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Insecticide Resistance in *Aedes aegypti* and Surveillance and Monitoring Efforts in India: A Critical Review

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Abstract

The increasing prevalence of insecticide resistance in Aedes mosquitoes poses a significant threat to vector control efforts and the management of mosquito-borne diseases such as dengue, chikungunya, and Zika in India. This review critically examines the spatial distribution, insecticide resistance status, and underlying resistance mechanisms in *Aedes aegypti* and Aedes albopictus populations across various Indian states. The review synthesizes data on resistance to multiple classes of insecticides, including organochlorines, organophosphates, pyrethroids, and carbamates. Resistance to DDT is widespread, while emerging and incipient resistance to pyrethroids such as permethrin and deltamethrin is increasingly reported, especially in urban centers and high-transmission zones. Mechanistically, both metabolic resistance mediated by elevated levels of detoxification enzymes like glutathione S-transferases, esterases, and cytochrome P450s and target site insensitivity primarily through kdr mutations (e.g., F1534C, V1016G) have been documented. The presence of multi-mechanistic resistance in several regions emphasizes the need for continuous surveillance, rotation of insecticide classes, and the integration of alternative control strategies. This review highlights critical knowledge gaps and urges the adoption of integrated vector management practices to sustainably combat the evolving threat of insecticide resistance in Aedes mosquitoes across India.

Keywords*:* Insecticide resistance, *Aedes aegypti*, Control, Management. India.

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Introduction

Aedes aegypti, a highly adaptive and anthropophilic mosquito, poses a significant global public health threat due to its role as the primary vector of arboviral diseases such as dengue, chikungunya, Zika, and yellow fever. These viruses are responsible for widespread morbidity and mortality, especially in tropical and subtropical regions. The global incidence of dengue alone has surged dramatically, with the World Health Organization (WHO) reporting a 30-fold increase over the past 50 years, leading to an estimated 390 million infections annually, of which 96 million manifest clinically (Bhatt *et al*., 2013; WHO, 2024). India, with its dense urban populations and tropical climate, has seen a significant increase in mosquito-borne diseases, especially dengue, with over 100,000 confirmed cases reported annually (NVBDCP, 2023). Rapid urbanization, climate change, global travel, and inadequate vector control have exacerbated the spread of A. aegypti, enabling it to colonize new habitats, including densely populated urban environments. This mosquito breeds in artificial containers and thrives in human dwellings, making traditional control measures increasingly difficult. The 2015–2016 Zika virus outbreak in the Americas highlighted the grave neurological and congenital impacts linked to A. aegypti-borne viruses, drawing attention to the urgent need for sustainable vector control strategies (Petersen *et al*., 2016). The economic burden is substantial, with billions spent on healthcare, surveillance, and vector control efforts annually. Furthermore, the social and psychological toll on affected populations is immense. With no specific antiviral treatments or widely effective vaccines for most A. aegypti-borne diseases, vector control remains the cornerstone of prevention, necessitating coordinated global efforts and innovative approaches to mitigate this expanding burden.

Review Methodology

This review was conducted to assess the current status of insecticide resistance in *Aedes aegypti* populations across India, with a focus on resistance mechanisms, geographic distribution, and vector control strategies. A comprehensive and systematic approach was employed to collect, evaluate, and synthesize relevant literature and data from both national and international sources. A literature search was performed using online databases including PubMed, Google Scholar, ScienceDirect, and WHO Global Health Library. Keywords used included "*Aedes aegypti*", "insecticide resistance", "India", "pyrethroid resistance", "kdr mutation", and "vector control". Studies published from 2000 to 2024 were included to ensure coverage of both historical trends and recent developments. Grey literature, including reports from the Ministry of Health and Family Welfare (MoHFW), National Centre for Vector Borne Diseases Control (NCVBDC), and the World Health Organization (WHO), was also incorporated. Inclusion criteria involved studies reporting insecticide bioassays, resistance mechanisms (biochemical and molecular), geographic distribution, and surveillance activities. Both field-based entomological studies and laboratory analyses were considered. Data from diverse regions of India were prioritized to identify patterns and zones of resistance. The results were tabulated for clarity. The study also incorporated a critical analysis of Insecticide Resistance Management (IRM) strategies and policy-level interventions. The review aims to offer actionable insights for researchers, public health officials, and policymakers.

