

Integrated Mosquito Vector Management Strategies for Reducing Malaria Transmission Risk

Ying Fu, Fangya Chen, Xueyan Chen ✉

Tropical Animal Resources Research Center, Hainan Institute of Tropical Agricultural Resources, Sanya, 572000, Hainan, China

✉ Corresponding email: xueyan.chen@hitar.org

Journal of Mosquito Research, 2026, Vol.16, No.1 doi: [10.5376/jmr.2026.16.0005](https://doi.org/10.5376/jmr.2026.16.0005)

Received: 10 Feb., 2025

Accepted: 13 Mar., 2025

Published: 23 Mar., 2026

Copyright © 2026 Fu et al., This is an open access article published under the terms of the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

Preferred citation for this article:

Fu Y., Chen F.Y., and Chen X.Y., 2026, Integrated mosquito vector management strategies for reducing malaria transmission risk, Journal of Mosquito Research, 16(1): 54-66 (doi: [10.5376/jmr.2026.16.0005](https://doi.org/10.5376/jmr.2026.16.0005))

Abstract This review examines integrated mosquito vector management (IVM) strategies for reducing malaria transmission risk. Malaria remains a major global public health burden, with transmission driven by Anopheles mosquitoes whose biological and ecological characteristics are shaped by environmental factors. The complex interactions among mosquito vectors, *Plasmodium parasites*, and human hosts, together with climate change and human activities, influence transmission dynamics. Conventional control methods, including insecticide-treated nets and indoor residual spraying, have achieved significant success but face limitations such as insecticide resistance and behavioral adaptation. Emerging approaches, including plant-based insecticides, genetic technologies, and nanotechnology-based delivery systems, provide promising alternatives. IVM integrates multiple strategies, emphasizing ecological sustainability, community participation, and policy support. Evaluating safety, environmental impact, and cost-effectiveness is essential for long-term success. Future efforts should address resistance management, climate challenges, and implementation barriers to enhance malaria control outcomes.

Keywords Malaria; Mosquito vectors; Integrated vector management; Insecticide resistance; Control strategies

1 Introduction

Malaria remains a major global public health challenge, particularly in tropical and subtropical regions where it causes significant morbidity and mortality. Despite decades of control efforts, the disease continues to impose a heavy burden, with sub-Saharan Africa bearing the highest incidence and prevalence rates worldwide. Vulnerable populations such as children under five years old and pregnant women are disproportionately affected, contributing to substantial socio-economic impacts in endemic countries. The persistence of malaria is driven by complex interactions among biological, environmental, and socio-economic factors that sustain transmission cycles and complicate eradication efforts (Akowe et al., 2025; Kombate et al., 2025).

Central to malaria transmission are mosquito vectors, primarily Anopheles species, which serve as the biological agents facilitating parasite spread between humans. Vector behavior, ecology, and population dynamics critically influence transmission intensity and patterns. Traditional vector control methods such as insecticide-treated nets (ITNs) and indoor residual spraying (IRS) have significantly reduced malaria incidence but face challenges including insecticide resistance, outdoor biting behaviors, and ecological variability among vector populations. These factors limit the effectiveness of single interventions and underscore the need for comprehensive approaches that address both indoor and outdoor transmission risks while adapting to evolving vector behaviors (Benelli and Beier, 2017; Sougoufara et al., 2020).

Integrated Vector Management (IVM) has emerged as a strategic framework that combines multiple vector control tools tailored to local contexts to enhance malaria control outcomes sustainably. IVM integrates traditional methods like ITNs and IRS with novel interventions such as larviciding, environmental management, house screening, community education, and emerging biotechnologies including Wolbachia-based strategies. Evidence from diverse settings demonstrates that integrated approaches achieve greater reductions in malaria transmission indicators compared to single interventions alone. Moreover, IVM promotes multisectoral collaboration, continuous surveillance, and adaptive management to overcome challenges like insecticide resistance and residual

transmission. This holistic approach is critical for advancing toward malaria elimination goals globally (Musoke et al., 2023; Otolorin et al., 2025).

2 Biological and Ecological Characteristics of Malaria Vectors

2.1 Major vector species and their distribution

The primary malaria vectors in sub-Saharan Africa include *Anopheles gambiae*, *Anopheles arabiensis*, *Anopheles funestus*, and *Anopheles coluzzii*, with *An. funestus* dominating transmission in many parts of east and southern Africa. This species is notable for its preference for permanent and semi-permanent aquatic habitats such as river streams, ponds, swamps, and spring-fed pools, enabling it to sustain populations year-round and mediate over 85% of malaria transmission events in some regions despite insecticide resistance challenges (Kahamba et al., 2022). In addition to these major vectors, secondary vectors like *Anopheles merus* along the East and Southern African coast are increasingly recognized for their role in residual malaria transmission due to their exophilic behavior and insecticide resistance; these species have expanded their geographical range and vectorial capacity over time (Bartilol et al., 2021).

In India, the major malaria vectors include species complexes such as *Anopheles culicifacies* and *Anopheles fluviatilis*, which exhibit distinct biological traits across diverse ecosystems. These vectors show varying resting behaviors-*An. culicifacies* is mainly endophilic except in some regions where behavioral shifts are observed-and display widespread insecticide resistance that complicates control efforts. Understanding the distribution patterns of sibling species within these complexes is critical for tailoring effective vector control strategies aligned with India's malaria elimination goals (Figure 1) (Subbarao et al., 2019; Rahi et al., 2022).

