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Insecticide Resistance in Agricultural Pests: Mechanisms, Monitoring and Sustainable Management

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Insecticide resistance is a major threat to the durability and reliability of crop protection because repeated selection can increase the frequency of heritable traits that reduce pest susceptibility. Resistance has been documented across many important agricultural pests and insecticide modes of action. The major mechanisms include metabolic resistance through enhanced detoxification, target-site resistance caused by changes in the insecticide target, reduced penetration through the cuticle and behavioural avoidance. Cross-resistance and multiple resistance mechanisms can further complicate management. Effective resistance management begins with early detection through systematic monitoring of pest susceptibility and field performance. Laboratory dose-response assays, diagnostic-dose bioassays, field efficacy observations and molecular or biochemical diagnostics can be combined to identify changes in susceptibility and characterize resistance mechanisms. Sustainable management requires integration of insecticide resistance management with broader integrated pest management, including economic thresholds, crop rotation, resistant cultivars, biological control, cultural practices, selective insecticides and carefully designed alternation or rotation of insecticide modes of action. Future approaches will increasingly use genomics, rapid molecular diagnostics, artificial intelligence, resistance-risk modelling, precision application and climate-informed decision support. This review discusses the mechanisms, detection, monitoring and sustainable management of insecticide resistance and highlights research priorities for maintaining effective crop protection while reducing selection pressure.

Introduction

Insecticides have played a central role in modern crop protection by reducing pest populations and preventing economically significant crop losses. However, the evolutionary response of insect populations to repeated insecticide exposure can progressively reduce susceptibility and eventually cause control failure. IRAC describes resistance as a genetically heritable reduction in sensitivity of a target pest population to an insecticide, while emphasizing that resistance evolution is driven by interactions among pest genetics, biology and insecticide use practices. Resistance has been reported for numerous insecticide groups, including older chemistries such as organochlorines, organophosphates, carbamates and pyrethroids as well as newer groups such as neonicotinoids and diamides. The problem is not restricted to a single crop or pest. It can affect sucking pests, chewing insects, mites and other arthropod targets, creating economic pressure on farmers and reducing the number of effective management options. The development of resistance is an evolutionary process. In a susceptible population, individual insects vary naturally in their sensitivity to an insecticide. Selection removes a larger proportion of susceptible individuals, allowing less-susceptible individuals to survive and reproduce. Repeated selection can therefore increase resistance-associated traits in the population. Intensive or inappropriate use of a single insecticide or related mode of action can accelerate this process. Resistance management should therefore begin before field failure becomes widespread. Monitoring provides an early-warning system, while integrated pest management reduces unnecessary selection pressure. FAO describes IPM as an ecological approach that combines biological, chemical, physical and crop-specific measures to discourage pest populations while minimizing pesticide risks.

Mechanisms of Insecticide Resistance

Resistance mechanisms are commonly grouped into metabolic resistance, target-site resistance, reduced penetration and behavioural resistance. These mechanisms can occur independently or together within the same pest population. Metabolic resistance is often especially important because enhanced detoxification systems can sometimes reduce susceptibility to multiple insecticides.