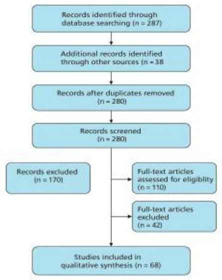

Figure 1. Representation of a PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) flow diagram that outlines the methodological flow of this review:

Role of Insecticides in Vector Control- Insecticides have long played a pivotal role in vector control strategies, particularly in managing mosquito populations responsible for transmitting diseases such as malaria, dengue, chikungunya, Zika, and yellow fever. Among the key vectors, *Aedes aegypti* and Anopheles species have been major targets of chemical interventions due to their efficiency in disease transmission and adaptation to urban environments. Adulticides (e.g., pyrethroids) and larvicides (e.g., temephos, methoprene, and Bacillus thuringiensis israelensis) are commonly employed to reduce mosquito populations. Space spraying and indoor residual spraying (IRS) are frequently used in outbreak responses, while larviciding is especially important in container habitats favored by *Aedes aegypti* (WHO, 2022). The integration of insecticides in long-lasting insecticidal nets (LLINs) and IRS campaigns has significantly reduced malaria burden globally (Bhatt *et al*., 2015). However, the overreliance on chemical insecticides has led to widespread insecticide resistance, particularly among *Aedes aegypti* populations, thereby undermining the efficacy of current control efforts (Liu, 2015). Resistance mechanisms include target-site mutations (e.g., kdr mutations), enhanced metabolic detoxification, and behavioral avoidance. This calls for the development of integrated vector management (IVM) approaches combining chemical, biological, environmental, and community-based interventions. Insecticides remain indispensable for rapid suppression during epidemics, but sustainable use requires resistance monitoring, rotation of insecticide classes, and investment in novel control tools such as insect growth regulators and genetically modified vectors.

Rising Threat of Insecticide Resistance in *Aedes aegypti*.

The increasing resistance of *Aedes aegypti* to insecticides poses a major challenge to global vector control efforts. This mosquito species is the primary vector for dengue, Zika, chikungunya, and yellow fever, and chemical insecticides have historically served as the first line of defense. However, the overuse and misuse of insecticides particularly pyrethroids, organophosphates, and carbamates have accelerated the development of resistance across multiple regions (Moyes *et al*., 2017). Resistance in A. aegypti arises from several mechanisms: target-site mutations such as knockdown resistance (kdr) mutations in the voltage-gated sodium channel gene, reduce insecticide binding, while metabolic resistance through elevated levels of detoxifying enzymes (e.g., cytochrome P450s, esterases, and glutathione S-transferases) increases insecticide degradation (Hemingway *et al*., 2016). Reports from India, Southeast Asia, Latin America, and Africa indicate widespread resistance to commonly used compounds like permethrin and deltamethrin (Vontas *et al*., 2012). This growing resistance reduces the efficacy of standard vector control measures, leading to persistent mosquito populations and a greater risk of disease outbreaks. Furthermore, insecticide resistance threatens to undermine emergency response efforts during epidemics and compromises long-term vector management programs. To address this, continuous resistance monitoring, rotation of insecticide classes, integration of non-chemical methods, and investment in alternative strategies such as Wolbachia-based control and genetically modified mosquitoes are critical.

Insecticides Used in India for *Aedes aegypti* Control

Classes of Insecticides- Organochlorines (e.g., DDT) – phased out due to resistance and toxicity. Organophosphates (e.g., malathion, temephos) – widely used in larval control. Carbamates (e.g., propoxur) – occasionally used. Pyrethroids (e.g., deltamethrin, permethrin, cyfluthrin) – preferred for their low mammalian toxicity and high knockdown effect (Table 1).

Table 1. Classes of Insecticides Used in Mosquito Vector Control.