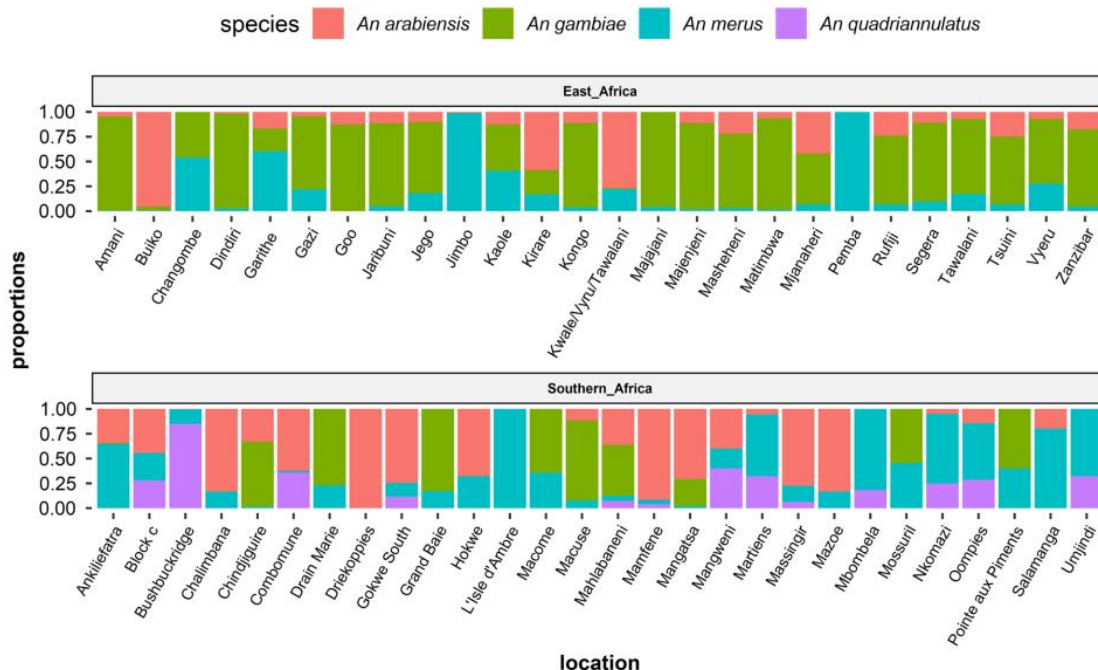


Figure 1 Proportions of *An. Gambiae* complex members: *An. Gambiae* (s.s.), *An. merus*, *An. quadriannulatus* and *An. arabiensis* in the different collection sites along the East and Southern African Coast. However, in Changombe, Drain Marie, Grand Baie, L'Isle d'Ambre, Pemba and Pointe aux Piments, *An. gambiae* (s.l.) were identified using a salt tolerance test and classified as saltwater *An. Gambiae* represented as *An. merus* in the figure or non-saltwater *An. Gambiae* (*An. arabiensis*, *An. quadriannulatus*, *An. Gambiae*), which are represented as *An. Gambiae* (Adopted from Subbarao et al., 2019)

2.2 Life cycle, feeding behavior, and reproductive traits

Malaria vectors undergo a complex life cycle involving aquatic larval stages followed by adult emergence; the duration and success of each stage are influenced by ecological conditions. For example, *An. funestus* females predominantly feed indoors on humans but can exhibit zoophagy in areas with abundant livestock; both males and females rest indoors, which makes them susceptible to indoor interventions despite some reports of outdoor biting

behavior (Kahamba et al., 2022). Similarly, Indian vectors like *An. culicifacies* show variations in feeding preferences with human blood indices ranging widely across regions; reproductive traits such as proportions of gravid mosquitoes also vary geographically, affecting transmission dynamics (Rahi et al., 2022).

Secondary vectors such as *Anopheles squamosus* demonstrate behavioral plasticity that allows them to evade conventional control measures by shifting biting times or locations. Their biology remains understudied but suggests they occupy similar ecological niches as primary vectors in certain African regions, highlighting the need for further research into their life history traits to inform control strategies (Nguyen et al., 2025). Feeding behavior diversity among vector species underscores the importance of integrated approaches that consider both indoor and outdoor transmission risks.

2.3 Influence of environmental factors on vector population dynamics

Environmental factors including land cover, climate variables (temperature, precipitation), topography, and human population density significantly influence the habitat suitability and population dynamics of malaria vectors. Studies using ecological niche modeling have shown that these factors can either facilitate or restrict the occurrence of key vector species such as *An. Gambiae* s.s., *An. coluzzii*, and *An. funestus* s.s., thereby affecting malaria transmission patterns even under intervention pressure like long-lasting insecticidal nets (LLINs) (Talbot et al., 2025). Seasonal changes also impact vector densities; for instance, saltwater-tolerant species like *Anopheles merus* peak during dry seasons when freshwater mosquito populations decline (Bartilol et al., 2021).

Moreover, environmental determinants shape the bionomics of zoonotic malaria vectors in Southeast Asia by influencing abundance and survival through temperature fluctuations, humidity levels, elevation gradients, precipitation patterns, land use changes, and seasonality. These complex interactions necessitate a One Health approach integrating human health with animal reservoirs and environmental management to effectively address malaria transmission risks (Masse et al., 2025). Continuous monitoring of environmental changes is essential for adapting vector control strategies to evolving ecological contexts.

3 Mechanisms and Determinants of Malaria Transmission

3.1 Development of Plasmodium within mosquito hosts

The development of *Plasmodium* parasites within mosquito vectors is a complex process essential for malaria transmission. After an infected female Anopheles mosquito takes a blood meal, *Plasmodium gametocytes* ingested from the human host undergo sexual reproduction in the mosquito's midgut, forming zygotes that develop into motile ookinetes. These ookinetes penetrate the midgut wall and form oocysts, where sporozoites mature over a period typically ranging from 7 to 30 days depending on the *Plasmodium* species and ambient temperature. Mature sporozoites migrate to the salivary glands, enabling the mosquito to infect new human hosts during subsequent blood meals (Rossati et al., 2016; Sato, 2021).

Temperature plays a critical role in modulating the rate of parasite development within mosquitoes, influencing transmission potential. Higher temperatures generally accelerate parasite maturation but may reduce mosquito lifespan, creating a trade-off that affects overall vectorial capacity. Different *Plasmodium* species exhibit variable thermal thresholds for development; for example, *P. falciparum* and *P. vivax* have distinct optimal temperature ranges that impact their geographic distribution and seasonality of transmission (Villena et al., 2022; Suh et al., 2024).

3.2 Interactions among host, vector, and pathogen

Malaria transmission depends on intricate interactions between the human host, mosquito vector, and *Plasmodium* parasite. Host factors such as immune responses and genetic traits influence gametocyte production and infectivity to mosquitoes, thereby affecting transmission efficiency. Conversely, mosquitoes possess immune mechanisms and genetic variations that determine their susceptibility to infection and ability to support parasite development. These dynamic interactions shape parasite sexual differentiation rates and vector competence, which are critical determinants of malaria epidemiology (Sollelis et al., 2024; Li et al., 2025).

The coevolutionary relationship between *Plasmodium parasites* and their hosts has led to remarkable plasticity in parasite traits that facilitate adaptation to changing environments and vector species shifts. This adaptability complicates control efforts by enabling parasites to evade interventions through altered transmission dynamics or resistance development. Understanding these biological determinants is vital for designing effective transmission-blocking strategies targeting both parasite stages in humans and vectors (Mukamurera, 2024; Sollelis et al., 2024).

3.3 Effects of climate change and human activities on transmission risk

Climate change significantly influences malaria transmission by altering environmental conditions that affect both mosquito vectors and *Plasmodium parasites*. Rising temperatures can accelerate mosquito development rates, increase biting frequency, extend lifespan under certain humidity conditions, and shorten parasite incubation periods within vectors—all factors that enhance transmission potential. Changes in rainfall patterns create new breeding habitats or eliminate existing ones, while extreme weather events such as floods or droughts can either amplify or suppress vector populations regionally (Idani et al., 2025; Megersa and Luo, 2025).