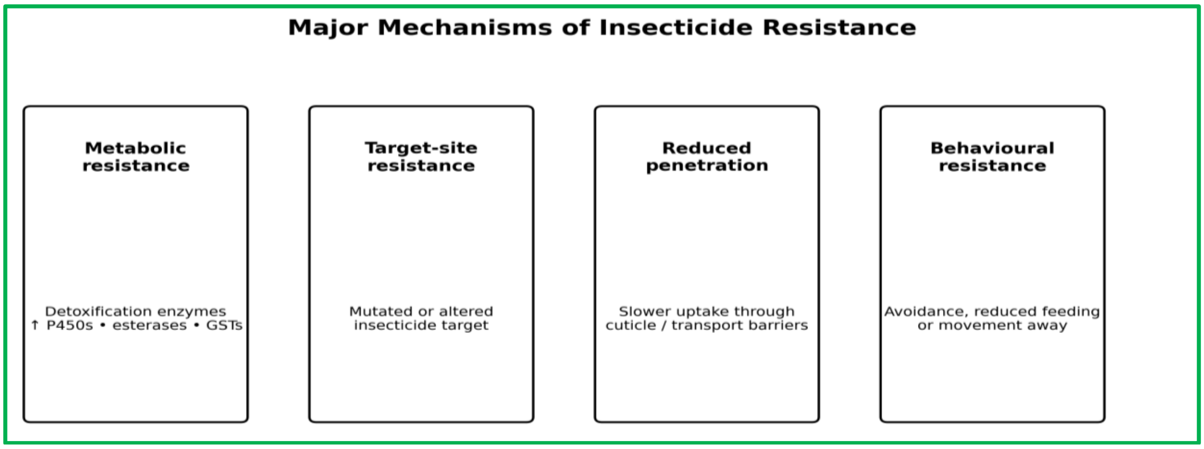

Figure 1. Principal mechanisms by which agricultural insect pests can evolve resistance to insecticides.

Metabolic Resistance

Metabolic resistance occurs when insects detoxify, sequester or eliminate insecticide molecules more efficiently than susceptible individuals. Enzyme systems involved can include cytochrome P450 monooxygenases, esterases and glutathione S-transferases. Increased expression or altered activity of these enzymes can reduce the concentration of active insecticide reaching its physiological target. Metabolic resistance can be particularly difficult to manage because a single biochemical system may act on more than one insecticide. This can create cross-resistance, in which resistance to one compound is associated with reduced susceptibility to another compound even when the two products have different target sites. Consequently, simply changing the commercial product may not solve the problem if the same metabolic mechanism remains effective. IRAC identifies metabolic resistance as a common and often challenging mechanism. Biochemical assays measuring enzyme activity and molecular assays examining expression of detoxification genes can help characterize metabolic resistance. However, elevated enzyme activity should be interpreted together with phenotypic susceptibility because the presence of a biochemical marker does not automatically demonstrate field-level control failure.

Target-Site Resistance

Target-site resistance occurs when genetic changes modify the protein or physiological site targeted by an insecticide. The alteration can reduce insecticide binding or interfere with the normal interaction between the insecticide and its target, allowing resistant insects to survive exposure. Target-site changes have been documented for several insecticide modes of action and are an important component of molecular resistance surveillance. Because target-site resistance is linked to specific molecular changes, DNA-based diagnostic assays can sometimes detect resistance alleles rapidly. Molecular monitoring is especially valuable when a validated mutation is strongly associated with a resistance phenotype. Nevertheless, molecular results should ideally be complemented by phenotypic assays because resistance can involve multiple mechanisms and allele frequency does not always predict the level of field control.

Reduced Penetration and Behavioural Resistance

Penetration resistance occurs when insecticide absorption through the insect cuticle is reduced. Changes in cuticular composition or structure can slow uptake and thereby reduce the amount of active ingredient reaching internal tissues. Reduced penetration may occur together with metabolic or target-site resistance and can intensify their effects. Behavioural resistance occurs when insects avoid contact with an insecticide or modify their behaviour after exposure. Examples include leaving treated areas, moving to protected parts of the crop canopy or reducing feeding. Although behavioural responses may be less obvious than biochemical resistance, they can reduce effective exposure and contribute to field-control problems.

Cross-Resistance and Multiple Resistance

Cross-resistance occurs when a resistance mechanism selected by one insecticide also reduces susceptibility to another insecticide. Multiple resistance refers to the presence of resistance to several insecticides or modes of action through different mechanisms. These conditions can substantially reduce the number of effective chemical options and make management more complex. Resistance-management programmes must therefore consider mechanism and mode of action rather than relying only on product names. IRAC recommends the use of alternations, sequences or rotations of compounds from different mode-of-action groups and cautions that metabolic cross-resistance can modify the expected benefit of simple rotations.

Factors Driving the Evolution of Resistance

Resistance evolution is influenced by the intensity and frequency of insecticide exposure, pest biology, generation time, dispersal, genetic variation, dominance of resistance alleles, migration and the availability of untreated refuges. Frequent applications of the same mode of action exert strong selection and can increase resistance frequency rapidly in pests with multiple generations per season. Application practices also influence selection. Under-dosing, poor coverage, inappropriate timing and repeated exposure of successive generations can leave partially susceptible insects alive and reproducing. Conversely, indiscriminate high-frequency spraying can eliminate natural enemies and increase the ecological dependence on insecticides. IRAC recommends using products only when economically justified and integrating them with other control strategies.

