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Insecticide Resistance Management: A Detailed Review

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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Review Article

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ABSTRACT

Insecticide resistance poses a significant threat to global agricultural practices, a threat to food security and economic stability. This resistance diminishes the effectiveness of chemical control methods, leading to increased pest infestations, higher production costs and environmental harm. Key resistance mechanisms include metabolic resistance, target site mutations, reduced penetration and behavioural changes. Factors such as high reproductive rates, short generation times and intense selection pressures further accelerate the spread of resistance within pest populations. Effective management strategies, including Integrated Pest Management (IPM), emphasize the importance of combining chemical, biological, and cultural control methods. This review emphasizes the necessity of continuous monitoring, education, and research to develop sustainable pest management solutions. Exploring recent studies and practical examples provides insights into overcoming the challenges posed by insecticide resistance and ensuring the sustainability of agricultural practices.

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1. INTRODUCTION

Insecticide resistance is a pervasive and growing problem in agricultural pest management, posing a substantial threat to food security and economic stability. The development of resistance in pest populations undermines the effectiveness of chemical control methods, leading to increased pest infestations, significant economic losses and compromised crop yields [1, 2]. As pests become resistant to widely used insecticides, farmers are forced to apply higher doses or switch to alternative chemicals, both of which can lead to higher production costs and environmental harm [3,4]. The persistence and spread of resistance threaten the sustainability of agricultural practices, necessitating a comprehensive understanding of resistance mechanisms and the implementation of effective insecticide resistance management (IRM) strategies [5].

Mechanisms of resistance in insect populations include metabolic resistance, target site resistance, reduced penetration and behavioural resistance. Metabolic resistance, often the most prevalent, involves the detoxification of insecticides by enhanced enzyme activity, such as cytochrome P450 monooxygenases, esterases and glutathione S-transferases [1, 6]. Target site resistance arises from mutations in the insecticide's target site, reducing its sensitivity to the chemical [3, 7]. Reduced penetration involves changes in the insect cuticle that slow the absorption of insecticides, while behavioural resistance includes changes in pest behaviour that decrease exposure to insecticides [8, 9]. The development of resistance is influenced by various factors, including the high reproductive rate of pests, short generation times, high selection pressure from frequent insecticide applications, lack of genetic diversity, and monoculture practices [1, 2]. These factors contribute to the rapid evolution and spread of resistance within pest populations, complicating control efforts and necessitating more sophisticated IRM approaches.

This review provides a comprehensive overview of the mechanisms behind insecticide resistance, the factors contributing to its development, and the various strategies employed to manage resistance. It highlights the importance of integrating chemical, biological, and cultural control methods, and underscores the need for continuous monitoring and education to implement effective IRM programs. Through a detailed examination of recent studies and examples, this review aims to inform and guide researchers in developing sustainable pest management solutions.

2. MECHANISMS OF INSECTICIDE RESISTANCE

Insecticide resistance can develop through several distinct mechanisms, each of which reduces the effectiveness of chemical control methods. Understanding these mechanisms is critical for devising effective insecticide resistance management strategies.

2.1 Metabolic Resistance

Metabolic resistance is the most prevalent mechanism of insecticide resistance, characterized by the enhanced detoxification of insecticides through increased enzyme activity. This mechanism involves several key enzyme families, including cytochrome P450 monooxygenases, esterases and glutathione S-transferases [5, 1,2].

- **Cytochrome P450 Monooxygenases**: These enzymes are involved in the oxidation of insecticides, making them more water-soluble and easier to excrete. Elevated levels of cytochrome P450 enzymes can significantly reduce the efficacy of insecticides. For instance, in the cotton bollworm (*Helicoverpa armigera*), resistance to pyrethroids is often due to increased levels of these enzymes [1, 6].
- **Esterases**: These enzymes hydrolyse ester bonds in insecticide molecules, rendering them inactive. Esterases are particularly important in conferring resistance to organophosphates and carbamates. Enhanced esterase activity has been documented in resistant populations of various pests, including the cotton aphid (*Aphis gossypii*) [10].
- **Glutathione S-transferases (GSTs)**: GSTs catalyse the conjugation of glutathione to insecticide molecules, facilitating their detoxification and

excretion. Elevated GST activity has been linked to resistance in various insect species, such as the malaria mosquito (*Anopheles gambiae*) [11].