Human activities including land use changes, urbanization, migration, and political instability further modify ecosystems in ways that impact malaria risk. Deforestation or agricultural expansion can increase vector habitats or bring humans into closer contact with vectors. Additionally, reduced funding for vector control programs due to socioeconomic factors exacerbates vulnerability to outbreaks despite climatic suitability for transmission. Integrated approaches combining climate-informed surveillance with sustainable public health interventions are essential to mitigate these evolving risks (Rossati et al., 2016; Megersa and Luo, 2025).

4 Conventional Mosquito Control Strategies and Their Limitations

4.1 Chemical control methods (insecticide-treated nets, indoor residual spraying)

Chemical control remains the cornerstone of malaria vector management, primarily through the use of insecticide-treated nets (ITNs) and indoor residual spraying (IRS). These interventions have significantly reduced malaria incidence by targeting mosquitoes that feed and rest indoors, thereby interrupting transmission cycles. However, their effectiveness is increasingly compromised by the widespread emergence of insecticide resistance among *Anopheles* vectors, which diminishes mortality rates and reduces the protective efficacy of these tools (Benelli and Beier, 2017; Namias et al., 2021). Additionally, ITNs and IRS mainly target indoor-biting mosquitoes, leaving outdoor and early-evening biting vectors less affected, which sustains residual transmission despite high coverage (Benelli and Beier, 2017).

Innovations such as insecticidal paints are being explored to enhance chemical control by providing longer-lasting residual effects and easier application compared to conventional spraying. These paints may improve cost-effectiveness and acceptability in endemic regions like India but still face challenges related to resistance development and environmental safety (Singh et al., 2024). Despite these advances, reliance on chemical methods alone is insufficient for sustainable malaria control due to ecological complexities and evolving vector behaviors that reduce contact with treated surfaces (Benelli and Beier, 2017).

4.2 Environmental management and biological control approaches

Environmental management strategies aim to reduce mosquito breeding sites through habitat modification or manipulation, such as drainage of stagnant water or improved water management practices. These approaches can be effective in limiting vector populations but often require sustained community engagement and infrastructure support, which may be challenging in resource-limited settings (Benelli and Beier, 2017). Biological control methods offer eco-friendly alternatives by utilizing natural predators like larvivorous fish, entomopathogenic fungi, bacteria (e.g., *Bacillus thuringiensis israelensis*), or genetically modified mosquitoes to suppress vector populations without chemical insecticides (Benelli et al., 2016; Hamed et al., 2022).

Biocontrol strategies are gaining attention due to their potential sustainability and reduced risk of resistance development. However, their implementation faces limitations including variable efficacy under field conditions,

species-specificity constraints, and logistical challenges in large-scale deployment (Figure 2) (Benelli et al., 2016; Dahmana and Mediannikov, 2020). Integrating biological controls with environmental management within an integrated vector management framework can enhance overall effectiveness but requires careful evaluation of ecological impacts and operational feasibility (Hamed et al., 2022).

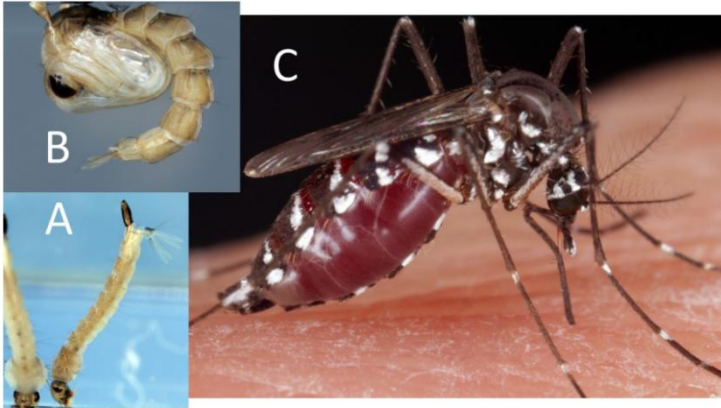


Figure 2 *Aedes albopictus* strain: (A) larvae, (B) pupa, and (C) adult (Adopted from Benelli et al., 2016)

4.3 Insecticide resistance and behavioral adaptations

The rapid evolution of insecticide resistance in mosquito populations poses a major threat to the continued success of chemical-based interventions. Resistance mechanisms include metabolic detoxification, target site mutations, and cuticular changes that reduce insecticide penetration or binding. Importantly, standard laboratory assays often fail to predict the practical impact of resistance on field efficacy due to differences in mosquito age, behavior, and environmental exposure (Namias et al., 2021). This discordance complicates resistance monitoring and necessitates improved guidelines that reflect real-world conditions for better programmatic decision-making.

Beyond physiological resistance, mosquitoes exhibit behavioral adaptations such as altered feeding times, increased outdoor biting, or avoidance of treated surfaces that reduce contact with insecticides. These plastic or constitutive behavioral changes undermine indoor interventions like IRS and ITNs by enabling vectors to evade lethal exposure (Benelli and Beier, 2017; Carrasco et al., 2019). Addressing both physiological resistance and behavioral shifts requires diversified control strategies incorporating novel tools alongside existing methods to sustain malaria transmission reduction efforts effectively (Figure 3) (Benelli and Beier, 2017; Carrasco et al., 2019).

5 Novel and Alternative Mosquito Control Technologies

5.1 Plant-based insecticides and natural product applications

Plant-based insecticides have emerged as promising eco-friendly alternatives to synthetic chemicals for mosquito control. These natural products, derived from various plant extracts and essential oils, exhibit larvicidal, adulticidal, and repellent properties that target multiple mosquito life stages. Their complex chemical compositions reduce the likelihood of resistance development in mosquito populations, making them valuable tools in integrated vector management. For example, neem oil contains bioactive compounds such as azadirachtin that disrupt mosquito development and behavior, demonstrating efficacy as ovicides, larvicides, and repellents while being environmentally safe (Chatterjee et al., 2023; Hillary et al., 2024).

Advances in green nanotechnology have further enhanced the potential of plant-based insecticides by enabling the synthesis of metallic nanoparticles using plant extracts. These nanoparticles exhibit broad-spectrum mosquitocidal activity with improved stability and targeted delivery compared to conventional formulations. Such green-synthesized nanoparticles offer biodegradable, non-toxic options that minimize environmental impact and can be tailored for specific vector species. However, challenges remain in scaling up production and ensuring consistent field efficacy under diverse ecological conditions (Kumar et al., 2020; Onen et al., 2023).

