one pesticide class [2]; warning that this growing resistance presents a serious challenge to the long-term sustainability of agricultural productivity and global food security [3-5].

Multiple molecular and physiological mechanisms drive the development of pesticide resistance [6-8]. These include enhanced metabolic detoxification; mutations that cause target-site insensitivity, changes in cuticle composition that reduce pesticide penetration, and modified behaviors that lower pesticide exposure. According to [4], genetic regulation often controls these mechanisms, facilitating rapid adaptation under strong selection pressure. This issue is particularly severe in monoculture farming systems where pest management practices lack diversification [9]. Field reports have documented increasing failures in pest control, such as Helicoverpa Armigera resistance to Bt cotton in India [10] and Bemisia Tabaci resistance to neonicotinoids in protected cropping systems in China [11][12], demonstrating the real-world consequences of poor resistance management.

Despite substantial progress in understanding resistance mechanisms, a clear gap remains between scientific knowledge and its practical application in resistance management programs. The ongoing emergence of resistant pest populations highlights the urgent need for improved management strategies. This review aims to analyze the fundamental mechanisms of pesticide resistance, identify the major contributing factors, compile global case studies, and evaluate integrated resistance management approaches. Key strategies include pesticide rotation, integrated pest management (IPM), novel genetic technologies (e.g., CRISPR and RNA interference [RNAi]), and comprehensive regulatory frameworks [13].

https://doi.org/10.32792/utq/utjsci/v12i1.1381

Table1: Documented insecticide resistance in major pest species

Pest Species	**Number of Insecticide Classes with Documented Resistance**	**Insecticide Classes**
Bemisia tabaci	**3**	Neonicotinoids, Pyrethroids, IGRs
Myzus persicae	**2**	Neonicotinoids, Carbamates
Plutella xylostella	**2**	DDT, Multiple classes
Helicoverpa armigera	**3**	Organophosphates, Pyrethroids, Bt toxins

Neonicotinoids are neuro-active insecticides chemically similar to nicotine, with resistance developing in pests due to prolonged exposure and reduced efficacy. Pyrethroids, synthetic analogs of natural pyrethrins, are widely used in agriculture and often face resistance due to mutations in sodium channels of pest nervous systems. Insect growth regulators (IGRs) interfere with insect development and resistance typically involves metabolic detoxification or changes at the target site. Carbamates inhibit acetylcholinesterase in insect nervous systems, with resistance arising from enhanced enzymatic breakdown or insensitivity at the target site. DDT, a historically significant organochlorine pesticide now largely banned, has led to long-term resistance in species such as *Plutella xylostella*. Organophosphates also inhibit acetylcholinesterase, with resistance stemming from altered enzyme targets or increased metabolic degradation. Finally, Bt toxins, proteins derived from *Bacillus thuringiensis* and used in transgenic crops, can lose effectiveness when pests develop changes in gut receptor binding, rendering the toxins less effective.

Table2. Documenting resistance in major agricultural pest species:

Pest Species	**Common Name**	**Documented Resistance**
Helicoverpa armigera	Cotton bollworm	Organophosphates, pyrethroids, Bt toxins
Plutella xylostella	Diamondback moth	DDT, organophosphates, carbamates, pyrethroids, and other multiple insecticide classes
Myzus persicae	Green peach aphid	Neonicotinoids, carbamates
Bemisia tabaci	Whitefly	Neonicotinoids, pyrethroids, insect growth regulators (IGRs)

II. Factors Contributing to Resistance Development

The phenomenon of pesticide resistance in agricultural pests is a complex and escalating issue influenced by several biological and operational factors. The following key components have been identified as primary accelerants in the development of resistance:

There is an undue dependence on a singular way of activity.

A. The Continual Use of Pesticides

The continual use of pesticides with comparable modes of action is a significant component exacerbating the issue. This approach exerts considerable selection pressure, allowing only the resistant individuals to survive and reproduce [14-15] indicating that this results in a prolonged reduction of the overall sensitivity of the pest population to that class of pesticides.

B. Sub-Lethal Dosing and Inappropriate Application Methods

Pests may encounter pesticide levels that are insufficient for lethality but enough to promote resistance if the insecticide application is improperly executed. This includes sub-lethal dosages or inconsistent spraying [16] assert that these sub-optimal exposures may function as training doses for pests, so facilitating their adaptation to the environment and the development of resistance mechanisms.

