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Resistance of *Anopheles* mosquitoes to insecticides in the Democratic Republic of the Congo: A literature review and future directions

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ABSTRACT

Introduction
Malaria remains one of the most prevalent and deadly parasitic infections in the Democratic Republic of the Congo (DRC), posing a significant public health challenge.

Purpose
This literature review aimed to investigate the resistance and sensitivity of *Anopheles* mosquitoes to insecticides used in the DRC.

Methods
A bibliographic search was conducted using search engines such as Google Scholar, ScienceDirect, PubMed, and Scopus with keywords including "resistant *Anopheles*," "insecticide resistance," and "susceptible *Anopheles*" specific to the DRC. Additional keywords such as "molecular target of insecticides," "modes of action of insecticides," and "mechanisms of insecticide resistance" were used without geographical restrictions. Articles were selected based on criteria including relevance to the subject, source reliability, and recency. Special emphasis was placed on studies with robust methodologies. To ensure comprehensiveness, diverse studies were included to provide a holistic overview of the subject.

Results
Numerous scientific articles and reports were selected for analysis. The findings indicate that *Anopheles* mosquitoes exhibit resistance to key pyrethroid insecticides (e.g., permethrin, deltamethrin, and alpha-cypermethrin) commonly used for treating long-lasting insecticidal nets (LLINs) and in indoor residual spraying (IRS). Evidence from primary and secondary sources suggests that insecticide resistance is spreading across regions and increasing, primarily due to the use of insecticides in agriculture. Of the 22 studies reviewed, 12 reported the restoration of *Anopheles* sensitivity to pyrethroid insecticides when synergist piperonyl butoxide (PBO) was used.

Conclusions
The findings of this review provide a valuable reference for policymakers and public health authorities working to design effective malaria control strategies in the DRC. The results highlight the current status of *Anopheles* insecticide resistance and the progress and challenges associated with malaria control efforts in the region. Further investigation into the use of nanoparticles (NPs) as complementary tools in malaria vector control is recommended, given their potential to target mosquitoes at various life stages and contribute to the eradication of the disease.

INTRODUCTION

Malaria **is** globally recognized as one of the world's most lethal diseases and a significant public health concern (Camponovo et al., 2024). Recent statistics from 2021 reported 247 million cases of malaria, resulting in 619,000 deaths globally (Kojom Foko & Singh, 2023; Mbama Ntabi et al., 2024). The majority of these deaths occur on the African continent (Monroe et al., 2022; Venkatesan, 2023; Yimam et al., 2021). Sub-Saharan Africa, with its tropical climate and high rainfall, remains the most severely affected region, accounting for approximately 94% of global cases and deaths (Leal Filho et al., 2023; Lubinda et al., 2021; Monroe et al., 2022; Yimam et al., 2021). The Democratic Republic of Congo (DRC) and Nigeria together account for nearly 40% of malaria-related morbidity and mortality (Venkatesan, 2023; World Health Organization [WHO], 2023). Pregnant women and children under five years of age are particularly vulnerable, experiencing the highest incidence of the disease (Emina et al., 2021; Kabalu Tshiongo et al., 2024).

The disease is caused by the bite of an infected female mosquito of the genus *Anopheles* during a blood meal (Basosila et al., 2022; Guttery et al., 2022; Xu et al., 2023; Yimam et al., 2021). Malaria in the DRC persists as a substantial public health concern, with 27.3 million cases and 24,880 deaths documented in the most recent year, reflecting an increase in both cases and mortality (Programme National de Lutte contre le Paludisme [PNLP], 2022, 2023; WHO, 2021, 2022b, 2023). This burden underscores the urgent need for effective vector control measures targeting *Anopheles* mosquitoes (Metelo et al., 2024; Ngbolua et al., 2011).

