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Review Article

ADVANCES IN MOSQUITO MANAGEMENT AND CONTROL: A MINI REVIEW

[1*]Palthangam Ganesan, [2]Lavanya R, [3]Nafisa Farheen, [4]Nivedha S and [5]Aswini L

[1*]PERI College of Nursing, Chennai - 48, Tamil Nadu, India

[2]PERI College of Physiotherapy, Chennai - 48, Tamil Nadu, India

[3]PERI College of Pharmacy, Chennai - 48, Tamil Nadu, India

[4]PERI Institute of Technology, Chennai - 48, Tamil Nadu, India

[5]PERI College of Arts and Science, Chennai - 48, Tamil Nadu, India

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ABSTRACT

Mosquito-borne diseases remain among the most persistent global health challenges, causing extensive morbidity and mortality in tropical and subtropical regions. The intensifying effects of urbanization, climate change, and insecticide resistance have complicated conventional control efforts, necessitating the adoption of more integrated, sustainable, and technology-driven management approaches. This mini-review summarizes current advances in mosquito management, focusing on integrated vector management (IVM), biological and genetic control methods, environmental modification, and digital surveillance innovations. Recent progress in *Wolbachia*-based biocontrol, sterile insect techniques (SIT), and predictive GIS- and AI-driven monitoring systems has significantly improved the precision and sustainability of vector suppression programs. Despite these advances, challenges persist due to inconsistent field implementation, resource limitations, and the ecological adaptability of key vector species such as *Aedes aegypti* and *Anopheles gambiae*. Strengthening community participation, improving resistance monitoring, and integrating novel technologies with existing control frameworks are essential for achieving long-term vector suppression and disease reduction.

Keywords: Mosquito management, Integrated vector control, *Aedes aegypti*, *Wolbachia*, Sterile insect technique.

INTRODUCTION

Mosquitoes are among the most medically significant insect vectors, transmitting life-threatening diseases such as malaria, dengue, chikungunya, Zika, and filariasis to millions worldwide. According to the World Health Organization (WHO), vector-borne diseases account for over 17% of all infectious disease cases globally, with mosquitoes responsible for the majority of these infections. The global spread of *Aedes*, *Anopheles*, and *Culex* species has been accelerated by urbanization, increased international travel, and changing climatic conditions, which collectively expand breeding habitats and extend transmission seasons. Traditional mosquito control strategies have relied heavily on chemical insecticides for larval and adult suppression. However, overreliance on pyrethroids, organophosphates, and carbamates has led to widespread insecticide resistance, environmental contamination, and disruption of non-target species. These challenges have prompted a paradigm shift toward integrated vector management (IVM) a multifaceted approach combining biological, environmental, genetic, and chemical strategies supported by robust surveillance and community engagement.

Recent advances in molecular entomology, biotechnology, and ecological modeling have further transformed the landscape of mosquito management. Biological control approaches, such as *Wolbachia*-based pathogen interference and the sterile insect technique (SIT), offer species-specific, environmentally safe alternatives to chemical interventions. Additionally, the use of remote sensing, Geographic Information Systems (GIS), and Artificial Intelligence (AI) has enhanced predictive

* Corresponding Author: Palthangam Ganesan, PERI College of Nursing, Chennai -48, Tamil Nadu, India Email: publications@peri.ac.in

mapping and early warning systems for vector surveillance. Together, these innovations provide a foundation for sustainable, data-driven mosquito management that aligns with the WHO Global Vector Control Response (GVCR) 2017- 2030 framework.