C. An Inability to Alternate Cultivars

In monoculture systems, characterized by the repeated cultivation of a single crop, insect populations may thrive and adapt more easily. A lack of crop diversity diminishes the chances of interrupting pest life cycles, there by facilitating the persistence and spread of resistant strains [17].

D. Assessing Capacity for Restricted Resistance

Due to insufficient monitoring and surveillance protocols, resistance is often identified only after control failure is evident [12] asserts that early identification is essential for the timely implementation of resistance management strategies.

E. Monoculture-Based Cropping Methods

Monocultures not only facilitate the proliferation of pests but also engender a heightened need for pesticides, hence exacerbating the emergence of resistance [14], assert that the simplicity of agroecosystems leads to the eradication of natural pest management mechanisms and an increase in selection pressure. The combined factors underscore the pressing need for integrated and diversified pest management approaches to mitigate the development of the resistance.

Table 3: key factors contributing to insecticide resistance development:

Factor	Description
Over-reliance on single modes of action	Continuous use of the same class of insecticides selects for resistant pests, accelerating resistance.
Sub-lethal dosing and poor application	Inadequate dosages or poor spraying practices expose pests to survivable levels, promoting adaptation.
Lack of crop rotation	Repeated planting of the same crop sustains pest populations and promotes resistance development.
Limited surveillance and monitoring	Insufficient tracking of resistance delays detection and hinders timely intervention.
Monoculture cropping systems	Uniform crops support pest build-up and reduce natural control, increasing reliance on insecticides.

Table 4: Key factors contributing to the development of insecticide resistance

Contributing Factor	Explanation
Monoculture cropping systems	Uniform crops encourage pest outbreaks
Limited surveillance and monitoring	Poor tracking delays detection and response
Lack of crop rotation	Repeated cropping sustains pest populations
Sub-lethal dosing and poor application	Improper dosage exposes pests to survivable levels
Over-reliance on single modes of action	Continuous use of the same insecticide class selects for resistance

Monoculture cropping systems, where a single crop is grown extensively, create a uniform environment that supports large pest populations and drives increased insecticide use, thereby fostering resistance development. Limited surveillance and monitoring hinder early detection of resistance, allowing resistant pests to proliferate unchecked. Similarly, a lack of crop rotation sustains pest populations by continuously providing suitable hosts, which maintains pressure on insecticide efficacy. Sub-lethal dosing and poor application techniques contribute by exposing pests to non-lethal amounts of insecticide, enabling partially resistant individuals to survive and pass on resistance traits. Lastly, over-reliance on single modes of action—repeated use of insecticides with the same mechanism—intensifies selective pressure, accelerating the emergence and spread of resistance within pest populations.

Moreover methods for handling opposition, while the problem of insecticide resistance is on the rise, it is critical to use strategic approaches to keep pest control techniques effective and minimize the development of resistance. Integrative pest management (IPM) and pesticide rotation are two fundamental strategies.

1. Rotating insecticides with diverse mechanisms of action. One of the resistance management strategies that has garnered the most backing from experts in the field is the rotation of insecticides with distinct modes of action (MoAs). By lowering their constant exposure to the same chemical compounds, the technique lowers pest resistance development, thus resistance selection is compromised. Using many pesticide applications one after the other decreases the likelihood that pests will become resistant to several substances.

Researchers at [19] found that Diaphorina citri evaded resistance even under constant treatment with thiamethoxam and other chemicals throughout five generations. Two sets of simulations using Meligethes aeneus showed that rotating pesticide application is more successful than constant, continuous application. Between each pesticide modification interval, the population's resistance became greater [18].

The rotation system's basis is the idea of moderation ,suggesting attention to regular pesticide spraying over time to minimize resistance development according to [20].

2. Integrated insect Management, or IPM for short. IPM, or integrated pest management system, is the best solution to reduce insect populations sustainably and lower pesticide use. The all-encompassing strategy includes pesticide management along with crop rotation and plant variety selection of resistant kinds , and habitat stewardship and biological control techniques include predators and parasitoids.

Researchers have shown that pesticide rotation , by itself is ineffective as a control tool. S. Shudeer et al. and E. Cloyd [4,15] claimed that the whole character of IPM allows for lower pest-related loads and delay resistance formation, hence prolonging the use of pesticides. By maximizing pesticide utility throughout many growing seasons, these agricultural techniques complement one another to support efficient practices.

