Malaria Vectors: Biology, Geographical Distribution And Challenges For Vector Control In The Era Of Insecticide Resistance

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ABSTRACT

Malaria remains one of the most important vector-borne diseases worldwide, particularly in sub-Saharan Africa, where it continues to cause substantial morbidity and mortality despite significant progress in control efforts. Effective malaria prevention depends largely on understanding the biology, ecology, geographical distribution, and behavior of mosquito vectors belonging to the genus Anopheles.

This review examines the biological characteristics of major malaria vectors, their global distribution, and their role in malaria transmission. Particular attention is given to the challenges associated with vector control in the context of increasing insecticide resistance. The article discusses the principal vector control interventions currently used, including long-lasting insecticidal nets (LLINs) and indoor residual spraying (IRS), as well as recent innovations such as piperonyl butoxide (PBO)-treated nets and dual-active ingredient insecticide-treated nets. Current mechanisms of insecticide resistance and their implications for malaria control programs are also reviewed.

In addition, the article highlights field experience from the Banfora Clinical Research Unit in Burkina Faso, where entomological surveillance and resistance monitoring contribute to evidence-based malaria control strategies. Emerging approaches, including genetic vector control technologies and climate-informed surveillance systems, are discussed as potential components of future malaria elimination efforts.

The review emphasizes that sustained investment in vector surveillance, operational research, innovative vector control tools, and adaptive management strategies will be essential for maintaining progress against malaria and addressing the growing challenges posed by insecticide resistance and environmental change.

Keywords: malaria, Anopheles mosquitoes, vector biology, insecticide resistance, vector control, long-lasting insecticidal nets, Burkina Faso, malaria surveillance.

1. INTRODUCTION

Malaria remains one of the most devastating infectious diseases affecting human populations worldwide. According to the World Health Organization (WHO), an estimated 263 million malaria cases and approximately 597,000 malaria deaths occurred globally in 2023, with the WHO African Region accounting for approximately 95% of malaria-related deaths worldwide **[1]**. Despite considerable progress achieved through large-scale vector control programs, improved diagnostic methods, and the deployment of artemisinin-based combination therapies, malaria continues to impose a substantial burden on public health systems and economic development.

The transmission of malaria depends primarily on female mosquitoes belonging to the genus Anopheles. These vectors play a critical role in maintaining the life cycle of Plasmodium parasites and determining transmission intensity within endemic regions **[2]**. Consequently, understanding vector biology, ecology, and geographical distribution remains essential for designing effective malaria control interventions.

This review examines the biological characteristics and geographical distribution of malaria vectors worldwide and discusses major challenges associated with vector control, particularly the growing threat of insecticide resistance.

2. BIOLOGY OF MALARIA VECTORS

Mosquitoes belong to the family Culicidae, which includes more than 3,400 species worldwide. However, only species belonging to the genus Anopheles are capable of transmitting human malaria parasites **[3]**. Approximately seventy Anopheles species have been implicated in malaria transmission, while forty-one dominant vector species or species complexes account for the majority of global malaria transmission **[4]**.

The life cycle of Anopheles mosquitoes consists of four developmental stages: egg, larva, pupa, and adult. Eggs are deposited on water surfaces and hatch into larvae, which undergo several molts before transforming into pupae. Adult mosquitoes emerge from pupae and subsequently disperse to seek food sources and breeding sites **[5]**.

Adult female mosquitoes require blood meals for egg maturation and are therefore responsible for malaria transmission. During feeding, infected mosquitoes inoculate Plasmodium sporozoites into the human bloodstream, initiating infection **[6]**.