Monitoring Insecticide Resistance

Resistance monitoring is essential for detecting changes in susceptibility before widespread field failure occurs. IRAC distinguishes proactive monitoring, which seeks early changes in susceptibility or product performance, from reactive monitoring, which investigates suspected control failures. Both approaches can contribute to resistance management when appropriately designed.

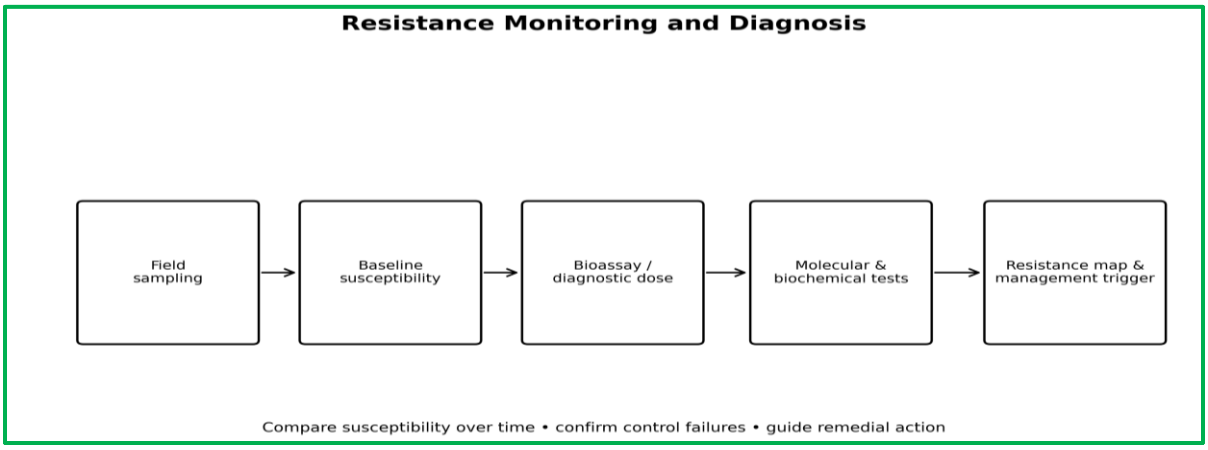

Figure 2. General workflow for monitoring insecticide resistance using field sampling, phenotypic assays and complementary molecular or biochemical approaches.

A strong monitoring programme begins with a baseline. Baseline susceptibility can be established using standardized concentration-response assays before extensive exposure to a product or in populations with known susceptibility. Subsequent field populations can then be compared with the baseline using the same methods. IRAC recommends consistency in bioassay methodology to enable meaningful comparisons over time and among locations.

Phenotypic Bioassays

Phenotypic bioassays measure the actual response of insects to defined insecticide concentrations. Concentration-response experiments can estimate parameters such as LC50 or LD50, while diagnostic or discriminating doses can be used for routine screening. Standardization of insect age, life stage, exposure method, temperature, humidity, formulation and observation period is essential because variation in assay conditions can affect results. A diagnostic-dose approach can efficiently screen large numbers of field-collected insects and identify populations with reduced susceptibility. When resistance is suspected, full dose-response testing can provide more detailed information about resistance magnitude. Field efficacy tests can complement laboratory assays by determining whether reduced susceptibility is translating into inadequate crop protection.

Biochemical and Molecular Monitoring

Biochemical assays can detect elevated activity of detoxification enzymes such as esterases, glutathione S-transferases and cytochrome P450-associated systems. Molecular approaches can identify target-site mutations or other genetic markers associated with resistance. These methods can be rapid and sensitive, particularly when validated markers are available. However, molecular or biochemical monitoring should not be considered a complete substitute for phenotypic assessment. IRAC notes that molecular methods should generally be complemented with phenotype-based monitoring because resistance can involve several mechanisms and the relationship between a marker and field susceptibility may vary.

Spatial and Temporal Monitoring

Resistance is rarely distributed uniformly across an agricultural region. Field history, cropping intensity, pesticide use, pest migration and landscape structure can create localized resistance hotspots. Systematic sampling across locations and seasons can therefore identify where resistance is increasing and where management changes should be prioritized. Geographic information systems and spatial modelling can convert monitoring results into resistance-risk maps. Combining resistance data with pesticide-use history, crop distribution, pest abundance and climate variables can improve prediction of areas at higher risk. Long-term monitoring is particularly valuable because it can reveal whether management interventions are slowing or reversing susceptibility declines.