2.2 Target Site Resistance

Target site resistance arises from mutations in the insecticide's target site, diminishing the sensitivity of the target site to the insecticide. This mechanism often involves changes in genes encoding the target proteins, which can prevent the insecticide from binding effectively [3, 7]. The *kdr* (knockdown resistance) mutation in the sodium channel gene is a well-known example of target site resistance. This mutation confers resistance to pyrethroids in the house fly (*Musca domestica*), preventing the insecticide from effectively binding to the sodium channels and thereby reducing its efficacy [3, 12].

2.3 Reduced Penetration

Reduced penetration resistance involves changes in the insect cuticle that slow down the absorption of insecticides. This can be due to alterations in cuticle thickness, composition, or structure, which act as a barrier to insecticide entry [13, 9]. Some populations of the German cockroach (*Blattella germanica*) exhibit reduced penetration resistance to pyrethroids. These changes in the cuticle reduce the rate at which the insecticide penetrates the insect's body, thereby reducing its effectiveness [13, 9].

2.4 Behavioural Resistance

Behavioural resistance involves changes in insect behaviour that reduce their exposure to insecticides. This can include behaviours such as avoiding treated surfaces, altered feeding patterns, or changes in habitat preference [14, 8]. For example, the mosquito *Anopheles gambiae*, a malaria vector, has exhibited behavioural resistance by avoiding insecticide-treated surfaces. This avoidance behaviour reduces their contact with the insecticide, thereby decreasing its impact on the population [14, 8].

Each of these resistance mechanisms poses a significant challenge to pest management efforts. Understanding the specific mechanisms at play in different pest populations is essential for developing targeted and effective insecticide resistance management strategies. Integrating knowledge of these mechanisms into pest management programs makes it possible to design more sustainable and effective approaches to controlling insecticide-resistant pest populations.

2.5 Factors Contributing to Resistance Development

A variety of biological and ecological factors influences the development of insecticide resistance in pest populations. Understanding these factors is essential for designing effective resistance management strategies.

High Reproductive Rate: Pests with high reproductive rates can rapidly increase the frequency of resistance alleles within a population. High fecundity ensures that even a small initial number of resistant individuals can produce a large number of offspring carrying the resistance alleles, thereby accelerating the spread of resistance [15, 1]. For example, the green peach aphid (*Myzus persicae*) has a high reproductive rate, which facilitates the rapid spread of resistance to various insecticides [16].

Short Generation Time: Short generation times accelerate the selection of resistant individuals, making resistance management more challenging. With each successive generation,

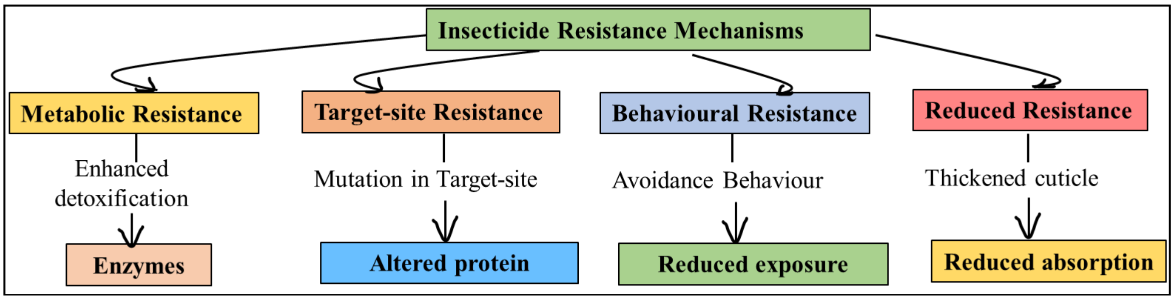

Fig. 1. Insecticide Resistance Mechanisms

the selective pressure exerted by insecticide applications can rapidly increase the proportion of resistant individuals in the population [1, 17]. The diamondback moth (*Plutella xylostella*), for instance, can complete its life cycle in as little as two weeks under optimal conditions, leading to rapid evolution of resistance [18].