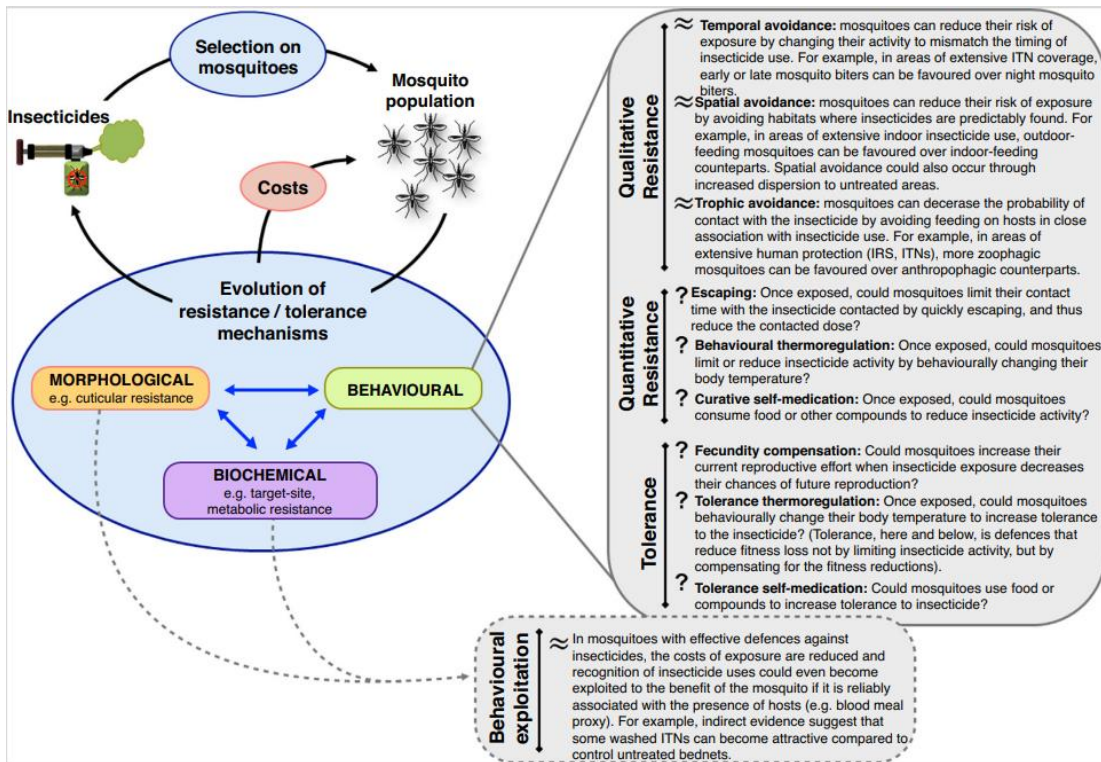


Figure 3 Expanding the field of mosquito insecticide resistance (Adopted from Benelli and Beier, 2017)

5.2 Biotechnological approaches

Biotechnological innovations are revolutionizing mosquito control by targeting vector populations at the genetic level. Gene drive systems use engineered genetic elements to spread traits through mosquito populations rapidly, such as reducing fertility or blocking pathogen transmission. This approach holds promise for sustainable suppression or modification of vector populations but requires careful assessment of ecological risks and ethical considerations before widespread deployment (Jones et al., 2020; Wang et al., 2021). Complementing gene drives, RNA interference (RNAi) technology enables selective silencing of essential mosquito genes involved in survival or reproduction, offering a species-specific bioinsecticide strategy with minimal off-target effects (Yadav et al., 2023).

RNAi-based methods have demonstrated effectiveness in laboratory settings by targeting genes critical at various developmental stages of mosquitoes. Delivery mechanisms include microinjection, feeding, or topical application of double-stranded RNA molecules designed to trigger gene silencing pathways. While promising, challenges such as stability of RNA molecules in field conditions and efficient delivery to wild mosquito populations must be addressed to realize practical applications. Together with gene drives, RNAi represents a cutting-edge toolkit for integrated vector management aiming to overcome limitations of traditional control methods (Wang et al., 2021; Yadav et al., 2023).

5.3 Advanced formulations and delivery systems

Nanotechnology offers innovative solutions for enhancing the efficacy and sustainability of mosquito control agents through advanced formulations and delivery systems. Nanopesticides formulated with plant-derived compounds or synthetic insecticides improve solubility, stability, and controlled release profiles, thereby increasing target specificity while reducing environmental contamination. These nanoformulations can penetrate mosquito cuticles more effectively or provide prolonged residual activity on treated surfaces compared to conventional products (Benelli et al., 2018; Kumar et al., 2020).

Moreover, nanocarriers enable novel delivery strategies such as slow-release larvicides in breeding habitats or attract-and-kill devices that exploit mosquito behavior for targeted control. Despite their potential benefits,

concerns about non-target effects and ecotoxicity require thorough evaluation before large-scale implementation. Integrating nanotechnology with biological controls and environmentally friendly compounds could form a multifaceted approach that addresses current challenges like resistance development and operational constraints in malaria vector management (Benelli, 2015; Benelli et al., 2018).

6 Development and Implementation of Integrated Vector Management (IVM)

6.1 Theoretical framework and core principles of IVM

Integrated Vector Management (IVM) is a rational decision-making process designed to optimize the use of resources for vector control by combining multiple strategies tailored to local contexts. Its core principles emphasize evidence-based decision-making, integration of various control methods, intersectoral collaboration, advocacy, social mobilization, legislation, and capacity building. This approach recognizes that effective vector control is not solely the responsibility of the health sector but requires coordinated efforts across multiple sectors and stakeholders to address the complex determinants of vector-borne diseases (Beier et al., 2008; Onoh et al., 2020). IVM aims to enhance efficacy, cost-effectiveness, ecological soundness, and sustainability by promoting interdisciplinary integration and adapting interventions to changing environmental and epidemiological conditions (Onoh et al., 2020; Tourapi and Tsioutis, 2022).

The theoretical framework of IVM also incorporates adaptability to emerging challenges such as climate change, urbanization, and evolving vector behaviors. It advocates for locally adapted strategies that consider environmental impacts from human activities and demographic shifts influencing disease transmission dynamics. The Circular Policy concept highlights the need for continuous planning, implementation, enforcement, and validation cycles within IVM programs to maintain effectiveness amid these dynamic factors. This holistic approach ensures that vector control remains responsive to new scientific knowledge and technological advancements while aligning with planetary health goals (Figure 4) (Tourapi and Tsioutis, 2022; Tiffin et al., 2025).