Class	Mode of Action	Target Mosquito Stage	Common Examples	Resistance Mechanisms	Citations
Organochlorines	Disrupt voltage-gated sodium channels, causing prolonged nerve excitation	Adults	DDT	*kdr* mutations, metabolic detoxification	WHO 2022; Liu 2015
Organophosphates	Inhibit acetylcholinesterase (AChE), causing nerve overstimulation	Larvae & Adults	Temephos, Malathion, Fenitrothion	AChE modification, elevated esterases	Hemingway *et al*. 2016; Vontas *et al*. 2012
Carbamates	Inhibit AChE, similar to organophosphates	Larvae & Adults	Propoxur, Bendiocarb	Modified AChE, metabolic resistance	Liu 2015
Pyrethroids	Disrupt sodium channels, causing paralysis and death	Adults	Permethrin, Deltamethrin, Cypermethrin	*kdr* mutations, increased P450 activity	Moyes *et al*. 2017; WHO 2020
Insect Growth Regulators (IGRs)	Mimic juvenile hormones or inhibit chitin synthesis, preventing molting	Larvae	Methoprene, Pyriproxyfen, Diflubenzuron	Reduced penetration, metabolic detoxification	WHO 2022; Vontas *et al*. 2012
Biological Larvicides	Bacterial toxins disrupt gut lining, causing lysis and death	Larvae	*Bacillus thuringiensis israelensis* (Bti), *Bacillus sphaericus*	Rare, possible receptor alterations	WHO 2022; Liu 2015
Neonicotinoids	Agonists of nicotinic acetylcholine receptors; causes neural overstimulation	Larvae & Adults	Imidacloprid, Thiamethoxam	Target site changes, detoxification enzymes	Vontas *et al*. 2012; Liu 2015
Spinosyns	Targets nicotinic ACh receptors & GABA-gated ion channels; causes paralysis	Larvae & Adults	Spinosad	Metabolic resistance, reduced receptor sensitivity	WHO 2020; Hemingway *et al*. 2016
Oxadiazines	Block sodium ion channels, leading to nerve dysfunction	Adults	Indoxacarb	Emerging enzyme-based resistance	WHO 2022; Moyes *et al*. 2017

Patterns of Insecticide Resistance in Ae. aegypti in India

Geographic Distribution of Resistance- Resistance patterns vary widely across states: Delhi: Resistance to DDT and permethrin reported (Kumar *et al*., 2021). Maharashtra: High resistance to temephos and deltamethrin (Pavithra *et al*., 2020). Tamil Nadu & Kerala: Widespread resistance to malathion and synthetic pyrethroids (Ramesh *et al*., 2019). West Bengal & Odisha: Resistance primarily to organophosphates and DDT (Roy *et al*., 2018) (Table 2).

Table 2. Geographic Distribution of Insecticide Resistance in *Aedes aegypti* – India

Region/State/City	Insecticides with Reported Resistance	Mechanisms Reported	Citations
Delhi (NCT)	Pyrethroids (permethrin, deltamethrin), temephos	*kdr* mutations (F1534C, S989P), esterase-based metabolic resistance	Kushwah *et al*., 2015; Singh *et al*., 2022
Tamil Nadu (Chennai)	Temephos, deltamethrin, malathion	Elevated esterases, monooxygenases	Thomas *et al*., 2012; Kumar *et al*., 2021
West Bengal (Kolkata)	Pyrethroids, temephos	*kdr* mutations, altered AChE	Saha *et al*., 2019
Maharashtra (Mumbai, Nagpur)	Pyrethroids, organophosphates	Multiple resistance, cross-resistance observed	Shinde *et al*., 2017
Karnataka (Bengaluru)	Permethrin, temephos	Target site insensitivity, P450 enzymes	Kumari *et al*., 2018
Uttar Pradesh (Lucknow, Kanpur)	Malathion, deltamethrin	Metabolic resistance (GSTs, esterases)	Dykes *et al*., 2016
Gujarat (Ahmedabad)	Pyrethroids, temephos	Developing resistance, esterase activity increasing	NVBDCP Reports; Patel *et al*., 2020
Rajasthan (Jaipur)	Temephos, deltamethrin	Reduced susceptibility noted	Sharma *et al*., 2019
Kerala (Thiruvananthapuram)	Malathion, permethrin	Moderate resistance, under surveillance	WHO SEARO, 2020
Goa	Deltamethrin, temephos	Mixed resistance response	Singh *et al*., 2022
Assam (Guwahati)	Temephos	Resistance emerging	NVBDCP, 2023