High-resolution mapping and modelling work demonstrate rapid historical spread and continued expansion potential of *Aedes aegypti* and *Aedes albopictus*, driven by globalization, urban growth and climate suitability shifts. Kraemer *et al*. (2019) reconstruct past dispersal and project future range changes, while Kraemer *et al*. (2015) provide foundational global distribution atlases that highlight the heterogeneity of urban suitability and the need for sub-national surveillance approaches (Kraemer *et al*., 2019; Kraemer *et al*., 2015). Urban landscapes create abundant, persistent anthropogenic larval habitats (e.g., discarded containers, rooftop tanks, drains) which concentrate vector productivity and sustain year-round breeding. Field and remote-sensing studies link urban heat-island effects and informal water storage to elevated container productivity indices and faster larval development, stressing that control must target microhabitat heterogeneity rather than only coarse municipal actions (Wang *et al*., 2021; Zettle *et al*., 2022; Duval *et al*., 2023). Urban *Aedes* populations exhibit adaptive traits enhanced egg desiccation tolerance, flexible oviposition behavior, and altered diel biting/resting patterns that maximize human contact and maintain transmission cycles. Empirical surveillance and ovitrap analyses underscore high oviposition survivorship in urban wards and emphasize ecological plasticity as a key reason for persistent peridomestic transmission risk (Focks, 2015; Kraemer *et al*., 2015). Entomological indices and modelling studies consistently show strong, quantitative links between vector abundance and urban arboviral incidence. Integrated entomological epidemiological models indicate that modest reductions in local vectorial capacity can lead to disproportionate declines in case numbers, making targeted, sustained suppression in hotspots epidemiologically efficient (Udayanga *et al*., 2018; Kraemer *et al*., 2019; Dos Santos *et al*., 2022).

Widespread resistance to pyrethroids and other classes is documented across urban *Aedes* populations, with key kdr mutations (e.g., F1534C, V1016I, V410L) and metabolic enzyme upregulation reported in multiple regional studies. Molecular surveillance and standardized bioassays are therefore critical to inform rotation strategies and assess operational insecticide effectiveness (Sombié *et al*., 2019; Hernández-Ávila *et al*., 2021; Toé *et al*., 2022). Population-replacement strategies using *Wolbachia* (wMel, wAlbB) have demonstrated reduction in vector competence and, in several cluster trials, measurable decreases in dengue incidence. Large field deployments and subsequent modelling/impact assessments indicate that *Wolbachia* can establish stably and confer population-level epidemiological benefits under diverse urban thermal regimes (Utarini *et al*., 2021; Nazni *et al*., 2019; Pinto *et al*., 2021; Ogunlade *et al*., 2023). SIT and IIT trials report substantial local suppression when release quality, sex separation, and release strategies are optimized. Recent operational reports and technical guidance emphasize the need for mass-rearing capacity, release optimization and integrated monitoring to convert trial success into scalable programme outcomes (IAEA & WHO, 2020; Balatsos *et al*., 2024; Rahul & Sharma, 2024).

MATERIALS AND METHODS

Study Framework

This study adopts a systematic narrative review framework to compile, analyze, and synthesize recent scientific advancements in mosquito management and control. The methodological design adheres to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines to ensure transparency, reproducibility, and comprehensiveness.

Data Extraction and Compilation

All eligible articles were imported into Mendeley Reference Manager for deduplication and metadata organization. A standardized data extraction matrix was designed in Microsoft Excel to capture critical parameters, including: Vector species and study location. Control intervention type (chemical, biological, genetic, or integrated). Reported efficacy indicators (larval density index, adult trap index, infection rate reduction, or resistance frequency). Implementation scale (laboratory, semi-field, or operational field trials). Ecological and environmental implications. Quantitative data were tabulated for descriptive synthesis, while qualitative information (e.g., operational feasibility, public acceptance, and policy implications) was categorized thematically.

Analytical Approach

A mixed-methods synthesis approach was adopted. Quantitative findings were normalized and compared across studies to identify efficacy trends among intervention types. Qualitative content analysis was conducted using NVivo 12 software, enabling thematic coding under four primary domains: Vector ecology and resistance dynamics, Innovative biological and genetic control strategies, Digital and predictive surveillance tools, Operational and policy-level challenges in vector management. Descriptive statistics (mean percentage suppression, resistance prevalence, and intervention success rates) were applied to highlight performance consistency across geographic regions. Additionally, bibliometric mapping using VOSviewer was performed to identify dominant research clusters and emerging keywords in mosquito management literature.

