

Insecticide Resistance in Mosquito Populations: Mechanisms and Management

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Abstract

Mosquito-borne diseases such as malaria, dengue, chikungunya, Zika, yellow fever and Japanese encephalitis remain major public-health challenges. Insecticides are an important component of mosquito-vector control, particularly through indoor residual spraying, insecticide-treated nets, larviciding and adult mosquito control. However, repeated and intensive use of insecticides has contributed to the evolution and spread of insecticide resistance in several mosquito species. Insecticide resistance is an inherited reduction in susceptibility that allows mosquitoes to survive exposure to doses that would normally kill susceptible individuals. The major mechanisms include target-site resistance, metabolic resistance, reduced penetration through the cuticle, and behavioural resistance. Target-site resistance commonly involves mutations such as *kdr* mutations in the voltage-gated sodium-channel gene, while metabolic resistance is associated with enhanced activity of cytochrome P450 monooxygenases, esterases and glutathione S-transferases. Resistance can reduce the effectiveness of vector-control programmes and may contribute to persistent transmission of mosquito-borne diseases. The World Health Organization (WHO) recommends systematic surveillance, standardized susceptibility testing, identification of resistance mechanisms and evidence-based selection of vector-control interventions. Integrated vector management, insecticide rotation or mosaic approaches where appropriate, synergists such as piperonyl butoxide (PBO) for suitable applications, biological control, environmental management and development of new vector-control technologies are important components of resistance management. This article reviews the mechanisms, causes, consequences, monitoring approaches and management strategies for insecticide resistance in mosquito populations and emphasizes the need for integrated and locally adapted approaches.

Keywords: *Mosquitoes; insecticide resistance; Anopheles; Aedes; Culex; kdr; metabolic resistance; vector control; integrated vector management; dengue; malaria.*

Introduction

Mosquitoes are among the most important vectors of infectious diseases affecting humans. Species belonging to the genera *Anopheles*, *Aedes* and *Culex* transmit malaria, dengue, chikungunya, Zika, yellow fever, Japanese encephalitis, West Nile fever and several other diseases. Consequently, mosquito control is an essential component of public-health programmes.

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Chemical insecticides have historically played a major role in mosquito control. They are used in indoor residual spraying, insecticide-treated nets, larval control, space spraying and other interventions. Insecticides can rapidly reduce mosquito populations and interrupt disease transmission. However, intensive and repeated exposure creates strong evolutionary selection pressure. Mosquitoes carrying genetic characteristics that permit survival are more likely to reproduce, gradually increasing the frequency of resistance-associated traits in subsequent generations. The WHO describes insecticide resistance as a major threat to effective vector control. Its current monitoring guidance emphasizes determining resistance levels and mechanisms so that vector-control decisions can be based on local evidence. Resistance is particularly important because it is not necessarily uniform. The same mosquito species may show different resistance profiles in different geographical locations, and resistance to one insecticide may occur through several mechanisms. Similarly, resistance to one insecticide can sometimes confer cross-resistance to other insecticides with related modes of action. The problem therefore requires more than simply changing the insecticide after control failure. Sustainable management requires continuous surveillance, understanding of mechanisms, appropriate insecticide selection and integration of chemical and non-chemical control measures.

Review of Literature

Early understanding of insecticide resistance

Insecticide resistance has been recognized as an evolutionary consequence of prolonged insecticide exposure. Earlier studies primarily focused on physiological resistance and changes in insecticide susceptibility. Subsequent biochemical and molecular research demonstrated that resistance can arise through modifications of insecticide target sites and increased detoxification. Classical research identified resistance to DDT and pyrethroids through alterations of voltage-gated sodium channels. Other studies demonstrated increased esterase, oxidase and glutathione S-transferase activity as important mechanisms of metabolic resistance.

WHO resistance-monitoring framework

The WHO has developed standardized procedures for monitoring resistance in mosquito vectors. Its 2022 manual provides procedures for assessing resistance and selecting appropriate vector-control interventions. The guidance covers important mosquito vectors including *Anopheles*, *Aedes* and *Culex*. WHO also conducted multicentre laboratory work to establish and validate discriminating concentrations for insecticides used against important *Anopheles* and *Aedes* species.