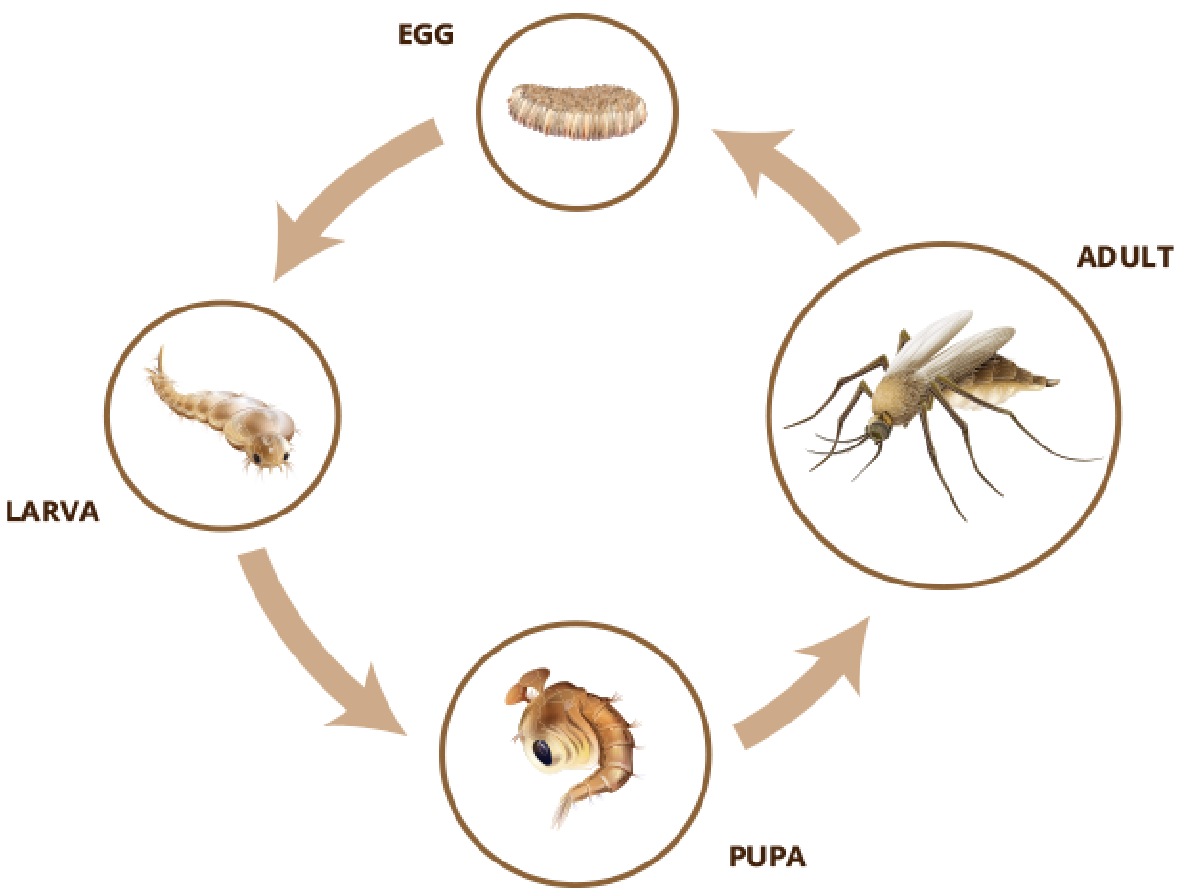


Figure 1: Mosquito life cycle considered for *Anopheles gambiae* s.l. http://www.mosquitoes.org/education/, [Accessed on 09-07-2016]).

3. GLOBAL DISTRIBUTION OF MALARIA VECTORS

The geographical distribution of malaria vectors varies considerably according to environmental and climatic conditions. Different species dominate different regions and contribute to distinct transmission patterns.

Table 1 summarizes the principal malaria vectors and associated Plasmodium species in major endemic regions.

Table 1: Geographic distribution of the major malaria vector species and the predominant human *Plasmodium* species worldwide.

Region	Major malaria vector species	Dominant Plasmodium species
Africa	*Anopheles gambiae*, *Anopheles arabiensis*, *Anopheles funestus*, *Anopheles nili*, *Anopheles moucheti*	*Plasmodium falciparum*
Asia	*Anopheles stephensi*, *Anopheles dirus*, *Anopheles minimus*, *Anopheles culicifacies*	*Plasmodium falciparum*, *P. vivax*, *P. knowlesi*
Americas	*Anopheles darlingi*, *Anopheles albimanus*, *Anopheles aquasalis*	*Plasmodium vivax*, *P. falciparum*
Europe/Middle East	*Anopheles atroparvus*, *Anopheles sacharovi*, *Anopheles labranchiae*	*Plasmodium vivax*, *P. malariae*

Africa hosts the most efficient malaria vectors worldwide, including members of the Anopheles gambiae complex, which recognized as the most important vectors of Plasmodium falciparum **[2]**. In Asia, malaria transmission sustained by species such as Anopheles stephensi and Anopheles dirus, while Anopheles darlingi remains the dominant vector in much of South America **[4]**.

The global distribution of dominant malaria vectors presented in Figure 2.