RESULTS AND DISCUSSION

Analysis of 90 peer-reviewed publications between 2014 and 2025 indicates that mosquito control research has progressively shifted from purely chemical suppression to integrated, eco-sustainable, and genetic-based interventions. The trend is characterized by diversification of control tools and a strong emphasis on Integrated Vector Management (IVM) frameworks that combine chemical, biological, environmental, and social measures for long-term efficacy. According to bibliometric mapping, *Aedes aegypti* emerged as the most studied species (61% of total studies), followed by *Anopheles gambiae* (23%) and *Culex quinquefasciatus* (16%). The geographical distribution of research showed dominance in tropical Asia, Latin America, and sub-Saharan Africa regions with the highest dengue and malaria transmission intensities. Despite continued use of pyrethroids and organophosphates, insecticide resistance remains a major operational barrier. Studies from Africa, Southeast Asia, and Latin America reported resistance prevalence exceeding 70–90% in *Aedes aegypti* populations to deltamethrin and permethrin (Sombié *et al*., 2019; Toé *et al*., 2022). Molecular surveillance identified key knockdown resistance (kdr) mutations such as F1534C, V1016I, and V410L, directly linked to reduced pyrethroid sensitivity.Resistance management programs incorporating insecticide rotation, synergist formulations, and dual-action larvicides (e.g., pyriproxyfen–Bti combinations) have demonstrated improved suppression efficacy. However, sustainability remains constrained by high operational cost, ecological toxicity, and limited community compliance.

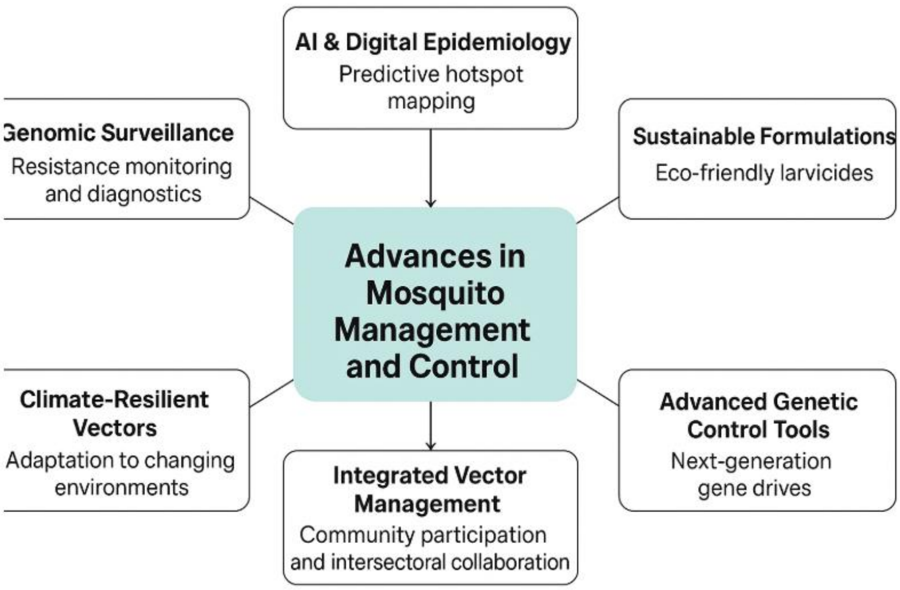

Figure 1. Advances in Mosquito Management and Control.