Global and regional efforts to combat malaria include managing parasite infections with antimalarial drugs and implementing vector control strategies such as insecticide-treated nets (ITNs), indoor residual spraying, and biological controls (Cohen et al., 2022; Obeagu & Obeagu, 2024; Ogunah et al., 2020; Thellier et al., 2024; Wilson et al., 2020). However, the emergence of resistance among vectors and parasites, exacerbated by climate change, poses a significant challenge to the effectiveness of these interventions (Conrad et al., 2023; Oke et al., 2022).

In response to the malaria burden in the DRC, the government established the National Malaria Control Programme (NMCP or PNLP/RDC) through Ministerial Order No. 1250/CAB/MIN/SP/008/1998 on July 22, 1998. The NMCP is responsible for formulating antimalaria policies, fostering partnerships, coordinating control activities, and advocating for malaria reduction. Its mission is to develop and implement strategies that ensure access to effective and affordable malaria interventions for all inhabitants of the DRC, thereby reducing socioeconomic losses. Core activities include the distribution of ITNs, promotion of indoor residual spraying, implementation of intermittent preventive treatment during pregnancy, promotion of rapid diagnostic tests, and management of cases with artemisinin-based combination therapies (Emina et al., 2021; PNLP, 2023).

The continued use of insecticide-impregnated mosquito nets, a long-standing malaria control measure, has faced constraints due to the emergence of insecticide-resistant vector populations (Basosila et al., 2022; Metelo-Matubi et al., 2022; Metelo et al., 2024; PNLP, 2022). This challenge significantly elevates the risk to human lives.

In the DRC, there are over 50 distinct species of *Anopheles* mosquitoes, four of which serve as principal vectors of malaria transmission (*Anopheles gambiae s.s.*, *Anopheles funestus*, *An. arabiensis*, and *An. coluzzii*), while eight are considered secondary vectors (*Anopheles nili*, *An. paludis*, *An. melas*, *An. rivulorum*, *An. leesoni*, *An. confusus*, *An. moucheti*, and *An. coustani*) (PNLP, 2022).

This literature review aims to summarize the current knowledge on the resistance of malaria vectors, particularly mosquitoes of the genus *Anopheles*, to insecticides used for public health in the DRC. It seeks to answer several research questions:

1. What are the mechanisms of resistance in *Anopheles* mosquitoes to insecticides?
2. What is the extent of resistance in the DRC?
3. How does this resistance affect malaria control efforts?

The general aim of this bibliographic study is to analyze the state of *Anopheles* resistance and susceptibility to insecticides in the DRC. Specifically, it seeks to (1) identify the mechanisms of resistance used by *Anopheles* mosquitoes and (2) analyze the implications of this resistance for malaria control programs.

Data on the state of *Anopheles* resistance in the DRC are dispersed and incomplete, with gaps in geographic coverage across the country. This is partly due to inadequate funding, despite the high malaria transmission risk in this endemic nation. This literature review aims to consolidate the current data on *Anopheles* resistance to major insecticides, inform decision-makers in developing new vector control strategies, and identify avenues for future research into alternative malaria control methods.

METHODOLOGY

A bibliographical study was conducted using selected search engines, including Google Scholar, ScienceDirect, PubMed, and Scopus. Keywords such as *Anopheles-resistant DRC*, *insecticide-resistant DRC*, and *Anopheles-susceptible DRC* were used. The search was extended to studies from other countries with keywords such as *molecular target of insecticides*, *modes of action of insecticides*, and *mechanism of insecticide resistance*. References from relevant articles were also examined to identify additional sources of information. Unpublished but relevant data were added to the dataset, including reports from the President's Malaria Initiative (PMI) and house-spraying activities in the Fungurume mining area.