High Selection Pressure: Frequent and high-dose applications of insecticides exert strong selection pressure for resistant individuals. This practice kills susceptible insects while allowing those with resistance traits to survive and reproduce, thereby increasing the frequency of resistance alleles in the population [1, 2]. In the case of the Colorado potato beetle (*Leptinotarsa decemlineata*), intense selection pressure from the widespread use of insecticides has led to resistance against multiple chemical classes [19].

Lack of Genetic Diversity: Inbreeding within pest populations can concentrate resistance alleles, facilitating the spread of resistance. Low genetic diversity reduces the likelihood that resistant individuals will mate with susceptible ones, thereby increasing the proportion of the population that carries resistance alleles [1, 20]. For example, the genetic bottleneck observed in some populations of the western corn rootworm (*Diabrotica virgifera virgifera*) has contributed to the rapid spread of resistance to *Bt* corn [21].

Monoculture Practices: Cultivating large areas with a single crop species can lead to high pest densities and increased insecticide use, promoting resistance. Monocultures provide an abundant and consistent food source for pests, which can result in large, genetically similar populations that are subjected to uniform selection pressures from insecticide applications [1, 22]. The widespread cultivation of *Bt* cotton has led to resistance in pests such as the pink bollworm (*Pectinophora gossypiella*) due to continuous exposure to the same selective agent [23].

3. RECENT CASE STUDIES IN INSECTICIDE RESISTANCE

3.1 Cotton Bollworm (*Helicoverpa armigera*)

The cotton bollworm has shown significant resistance to multiple classes of insecticides, including pyrethroids, organophosphates, and carbamates. Recent studies highlight the role of metabolic resistance, particularly through elevated cytochrome P450 activity, as a key mechanism in resistance development [24, 1]. Integrated pest management strategies, such as the rotation of insecticides, the use of natural enemies, and crop rotation, have been employed to manage resistance. For example, the use of natural enemies like parasitoid wasps has been shown to help control resistant populations of cotton bollworm [25].

3.2 Diamondback Moth (*Plutella xylostella*)

The diamondback moth is known for its rapid development of resistance to a range of insecticides, including *Bt* toxins. Resistance management strategies have included the use of refuges, rotation of insecticides and integrated pest management [26]. Recent research has emphasized the effectiveness of combining *Bt* crops with non-*Bt* refuges to delay resistance development [27]. Additionally, the use of multiple *Bt* toxins in crops has been reported to manage resistance more effectively [28].

3.3 Malaria Mosquito (*Anopheles gambiae*)

Anopheles gambiae has developed resistance to several insecticides used in malaria control, including pyrethroids and organochlorines. Mechanisms of resistance include target site mutations and metabolic resistance [8]. Strategies to manage resistance include the rotation of insecticides, the use of insecticide-treated nets with different chemicals, and enhanced surveillance and monitoring. Recent studies have shown that rotating different classes of insecticides in treated nets can help delay resistance.

3.4 Western Corn Rootworm (*Diabrotica virgifera virgifera*)

The western corn rootworm has developed resistance to *Bt* corn expressing *Cry*3Bb1 toxin. Resistance management strategies have included the use of non-*Bt* corn refuges and the development of *Bt* crops expressing multiple toxins [12]. Recent research has highlighted the importance of stacking multiple *Bt* genes to delay resistance [29].

3.5 Green Peach Aphid (*Myzus persicae*)

The green peach aphid has shown resistance to various classes of insecticides, including neonicotinoids and organophosphates. Recent studies have identified metabolic resistance as a major mechanism, with increased esterase activity being particularly significant [30]. Strategies to manage resistance include rotating insecticides and integrating biological control measures [16].

3.6 German Cockroach (*Blattella germanica*)

The German cockroach has developed resistance to multiple insecticides, including pyrethroids and carbamates. Recent research has identified changes in cuticle structure as a mechanism of reduced penetration resistance [9]. Resistance management strategies have included the rotation of insecticides and the use of integrated pest management approaches [31].

3.7 Fruit Fly (*Drosophila melanogaster*)

The fruit fly has developed resistance to various insecticides, including organophosphates and pyrethroids. Studies have identified both target site mutations and metabolic resistance mechanisms [32]. Recent strategies to manage resistance include using insecticide mixtures and employing genetic control methods.