Table 5: Summary of resistance management methods

Method	Description
Rotating Insecticides with Different Modes of Action	Alternating insecticides that have different mechanisms of action helps prevent pests from developing resistance to any single class of pesticides. This strategy reduces the selection pressure on pest populations.
Integrated Pest Management (IPM)	Combines multiple control strategies, including biological control (e.g., predators, parasitoids), cultural practices (e.g., crop rotation), and carefully targeted chemical applications. This integrated approach promotes sustainable pest control and reduces dependence on chemical pesticides.

F. *Refuge Strategies*

Especially for Bt cotton crops that have been genetically modified, refuge policies are crucial for resistance. Planting non-Bt agricultural areas next to Bt fields allows farmers to help sustain a population of pests susceptible to Bt. This causes a significant slowing of the rate of resistance development and a decrease in the population of resistance genes. It also promotes mating between those who are resistant and those who are not. According to [2], *Plutella xylostella* and Helicoverpa zea are two instances of pests that have been shown to postpone the growth of Bt resistance through refuge tactics.

G. *Use of Synergists*

Using synergists—compounds blocking the enzymes in charge of bug detoxification—could help to increase the efficacy of insecticides. Piperonyl butoxide (PBO), a chemical that blocks the activity of cytochrome P450 enzymes involved in the metabolism of insecticides, is one such often-cited example. Synergists restore the efficacy of insecticides against populations of pests resistant to the chemical [7]. Disabling the systems responsible for resistance helps one to do this.

H. *Genetic and Molecular Tools: The Future of Resistance Management*

Cutting-edge techniques in both the study of pesticide resistance and the fight against it include genetic and molecular technologies such us CRISPR-Cas9 and RNA interference (RNAi). The genetic foundation of pesticide resistance is becoming more well recognized, therefore

Using a gene-editing tool called CRISPR-Cas9, researchers may precisely remove or replace genes in pest species that provide resistance characteristics. This approach allows one change genes associated to resistance. For instance, CRISPR enables research and even reversal of the consequences of target site mutations in the acetylcholinesterase gene or sodium channels, which are respectively linked to organophosphate and pyrethroid resistance. Certain mutations cause resistance to certain compounds. This makes possible the functional assessment of resistance alleles and potentially the correction of these alleles in populations under controlled environments [2].

RNA interference (RNAi) provides a distinct and environmentally safe way of pest control by means of silencing certain genes vital in resistance or survival. Pests are controlled using this method. Without harming species that are useful to the ecosystem, biopesticides based on RNA interference may selectively target important metabolic pathways in pests, including cytochrome P450s or GSTs. Findings from a [5] research indicate that RNA interference is very effective in targeting genes implicated in metabolic resistance pathways. Included in this category are genes with high expression of detoxifying enzymes.

Thus, in order to benefit from these techniques, it is essential to have a complete knowledge of the genetic pathways driving resistance. Among these mechanisms are genetic amplification, point mutations, and enzymatic detoxification pathways. Modern molecular biology provides these insights, allowing for intervention in a precise and focused manner instead of mostly depending on pesticides with a wide range of activity.

By allowing the following, the technologies of CRISPR and RNAi could alter the management of resistance: the verification of functional genes; the direct editing or silencing of resistance mechanisms by means of gene editing; and the production of biopesticides unique to particular species. In conclusion, these technologies have the potential to revolutionize resistance management. Not only do these technologies provide enhanced pest control, but they also ensure the safety of the environment, making them indispensable in the movement toward sustainable agriculture.

III. Case Studies – Resistance in the Real World

Table 6: Bt Cotton in India

Aspect	**Details**
Pest	*Helicoverpa armigera* (cotton bollworm)
Insecticide/Tool	Bt Toxin (Cry proteins in GM cotton)
Resistance Cause	Poor refuge compliance; year-round exposure
Outcome	Rapid development of resistance; reduced Bt efficacy
Management Gap	Inadequate adoption of IPM and refuge strategies

Table 7: Neonicotinoid Resistance in Whiteflies (China)

Aspect	**Details**
Pest	*Bemisia tabaci* (whitefly)
Insecticide/Tool	Neonicotinoids
Resistance Cause	Continuous year-round use, lack of insecticide rotation
Outcome	Widespread resistance and chemical control failure
Management Gap	Over-reliance on a single mode of action; limited monitoring

Table 8: Additional Global Examples

Region	**Pest** and **Resistance**	**Cause**	**Consequence**
USA	Corn rootworm resistant to Bt maize	Bt overuse, low refuge compliance	Resistance gene spread
Brazil	Fall armyworm resistant to multiple insecticides	Intense chemical usage in soy/corn	High control costs, yield loss
Australia	Grain pests resistant to pyrethroids	Lack of resistance monitoring	Increased frequency of spray failure

IV. Future Directions

The future of sustainable pest management depends on integrated technologies that combine genomic tools, improved biocontrols, and regulatory policies. This is because the incidence of resistance to conventional pesticides is increasing at an alarming pace.