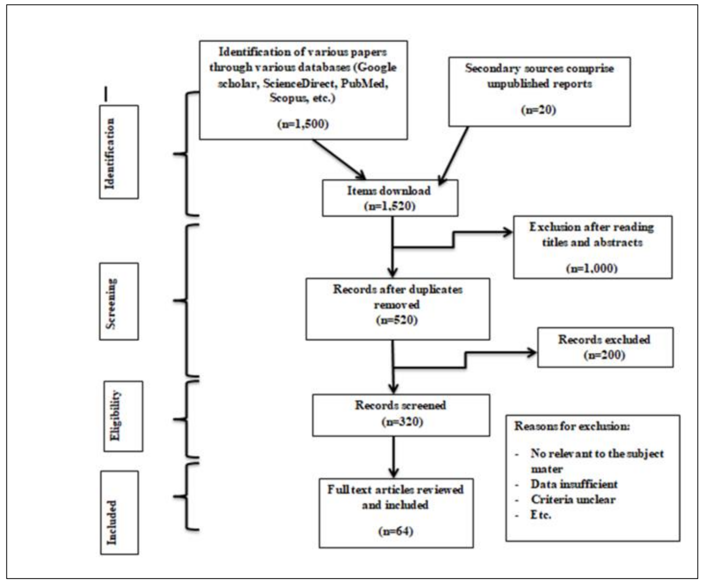
Inclusion Criteria

Items were selected based on the following criteria:

1. **Relevance to the Subject:** Articles needed to address the specific topic of insecticide resistance in *Anopheles* mosquitoes.
2. **Reliability of Sources:** Only articles from reputable, peer-reviewed scientific journals were considered, regardless of language or geographic location.
3. **Recency:** Documents published within the last five years were prioritised.
4. **Robust Methodology:** Studies employing rigorous research and analysis methods with clear, relevant conclusions were favoured (see Figure 1).
5. **Diversity:** A wide range of studies was included to ensure a comprehensive overview of the subject.

A total of 1,500 articles were identified from the databases, with an additional 20 articles sourced from secondary data. After removing 200 duplicates, 1,320 works remained. Following a review of titles and abstracts, 1,000 papers were selected for further consideration. Of these, 320 underwent full-text evaluation, resulting in the exclusion of 256 articles due to insufficient relevance, observational study designs, or inadequate data. Ultimately, 64 articles were included in the meta-analysis (Figure 1).

Figure 1:
PRISMA diagram of documents selection



RESULTS AND DISCUSSION

Numerous scientific articles and documents were retrieved from search engines or provided by partners. After careful sorting, only relevant documents were retained for the writing of this review. Despite the Democratic Republic of Congo (DRC) being an epicenter of the global malaria pandemic, literature on cases of *Anopheles* resistance remains sparse.

This study utilized data from both scientific publications (primary sources) and unpublished national reports (secondary sources). While national reports contribute valuable insights, they lack the peer-review process undergone by primary sources. Nonetheless, incorporating both types of sources allowed for a more comprehensive overview of the resistance situation.

Research on *Anopheles* resistance has been conducted across significant portions of the DRC, particularly in areas

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with National Malaria Control Programme (NMCP) sentinel sites. For this study, the analysis was restricted to studies meeting the predefined inclusion criteria, including publication dates for primary sources and report dates for secondary sources.

To facilitate understanding, findings have been organised at the regional or provincial level, enhancing clarity and accessibility for readers.

Resistance Levels Across Regions

A. Kinshasa

Table 1:
Resistance Status in Kinshasa

Insecticide Susceptibility/Work	Without PBO	With PBO	Reference
Pyrethroid	Permethrin	Resistance	Resistance
	Deltamethrin	Resistance	Resistance
	Alpha-cypermethrin	Resistance	Resistance
Pyrethroid	Permethrin	Resistance	Resistance
	Deltamethrin	Resistance	95% and 99%
Pyrethroid	Permethrin	Resistance	Resistance
	Deltamethrin	Resistance	Heterogeneous Resistance
	Alpha-cypermethrin	Resistance	Resistance
Pyrroles	Chlorfenapyr	Susceptibility	Susceptibility
Carbamate	Bendiocarb	Susceptibility	Susceptibility
Pyrethroid	Permethrin	Resistance	Resistance
	Deltamethrin	Resistance	Resistance
Organochlorines	DDT	Resistance	Heterogeneous Resistance
Organophosphorus	Malathion	Susceptibility	Susceptibility
Carbamate	Bendiocarb	Susceptibility	Susceptibility
Organophosphorus	Pirimiphos-methyl	Susceptibility	Susceptibility
Pyrethroid	Alpha-cypermethrin	Resistance	Resistance
	Permethrin	Resistance	Resistance
	Deltamethrin	Resistance	Susceptibility