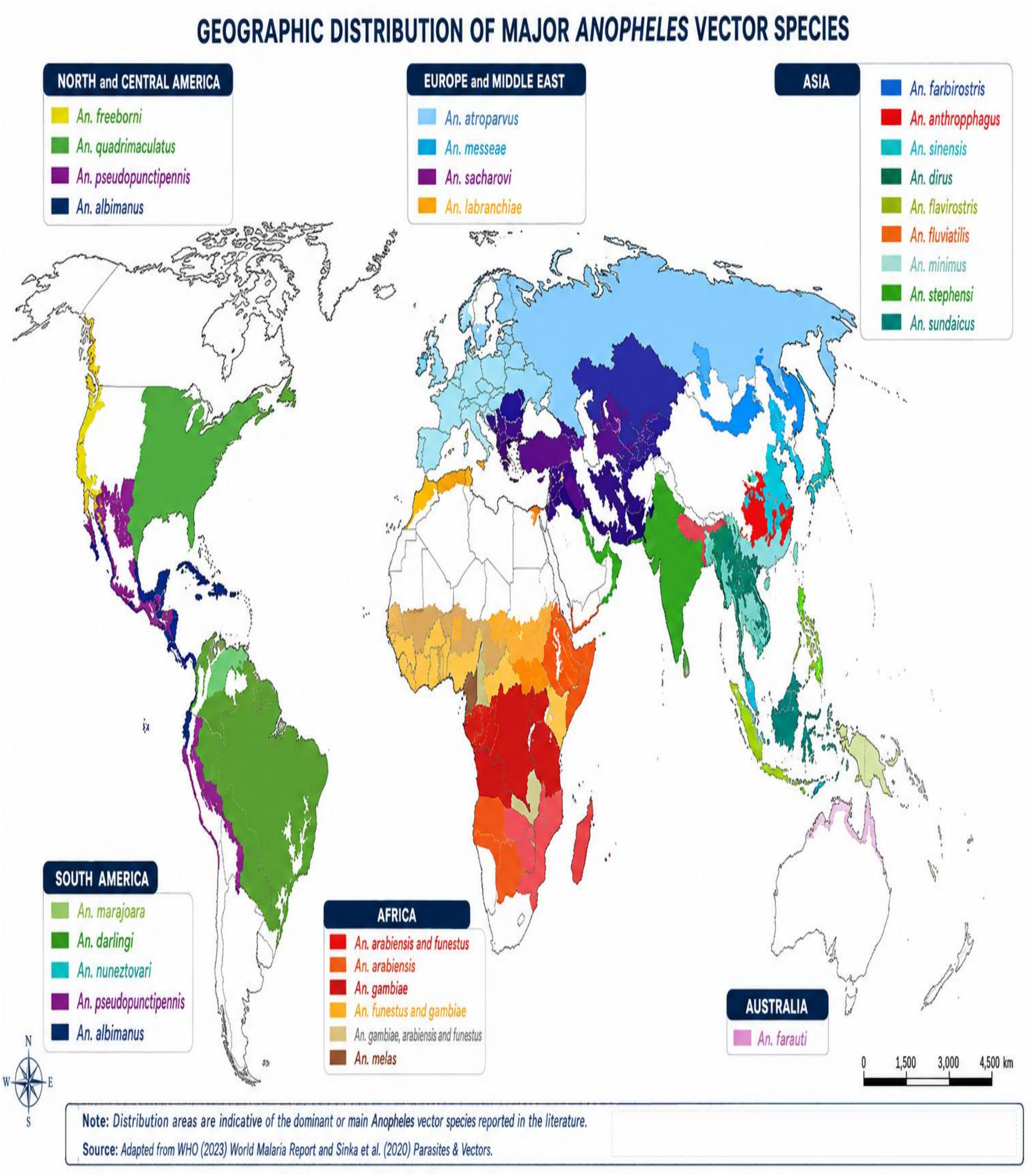


Figure 2 - Distribution of predominant malaria vectors.