Resistance in *Aedes* mosquitoes

Resistance in *Aedes aegypti* and *Aedes albopictus* is of particular importance because these species transmit dengue, chikungunya and Zika viruses. A WHO South-East Asia regional assessment reported considerable variation in insecticide-resistance data between and within countries and highlighted the need for standardized and longitudinal monitoring. The regional evidence also demonstrates the importance of identifying the molecular and biochemical mechanisms underlying observed resistance rather than relying only on mortality tests.

Recent research

Recent systematic research continues to identify target-site, metabolic and physiological mechanisms as central to mosquito insecticide resistance. A systematic review published in 2026, based on literature through December 2024, examined biochemical and physiological mechanisms across *Anopheles*, *Aedes* and *Culex* mosquitoes and emphasized the need for mechanism-based approaches to sustainable vector control.

Objectives of the Study

The major objectives of this article are:

1. To explain the concept and evolutionary basis of insecticide resistance in mosquito populations.

2. To examine the major mechanisms responsible for insecticide resistance.
3. To identify factors contributing to the development and spread of resistance.
4. To assess the implications of resistance for mosquito-borne disease control.
5. To examine methods used for resistance surveillance and detection.
6. To discuss integrated strategies for preventing and managing resistance.
7. To suggest research and policy measures for sustainable mosquito control.

Major Insecticides Used in Mosquito Control

Several classes of insecticides have historically been used for mosquito control.

Insecticide class	Examples	Principal target/action
Organochlorines	DDT	Voltage-gated sodium channels
Pyrethroids	Permethrin, deltamethrin, lambda-cyhalothrin	Voltage-gated sodium channels
Organophosphates	Malathion, pirimiphos-methyl	Acetylcholinesterase
Carbamates	Bendiocarb, propoxur	Acetylcholinesterase
Insect growth regulators	Pyriproxyfen, methoprene	Disrupt mosquito development
Microbial larvicides	<i>Bacillus thuringiensis</i> subsp. <i>israelensis</i>	Larval midgut toxicity

The choice of an insecticide should be based on vector species, local susceptibility, intervention type, operational considerations and resistance information rather than on chemical availability alone.

Mechanisms of Insecticide Resistance

Insecticide resistance is a complex phenomenon. The principal mechanisms can be grouped into four broad categories.

Target-Site Resistance: Target-site resistance occurs when mutations alter the biological molecule on which an insecticide acts.

Voltage-gated sodium channel mutations: Pyrethroids and DDT act primarily on voltage-gated sodium channels in mosquito nerve cells. Mutations in the sodium-channel gene can reduce insecticide binding or alter channel sensitivity.

These mutations are commonly referred to as **knockdown resistance or *kdr* mutations**.

For example: **Insecticide → sodium channel → normal nerve function disrupted → mosquito paralysis/death**

With a resistance-associated mutation: **Insecticide → altered sodium channel → reduced insecticide effect → mosquito survives**

WHO identifies mutations in the voltage-sensitive sodium-channel gene as one of the best-characterized target-site resistance mechanisms.

Acetylcholinesterase resistance: Organophosphate and carbamate insecticides interfere with acetylcholinesterase, an enzyme involved in nerve transmission. Changes in the enzyme can reduce insecticide sensitivity and allow mosquitoes to survive exposure.

GABA-receptor resistance: Resistance to certain insecticides such as cyclodienes can involve mutations affecting GABA receptors. Target-site alterations therefore differ according to the insecticide's mode of action.

Metabolic Resistance

Metabolic resistance occurs when mosquitoes increase their ability to detoxify or break down insecticides before the chemicals reach their physiological targets. Three major enzyme systems are particularly important.