B. Kwilu

Table 2:
Resistance Status in Kwilu

Insecticide Susceptibility/Work	Without PBO	With PBO	Reference
Pyrethroid	Permethrin	Resistance	Resistance
	Deltamethrin	Resistance	Resistance
Carbamate	Bendiocarb	Susceptibility	Susceptibility
Organochlorines	DDT	Resistance	Resistance
Pyrethroid	Permethrin	Resistance	Resistance
	Deltamethrin	Resistance	Heterogeneous Resistance
Carbamate	Bendiocarb	Susceptibility	Susceptibility

C. Sud-kivu and Nord-kivu

Table 3:
Resistance statue in Sud-kivu and Nord-kivu

Insecticide susceptibility/work		Without PBO	With PBO	Reference
Pyrethroid	Permethrin,	Resistance	Resistance	(PMI, 2020)
	Deltamethrin	Resistance	Resistance	
Organophosphorus	Pirimiphos methyl	Susceptibility	Susceptibility	(N'do et al., 2021)
Carbamate	Propoxur	Susceptibility	Susceptibility	
Organophosphorus	Malathion	Susceptibility	Susceptibility	
Carbamate	Fenitrothion	Susceptibility	Susceptibility	
Pyrethroid	Permethrin	Resistance	Resistance	
	Deltamethrin	Resistance	Resistance	
Pyrethroid	Permethrin,	Resistance	Resistance	(Loonen et al., 2020)
	Deltamethrin	Resistance	Resistance	
Organophosphorus	Pirimiphos methyl	Susceptibility	Susceptibility	
Carbamate	Bendiocarb	Susceptibility	Susceptibility	

D. Kongo Central

Table 4:
Resistance statue in Kongo Central

Insecticide susceptibility/work		Without PBO	With PBO	Reference
Pyrethroid	Permethrin,	Resistance	Resistance	(PMI, 2020)
	Deltamethrin	Resistance	Resistance	
	Alpha-cypermethrin	Resistance	Resistance	
	Deltamethrin	Resistance	Heterogene resistance	
Pyrethroid	Permethrin,	Resistance	Resistance	(PMI, 2021)
	Deltamethrin	Resistance	Heterogene resistance	
	Alpha-cypermethrin	Resistance	Resistance	
Pyrroles	Chlorfenapyr	Susceptibility	Susceptibility	(Oxborough et al., 2021)

E. Tanganyika

Table 5:
Resistance statue in Tanganyika

Insecticide susceptibility/work		Without PBO	With PBO	Reference
Pyrethroid	Permethrin,	Resistance	Resistance	(PMI, 2020)
	Deltamethrin	Resistance	Resistance	
	Alpha-cypermethrin	Resistance	Resistance	
	Deltamethrin	Resistance	Resistance	
Pyrethroid	Permethrin,	Resistance	Resistance	(PMI, 2021)
	Deltamethrin	Resistance	Heterogene resistance	
	Alpha-cypermethrin	Resistance	Resistance	
Pyrroles	Chlorfenapyr	Susceptibility	Susceptibility	(Oxborough et al., 2021)

F. Sud-Ubangi

Table 6:
Resistance statue in Sud-Ubangi

Insecticide susceptibility/work		Without PBO	With PBO	Reference
Pyrethroid	Permethrin,	Resistance	Resistance	(PMI, 2021)
	Deltamethrin	Resistance	Heterogene resistance	
	Alpha-cypermethrin	Resistance	Resistance	