IVM: Responding to Complex Systems

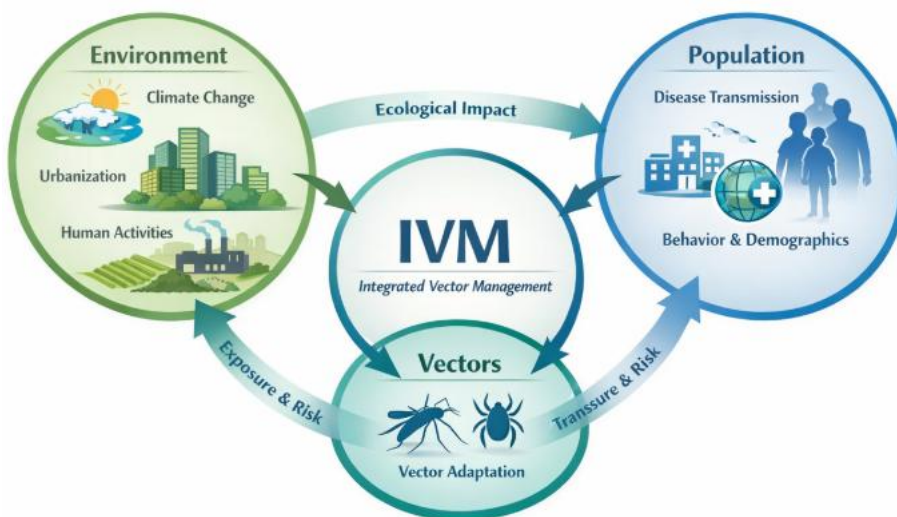


Figure 4 Interactions among environment, vectors, and human populations within the Integrated Vector Management (IVM) framework under dynamic socio-environmental changes (Adopted from Tourapi and Tsioutis, 2022)

6.2 Multi-strategy integration models

Multi-strategy integration within IVM involves combining chemical, biological, environmental, and genetic control methods in a complementary manner to maximize impact on vector populations. For example, integrating insecticide-treated nets with larval source management and biological agents like Wolbachia-infected mosquitoes can address different mosquito life stages and behaviors simultaneously. Such combinations help mitigate

limitations inherent in single-method approaches, including insecticide resistance and behavioral adaptations by vectors (Abbasi, 2025). The integration model also supports the inclusion of novel genomic tools like gene drives alongside traditional interventions to achieve sustainable reductions in disease transmission.

Successful multi-strategy models require robust surveillance systems to guide targeted interventions based on local entomological and epidemiological data. Frameworks like Integrated Aedes Management (IAM) exemplify this approach by incorporating integrated vector surveillance, community mobilization, intersectoral collaboration, capacity building, research, advocacy, and supportive policies. These pillars ensure that diverse tools are deployed effectively according to risk scenarios while fostering adaptability and sustainability in vector control programs (Beier et al., 2008; Roiz et al., 2018).

6.3 Community participation and public health policy support

Community participation is fundamental to the success of IVM as it fosters local ownership, enhances compliance with control measures, and facilitates sustainable behavior change. Engaging communities through education campaigns, social mobilization events such as “mosquito days,” and involvement in environmental management activities empowers residents to contribute actively to vector reduction efforts. Partnerships with local organizations and government departments further strengthen these initiatives by integrating income-generating activities like fish farming or tree planting that align with vector control goals (Ng’ang’a et al., 2021; Ni et al., 2025). Such multisectoral collaboration enhances resource mobilization and capacity building at the grassroots level.

Public health policy support is equally critical for institutionalizing IVM frameworks within national malaria control programs. Strong leadership from governments ensures sustained funding, regulatory backing for innovative tools, and coordination across sectors involved in vector management. Policies aligned with global strategies like the WHO Global Vector Control Response provide guidance for scaling up integrated approaches while addressing emerging challenges such as insecticide resistance or climate change impacts (Roiz et al., 2018; Tourapi and Tsioutis, 2022). Together with community engagement, supportive policies create an enabling environment for effective implementation of IVM strategies that reduce malaria transmission risk sustainably (Beier et al., 2008; Ni et al., 2025).

7 Safety, Environmental Impact, and Sustainability Assessment

7.1 Toxicity to non-target organisms and ecological risks

The use of pesticides in mosquito control poses significant risks to non-target organisms across terrestrial and aquatic ecosystems. Studies have documented adverse effects on growth, reproduction, behavior, and physiological functions in a wide range of species including invertebrates, vertebrates, plants, and microorganisms. These negative impacts contribute to biodiversity loss and ecosystem disruption, with insecticidal compounds such as neonicotinoids notably affecting amphibians and other sensitive taxa. The severity of these effects varies by region but remains consistent across different environments even under realistic exposure scenarios, raising concerns about the sustainability of current pesticide practices (Silva et al., 2023; Wan et al., 2025). Furthermore, natural bioherbicides like matricaria lactones show variable toxicity profiles; while they degrade rapidly in the environment, they can still pose acute risks to aquatic organisms through runoff or leaching, indicating that even plant-based alternatives require careful ecotoxicological evaluation (Suarez et al., 2025).

Ecological risk assessments increasingly emphasize the need to consider indirect effects on food webs and ecosystem services alongside direct toxicity. Emerging methodologies advocate integrating molecular to ecosystem-level endpoints to better capture the complex consequences of pesticide exposure on wildlife populations. However, regulatory frameworks often lag behind scientific advances in assessing these broader ecological impacts comprehensively. This gap underscores the importance of developing more holistic risk assessment approaches that incorporate both standard toxicity data and novel biomarkers to safeguard biodiversity while maintaining vector control efficacy (Rattner et al., 2023; Wan et al., 2025).

7.2 Environmental degradation, residue, and ecological impact

Pesticide residues persist widely in soils, water bodies, sediments, crops, air, and indoor dust environments due to intensive agricultural and vector control applications. Monitoring studies reveal that a majority of environmental samples contain multiple pesticide residues at varying concentrations, including both approved and non-approved compounds. These residues contribute to contamination of food chains and drinking water sources with potential human health implications. The presence of complex mixtures complicates risk assessments since interactions among chemicals may amplify toxic effects beyond those predicted for individual substances (Damalas and Eleftherohorinos, 2011; Silva et al., 2023). Although newer pesticides tend to be more biodegradable than legacy compounds, their degradation products can still affect soil microbiota and aquatic ecosystems adversely if not properly managed (Carvalho, 2017; Suarez et al., 2025).

Efforts to reduce environmental contamination focus on improving pesticide formulations and application techniques alongside promoting alternative pest management strategies. Sustainable agriculture practices such as organic farming or integrated pest management reduce reliance on chemical inputs while enhancing ecosystem resilience. Additionally, regulatory policies increasingly call for comprehensive environmental risk evaluations that include persistence data and ecotoxicity profiles during product approval processes. These measures aim to minimize long-term ecological damage while ensuring effective vector control interventions remain available (Carvalho, 2017; Giovagnoni et al., 2025).

7.3 Cost-effectiveness and long-term sustainability

Assessing the cost-effectiveness of mosquito control strategies requires balancing immediate public health benefits against potential environmental costs and sustainability considerations. While chemical insecticides often provide rapid reductions in vector populations at relatively low initial costs, their long-term use can lead to resistance development, non-target toxicity, and environmental degradation that undermine overall program success (Damalas and Eleftherohorinos, 2011; Hauschild et al., 2022). Incorporating sustainability metrics into decision-making frameworks helps identify interventions that optimize health outcomes without compromising ecosystem integrity or future resource availability.