Key Resistance Patterns Observed:- Pyrethroid Resistance: Pyrethroids like permethrin, deltamethrin, and cyfluthrin, commonly used in space spraying and impregnated nets, have shown widespread resistance in Ae. aegypti across Indian cities such as Delhi, Chennai, Bengaluru, Mumbai, and Kolkata. This is largely due to knockdown resistance (kdr) mutations like F1534C, V1016G, and S989P in the voltage-gated sodium channel gene (Kushwah *et al*., 2015; Saha *et al*., 2019). Organophosphate Resistance: Resistance to temephos, a larvicide used in domestic water containers, has been reported from multiple states, including Maharashtra, Tamil Nadu, and West Bengal. The mechanism often involves elevated carboxylesterase activity, leading to metabolic detoxification (Kumar *et al*., 2021).

Carbamate Resistance:- Resistance to propoxur has been reported sporadically. However, lower usage compared to other classes has kept resistance at moderate levels (Dai *et al*., 2021). Multiclass Resistance:

Several studies have confirmed cross-resistance to multiple classes (pyrethroids, organophosphates, and carbamates), especially in urban areas with intense vector control activity. This suggests the need for rotational or combination approaches (Singh *et al*., 2022).

Mechanisms of Resistance

The most common is target site resistance, particularly mutations in the voltage-gated sodium channel gene, known as kdr (knockdown resistance), which reduce sensitivity to pyrethroids and DDT (Kushwah *et al*., 2015). Metabolic resistance is also widespread, involving overexpression of detoxifying enzymes such as cytochrome P450 monooxygenases, glutathione S-transferases, and esterases, which degrade or sequester insecticides before they reach their targets (Hemingway *et al*., 2016; Moyes *et al*., 2017; Kumar *et al*., 2021). Behavioral resistance allows mosquitoes to avoid contact with insecticides, while cuticular resistance involves thickening or modification of the insect cuticle, reducing insecticide penetration (Balabanidou *et al*., 2016) (Table 3). These mechanisms, alone or in combination, severely limit the effectiveness of conventional vector control strategies and highlight the need for integrated and sustainable mosquito management approaches. Continuous monitoring and molecular surveillance are essential to track resistance evolution and guide appropriate interventions.

Table 3. Mechanisms of Insecticide Resistance in *Aedes aegypti*

Mechanism Type	Description	Associated Insecticides	Examples / Key Mutations / Enzymes	Citations
1. Target-Site Resistance	Mutations at the insecticide's binding site reduce sensitivity	Pyrethroids, DDT, Organophosphates, Carbamates	- *kdr* mutations: F1534C, V1016G, S989P (voltage-gated sodium channel) - Ace-1 mutation (G119S) in acetylcholinesterase	Kushwah *et al*., 2015; Saha *et al*., 2019; Liu, 2015
2. Metabolic Resistance	Overexpression of detoxifying enzymes that break down or sequester insecticides	All major classes	- Cytochrome P450 monooxygenases (e.g., CYP9J32) - Carboxylesterases (CCEae3a, CCEae6a) - Glutathione S-transferases (GSTe2)	Hemingway *et al*., 2016; Moyes *et al*., 2017; Kumar *et al*., 2021
3. Penetration Resistance	Cuticular thickening or composition changes slow insecticide	Pyrethroids, Organophosphates	- Increased cuticular hydrocarbons - Changes in cuticle proteins	Balabanidou *et al*., 2016; WHO, 2020

	absorption			
4. Behavioral Resistance	Changes in feeding or resting behavior reduce contact with insecticides	Pyrethroids (IRS, fogging)	- Avoidance of treated surfaces - Daytime biting and outdoor resting	WHO, 2022; Ranson & Lissenden, 2016
5. Sequestration	Binding or trapping insecticides in tissues or compartments	Pyrethroids, Organophosphates	- Lipid sequestration or cuticular binding	Liu, 2015; Vontas *et al*., 2012
6. Gene Amplification	Duplication of detoxifying genes increases expression levels	Mainly organophosphates & pyrethroids	- Esterase gene amplification - P450 gene cluster amplification	Riveron *et al*., 2018; Kumar *et al*., 2021