- ❖ **Cytochrome P450 monooxygenases:** Elevated or altered cytochrome P450 activity can metabolize or modify several insecticides. Increased P450 activity is particularly important in resistance to pyrethroids and some other insecticide groups.
- ❖ **Esterases:** Esterases can hydrolyse or sequester insecticide molecules, reducing the amount reaching the target site.
- ❖ **Glutathione S-transferases:** Glutathione S-transferases participate in detoxification processes and can contribute to resistance to certain insecticides. WHO identifies P450 monooxygenases, esterases/carboxylesterases and glutathione S-transferases among the major metabolic mechanisms associated with mosquito insecticide resistance.

Cuticular Resistance

The mosquito cuticle forms a physical barrier between the insecticide and the internal tissues. Changes in cuticle structure or composition can reduce the rate at which insecticides penetrate the mosquito.

The general process can be represented as:

Thicker/modified cuticle → slower insecticide penetration → greater detoxification opportunity → increased survival

Cuticular resistance is generally considered less extensively studied than target-site and metabolic mechanisms, but it can contribute to the resistance phenotype.

Behavioural Resistance

Some mosquitoes can modify their behaviour in ways that reduce contact with insecticides. Examples include:

- Avoiding Treated Surfaces;
- Changing Resting Locations;
- Changing Biting Times;
- Changing Host-Seeking Behaviour;
- Spending More Time Outdoors Rather Than Indoors.

Behavioural changes can reduce the mosquito's exposure to insecticides even when the mosquito has not developed strong physiological resistance. This is particularly important when mosquito behaviour changes in response to vector-control interventions.

Factors Responsible for Development of Resistance: Several factors contribute to insecticide resistance.

1. **Repeated insecticide exposure:** Continuous use of the same insecticide exerts strong selection pressure.
2. **Extensive agricultural pesticide use:** Agricultural insecticides may expose mosquito populations to chemicals with similar modes of action, contributing to selection for resistance.
3. **Improper insecticide application:** Incorrect concentration, poor-quality application and inadequate coverage can expose mosquitoes to sublethal doses.
4. **Cross-resistance:** Resistance to one insecticide may sometimes confer resistance to another insecticide because of a shared target site or detoxification mechanism.
5. **Gene flow:** Movement of mosquitoes between populations can facilitate the geographical spread of resistance-associated alleles.

6. **Environmental conditions:** Temperature, breeding-site characteristics, urbanization and ecological changes can influence mosquito population dynamics and exposure to insecticides.
7. **Inadequate surveillance:** Failure to monitor susceptibility means that resistance may remain undetected until vector-control effectiveness declines.

Consequences of Insecticide Resistance

- a. **Reduced vector-control effectiveness:** The most direct consequence is decreased mosquito mortality following insecticide exposure. CDC guidance notes that repeated use of insecticides can result in products becoming less effective or only partially effective against resistant mosquito populations.
- b. **Increased disease-transmission risk:** If vector-control interventions become less effective, mosquito populations may remain sufficiently high to sustain disease transmission.
- c. **Increased operational costs:** Programmes may require additional surveillance, alternative insecticides, additional interventions and more frequent control activities.
- d. **Limited insecticide choices:** Resistance can reduce the number of effective chemical options available to public-health programmes.
- e. **Risk of resistance spread:** Resistance-associated genes can spread between mosquito populations through migration and reproduction.

Monitoring and Detection of Insecticide Resistance:

1. **Phenotypic Susceptibility Testing:** Mosquito populations should be routinely tested using standardized insecticide susceptibility assays to determine mortality and resistance status. WHO-recommended bioassays help classify mosquito populations as susceptible or resistant and allow comparison of resistance levels across locations and time.
2. **Molecular Detection of Resistance Mechanisms:** Molecular techniques such as PCR and DNA-based assays can identify specific resistance-associated mutations, including **knockdown resistance (*kdr*) mutations** in voltage-gated sodium-channel genes and mutations associated with acetylcholinesterase resistance. Molecular surveillance helps track the distribution and frequency of resistance alleles.
3. **Biochemical and Enzyme Assays:** Biochemical investigations can determine increased activity of detoxification enzymes such as **cytochrome P450 monooxygenases, esterases and glutathione S-transferases (GSTs)**. These assays are useful for identifying metabolic mechanisms responsible for resistance.
4. **Resistance Intensity and Synergist Testing:** Testing at multiple insecticide concentrations can determine the **intensity of resistance**, while synergist assays using compounds such as **piperonyl butoxide (PBO)** can help assess whether enhanced metabolic detoxification contributes to pyrethroid resistance. Combining these approaches provides stronger evidence about underlying mechanisms.
5. **Geographical and Longitudinal Surveillance:** Resistance monitoring should be conducted repeatedly across different geographical locations and seasons. Results should be recorded in resistance databases and mapped to identify emerging hotspots, changes in resistance frequency and spread of resistance mechanisms. Continuous surveillance enables vector-control programmes to select appropriate insecticides and modify interventions before resistance significantly reduces control effectiveness.