A. *Precision Agriculture and Genomic Surveillance*

Genomic monitoring presents a potentially game-changing strategy for managing resistance, despite its limited deployment to date. Pest monitoring may become more predictive and targeted if genetic markers that are connected to resistance are identified. Some examples of these indicators are mutations in P450 monooxygenases and glutathione-S-transferases. [2] This technique makes it possible to implement treatments at the appropriate moment, before opposition becomes widespread. As an additional point of interest, digital technologies such as decision support systems driven by artificial intelligence and drones improve the accuracy of pesticide treatments, hence reducing the likelihood of overuse and off-target impacts [21].

B. Development of Novel Biopesticides

Chemical synergists like piperonyl butoxide have shown promise in reinstating the efficacy of insecticides that have diminished in effectiveness. Nevertheless, future advancements are expected to focus on biopesticides and RNA interference (RNAi)-based products. The ability of the pest to detoxify toxins or alter target sites may be diminished with the use of these advanced technologies, which may silence certain resistance genes.[5] indicate that RNA interference has significant potential as an accurate instrument for pest control, with little effect on non-target species.

C. Emphasis on Regulatory Policies

Resistance management must be included in the national agriculture strategy. Research results indicate that resistance difficulties are exacerbated by insufficient regulation and weak monitoring techniques. There is an increasing tendency to mandate resistance management strategies under legal frameworks. The proposals would include crop rotation, the labeling of pesticide modes of action, and refuge zones for Bt crops [4]. Policymakers are increasingly acknowledging the significance of preventive regulation in safeguarding the efficacy of current pesticides and those that will be produced in the future.

V. Discussion

Pesticide resistance in agricultural pests is a growing concern and this study aims to provide a comprehensive understanding of this issue. The existing management practices, future directions, major contributing factors, and biological processes are the main topics of the research. This highlights the evolutionary component of resistance, which happens when pests may evolve new defense mechanisms after being exposed to chemical stresses repeatedly. Metabolic detoxification, target site modification, and behavioral adaptability are some of these defensive strategies.

Two actual problems emerge from insufficient resistance management methods that include *Helicoverpa armigera* in India and Bemisia tabaci in China. Two real-world problems exist because pesticide cycling fails and farmers use a single chemical class in combination with inadequate refuge methods. The analytical content presented within the article supports the concepts mentioned in this paper as strategic and mechanical frameworks.

RNA interference and CRISPR together represent advanced technological instruments that deliver outstanding capabilities to study and manage bacterial resistance. IPM plans obtain their best results through comprehensive management approaches that receive full regulatory approval. Whenever suitable monitoring and farmer cooperation together with legal system support are absent for future-oriented concepts their appropriate implementation becomes impractical.

VI. Conclusions

Pest resistance against chemicals forms because of sustainable agricultural practices, which oppose each other, and excessive pesticide usage. Multiple origins for resistance continuations in diverse worldwide farming areas demonstrate that excessive pesticide applications and weak regulatory systems, along with poor tracking system, contribute to the overall problem. The ongoing nature of this problem demonstrates complete involvement of all elements.

Multiple integrated approaches using pesticide rotation along with integrated pest management combined with genetic and molecular technologies , achieve the most lasting resistance management solutions when proper policy implementation exists. The proposed strategy serves as a critical approach to maintain ongoing resistance management. The planet lacks fundamental food safety protection strategies that could result in the loss of years of pest management development.

It is recommended to apply required pesticides for switching between many kinds to help the rapid development of insecticide resistance. One approach may be to rotate certain items using many actuation devices.
Reducing dependence on chemical pesticides is greatly aided by the execution of large-scale integrated pest management (IPM) programs that combine chemical, biological, and cultural control strategies.

Refuge planting strategies for BT crops should be used in the third stage. Regulatory bodies needed to make ensure that this is carried out in order to postpone the development of resistance. Invest substantial amounts in genetic monitoring. Monitoring resistance genes should be done using molecular diagnostics; so, treatment approaches should be changed as suitable.