3.8 House Fly (*Musca domestica*)

The house fly has shown resistance to multiple insecticides, including pyrethroids and organophosphates. Recent research has focused on the *kdr* (knockdown resistance) mutation in the sodium channel gene as a key resistance mechanism [3]. Management strategies have included rotation of insecticides and use of biological control agents [33].

3.9 Cotton Leafworm (*Spodoptera litura*)

The cotton leafworm has developed resistance to *Bt* cotton and other insecticides. Recent studies have highlighted the role of metabolic resistance and target site mutations in resistance. Strategies to manage resistance include using *Bt* crops with multiple toxins and rotating different classes of insecticides [34].

3.10 Rice Brown Planthopper (*Nilaparvata lugens*)

The rice brown planthopper has developed resistance to insecticides such as imidacloprid and chlorpyrifos. Recent research has identified metabolic resistance and target site mutations as significant mechanisms [35]. Resistance management strategies have included the use of resistant rice varieties and rotation of different insecticides [36].

4. CHALLENGES AND FUTURE DIRECTIONS IN INSECTICIDE RESISTANCE MANAGEMENT

4.1 Detection and Monitoring

Improving the detection and monitoring of insecticide resistance is crucial for timely and effective management. Advances in molecular tools and bioassays offer the potential for early detection of resistance development. For instance, polymerase chain reaction (PCR) techniques and high-throughput sequencing have become invaluable for identifying resistance-associated genetic markers in pest populations [37]. Recent studies have demonstrated that integrating molecular diagnostics with traditional bioassays can enhance the accuracy and speed of resistance detection, thus enabling more proactive resistance management strategies. Regular monitoring through these advanced techniques allows for early intervention and helps to prevent widespread resistance issues.

4.2 New Insecticides

The development of new insecticides with novel modes of action is vital for combating resistance. Novel compounds that target unique biological pathways can provide additional tools for resistance management. For example, recent innovations in insecticide chemistry have led to the development of products targeting insect neuropeptide systems and other new targets [38]. However, the process of developing these new insecticides requires substantial investment in research and development, as well as rigorous testing to ensure efficacy and safety [39]. Furthermore, the introduction of new insecticides into the market must be accompanied by effective resistance management strategies to prevent the rapid development of resistance to these new products.

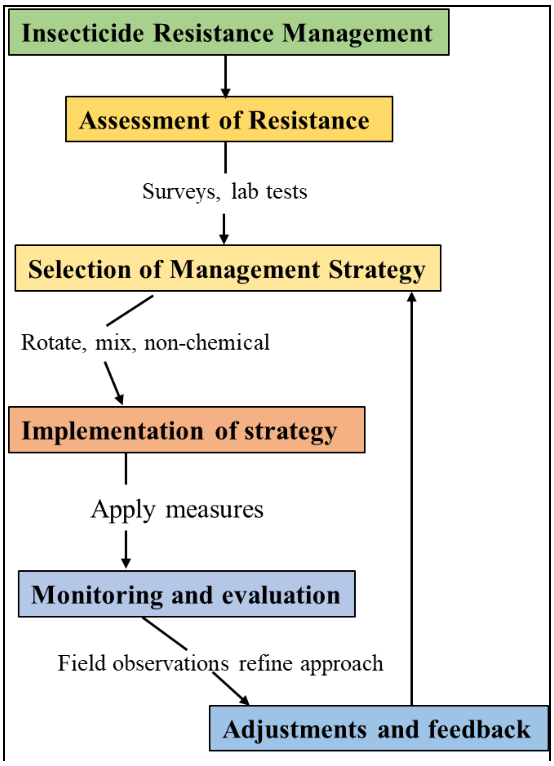

Fig. 2. Insecticide Resistance Management

4.3 Resistance Management Education

Educating farmers and pest control professionals about resistance management strategies is essential for the effective implementation of these practices. Training programs and extension services play a crucial role in disseminating knowledge about best practices in resistance management. Recent initiatives have focused on enhancing farmer education through workshops, field demonstrations, and digital platforms to increase awareness and adoption of integrated pest management (IPM) practices [40]. Studies have shown that well-informed farmers are more likely to employ strategies such as insecticide rotation and refuges, which are critical for managing resistance effectively [41]. Continuing education and outreach efforts are needed to ensure that resistance management strategies are implemented correctly and consistently.