Sustainable vector management increasingly integrates economic analyses with environmental risk assessments to support safe-and-sustainable-by-design approaches. This combined evaluation facilitates robust policy decisions by highlighting trade-offs between efficacy, safety, cost, and ecological impact throughout a product's lifecycle. Moreover, expanding benefit-risk assessments to include environmental data enables healthcare providers and policymakers to select interventions that align with planetary health goals while maintaining disease control effectiveness (Hauschild et al., 2022; Giovagnoni et al., 2025). Ultimately, fostering multi-sectoral collaboration and investing in innovative technologies will be critical for achieving durable malaria transmission reduction within sustainable development frameworks.

8 Discussion and Future Perspectives

Integrated vector management (IVM) strategies that combine multiple control methods have demonstrated significant potential in reducing malaria transmission, particularly in high-burden regions such as sub-Saharan Africa. Systematic reviews indicate that combining insecticide-treated nets (ITNs), indoor residual spraying (IRS), larval source management, and environmental modifications results in greater reductions in malaria incidence and mosquito density compared to single interventions. These integrated approaches address different mosquito life stages and behaviors, enhancing overall effectiveness and mitigating the limitations of individual methods. Moreover, the use of advanced surveillance tools, including molecular diagnostics and geographic information systems (GIS), supports targeted deployment of interventions, improving resource allocation and program outcomes. Despite these successes, the heterogeneity of local ecological and social contexts means that integrated strategies must be tailored to specific settings for optimal impact. Evidence suggests that community engagement and multisectoral collaboration are critical components that enhance uptake and sustainability of interventions. Additionally, integrating novel technologies such as genetically modified mosquitoes or Wolbachia-infected

vectors with traditional methods shows promise but requires further evaluation under field conditions. Overall, integrated strategies represent a comprehensive framework capable of adapting to evolving transmission dynamics while maximizing public health benefits.

Resistance to insecticides among mosquito populations remains a major obstacle undermining the long-term efficacy of vector control programs. The widespread emergence of resistance mechanisms reduces the effectiveness of chemical-based interventions like ITNs and IRS, necessitating the development of new insecticides and resistance management strategies. Climate change further complicates malaria control by altering vector distribution, breeding patterns, and transmission seasons through rising temperatures and changing rainfall patterns. These environmental shifts expand malaria risk zones into previously unaffected areas, challenging existing control frameworks. Predictive models incorporating climate data are increasingly used to anticipate outbreaks but require integration into operational planning. Implementation barriers also hinder progress in many endemic countries. Weak health infrastructure, inadequate funding, fragmented policy coordination, and limited intersectoral collaboration reduce program efficiency. Studies from Kenya and Zambia highlight gaps between climate-resilient malaria policies and their execution due to misaligned stakeholder roles and insufficient monitoring systems. Social factors such as low community awareness, cultural barriers, and limited access to healthcare further impede intervention uptake. Addressing these multifaceted challenges demands strengthened governance, capacity building, and inclusive policy frameworks that integrate climate adaptation with malaria control.

Future research should prioritize filling critical knowledge gaps related to vector biology in diverse ecological settings, especially urban environments where transmission dynamics differ markedly from rural areas. Investigations into non-vector transmission pathways alongside vector control will provide a more comprehensive understanding of malaria epidemiology. The development of novel tools such as vaccines tailored to region-specific parasite strains and gene-drive technologies for vector population suppression warrants accelerated evaluation through rigorous field trials. Policy recommendations emphasize the need for multi-sectoral collaboration integrating public health, environmental management, climate science, and community stakeholders to design adaptive malaria control programs resilient to emerging threats. Strengthening surveillance systems with real-time data integration will enhance early warning capabilities for outbreaks driven by climatic variability. Additionally, sustainable financing mechanisms coupled with capacity building at local levels are essential for scaling up integrated approaches effectively. Emphasizing equity by addressing social determinants of health will improve intervention reach among vulnerable populations. Collectively, these efforts can advance toward durable malaria reduction aligned with global health goals amid changing environmental landscapes.

Acknowledgments

The authors appreciate the modification suggestions from two anonymous peer reviewers on the manuscript of this study.

Conflict of Interest Disclosure

The authors affirm that this research was conducted without any commercial or financial relationships that could be construed as a potential conflict of interest.

References

- Abbasi E., 2025, Innovative approaches to vector control: integrating genomic, biological, and chemical strategies, *Annals of Medicine and Surgery*, 87: 5003-5011.
<https://doi.org/10.1097/ms9.0000000000003469>
- Akowe E., Ahman Q., Agbata B., Joseph S., Senewo E., Danjuma A., and Yahaya D., 2025, A novel malaria mathematical model: integrating vector and non-vector transmission pathways, *BMC Infectious Diseases*, 25: 10653.
<https://doi.org/10.1186/s12879-025-10653-8>
- Bartilol B., Omedo I., Mbogo C., Mwangangi J., and Rono M., 2021, Bionomics and ecology of *Anopheles merus* along the East and Southern Africa coast, *Parasites & Vectors*, 14: 582.
<https://doi.org/10.1186/s13071-021-04582-z>