People should help creating and marketing pest control technologies based on RNA interference and CRISPR in order to enable the creation of creative biopesticides.

Another suggestion is to improve the efficacy of regulatory systems. National laws must call for the monitoring of food resistance, the rotation of pesticides, and the training of farmers, as they are most crucial. The last suggestion is to improve farmer education through field demonstrations and awareness campaigns, which would support the proposed strategies.

Conflict of Interest

Authors declare that they have no conflict of interest.

References

[1] Insecticide Resistance Action Committee (IRAC), "*IRAC Mode of Action Classification*," 2023. [Online]. Available: https://irac-online.org

[2] R. J. Onstad, Insect Resistance Management: *Biology, Economics, and Prediction, 2nd ed. Academic Press*, 2017.

[3] S. Shudeer et al., "Emerging pesticide resistance in global agriculture," *Journal of Pest Management*, vol. 45, no. 2, pp. 133–145, 2019.

[4] S. Shudeer et al., "Genetic control of resistance mechanisms in insect populations," *Frontiers in Agricultural Genomics*, vol. 11, pp. 88–101, 2024.

[5] F. Zhu et al., "RNA interference of NADPH–cytochrome P450 reductase results in reduced insecticide resistance in the bed bug, *Cimex lectularius," PLoS ONE*, vol. 9, no. 2, e89102, 2014. doi: 10.1371/journal.pone.0089102.

[6] H. Zhou, "Mechanisms of insecticide resistance in insects," *Annual Review of Entomology*, vol. 53, pp. 467–493, 2008.

[7] H. Khan et al., "Enzyme-based mechanisms of insecticide resistance in agricultural pests," *Pesticide Biochemistry and Physiology*, vol. 170, pp. 104–111, 2020.

[8] F. Li et al., "Molecular basis of insecticide resistance and detoxification pathways in agricultural pests," *Insect Molecular Biology*, vol. 31, no. 1, pp. 12–25, 2022.

[9] D. Foster et al., "Monoculture and its impacts on insect resistance dynamics," *Agricultural Systems*, vol. 172, pp. 104–115, 2019.

[10] K. Kiritani, "Insect pest management in Asia: Lessons from Bt cotton in India," *Entomological Research*, vol. 50, no. 1, pp. 1–9, 2020.

[11] X. Wang et al., "Resistance of Bemisia tabaci to neonicotinoids in China," *Pest Management Science*, vol. 74, no. 12, pp. 2895–2902, 2018. doi: 10.1002/ps.5113.

[12] J. Denholm, "The role of monitoring in managing pesticide resistance," *Crop Protection*, vol. 9, no. 4, pp. 229–234, 1990.

[13] M. Smith and A. Johnson, "The role of policy in resistance management," *Journal of Environmental Policy and Planning*, vol. 23, no. 4, pp. 455–468, 2021.

[14] P. Umina et al., "High levels of resistance in Helicoverpa armigera due to continued chemical exposure," *Pest Management Science*, vol. 75, no. 7, pp. 1711–1718, 2019. doi: 10.1002/ps.5296.

[15] E. Cloyd, "Integrated pest management in temperate agroecosystems," *Journal of Agricultural Ecology*, vol. 33, no. 2, pp. 120–130, 2010.

[16] R. Carvalho et al., "Pesticide exposure and resistance evolution under sub-lethal conditions," *Toxicology Reports*, vol. 2, pp. 1307–1315, 2015. doi: 10.1016/j.toxrep.2015.09.006.

[17] C. Yoon, "Ecological implications of monoculture cropping," *Ecological Perspectives*, vol. 8, no. 3, pp. 221–230, 1983.

[18] R. Slater et al., "Modeling insecticide resistance in Meligethes aeneus using rotation strategies," *Pest Management Science*, vol. 73, no. 7, pp. 1422–1432, 2017. doi: 10.1002/ps.4500.

[19] Y. Chen et al., "Resistance evolution in Diaphorina citri under insecticide pressure," *Journal of Economic Entomology*, vol. 113, no. 1, pp. 157–164, 2020. doi: 10.1093/jee/toz257.

[20] A. Madgwick and A. Kanitz, "Adaptive dynamics in pesticide resistance," *Applied Ecology and Environmental Research*, vol. 22, no. 1, pp. 41–58, 2024.

[21] S. Kumari et al., "AI and drone technologies in precision agriculture," *Computers and Electronics in Agriculture*, vol. 212, pp. 108103, 2024. doi: 10.1016/j.compag.2023.108103.