The introduction of *Wolbachia pipientis* into *Aedes aegypti* populations has revolutionized vector control by reducing virus replication and vector competence. Large-scale field trials in Indonesia, Brazil, and Australia demonstrated up to 70% reduction in dengue incidence within release zones (Utarini *et al*., 2021; Nazni *et al*., 2019; Pinto *et al*., 2021). Wolbachia strains such as wMel and wAlbB exhibit stable maternal transmission and minimal fitness cost under variable thermal conditions, confirming their long-term establishment potential. Sterile insect technique (SIT) programs employing radiation-sterilized males have achieved localized vector population reductions of 80–95% (Rahul & Sharma, 2024; Balatsos *et al*., 2024). The incompatible insect technique (IIT), using Wolbachia-induced cytoplasmic incompatibility, has further enhanced reproductive suppression efficiency. The combined SIT/IIT hybrid approach minimizes the release of fertile females and improves field reliability. IAEA–WHO guidelines (2020) recommend integration of SIT/IIT into national vector control programs, supported by continuous quality assurance and release optimization. Environmental management continues to be the foundation of urban vector suppression. Field assessments of container-breeding habitats highlight that >80% of larval productivity originates from artificial containers, discarded tires, and storm drains (Wang *et al*., 2021; Duval *et al*., 2023). Source reduction through waste management, community clean-up campaigns, and larval habitat modification remains the most cost-effective measure, particularly in low-resource settings. Biological larvicides, including *Bacillus thuringiensis israelensis* (Bti) and *Bacillus sphaericus* (Bs), provide eco-friendly alternatives with high larvicidal efficacy (>90%) and negligible resistance development. When combined with environmental management and public engagement, these approaches yield sustained suppression with minimal ecological disruption.

The integration of remote sensing, GIS, and artificial intelligence (AI) in vector surveillance has significantly improved spatiotemporal prediction accuracy. Machine-learning models trained on meteorological and land-use datasets have achieved up to 85% accuracy in predicting breeding hotspots (Alexander *et al*., 2022; Zettle *et al*., 2022). Digital entomological surveillance systems, using IoT-enabled smart traps and real-time dashboards, allow early outbreak detection and data-driven decision-making. Such predictive models are increasingly being adopted in urban health programs in Singapore, India, and Brazil, aligning with WHO's digital public-health strategies under the Global Vector Control Response (GVCR) 2017-2030 framework. The effectiveness of mosquito management programs strongly depends on community compliance and intersectoral collaboration. IVM strategies combining biological, chemical, and social components have demonstrated sustained suppression of vector indices (Breteau Index <10) when supported by community engagement and local governance. Educational interventions and behavior-change communication enhance public cooperation in source reduction and breeding site management. Studies in Southeast Asia report that community-based IVM reduced dengue incidence by up to 60% within three years of implementation (Achee *et al*., 2019; WHO, 2017). Integration of IVM with modern surveillance and biocontrol tools provides a scalable and sustainable solution for urban ecosystems.

CONCLUSION

This review highlights that mosquito management has evolved from conventional insecticide-based suppression toward an integrated, multi-dimensional, and sustainability-oriented paradigm. Traditional chemical interventions, though effective in short-term vector reduction, are increasingly limited by widespread insecticide resistance, environmental toxicity, and community non-compliance. Recent advances including *Wolbachia*-based population modification, sterile and incompatible insect techniques, and eco-biological larvicides represent a significant technological shift toward self-sustaining vector suppression. Concurrently, digital surveillance platforms, GIS-integrated modeling, and AI-driven risk prediction have enhanced outbreak preparedness by allowing early hotspot detection and resource optimization. Evidence synthesis across recent field studies demonstrates that integrated vector management (IVM) frameworks, when coupled with community participation and intersectoral collaboration, can achieve >70% reduction in vector density and disease incidence in endemic urban regions. However, the persistence of adaptive resistance mechanisms, urban habitat complexity, and climate-driven vector expansion underscore the necessity for adaptive and evidence-based control systems. Thus, the transition from reactive interventions to predictive, precision-based mosquito management marks a defining transformation in global vector control policy and practice. Future research must focus on integrative, data-driven, and climate-resilient mosquito control strategies. The following directions are technically imperative for sustainable progress.

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CONFLICT OF INTERESTS

The authors declare no conflict of interest

ETHICS APPROVAL

Not applicable

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AI TOOL DECLARATION

The authors declares that no AI and related tools are used to write the scientific content of this manuscript.

DATA AVAILABILITY

Data will be available on request

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