4.4 Global Collaboration

Addressing insecticide resistance in migratory pests and those affecting multiple countries requires international collaboration. Global sharing of data, research findings and management strategies can significantly enhance resistance management efforts. For instance, international networks and databases such as the Insect Resistance Action Committee (IRAC) facilitate the exchange of information on resistance patterns and management strategies [42]. Collaborative efforts also enable countries to develop coordinated action plans and share resources for research and monitoring [43]. Strengthening global partnerships is essential for tackling resistance issues that cross national boundaries and for developing comprehensive and effective resistance management strategies on a global scale.

This study offers an extensive examination of the diverse mechanisms behind insecticide resistance, providing a clear understanding of metabolic resistance, target site mutations, reduced penetration, and behavioural changes. The review also highlights the complex interplay of biological and ecological factors, such as high reproductive rates and monoculture practices, that accelerate resistance development. The recent case studies, not only underscore the practical challenges faced in managing resistance across various pests but also presents innovative strategies like the use of molecular diagnostics and novel insecticides with unique modes of action. Furthermore, it emphasizes the importance of global collaboration and education in enhancing the effectiveness of resistance management programs, making it a valuable resource for researchers and practitioners in developing sustainable agricultural practices.

The scope of this article focuses on the growing challenge of insecticide resistance in agricultural pest management and its implications for global food security and economic stability. The article comprehensively examines the mechanisms by which pests develop resistance, such as metabolic changes, target site mutations, reduced penetration, and behavioural adaptations. It further explores the contributing factors, including high reproductive rates, short generation times, and monoculture practices, that accelerate resistance development. The review highlights various insecticide resistance management (IRM) strategies, emphasizing the importance of integrating chemical, biological, and cultural control methods. Additionally, it addresses the need for continuous monitoring, education, and international collaboration to develop sustainable pest management solutions. This knowledge helps in overcoming the challenges posed by insecticide resistance and ensuring the sustainability of agricultural practices.

5. CONCLUSION

Insecticide resistance significantly hampers sustainable pest management, threatening crop yields and agricultural productivity. A thorough understanding of resistance mechanisms and the implementation of effective Insecticide Resistance Management (IRM) strategies are essential for preserving the efficacy of insecticides. Integrating chemical, biological, and cultural control methods, along with ongoing monitoring and education, is crucial for managing resistance effectively and ensuring the long-term health of our agricultural systems.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc) and text-to-image generators have been used during writing or editing of manuscripts.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