- Beier J., Keating J., Githure J., Macdonald M., Impoinvil D., and Novak R., 2008, Integrated vector management for malaria control, *Malaria Journal*, 7(S1): S4.
<https://doi.org/10.1186/1475-2875-7-s1-s4>
- Benelli G., 2015, Research in mosquito control: current challenges for a brighter future, *Parasitology Research*, 114(8): 2801-2805.
<https://doi.org/10.1007/s00436-015-4586-9>
- Benelli G., and Beier J., 2017, Current vector control challenges in the fight against malaria, *Acta Tropica*, 174: 91-96.
<https://doi.org/10.1016/j.actatropica.2017.06.028>
- Benelli G., Jeffries C., and Walker T., 2016, Biological control of mosquito vectors: past, present, and future, *Insects*, 7(4): 52.
<https://doi.org/10.3390/insects7040052>
- Benelli G., Maggi F., Pavela R., Murugan K., Govindarajan M., Vaseeharan B., Petrelli R., Cappellacci L., Kumar S., Hofer A., Youssefi M., Alarfaj A., Hwang J., and Higuchi A., 2018, Mosquito control with green nanopesticides: towards the one health approach? a review of non-target effects, *Environmental Science and Pollution Research*, 25(11): 10184-10206.
<https://doi.org/10.1007/s11356-017-9752-4>
- Carrasco D., Lefèvre T., Moiroux N., Pennetier C., Chandre F., and Cohuet A., 2019, Behavioural adaptations of mosquito vectors to insecticide control, *Current Opinion in Insect Science*, 34: 48-54.
<https://doi.org/10.1016/j.cois.2019.03.005>
- Carvalho F., 2017, Pesticides, environment, and food safety, *Food and Energy Security*, 6(2): 48-60.
<https://doi.org/10.1002/fes3.108>
- Chatterjee S., Bag S., Biswal D., Paria D., Bandyopadhyay R., Sarkar B., Mandal A., and Dangar T., 2023, Neem-based products as potential eco-friendly mosquito control agents over conventional eco-toxic chemical pesticides-a review, *Acta Tropica*, 247: 106858.
<https://doi.org/10.1016/j.actatropica.2023.106858>
- Dahmana H., and Mediannikov O., 2020, Mosquito-borne diseases emergence/resurgence and how to effectively control it biologically, *Pathogens*, 9(4): 310.
<https://doi.org/10.3390/pathogens9040310>
- Damalas C., and Eleftherohorinos I., 2011, Pesticide exposure, safety issues, and risk assessment indicators, *International Journal of Environmental Research and Public Health*, 8(5): 1402-1419.
<https://doi.org/10.3390/ijerph8051402>
- Giovagnoni E., Mattoli L., Cossu A., and Murgia V., 2025, Integrating environmental effects in the benefit-risk assessment of therapeutic products: a proposal and example for sustainable health and healthcare, *Frontiers in Drug Safety and Regulation*, 4: 1519142.
<https://doi.org/10.3389/fdsfr.2024.1519142>
- Hamed A., El-Sherbini M., and Abdeltawab M., 2022, Eco-friendly mosquito-control strategies: advantages and disadvantages, *egyptian academic journal of biological sciences, E. Medical Entomology and Parasitology*, 14: 221601.
<https://doi.org/10.21608/eajbse.2022.221601>
- Hauschild M., McKone T., Arnbjerg-Nielsen K., Hald T., Nielsen B., Mabit S., and Fantke P., 2022, Risk and sustainability: trade-offs and synergies for robust decision making, *Environmental Sciences Europe*, 34(1): 1-13.
<https://doi.org/10.1186/s12302-021-00587-8>
- Hillary V., Ceasar S., and Ignacimuthu S., 2024, Efficacy of plant products in controlling disease vector mosquitoes, a review, *Entomologia Experimentalis et Applicata*, 172(3): 195-214.
<https://doi.org/10.1111/eea.13401>
- Idani C., Aduda J., and Karanja S., 2025, Stochastic and climate-driven modeling of malaria transmission in rwanda: a vector-human interaction approach, *International Journal of Environmental Sciences*, 9: 49.
<https://doi.org/10.64252/x3nk7s49>
- Jones R., Ant T., Cameron M., and Logan J., 2020, Novel control strategies for mosquito-borne diseases, *Philosophical Transactions of the Royal Society B: Biological Sciences*, 376(1818): 20190802.
<https://doi.org/10.1098/rstb.2019.0802>
- Kahamba N., Finda M., Ngowo H., Msugupakulya B., Baldini F., Koekemoer L., Ferguson H., and Okumu F., 2022, Using ecological observations to improve malaria control in areas where *Anopheles funestus* is the dominant vector, *Malaria Journal*, 21: 198.
<https://doi.org/10.1186/s12936-022-04198-3>
- Kombate G., Djalogue L., Ngangue P., Soubeiga K., Grobbee D., and Van Der Sande M., 2025, Integrated malaria vector control strategies and their effectiveness in sub-Saharan Africa: a systematic review protocol for interventional studies, *BMJ Open*, 15(1): e091569.
<https://doi.org/10.1136/bmjopen-2024-091569>
- Kumar D., Kumar P., Singh H., and Agrawal V., 2020, Biocontrol of mosquito vectors through herbal-derived silver nanoparticles: prospects and challenges, *Environmental Science and Pollution Research*, 27(21): 25987-26024.
<https://doi.org/10.1007/s11356-020-08444-6>
- Li Y., Tang J., Tang W., Liu C., and Li Z., 2025, Host factors influencing sexual differentiation and transmission of plasmodium: a comprehensive review, *Acta Tropica*, 260: 107634.
<https://doi.org/10.1016/j.actatropica.2025.107634>

- Masse R., Vythilingam I., Fornace K., Othman H., Liu X., Jaafar A., Shahar M., Rahman N., Azman A., and Jeyaprakasam N., 2025, Impact of environmental factors on the bionomics of Anopheles mosquito vectors of zoonotic malaria: A narrative review, *One Health*, 21: 101141.
<https://doi.org/10.1016/j.onehlt.2025.101141>
- Megersa D., and Luo X., 2025, Effects of climate change on malaria risk to human health: a review, *Atmosphere*, 16(1): 71.
<https://doi.org/10.3390/atmos16010071>
- Mukamurera N.P., 2024, Transmission dynamics: from human host to mosquito vector, *IDOSR Journal of Biological and Chemical Physics*, 24(93): 1115000.
<https://doi.org/10.59298/idosr/jbcp/24/93.1115000>
- Musoke D., Atusingwize E., Namata C., Ndejjo R., Wanyenze R., and Kamya M., 2023, Integrated malaria prevention in low- and middle-income countries: a systematic review, *Malaria Journal*, 22: 500.
<https://doi.org/10.1186/s12936-023-04500-x>
- Namias A., Jobe N., Paaijmans K., and Huijben S., 2021, The need for practical insecticide-resistance guidelines to effectively inform mosquito-borne disease control programs, *eLife*, 10: e65655.
<https://doi.org/10.7554/elife.65655>
- Ng'ang'a P., Aduogo P., and Mutero C., 2021, Strengthening community and stakeholder participation in the implementation of integrated vector management for malaria control in western Kenya: a case study, *Malaria Journal*, 20: 692.
<https://doi.org/10.1186/s12936-021-03692-4>
- Nguyen V., Dryden D., Broder B., Tadimari A., Tanachaiwiwat P., Mathias D., Thongsripong P., Reeves L., Ali R., Gebhardt M., Saili K., Simubali L., Simulundu E., Norris D., and Lee Y., 2025, A Comprehensive Review: Biology of *Anopheles squamosus*, an Understudied Malaria Vector in Africa, *Insects*, 16(2): 110.
<https://doi.org/10.3390/insects16020110>
- Ni J., Wang J., Zhang W., Chen E., Gao Y., Sun J., Huang W., Xia J., Zeng W., Guo J., and Gong Z., 2025, Sustainable control and integrated management through a one health approach to mitigate vector-borne disease, *One Health*, 20: 101018.
<https://doi.org/10.1016/j.onehlt.2025.101018>
- Onen H., Luzala M., Kigozi S., Sikumbili R., Muanga C., Zola E., Wendji S., Buya A., Balčiūnaitienė A., Viškelis J., Kaddumukasa M., and Memvanga P., 2023, Mosquito-borne diseases and their control strategies: an overview focused on green synthesized plant-based metallic nanoparticles, *Insects*, 14(3): 221.
<https://doi.org/10.3390/insects14030221>
- Onoh C., Aguocha J., and Nwabueze R., 2020, Integrated vector management: panacea for malaria control, *Journal of Mosquito Research*, 10(1): 1-6.
- Otolorin G., Castellanos M., Adegboye O., and McBryde E., 2025, Integrated vector management for malaria control: a review of approaches and effectiveness, *Transactions of the Royal Society of Tropical Medicine and Hygiene*, 119(10): 1223-1232.
<https://doi.org/10.1093/trstmh/traf084>
- Rahi M., Mishra A., Chand G., Baharia R., Hazara R., Singh S., Khan S., Sreehari U., Kamaraju D., Kumar G., Gupta S., Sharma A., Raghavendra K., Gunasekaran K., Singh O., and Subbarao S., 2022, Malaria vector bionomics: countrywide surveillance study on implications for malaria elimination in India, *JMIR Public Health and Surveillance*, 10: e42050.
<https://doi.org/10.2196/42050>
- Rattner B., Bean T., Beasley V., Berny P., Eisenreich K., Elliott J., Eng M., Fuchsman P., King M., Mateo R., Meyer C., O'Brien J., and Salice C., 2023, Wildlife ecological risk assessment in the 21st century: Promising technologies to assess toxicological effects, *Integrated Environmental Assessment and Management*, 20(1): 4806.
<https://doi.org/10.1002/ieam.4806>
- Roiz D., Wilson A., Scott T., Fonseca D., Jourdain F., Müller P., Velayudhan R., and Corbel V., 2018, Integrated Aedes management for the control of Aedes-borne diseases, *PLoS Neglected Tropical Diseases*, 12(12): e0006845.
<https://doi.org/10.1371/journal.pntd.0006845>
- Rossati A., Bargiacchi O., Kroumova V., Zaramella M., Caputo A., and Garavelli P., 2016, Climate, environment and transmission of malaria, *Le Infezioni in Medicina*, 24(2): 93-104.
- Sato S., 2021, Plasmodium-a brief introduction to the parasites causing human malaria and their basic biology, *Journal of Physiological Anthropology*, 40: 28.
<https://doi.org/10.1186/s40101-020-00251-9>
- Silva V., Gai L., Harkes P., Tan G., Ritsema C., Alcon F., Contreras J., Abrantes N., Campos I., Baldi I., Bureau M., Christ F., Mandrioli D., Sgargi D., Pasković I., Pasković M., Glavan M., Hofman J., Lwanga H., Norgaard T., Bilková Z., Osman R., Khurshid C., Navarro I., De La Torre A., Sanz P., Martínez M., Dias J., Mol H., Gort G., Figueiredo D., Scheepers P., Schlünssen V., Vested A., Alaoui A., and Geissen V., 2023, Pesticide residues with hazard classifications relevant to non-target species including humans are omnipresent in the environment and farmer residences, *Environment International*, 181: 108280.
<https://doi.org/10.1016/j.envint.2023.108280>
- Singh B., Kumar D., Kumar G., Saroha P., Vikram K., Gupta S., and Singh H., 2024, Insecticidal paint: an alternate integrated vector management strategy for mosquito control, *Process Safety and Environmental Protection*, 184: 118.
<https://doi.org/10.1016/j.psep.2024.03.118>
- Solleis L., Howick V., and Marti M., 2024, Revisiting the determinants of malaria transmission, *Trends in Parasitology*, 40(6): 1-10.
<https://doi.org/10.1016/j.pt.2024.02.001>