G. Mayi-ndombe

Table 7:
Resistance statue in Sud-kivu and Nord-kivu

Insecticide susceptibility/work		Without PBO	With PBO	Reference
Pyrethroid	Permethrin,	Resistance	Resistance	(PMI, 2020)
	Deltamethrin	Resistance	Resistance	
	Alpha-cypermethrin	Resistance	Resistance	
	Deltamethrin	Resistance	Resistance	
Pyrethroid	Permethrin,	Resistance	Resistance	(PMI, 2021)
	Deltamethrin	Resistance	resistance	
	Alpha-cypermethrin	Resistance	Resistance	

H. Lomami

Table 8:
Resistance statue in Sud-kivu and Nord-kivu

Insecticide susceptibility/work		Without PBO	With PBO	Reference
Pyrethroid	Permethrin,	Resistance	Resistance	(PMI, 2021)
	Deltamethrin	Resistance	Resistance	
	Alpha-cypermethrin	Resistance	Resistance	

As demonstrated by the data presented in **Tables 1** through 8, the resistance of *Anopheles* mosquitoes is widespread throughout the Democratic Republic of Congo (DRC). The assessment of mosquito resistance or susceptibility employs a range of techniques, some of which provide insight into the phenotypic state of resistance, while others facilitate a more comprehensive understanding by identifying the genes responsible for resistance.

The first group of methods includes the World Health Organization (WHO) standard test and the Centers for Disease Control and Prevention (CDC) bottle assay, which provide data on mosquito susceptibility or resistance according to specific criteria. These tests yield the following outcomes: a mortality rate of 98–100% indicates sensitivity; 90–97% suggests possible resistance that requires confirmation; and less than 90% indicates resistance. Further, a mortality rate of 98–100% at a 5× concentration (though <90% at a 1× concentration) indicates a low level of resistance. A mortality rate of <98% at a 5× concentration but 98–100% at a 10× concentration indicates a moderate level of resistance. Finally, a mortality rate of <98% at a 10× concentration indicates a high level of resistance (Praulins et al., 2024; WHO, 2022a).

The second group employs molecular techniques to identify mutant genes responsible for resistance in vectors (Althoff & Huijben, 2022; Loonen et al., 2020).

The National Malaria Control Program (NMCP) of the DRC distributes multiple long-lasting insecticidal nets (LLINs) to establish a barrier between vectors and humans, thereby safeguarding public health (Metelo-Matubi et al., 2021). Unfortunately, studies have indicated a decline in the efficacy of LLINs in preventing malaria transmission (Basosila et al., 2022; Matubi et al., 2020; Metelo-Matubi et al., 2022; Narcisse et al., 2024). Mosquitoes have demonstrated a high level of resistance to insecticides used in indoor residual spraying (IRS) and to other classes of insecticides employed in vector control (PMI, 2021).

Resistance Genes Identified

Numerous resistance genes are implicated in the insecticide resistance of the *Anopheles* genus. Among these are knockdown resistance (kdr) mutations in the voltage-gated sodium channel (VGSC), including kdr L1014F/S, V410L, F1508C, N1549Y, and D1763Y, which confer resistance to pyrethroids and dichlorodiphenyltrichloroethane (DDT). The acetylcholinesterase-1 (AChE-1) gene is associated with resistance to organophosphates and carbamates. The *rdl* (resistant to dieldrin) mutation is linked to cyclodienes, a subgroup of organochlorines. Metabolically mediated resistance mutations include the L119F mutation in the glutathione-S-transferase epsilon 2 (*GSTe2*) gene, linked to DDT resistance. Additional studies have identified resistance-associated alleles in cytochrome P450 genes, such as *CYP6P9a* and *CYP6P4*, which are linked to pyrethroid resistance (Mugenzi et al., 2022).

The involvement of these genes in mosquito resistance has been documented extensively in the DRC. For instance, Acford-Palmer et al. (2023) reported nine genes with mutations linked to insecticide resistance (*ace-1*, *CYP6P4*, *CYP6P9a*, *GSTe2*, *vgsc*, and *rdl*) and mosquito speciation (*cox-1*, *mtND5*, and *ITS2*) in *An. funestus* from Sud-Kivu. Furthermore, studies have identified resistance genes such as kdr-East and kdr-West, cytochrome P450, and *ace-1R* in Kinshasa (Nguiffo-Nguete et al., 2023; PMI, 2021; Wat'senga et al., 2020; Zanga et al., 2022). Similar findings have been reported in other regions of the country

(Bandibabone et al., 2021; Matubi et al., 2020; Metelo-Matubi et al., 2021, 2022; N'do et al., 2021).