Insecticide Resistance Management within IPM

Sustainable resistance management should be integrated with IPM rather than implemented as a stand-alone pesticide rotation programme. IRAC recommends combining field monitoring, economic thresholds and multiple pest-control tactics. FAO similarly emphasizes integration of biological, cultural, physical and chemical methods to reduce pesticide reliance and discourage pest resurgence and resistance.

Mode-of-Action Rotation and Alternation

One of the central principles of insecticide resistance management is diversification of modes of action. Successive generations of a pest should not be repeatedly exposed to the same mode of action. Alternation, sequence or rotation of appropriate mode-of-action groups can reduce selection pressure on any single resistance mechanism. IRAC recommends organizing applications into appropriate windows or blocks according to crop development and pest biology. Rotation should not be based simply on switching brand names. Products with the same mode of action or known cross-resistance should not be treated as independent selection events. Local IRAC recommendations and registered-label instructions should be followed because appropriate rotations differ among pest–crop systems.

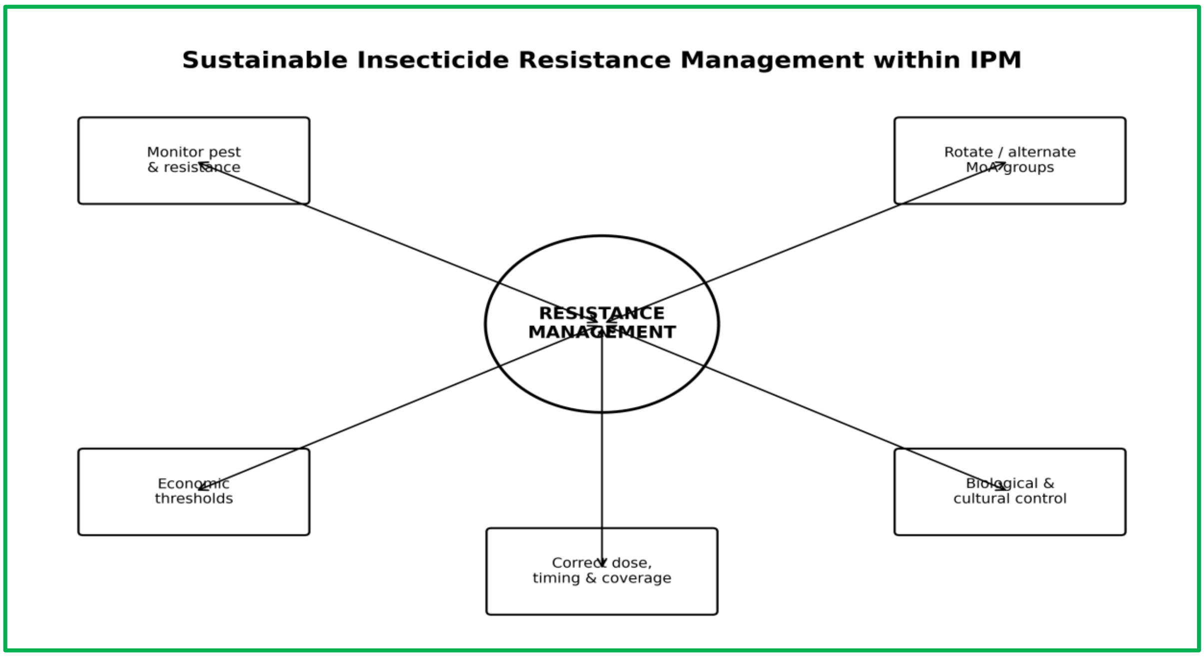

Figure 3. Core components of sustainable insecticide resistance management integrated with broader IPM

Economic Thresholds and Judicious Insecticide Use

Economic thresholds are an important resistance-management tool because unnecessary applications expose pest populations to selection pressure without providing proportional economic benefit. Insecticides should generally be used when pest abundance or expected damage reaches the locally appropriate economic threshold, with exceptions where preventive treatments are specifically justified. Correct application rate, timing and coverage are also important. Poor application may leave survivors that reproduce and contribute to resistance while failing to provide adequate control. IRAC emphasizes following label rates and intervals and targeting the most vulnerable pest life stage.