- Sougoufara S., Otihi E., and Triplet F., 2020, The need for new vector control approaches targeting outdoor biting *Anopheles malaria* vector communities, *Parasites & Vectors*, 13: 295.
<https://doi.org/10.1186/s13071-020-04170-7>
- Suarez E., Zorrilla J., Spampinato M., Pannullo T., Esposito F., Fernández-Aparicio M., Libralato G., Siciliano A., Masi M., and Cimmino A., 2025, Toxicity assessment of (4Z)-lachnophyllum and (4Z,8Z)-matricaria lactones: implications for environmental safety of bioherbicides, *Toxins*, 17(4): 169.
<https://doi.org/10.3390/toxins17040169>
- Subbarao S., Nanda N., Rahi M., and Raghavendra K., 2019, Biology and bionomics of malaria vectors in India: existing information and what more needs to be known for strategizing elimination of malaria, *Malaria Journal*, 18: 3011.
<https://doi.org/10.1186/s12936-019-3011-8>
- Suh E., Stopard I., Lambert B., Waite J., Dennington N., Churcher T., and Thomas M., 2024, Estimating the effects of temperature on transmission of the human malaria parasite, *Plasmodium falciparum*, *Nature Communications*, 15: 47265.
<https://doi.org/10.1038/s41467-024-47265-w>
- Talbot B., Alou L., Koffi A., Sih C., Dangbénon E., Zoh M., Camara S., Assi S., N'Guessan R., Messenger L., Protopopoff N., Cook J., and Kulkarni M., 2025, Ecological drivers of malaria vector habitat and transmission over 1 year of long-lasting insecticidal net intervention in Côte d'Ivoire, *Parasites & Vectors*, 18: 6984.
<https://doi.org/10.1186/s13071-025-06984-9>
- Tiffin H., Gordon J., and Poh K., 2025, One Health, many approaches: integrated vector management strategies support one health goals, *Frontiers in Insect Science*, 5: 1549348.
<https://doi.org/10.3389/finsec.2025.1549348>
- Tourapi C., and Tsioutis C., 2022, Circular policy: a new approach to vector and vector-borne diseases' management in line with the global vector control response (2017-2030), *Tropical Medicine and Infectious Disease*, 7(7): 125.
<https://doi.org/10.3390/tropicalmed7070125>
- Villena O., Ryan S., Murdock C., and Johnson L., 2022, Temperature impacts the environmental suitability for malaria transmission by *Anopheles gambiae* and *Anopheles stephensi*, *Ecology*, 103(4): e3685.
<https://doi.org/10.1002/ecy.3685>
- Wan N., Fu L., Dainese M., Kiær L., Hu Y., Xin F., Goulson D., Woodcock B., Vanbergen A., Spurgeon D., Shen S., and Scherber C., 2025, Pesticides have negative effects on non-target organisms, *Nature Communications*, 16: 56732.
<https://doi.org/10.1038/s41467-025-56732-x>
- Wang G., Gamez S., Raban R., Marshall J., Alphey L., Li M., Rasgon J., and Akbari O., 2021, Combating mosquito-borne diseases using genetic control technologies, *Nature Communications*, 12: 4654.
<https://doi.org/10.1038/s41467-021-24654-z>
- Yadav M., Dahiya N., and Sehwat N., 2023, Mosquito gene targeted RNAi studies for vector control, *Functional and Integrative Genomics*, 23: 1072.
<https://doi.org/10.1007/s10142-023-01072-6>



Disclaimer/Publisher's Note

The statements, opinions, and data contained in all publications are solely those of the individual authors and contributors and do not represent the views of the publishing house and/or its editors. The publisher and/or its editors disclaim all responsibility for any harm or damage to persons or property that may result from the application of ideas, methods, instructions, or products discussed in the content. Publisher remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.