Implications

The results of this study provide substantial evidence that mosquito populations are increasingly resistant to the primary insecticides used for vector control. These findings underscore the vulnerabilities and limitations of existing malaria control strategies. In light of these observations, it is imperative for authorities to address this evolving threat and develop innovative approaches to complement current strategies.

Nanotechnologies, particularly nanoparticles, present a promising avenue for developing effective malaria vector control methods. However, it is important to note that resistance alleles naturally occur in vector populations at very low frequencies before insecticide treatments, rendering them nearly undetectable. The repeated local use of insecticides can lead to the selection of resistance alleles, which may subsequently spread rapidly across global populations. Additionally, other selection pressures, such as the use of plant protection products containing similar active ingredients or pollutants (e.g., polycyclic aromatic hydrocarbons) from human activities, can influence the dynamics of resistance alleles (Anses, 2021).

Figure 2:
Proportion of different anopheles genes reported in DRC

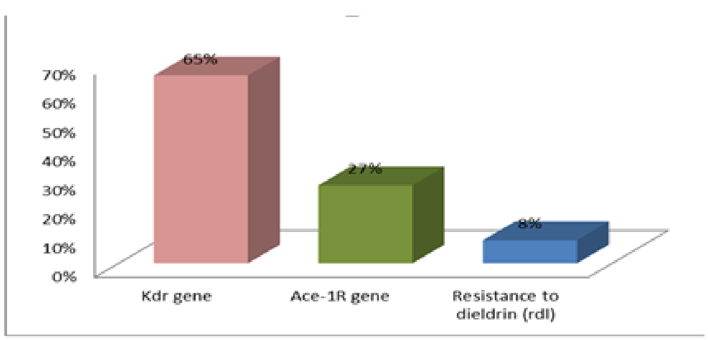


Table 9:
Site target and mechanism of action of the main insecticides

Insecticide families	Site target	Mechanisms of action	Reference
Carbamate	Acetylcholinesterase (AchE) inhibitors	Affects the transmission of nerve signals, leading to the death of the pest by poisoning.	(Siddiqui et al., 2023)
Organochlorines	Acetylcholinesterase (AchE) inhibitor	Inhibition of acetylcholinesterase by preventing the breakdown of acetylcholine molecules at the synapses of insect nerve cells, causing uninterrupted signal transmission, so that insects continue to contract their muscles until death.	(Siddiqui et al., 2023; Trinh et al., 2021)
Organophosphorus	Acetylcholinesterase	Inhibition of acetylcholinesterase at the synapses of insect nerve cells, causing uninterrupted signal transmission until the insects die.	(Siddiqui et al., 2023)
Pyrethroids	Sodium channel modulators (Nav) Pyrethroids	Attacks both the peripheral and central nervous systems, provoking a pronounced convulsive phase that leads to death through depolarization of axons and nerve endings thanks to the insecticidal a-benzyl cyano group and insect sodium channels.	(Siddiqui et al., 2023)
Pyrroles	Mitochondria	Disruption of mitochondrial oxidative phosphorylation leading to impaired adenosine triphosphate synthesis and subsequent death	(Chung et al., 2022)

MECHANISMS OF ACTION AND RESISTANCE IN *Anopheles*

There are five main groups of resistance mechanisms: behavioral resistance, target-site resistance, cutaneous resistance, and metabolic resistance (Siddiqui et al., 2023). Behavioral resistance occurs when modifications in the insect's behavior help it avoid lethal insecticides. These adaptations include changes in feeding or resting behaviors to minimize insecticide exposure.