4. VECTOR CONTROL STRATEGIES

Modern malaria control relies heavily on vector management interventions. Long Lasting Insecticidal Nets (LLINs) and indoor residual spraying (IRS) remain the cornerstones of malaria prevention and have contributed significantly to reductions in malaria incidence observed over the past two decades **[1]**. Based on accumulating evidence, the World Health Organization recommends the deployment of PBO-treated nets in areas where metabolic resistance has been documented **[7]**. Piperonyl butoxide (PBO)-treated nets have demonstrated improved effectiveness against resistant malaria vectors by inhibiting detoxification enzymes involved in metabolic resistance **[8].** WHO has recently recommended dual-active ingredient insecticide-treated nets combining pyrethroids with chlorfenapyr or pyriproxyfen **[9]**.

Additional strategies include larval source management, environmental modification, biological control methods, and personal protective measures. The effectiveness of these interventions depends largely on vector behavior, ecological conditions, and the susceptibility of mosquito populations to insecticides.

Sustained investment in vector control remains essential for achieving long-term reductions in malaria transmission.

5. INSECTICIDE RESISTANCE: A GROWING THREAT

One of the most important challenges facing malaria control programs today is the emergence and spread of insecticide resistance. Resistance has been documented in numerous malaria vector populations throughout Africa, Asia, and Latin America **[10]**.

Several resistance mechanisms have been identified. Metabolic resistance involves enhanced detoxification of insecticides by mosquito enzymes. Target-site resistance results from genetic mutations affecting insecticide binding sites, while behavioral resistance occurs when mosquitoes modify their feeding or resting behavior to avoid insecticide exposure **[10, 11]**.

These resistance mechanisms reduce the effectiveness of LLINs and IRS and may compromise progress achieved through malaria control programs (Fig 3).

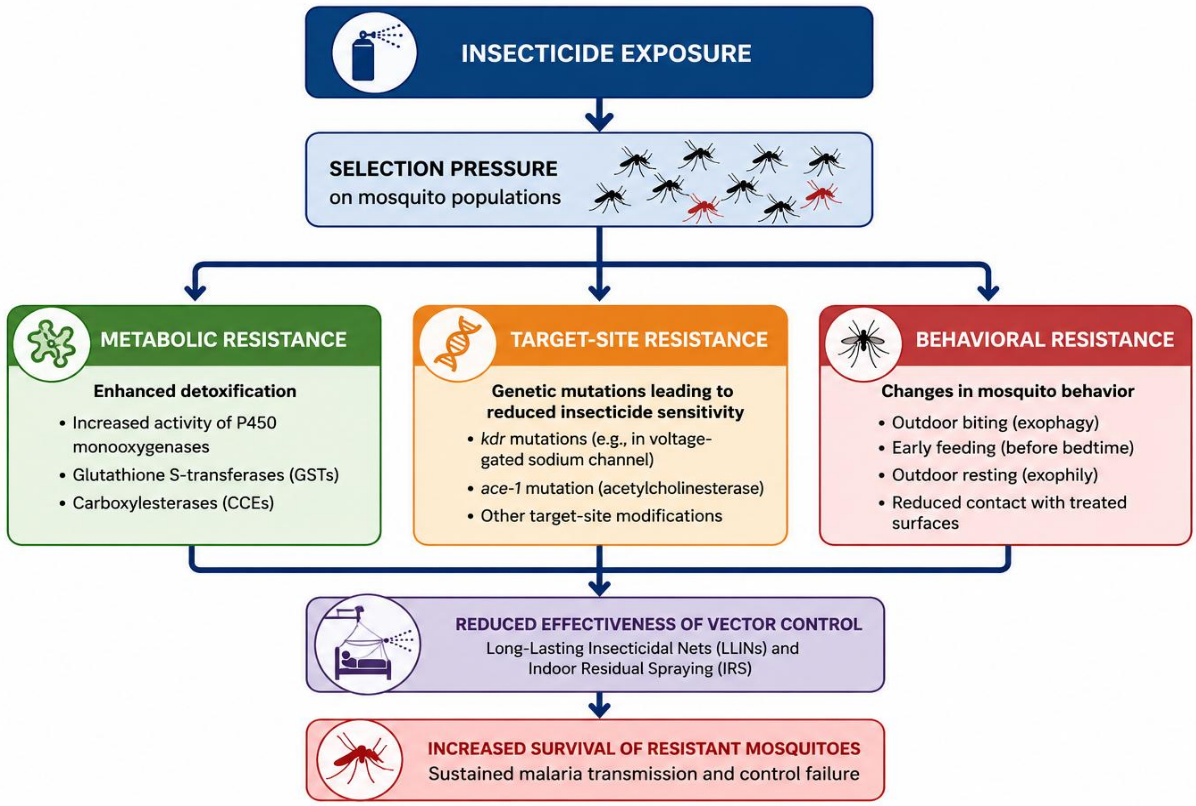


Figure 3. Major mechanisms of insecticide resistance in malaria vectors.