Biological and Cultural Tactics

Biological control, host-plant resistance, crop rotation, sanitation, trap crops, habitat management and other cultural tactics can reduce dependence on insecticides. Preserving predators and parasitoids is especially important because broad-spectrum insecticides can remove natural enemies and trigger secondary pest outbreaks. Cultural practices can also reduce the number of pests exposed to insecticides. Crop residues may provide overwintering habitat for some pests, while crop rotation can interrupt pest life cycles. However, individual practices should be evaluated for the specific crop and pest system and balanced with soil-conservation requirements. IRAC includes crop residue management and preservation of susceptible insects through refuges or untreated habitats among resistance-management considerations.

Refuges and Preservation of Susceptibility

Refuges or untreated areas can maintain susceptible individuals in some pest-management systems. When susceptible insects survive and interbreed with resistant individuals, the frequency of resistance alleles may be diluted under appropriate genetic conditions. Refuge design is particularly important for some transgenic crop systems and should follow crop- and pest-specific recommendations. The usefulness of refuges depends on resistance genetics, pest movement, mating behaviour and landscape structure. Therefore, refuge strategies should be evidence-based rather than applied uniformly to all insecticide-resistance problems.

Case Examples of Resistance Challenges in Agricultural Pests

Resistance has been documented across numerous economically important pests. Whiteflies, aphids, thrips, diamondback moth, diamondback moth relatives, bollworms, fall armyworm and other pests have developed resistance to multiple insecticide groups in different regions. The specific mechanism and resistance level vary among populations, making local monitoring essential. Fall armyworm provides a prominent example of a highly mobile pest in which repeated insecticide use can create strong selection pressure. IRAC maintains specific resistance-management guidance for fall armyworm and other chewing pests, illustrating the need to adapt management to pest biology and available modes of action. Resistance management is also increasingly relevant to newer insecticide chemistries. The appearance of resistance to relatively recent modes of action demonstrates that introducing a new product does not eliminate evolutionary risk. Proactive monitoring and diversification should therefore begin early in the product-use cycle rather than after widespread control failure.

Role of Climate Change in Resistance Evolution

Climate change may modify resistance dynamics indirectly by changing pest generations, geographical distribution, crop phenology and insecticide exposure patterns. Warmer conditions can increase the number of generations completed by some pests, potentially increasing the number of selection events per season. Changes in pest distribution may also introduce resistant populations into new agricultural regions. Temperature can influence insecticide toxicity, detoxification enzyme activity and insect development, potentially changing the expression of resistance under field conditions. Consequently, resistance-management planning should increasingly consider climate variability alongside pesticide-use history and pest biology.

Future Technologies for Resistance Monitoring and Management

Future resistance surveillance is likely to combine conventional bioassays with molecular diagnostics, genomics and digital technologies. Rapid detection of validated resistance mutations could allow extension services to identify emerging resistance before widespread control failure. Genomic surveillance may also reveal population structure, migration and the spread of resistance alleles.