Behavioral Resistance- In India, urban *Aedes aegypti* populations have shown a tendency to avoid fogged or IRS-treated zones, leading to survival despite ongoing insecticide use (Kumar *et al*., 2021). In Latin America and Southeast Asia, behavioral changes have been observed as a significant component of reduced insecticide efficacy (Achee *et al*., 2015) (Table 4).

Table 4. Key Characteristics of Behavioral Resistance in *Aedes aegypti*:

Aspect	Details	Citations
Avoidance of treated surfaces	Mosquitoes detect and avoid resting or landing on insecticide-treated surfaces like walls or nets. This reduces exposure to IRS or LLINs.	Ranson & Lissenden, 2016; WHO, 2020
Altered resting behavior	Instead of resting indoors (endophily), *Aedes aegypti* may shift to outdoor resting (exophily), avoiding areas that are commonly treated with insecticides.	WHO SEARO, 2020; Vontas *et al*., 2012
Change in biting time	Mosquitoes may shift their biting time to early morning, evening, or twilight hours, when fogging is minimal.	Achee *et al*., 2015; Saha *et al*., 2019
Change in host-seeking behavior	Alteration in host preference or feeding site (e.g., biting on lower legs) may help avoid repellent-treated clothing or skin.	Dusfour *et al*., 2019
Avoidance of space sprays	Mosquitoes fly away from areas with aerosol or thermal fog insecticides, reducing exposure during control operations.	Kumar *et al*., 2021

Vector Control Programmes in India

India faces a high burden of vector-borne diseases (VBDs) including malaria, dengue, chikungunya, filariasis, kala-azar, and Japanese encephalitis. In response, the Government of India, under the National Centre for Vector Borne Diseases Control (NCVBDC), has implemented comprehensive vector control programmes aimed at integrated prevention and elimination (Table 5).

Key initiatives include the National Malaria Elimination Programme (NMEP), which targets malaria elimination by 2030 using indoor residual spraying (IRS), long-lasting insecticidal nets (LLINs), and early diagnosis and treatment (MoHFW, 2023). The National Dengue and Chikungunya Control Programme emphasizes anti-larval measures, source reduction, fogging during outbreaks, and community awareness (WHO India, 2022).

The National Filaria Control Programme (NFCP) focuses on mass drug administration (MDA) along with vector control using larvicides like temephos. Similarly, Kala-azar elimination efforts rely on IRS with synthetic pyrethroids in endemic states like Bihar and Jharkhand (WHO SEARO, 2020). For Japanese Encephalitis, control strategies include vaccination, vector control in pig and paddy fields, and larval source management.

India has also adopted Integrated Vector Management (IVM), combining chemical, biological, environmental, and social strategies to reduce vector breeding sustainably. In addition, the Insecticide Resistance Management (IRM) framework promotes insecticide rotation, resistance monitoring, and community engagement to address rising insecticide resistance in vectors like *Aedes aegypti* (Kumar *et al*., 2021).

These programmes are supported by intersectoral collaboration, public awareness, and ongoing surveillance, forming the backbone of India's fight against VBDs.