LLINs and Indoor Residual Spraying resistance may arise through enhanced detoxification of insecticides (metabolic resistance), genetic mutations affecting insecticide target sites (target-site resistance), or behavioral adaptations that reduce contact between mosquitoes and insecticides (behavioral resistance). These mechanisms can decrease the effectiveness of long-lasting insecticidal nets (LLINs) and indoor residual spraying (IRS).

Recent studies conducted in Burkina Faso have documented increasing levels of pyrethroid resistance among populations of Anopheles gambiae sensu lato. Both metabolic and target-site resistance mechanisms have been reported, highlighting the need for continuous resistance monitoring and adaptation of vector control strategies **[12]**.

6. FIELD EXPERIENCE FROM BURKINA FASO

Burkina Faso remains among the countries most heavily affected by malaria worldwide. The National Center for Research and Training on Malaria (CNRFP) plays a central role in malaria research, vector surveillance, and evaluation of malaria control interventions.

At the Banfora Clinical Research Unit (URCB), entomological activities include mosquito collection, species identification, insectary rearing, insecticide susceptibility testing, molecular characterization of vector populations, and experimental hut evaluations. These activities contribute significantly to understanding vector behavior and resistance dynamics under field conditions.

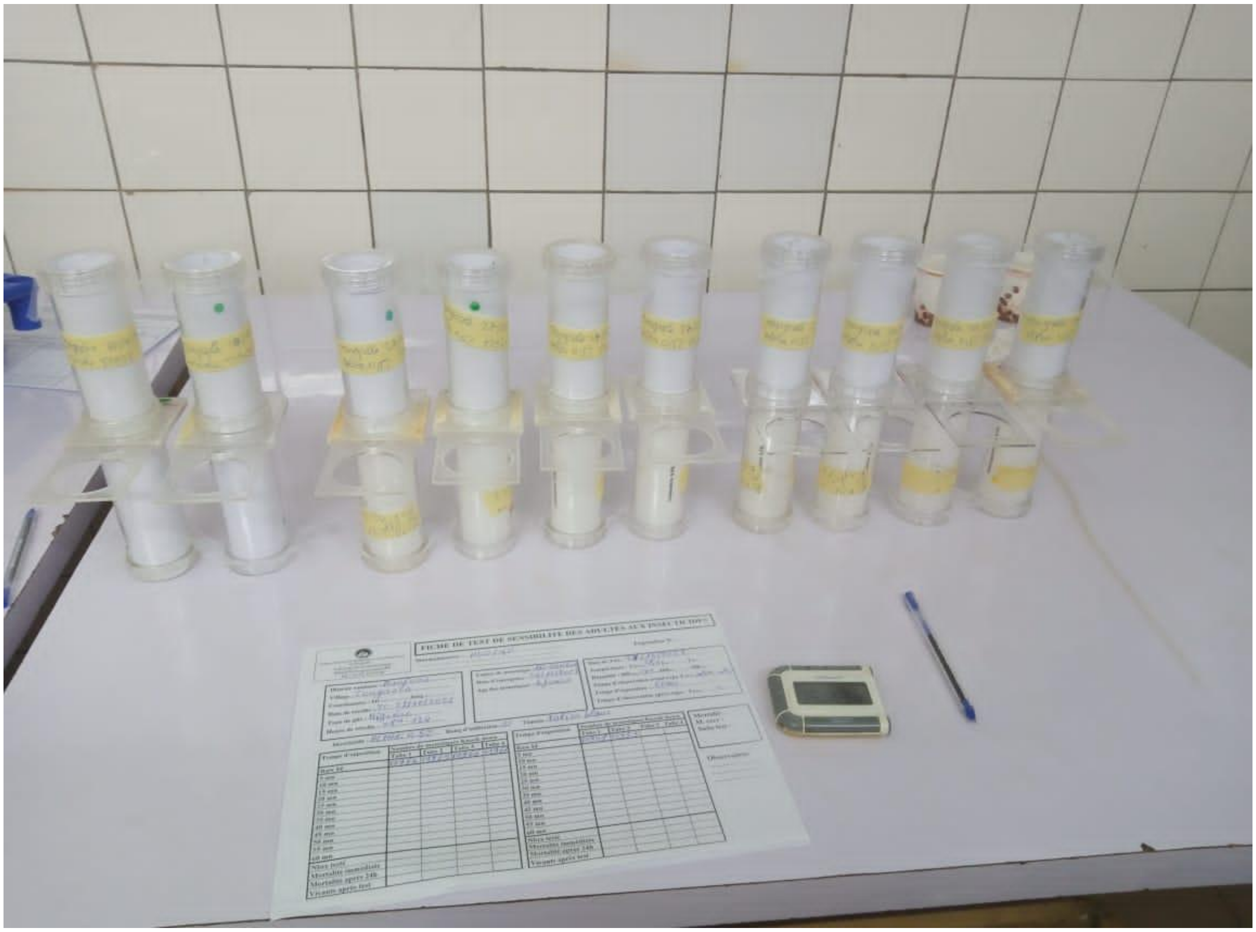
Data generated through these surveillance activities have supported the introduction of next-generation mosquito nets containing piperonyl butoxide (PBO) and have strengthened evidence-based decision-making within national malaria control programs.