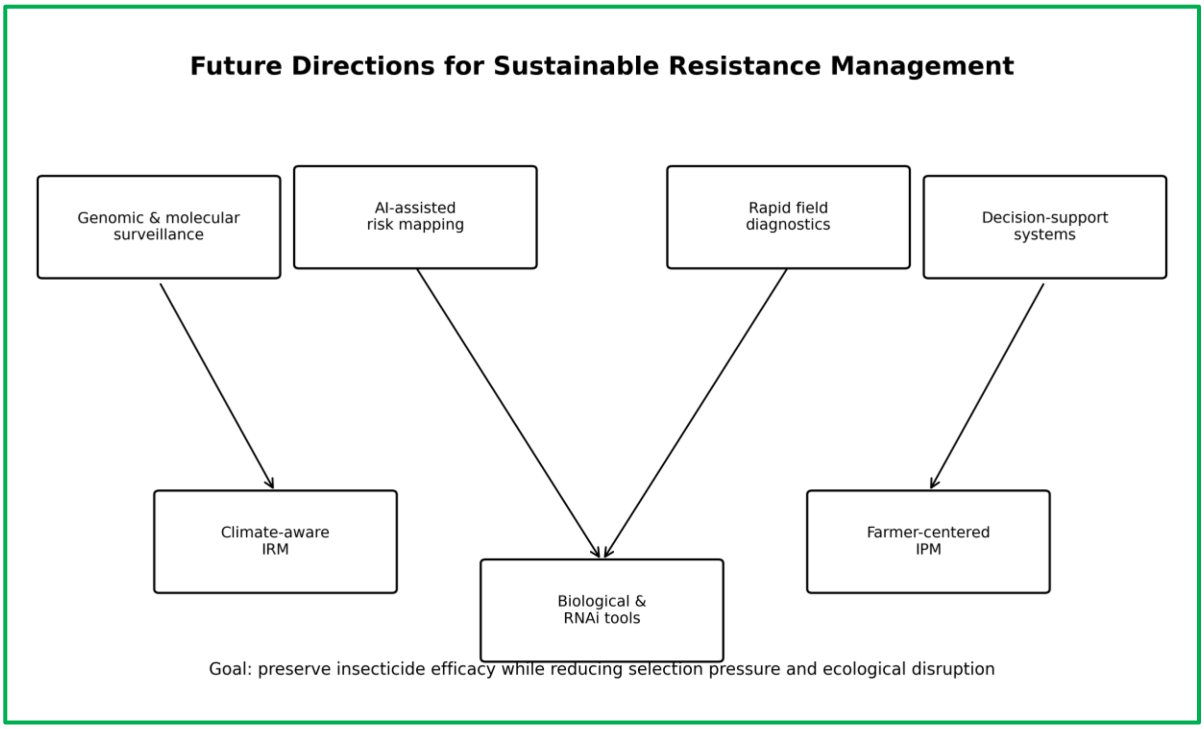

Figure 4. Emerging technologies and management approaches for future insecticide resistance monitoring and sustainable control

Artificial intelligence and machine learning can support resistance-risk mapping by integrating pest abundance, insecticide-use history, climate, crop distribution and resistance-monitoring data. Decision-support systems could provide location-specific warnings and recommend diversification of control measures. These tools should support rather than replace field validation and expert interpretation. Precision agriculture may further reduce selection pressure by applying insecticides only where pest populations exceed thresholds. Variable-rate application, automated scouting and targeted spraying can reduce unnecessary treatment area. Combining precision application with biological control and resistant cultivars may extend the effective life of available insecticides. RNA interference, microbial insecticides and other novel biological tools may provide additional modes of action and reduce dependence on conventional chemistries. However, these technologies can also face evolutionary resistance, so diversification and proactive monitoring should remain central principles.

Challenges in Implementing Resistance Management

Effective resistance management requires coordination among farmers, researchers, extension personnel, regulators and pesticide developers. Monitoring can be expensive and technically demanding, especially when pest populations must be collected from many locations and maintained for laboratory testing. Smallholder farming systems may have limited access to diagnostic facilities and expert advice. Another challenge is the interpretation of resistance data. A laboratory shift in LC50 does not always mean immediate field failure, while field control failure may result from poor application, pest misidentification, weather or insufficient coverage rather than resistance. Resistance diagnosis should therefore consider the complete pest-management context. Communication is also critical. Monitoring results need to be translated into practical recommendations that farmers can implement. IRAC emphasizes transparency, collaboration and shared understanding of monitoring objectives and remedial action plans among stakeholders.

Conclusion

Insecticide resistance is an evolutionary challenge that can progressively reduce the effectiveness of crop-protection products. Metabolic resistance, target-site modification, reduced penetration and behavioural avoidance may occur alone or in combination, while cross-resistance and multiple resistance can further restrict management options. Because resistance can evolve before obvious field failure becomes widespread, systematic monitoring and early intervention are essential. Sustainable management requires a shift from repeated dependence on individual insecticides toward diversified IPM and insecticide resistance management. Economic thresholds, biological control, cultural practices, resistant cultivars, correct application and carefully planned alternation or rotation of different modes of action can reduce selection pressure. Monitoring should combine standardized phenotypic assays with validated molecular and biochemical diagnostics where appropriate. Future resistance management will benefit from genomics, rapid diagnostics, spatial modelling, artificial intelligence, precision application and climate-aware decision support. The central objective should remain preservation of insecticide efficacy while minimizing unnecessary exposure and ecological disruption. Coordinated, farmer-oriented and evidence-based resistance management will be essential for maintaining productive and sustainable agricultural systems.

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