Surveillance and Monitoring Efforts in India

Table 5. Key Surveillance and Monitoring Efforts in India

Effort/Agency	Description	Citations
National Centre for Vector Borne Diseases Control (NCVBDC)	Coordinates national-level surveillance for resistance in vectors including *Aedes aegypti*. Conducts insecticide bioassays and collects data from endemic states.	NCVBDC, 2023; MoHFW, 2022
Insecticide Resistance Monitoring (IRM) Network	Established under NVBDCP to monitor resistance trends to key insecticides in vectors. Includes bioassays using WHO and CDC protocols.	WHO SEARO, 2020; NVBDCP Annual Reports
Regional Medical Research Centres (RMRCs) & ICMR Institutes (e.g., NIMR, VCRC)	Perform advanced resistance testing (biochemical assays, molecular markers, *kdr* detection), mapping hotspots of resistance in urban and peri-urban areas.	Kumar *et al*., 2021; ICMR-NIMR Annual Report, 2022
Integrated Disease Surveillance Programme (IDSP)	Provides indirect support through epidemiological data to correlate vector resistance trends with disease outbreaks.	IDSP, 2021
Periodic Vector Susceptibility Testing (WHO Bioassay Kit)	Regular testing against pyrethroids (deltamethrin, permethrin), organophosphates (temephos), and carbamates in sentinel sites across India.	Vontas *et al*., 2012; WHO, 2020
Entomological Surveillance Units (State Level)	Conduct larval surveys, breeding site mapping, and local resistance assessments in dengue hotspots such as Delhi, Chennai, Mumbai, and Kolkata.	NVBDCP, 2023; Saha *et al*., 2019

Challenges Noted in Surveillance- Inconsistent reporting across states, Lack of molecular diagnostics in several zones, Underfunded laboratory capacity in rural areas and Limited data sharing and publication

Implications for Vector Control and Public Health

The implications are multifaceted, affecting disease transmission dynamics, control program efficiency, and the long-term sustainability of current interventions (Table 6).

Reduced Effectiveness of Insecticide-Based Interventions

As resistance develops, commonly used insecticides such as pyrethroids and organophosphates become less effective, leading to persistent vector populations even after spraying or fogging. IRS (Indoor Residual Spraying) and ULV (Ultra-Low Volume fogging) show decreased impact in areas with high resistance. This results in increased vector density, enhancing disease transmission risks. In India, resistance to permethrin and deltamethrin has already compromised control efforts in urban centers (Kushwah *et al*., 2015; Saha *et al*., 2019).

Increased Disease Burden- Poor vector control directly contributes to surges in dengue, chikungunya, and Zika outbreaks. Resistance allows mosquitoes to survive longer, feed more frequently, and transmit pathogens more efficiently. In cities like Delhi, Kolkata, and Chennai, seasonal dengue outbreaks correlate with resistant Ae. aegypti populations (Kumar *et al*., 2021). WHO estimates that over 3.9 billion people globally are at risk of dengue, and India accounts for nearly 50% of the global burden (WHO, 2022).

Economic and Logistical Costs- As insecticides lose efficacy, programs require more frequent applications, higher doses, or multiple combinations, all of which raise operational costs and strain public health resources. Additional spending on insecticides and vector monitoring may divert funds from other critical health services. Resistance management (e.g., rotating insecticides, monitoring resistance markers) is resource-intensive.

Environmental and Health Risks- Overuse or rotation of multiple insecticide classes in response to resistance can increase ecological toxicity and risk non-target effects (e.g., on pollinators, aquatic organisms, or human health). Misuse of organophosphates like malathion and temephos in domestic settings may lead to residues in water sources and insecticide poisoning incidents (Liu, 2015).

Urgent Need for Alternative and Integrated Strategies- The failure of chemical control demands urgent investment in Integrated Vector Management (IVM) approaches, including: Biological control (e.g., Wolbachia, larvivorous fish), Environmental management (eliminating breeding sites), Community participation and health education, Genetic control (e.g., Sterile Insect Technique, gene drives). ICMR, NCVBDC, and WHO advocate integrated, evidence-based, and locally adaptive control models (WHO, 2020; Dusfour *et al*., 2019).

Strategies for Insecticide Resistance Management (IRM)

Table 6. Strategies for Insecticide Resistance Management (IRM) in *Aedes aegypti*