REFERENCES

1. Hemingway J, Field L, Vontas J. An overview of insecticide resistance. Science. 2002;298(5591):96-7.
2. Sparks TC, Nauen R. IRAC: Mode of action classification and insecticide resistance management. Pesticide Biochemistry and Physiology. 2015;121: 122-8.
3. Davies TG, Field LM, Usherwood PN, Williamson MS. DDT, Pyrethrins, pyrethroids and insect sodium channels. IUBMB life. 2007;59(3):151-62.
4. Kaleem Ullah RM, Gao F, Sikandar A, Wu H. Insights into the effects of insecticides on aphids (Hemiptera: Aphididae): Resistance mechanisms and molecular basis. International Journal of Molecular Sciences. 2023;24(7):6750.
5. Bass C, Denholm I, Williamson MS, Nauen R. The global status of insect resistance to neonicotinoid insecticides. Pesticide Biochemistry and Physiology. 2015;121: 78-87.
6. Ye M, Nayak B, Xiong L, Xie C, Dong Y, You M, Yuchi Z, You S. The role of insect cytochrome P450s in mediating insecticide resistance. Agriculture. 2022;12(1):53.
7. Rinkevich FD, Du Y, Dong K. Diversity and convergence of sodium channel mutations involved in resistance to pyrethroids. Pesticide Biochemistry and Physiology. 2013;106(3):93-100.
8. Corbel V, N'Guessan R. Distribution, mechanisms, impact and management of insecticide resistance in malaria vectors: A pragmatic review. In Anopheles mosquitoes-New insights into malaria vectors. Intech Open; 2013.
9. Valles SM, Yu SJ. Detection and biochemical characterization of insecticide resistance in the German cockroach (Dictyoptera: Blattellidae). Journal of Economic Entomology. 1996;89(1):21-6.
10. Koo HN, An JJ, Park SE, Kim JH, Kim GH, Kang CY. Esterase-mediated resistance to organophosphates and carbamates in *Aphis gossypii* (Glover). Journal of Asia-Pacific Entomology. 2014;17(4):837-842.
11. Riveron JM, Yunta C, Ibrahim SS, Djouaka R, Irving H, Menze BD, Ismail HM, Hemingway J, Ranson H, Albert A, Wondji CS. A single mutation in the GSTe2 gene allows tracking of metabolically based insecticide resistance in a major malaria vector. Genome Biology. 2014;15:1-20.
12. Kasai S, Sun H, Scott JG, Yoshida T. Voltage-gated sodium channel gene mutations in pyrethroid-resistant house flies. Archives of Insect Biochemistry and Physiology. 2014;86(1):1-13.
13. Balabanidou V, Kampouraki A, MacLean M, Blomquist GJ, Tittiger C, Juárez MP, Mijailovsky SJ, Chalepakis G, Anthousi A, Lynd A, Antoine S. Cytochrome P450 associated with insecticide resistance catalyzes cuticular hydrocarbon production in *Anopheles gambiae*. Proceedings of the National Academy of Sciences. 2016; 113(33):9268-73.
14. Azizi S, Mbewe NJ, Mo H, Edward F, Sumari G, Mwacha S, Msapalla A, Mawa B, Mosha F, Matowo J. Is *Anopheles gambiae* (sensu stricto), the principal malaria vector in Africa prone to resistance development against new insecticides? Outcomes from laboratory exposure of *An. gambiae* (ss) to sub-lethal concentrations

of chlorfenapyr and clothianidin. Current Research in Parasitology and Vector-Borne Diseases. 2024;5:100172.

15. Alyokhin A, Dively G, Patterson M, Castaldo C, Rogers D, Mahoney M, Wollam J. Resistance and cross-resistance to imidacloprid and thiamethoxam in the Colorado potato beetle *Leptinotarsa decemlineata*. Pest Management Science: Formerly Pesticide Science. 2007;63(1): 32-41.
16. Foster SP, Devine G, Devonshire AL. Insecticide resistance. In Aphids as crop pests. Wallingford UK: CABI. 2017;426-447.
17. Roush R, Tabashnik BE, editors. Pesticide resistance in arthropods. Springer Science and Business Media. 2012.
18. Furlong MJ, Wright DJ, Dosdall LM. Diamondback moth ecology and management: Problems, progress, and prospects. Annual Review of Entomology. 2013;58(1):517-41.
19. Bras A, Roy A, Heckel DG, Anderson P and Karlsson Green K. Pesticide resistance in arthropods: Ecology matters too. Ecology Letters. 2022;25(8):1746-1759.
20. Levene M, Fenner T, Loizou G, Wheeldon R. A stochastic model for the evolution of the web. Computer Networks. 2002; 39(3):277-87.
21. Gassmann AJ, Petzold-Maxwell JL, Keweshan RS, Dunbar MW. Field-evolved resistance to Bt maize by western corn rootworm. Plos One. 2011;6(7):e22629.
22. Matson PA, Parton WJ, Power AG, Swift MJ. Agricultural intensification and ecosystem properties. Science. 1997;277 (5325):504-9.
23. Tabashnik BE, Van Rensburg JB, Carrière Y. Field-evolved insect resistance to Bt crops: Definition, theory, and data. Journal of Economic Entomology. 2009;102(6): 2011-25.
24. Bade AS. Insecticidal resistance in *Helicoverpa armigera* (Hubner) infesting chickpea. Indian Journal of Entomology. 2024:204-7.
25. Malinga LN, Laing MD. Efficacy of biopesticides in the management of the cotton bollworm, *Helicoverpa armigera* (Noctuidae), under field conditions. Insects. 2022;13(8):673.
26. Shelton AM, Robertson JL, Tang JD, Perez C, Eigenbrode SD, Preisler HK, Wilsey WT, Cooley RJ. Resistance of diamondback moth (Lepidoptera: Plutellidae) to *Bacillus thuringiensis* subspecies in the field. Journal of Economic Entomology. 1993;86(3):697-705.
27. Gassmann AJ and Petzold-Maxwell JL. Bt crop resistance management: A review of current strategies and future directions. Pest Management Science. 2022;78(3): 643-656.
28. Riley DG, Sparks Jr AN. Insecticide resistance management: Diamondback moth in cole crops. Georgia Coop. Ext. Service. Circular. 2011;899(2).
29. Meinke LJ, Reinders JD, Dang TB, Krumm JT, Pilcher CD, Carroll MW, Head GP. Resistance management and integrated pest management insights from deployment of a Cry3Bb1+ Gpp34Ab1/Tpp35Ab1 pyramid in a resistant western corn rootworm landscape. Plos One. 2024;19(3): e0299483.
30. Silva AX, Jander G, Samaniego H, Ramsey JS, Figueroa CC. Insecticide resistance mechanisms in the green peach aphid *Myzus persicae* (Hemiptera: Aphididae) I: A transcriptomic survey. Plos One. 2012;7(6):e36366.
31. DeVries ZC, Santangelo RG, Crissman J, Suazo A, Kakumanu ML and Schal C. Pervasive resistance to pyrethroids in German cockroaches (Blattodea: Ectobiidae) related to lack of efficacy of total release foggers. Journal of Economic Entomology. 2019;112(5):2295-2301.
32. Khan S, Uddin MN, Rizwan M, Khan W, Farooq M, Shah AS, Subhan F, Aziz F, Rahman KU, Khan A, Ali S. Mechanism of Insecticide Resistance in Insects/Pests. Polish Journal of Environmental Studies. 2020;29(3).
33. Wang JN, Hou J, Wu YY, Guo S, Liu QM, Li TQ, Gong ZY. Resistance of house fly, *Musca domestica L*. (Diptera: Muscidae), to five insecticides in Zhejiang Province, China: The situation in 2017. Canadian Journal of Infectious Diseases and Medical Microbiology. 2019;2019(1): 4851914.
34. Coudron TA and Wu K. Resistance management for *Spodoptera litura* in Bt cotton systems. Crop Protection, 2022; 149:105826.