Management of Insecticide Resistance

- ❖ **Regular Resistance Surveillance:** Continuous monitoring of mosquito populations should be undertaken using standardized susceptibility tests, molecular assays and biochemical methods. Early detection of resistance enables vector-control programmes to modify interventions before resistance becomes widespread.
- ❖ **Insecticide Rotation and Use of Different Modes of Action:** Repeated use of the same insecticide should be avoided wherever appropriate. Insecticides with different modes of action can be rotated or used

strategically according to local resistance patterns, thereby reducing selection pressure for a single resistance mechanism.

- ❖ **Integrated Vector Management (IVM):** Chemical control should be combined with **environmental management, larval-source reduction, biological control, physical barriers and community participation**. Reducing dependence on insecticides can slow the development of resistance while maintaining effective mosquito control.
- ❖ **Use of Synergists and Novel Control Technologies:** Where scientifically appropriate, synergists such as **piperonyl butoxide (PBO)** can be incorporated into suitable vector-control interventions to address certain metabolic resistance mechanisms. Research and deployment of new insecticides, biological agents, *Wolbachia*-based approaches and other innovative technologies can further diversify mosquito-control options.
- ❖ **Evidence-Based and Community-Supported Management:** Resistance-management decisions should be based on local entomological surveillance and regularly updated resistance data. Public-health authorities should coordinate with research institutions, agricultural agencies and communities to promote responsible insecticide use, eliminate mosquito breeding sites and strengthen long-term integrated vector-control programmes.

Biological Control of Mosquitoes

- a. **Microbial Larvicides:** Microorganisms such as *Bacillus thuringiensis* subsp. *israelensis* (Bti) and *Bacillus sphaericus* (*Lysinibacillus sphaericus*) are effective biological larvicides. Their toxins specifically target mosquito larvae and can reduce larval populations with relatively limited effects on many non-target organisms.
- b. **Larvivorous Fish:** Mosquito-eating fish such as *Gambusia affinis* and *Poecilia reticulata* (guppy) can consume large numbers of mosquito larvae. They may be introduced into suitable permanent water bodies, wells and other breeding habitats as part of integrated mosquito management.
- c. **Predatory Aquatic Organisms:** Aquatic predators such as dragonfly nymphs, copepods and certain aquatic insects can prey upon mosquito larvae. Their conservation or targeted use can contribute to natural suppression of mosquito populations, particularly in appropriate breeding habitats.
- d. **Wolbachia-Based Biological Control:** *Wolbachia* bacteria are being used in innovative mosquito-control programmes, particularly involving *Aedes aegypti*. Depending on the strategy, *Wolbachia*-infected mosquitoes can reduce the ability of mosquitoes to transmit certain viruses or can contribute to population suppression through reproductive effects.
- e. **Sterile Insect and Genetic Approaches:** The **Sterile Insect Technique (SIT)** involves releasing sterile male mosquitoes that mate with wild females, resulting in reduced production of viable offspring. Related genetic and biological approaches are being developed as complementary tools for sustainable mosquito population management and can reduce reliance on conventional insecticides.