IRM Strategy	Implementation Approach	Objective/Benefit	Examples	Citations
Insecticide Rotation	Alternate use of insecticides with different modes of action	Prevent selection pressure for any one resistance mechanism	Rotate pyrethroids with organophosphates or carbamates	WHO 2022; Dusfour *et al*., 2019
Mixture of Insecticides	Apply two or more insecticides simultaneously with different targets	Delay resistance by requiring multiple resistance mechanisms	Mixtures of deltamethrin + pirimiphos-methyl	WHO, 2020; Moyes *et al*., 2017
Mosaic Approach	Different insecticides used in different locations or seasons	Reduces uniform selection pressure over space and time	Using IRS with pyrethroids in one zone, organophosphates in another	Hemingway *et al*., 2016
Use of Synergists	Combine insecticides with enzyme inhibitors to	Overcome metabolic resistance (e.g., P450 inhibition)	Piperonyl butoxide (PBO) with pyrethroids	Ranson *et al*., 2011; Liu 2015

	restore susceptibility			
Integrated Vector Management (IVM)	Combines chemical, biological, environmental, and mechanical tools	Minimize reliance on chemicals and sustain vector control	Environmental management, larvivorous fish, *Wolbachia*, community participation	WHO, 2012; NCVBDC 2023
Targeted Use of Larvicides	Apply larvicides where breeding sites are confirmed; avoid blanket use	Reduce overexposure and resistance development in larvae	Focal temephos or Bti application	Kumar *et al*., 2021
Surveillance & Resistance Monitoring	Routinely test mosquito populations for resistance status	Detect early resistance and guide IRM planning	WHO susceptibility bioassays, kdr genotyping	Kushwah *et al*., 2015; WHO, 2022
Community Engagement & IEC	Educate public to reduce breeding sources and limit insecticide misuse	Reduce selection pressure from domestic use	Clean water storage, use of nets, behavior change campaigns	WHO, 2017; Achee *et al*., 2015
Policy & Regulatory Measures	Regulate use and sale of public health insecticides	Prevent misuse and overuse of insecticides	Licensing, banning obsolete products	MoHFW 2021; NVBDCP 2023

Research Gaps and Future Directions

Despite advances in understanding insecticide resistance in *Aedes aegypti*, several critical research gaps remain. One major limitation is the lack of real-time, geo-referenced resistance data across India, which hampers evidence-based vector control decisions (Kumar *et al*., 2021). Moreover, longitudinal studies on the evolution of resistance and its impact on disease transmission are scarce. There is limited understanding of the interplay between resistance mechanisms—especially when multiple (e.g., kdr, metabolic, and behavioral) coexist in populations (Dusfour *et al*., 2019). Additionally, standardized diagnostic doses and protocols for insecticide susceptibility testing in Aedes mosquitoes need refinement and wider implementation (WHO, 2022). The role of novel tools such as RNA interference, gene editing (e.g., CRISPR), and symbiont-based approaches like Wolbachia requires further investigation and operational scaling. Future directions must focus on developing sustainable, integrated vector management (IVM) frameworks, strengthening community participation, and translating genomic data into operational strategies. Investment in resistance prediction modeling and AI-enabled surveillance platforms could revolutionize early warning systems. Finally, policy-level integration of IRM into national health programs remains a priority for long-term impact.

Conclusion

Insecticide resistance in *Aedes aegypti* has emerged as a significant barrier to effective vector control, especially in countries like India where dengue and other arboviral diseases are endemic. The increasing detection of resistance to multiple classes of insecticides—particularly pyrethroids and organophosphates has severely compromised the success of traditional control strategies such as fogging, indoor residual spraying, and larviciding. Mechanisms such as target-site mutations, metabolic detoxification, behavioral avoidance, and reduced cuticular penetration have all contributed to this resistance. Given the scale and complexity of the challenge, it is clear that reliance on chemical control alone is no longer sustainable. There is an urgent need for a shift toward Integrated Vector Management (IVM), incorporating chemical, biological, environmental, and social interventions. Strengthening routine insecticide resistance surveillance, standardizing monitoring protocols, and implementing resistance management strategies—such as insecticide rotation and the use of synergists—will be essential. Furthermore, community engagement, regulatory oversight of insecticide use, and investment in novel tools like Wolbachia, sterile insect techniques, and genetic modifications offer promising future directions.

To sustain vector control and reduce disease transmission, India must integrate these insights into national policies, ensuring that research, surveillance, and control operations evolve in tandem. A coordinated, data-driven, and adaptive approach will be key to overcoming the growing threat of insecticide resistance and safeguarding public health.

Conflict of interest- The authors declare that there is no conflict of interest regarding the publication of this review.

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