35. Khan MN and Khan AA. Resistance mechanisms and management strategies for *Nilaparvata lugens* in rice fields. Journal of Agricultural and Food Chemistry. 2022; 70(15):4685-4696.
36. Datta J, Banik SC. Insecticide resistance in the brown planthopper, *Nilaparvata lugens* (Stål): Mechanisms and status in Asian countries. Journal of the Entomological Research Society. 2021;23(3):225-38.
37. Yin J, Yamba F, Zheng C, Zhou S, Smith SJ, Wang L, Li H, Xia Z, Xiao N. Molecular detection of insecticide resistance mutations in *Anopheles gambiae* from Sierra Leone using multiplex snapshot and sequencing. Frontiers in Cellular and Infection Microbiology. 2021; 11:666469.
38. David J and F Xu P. Novel insecticide targets: Recent advances in chemistry and efficacy. Pesticide Biochemistry and Physiology. 2021;171:104743.
39. Chandler D, Bailey AS, Tatchell GM, Davidson G, Greaves J, Grant WP. The development, regulation and use of biopesticides for integrated pest management. Philosophical Transactions of the Royal Society B: Biological Sciences. 2011;366(1573):1987-98.
40. Thapa S, Piras G, Thapa S, Goswami A, Bhandari P, Dahal B. Study on farmers' Pest management strategy, knowledge on pesticide safety and practice of pesticide use at Bhaktapur district, Nepal. Cogent Food and Agriculture. 2021;7(1):1916168.
41. Sahu KK, Bardhan R, Chouhan NS, Dixit D, Tripathi S, Pandey A, Ahmed R. A Comprehensive review on role of agricultural extension services in the sustainable development of global agriculture. International Journal of Environment and Climate Change. 2023; 13(10):3514-25.
42. Hemingway J and Lane JPRM. Global efforts in insecticide resistance management: A review. Annual Review of Entomology. 2023;68:123-145.
43. Ding Y and R Zhao Z. International collaboration in managing insecticide resistance: Case studies and recommendations. International Journal of Pest Management. 2023;69(1):45-60.

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