Environmental Management for Mosquito Control

1. **Elimination of Mosquito Breeding Sites:** Regular removal of stagnant water from containers, discarded tyres, flowerpots, construction materials and other artificial receptacles can significantly reduce mosquito breeding. Proper drainage and disposal of water-holding waste should be promoted in residential and public areas.
2. **Improvement of Drainage and Water Management:** Properly designed and maintained drainage systems prevent the accumulation of stagnant water. Periodic cleaning of drains, canals and water-storage structures can reduce suitable breeding habitats for mosquitoes, particularly *Culex* and *Aedes* species.
3. **Proper Management of Water-Storage Containers:** Household and community water-storage tanks, barrels and other containers should be properly covered and regularly cleaned. Preventing mosquitoes from

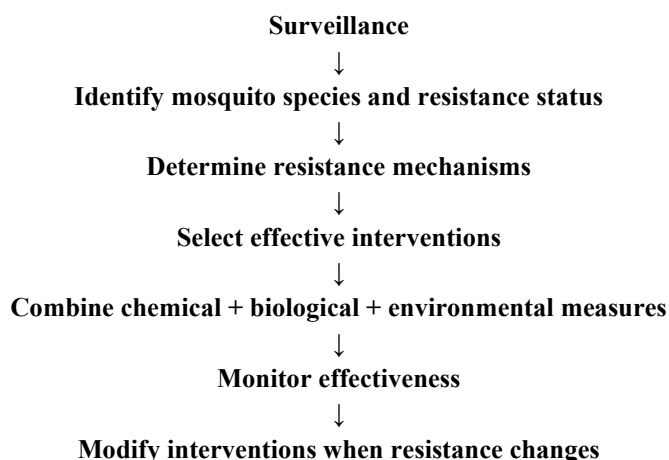
accessing stored water is particularly important for controlling container-breeding species such as *Aedes aegypti*.

4. **Solid-Waste and Sanitation Management:** Effective collection and disposal of solid waste can eliminate numerous artificial breeding habitats. Community sanitation programmes should focus on discarded plastic containers, coconut shells, bottles, tyres and other materials capable of retaining rainwater.
5. **Community Participation and Sustainable Urban Planning:** Community involvement is essential for maintaining mosquito-free surroundings. Public awareness programmes should encourage weekly inspection of potential breeding sites, while urban planning should incorporate effective drainage, waste management, water infrastructure and green-space management to minimize mosquito habitats.

Role of Integrated Mosquito Management

A sustainable strategy should not depend exclusively on chemical insecticides.

A conceptual integrated approach is:



This adaptive approach is consistent with WHO and CDC emphasis on resistance surveillance and evidence-based vector-control decisions.

Findings: The major findings of the review are as follows:

1. **Insecticide resistance is an evolutionary phenomenon** driven largely by selection pressure from insecticide exposure.
2. **Target-site and metabolic resistance are the two major mechanisms** currently best characterized in mosquito populations.
3. **Metabolic resistance** commonly involves enhanced activity of P450 monooxygenases, esterases and glutathione S-transferases.
4. **Target-site resistance** can involve mutations affecting voltage-gated sodium channels and other insecticide targets.
5. **Resistance patterns differ geographically and among mosquito species**, making local surveillance essential.
6. Resistance can occur simultaneously through **multiple mechanisms**, making management more difficult.
7. *Aedes aegypti*, *Aedes albopictus*, *Anopheles* spp. and *Culex* spp. require continued monitoring because their resistance profiles may change over time.
8. Standardized surveillance is essential because inconsistent testing methods can make resistance data difficult to compare between locations. WHO's South-East Asia assessment specifically highlighted methodological variation and the need for longitudinal standardized monitoring.

9. **Integrated vector management** is more sustainable than dependence on a single insecticide or intervention.
10. Molecular and biochemical surveillance can complement conventional phenotypic resistance testing by identifying the mechanisms responsible for resistance.

Suggestions and Recommendations: Based on the review, the following measures are recommended.