These observations are consistent with current WHO recommendations supporting the deployment of PBO-treated and dual-active ingredient insecticide-treated nets in areas affected by insecticide resistance **[7, 9]**.

Figure 4: Entomological Surveillance Activities at the Banfora Clinical Research Unit (URCB), Burkina Faso.

Source : Photo d'illustration, auteur : SOURABIE Foromine, Octobre 2022

Panel A: Selection/sorting of larvae by pipetting after collection from the sites; Insectarium URCB.



Source : Photo d'illustration, Auteur : SIRIBIE Mafama, Décembre 2020

Panel B: WHO insecticide susceptibility testing carried out in the URCB Bioassay department

Source : Photo d'illustration, Auteur : SIRIBIE Mafama, Décembre 2020

Panel C: Experimental hut studies, monitoring the lifespan of Anopheles (An. gambiae s.l.) after capture in the experimental huts of Tengrela (URCB).

7. FUTURE DIRECTIONS

Future malaria control efforts should prioritize continuous resistance monitoring, development of novel insecticides, integration of genetic vector control approaches, and strengthening of entomological surveillance systems.

Emerging technologies such as gene-drive systems, next-generation insecticidal nets, and integrated vector management approaches offer promising opportunities for reducing malaria transmission in endemic regions **[13]**. Gene-drive technologies, which aim to reduce mosquito populations or alter their capacity to transmit malaria parasites, may provide an additional tool for malaria control in the future **[14]**. Climate change is increasingly recognized as a factor influencing the geographical distribution, abundance, and seasonal dynamics of malaria vectors. Variations in temperature, rainfall patterns, and environmental conditions may alter transmission patterns and potentially expand malaria risk into previously unaffected regions **[15]**.

Continued collaboration between research institutions, national malaria control programs, and international partners will be critical for sustaining progress toward malaria elimination.

Author's Professional Perspective

My professional experience at the Banfora Clinical Research Unit (URCB), a satellite site of the National Center for Research and Training on Malaria (CNRFP), provided practical exposure to malaria vector surveillance and insecticide resistance monitoring. Participation in larval collection, insectary activities, WHO susceptibility bioassays, and experimental hut studies contributed to a better understanding of vector ecology and the operational challenges faced by malaria control programs. These experiences highlighted the importance of continuous entomological surveillance in guiding evidence-based vector control strategies and adapting interventions to local resistance patterns.

8. CONCLUSION

Malaria vector biology remains a cornerstone of malaria control and elimination efforts worldwide. The distribution, behavior, and ecological adaptations of Anopheles mosquitoes continue to shape malaria transmission patterns, particularly in sub-Saharan Africa where the disease burden remains highest. While vector control interventions such as long-lasting insecticidal nets and indoor residual spraying have substantially reduced malaria transmission over the last two decades, the emergence and spread of insecticide resistance threaten these achievements.

Experiences from Burkina Faso demonstrate the critical role of entomological surveillance in supporting evidence-based malaria control policies. Continuous monitoring of vector populations, investment in innovative control technologies, and strengthened collaboration between research institutions and public health authorities will be essential to sustain progress toward malaria elimination. Future malaria control strategies should integrate novel vector management approaches, next-generation insecticidal tools, and advanced surveillance systems to address the evolving challenges posed by vector adaptation and environmental change.

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