- **Establish continuous surveillance:** National and regional vector-control programmes should establish regular insecticide-resistance monitoring networks.
- **Develop local resistance maps:** Resistance information should be geographically mapped to identify hotspots and changes over time.
- **Standardize testing:** WHO-recommended procedures and appropriate discriminating concentrations should be used to improve comparability among studies.
- **Combine phenotypic and molecular approaches:** Mortality/susceptibility tests should be complemented by molecular and biochemical investigations whenever resources permit.
- **Reduce unnecessary insecticide exposure:** Insecticides should be used judiciously and only when they provide an appropriate public-health benefit.
- **Promote integrated vector management:** Chemical control should be combined with environmental management, biological control, source reduction and community participation.
- **Strengthen research capacity:** Universities, public-health laboratories and vector-control agencies should develop capacity for molecular diagnostics, biochemical assays and resistance surveillance.
- **Improve agricultural-public-health coordination:** Because agricultural pesticide exposure may contribute to selection pressure, greater coordination between agricultural and public-health authorities is desirable.
- **Develop new modes of action:** Research should continue into novel insecticides and non-insecticidal technologies to expand the available vector-control toolkit.
- **Strengthen community participation:** Public awareness programmes should emphasize eliminating breeding sites, maintaining sanitation and using personal protection measures.

Conclusion

Insecticide resistance represents one of the most important challenges to sustainable mosquito control. The continued use of insecticides has created evolutionary selection pressure that can favour mosquitoes possessing target-site mutations, enhanced detoxification enzymes, reduced insecticide penetration or behavioural avoidance mechanisms. The problem is particularly important for malaria, dengue and other mosquito-borne diseases because reduced insecticide effectiveness can undermine established vector-control programmes. Nevertheless, insecticide resistance does not mean that mosquito control is impossible. Rather, it requires a transition from dependence on individual insecticides toward evidence-based, integrated and adaptive vector management. Routine resistance surveillance should be the foundation of management. Phenotypic testing should be supported by molecular and biochemical investigations to identify the mechanisms involved. Where appropriate, programmes should employ different modes of action, synergist-based tools, biological control, environmental management and other innovative technologies. Ultimately, successful resistance management requires cooperation among public-health authorities, entomologists, researchers, environmental agencies, agricultural authorities and local communities. Continuous surveillance, responsible insecticide use and diversification of vector-control methods will be essential for preserving the effectiveness of mosquito-control programmes and protecting populations from vector-borne diseases.

References

1. World Health Organization (WHO). (2022). Manual for monitoring insecticide resistance in mosquito vectors and selecting appropriate interventions. Geneva: World Health Organization.

2. World Health Organization. (2022). Determining discriminating concentrations of insecticides for monitoring resistance in mosquitoes: Report of a multi-centre laboratory study and WHO expert consultations. Geneva: WHO.
3. World Health Organization. (2023). Report on insecticide resistance in *Aedes* mosquitoes (*Aedes aegypti*, *Aedes albopictus*, *Aedes vittatus*) in WHO South-East Asia Region countries. New Delhi: WHO Regional Office for South-East Asia.
4. World Health Organization. (2023). Determining discriminating concentrations of insecticides for monitoring resistance in *Culex quinquefasciatus* and *Culex tarsalis*. Geneva: WHO.
5. World Health Organization. (2014). Management of insecticide resistance among vectors of public health importance. Geneva: WHO.
6. World Health Organization. Global Malaria Programme: Insecticide resistance. Geneva: WHO.
7. Centers for Disease Control and Prevention. (2016). An Operational Framework for Insecticide Resistance Management Planning. *Emerging Infectious Diseases*, 22(5).
8. Centers for Disease Control and Prevention. (1998). Insecticide Resistance and Vector Control. *Emerging Infectious Diseases*, 4(4).
9. World Health Organization. (2016). Monitoring and managing insecticide resistance in *Aedes* mosquito populations: Interim guidance for entomologists. Geneva: WHO.
10. Mechanisms of insecticide resistance in mosquitoes: A systematic review of biochemical and physiological perspectives for sustainable vector control. (2026). Systematic review of evidence covering literature through December 2024.
11. World Health Organization. (2011). Global insecticide use for vector-borne disease control: A 10-year assessment (2000–2009). Geneva: WHO.