Target-site resistance arises when the molecular target of an insecticide is altered, reducing binding efficiency and rendering the insecticide ineffective. Mutations such as *kdr* resistance mutations affect acetylcholinesterase (the target for organophosphates and carbamates) or sodium channels targeted by pyrethroids and DDT. These insecticides act on the voltage-gated sodium channel (VGSC) in neuronal membranes (Wipf et al., 2022).

Cutaneous resistance involves modifications to the insect cuticle, which reduce the absorption of insecticides and delay or prevent their penetration.

Metabolic resistance is mediated by enzyme systems such as esterases, monooxygenases, and glutathione Stransferases, which detoxify foreign chemicals. These enzymes degrade insecticides, making metabolic resistance a critical concern. Each insecticide class is detoxified by specific enzymes, emphasizing the complexity of this resistance mechanism.

Understanding these mechanisms is essential for designing effective resistance management strategies and preventing potential outbreaks.

Nanotechnology offers promising solutions in malaria vector control. Nanoparticles synthesized from plants or microorganisms have demonstrated potent ovicidal, larvicidal, and adulticidal activities across mosquito life stages (Baghela & Kachhwaha, 2021; Basosila et al., 2024; Onen et al., 2023; Palanisamy et al., 2023; Sivapunniyam et al., 2024; Wilson et al., 2022). These nanoparticles provide advantages such as reduced toxicity to non-target organisms and minimal environmental impact, positioning them as a sustainable alternative to conventional insecticides.

Table 10:
Mechanisms of insecticide resistance in the two major malaria vectors in the DRC, adapted from PNLP (PNLP, 2022)

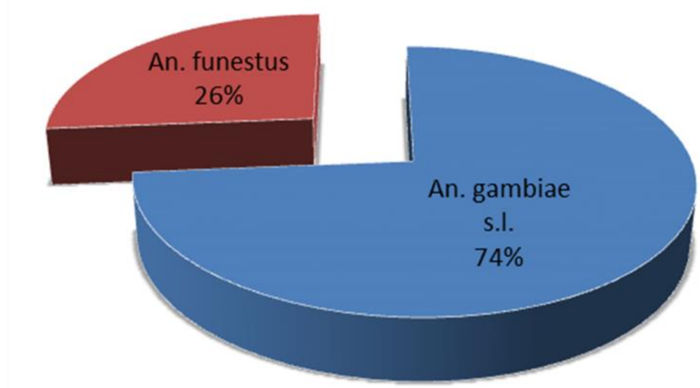
Vectors	Type of insecticides							
	Pyrethroids		DDT		Organophosphorus		Carbamates	
	MC	Met.	MC	Met.	MC	Met.	MC	Met.
An. gambiae s.s.	√	√	√	√	√		√	√
An. funestus			√					√

Legend: MC: Mutation of target; Met.: Metabolic

Table 10 illustrates the two resistance mechanisms of malaria vectors in the Democratic Republic of the Congo (DRC), as outlined in the DRC National Malaria Control Program (PNLP, 2022). It follows that the ability of *Anopheles* mosquitoes to resist insecticides depends largely on target-site mutations and metabolic resistance, which detoxifies insecticides. However, due to limited surveillance data and analytical techniques, these mechanisms cannot be definitively stated as the sole determinants of *Anopheles* resilience to key insecticides in this region.

Sensitivity tests revealing these differential resistance mechanisms were conducted on *An. gambiae* and *An. funestus*, the two most prevalent species in the DRC (Basosila et al., 2022; Narcisse et al., 2024).

Figure 3:
Proportion of ***An. gambiae*** Used in Resistance Studies



An. gambiae remains the most frequently used species for evaluating mosquito resistance to insecticides in the DRC. It is reported that *An. gambiae s.l.* is the most widespread species complex across the region. It is highly anthropophilic, endophagic, and endophilic, making it the most efficient malaria vector in the DRC (Metelo-Matubi et al., 2021; PNLP, 2022). Its widespread presence and efficiency make it highly useful for insecticide susceptibility studies.

Moreover, *An. gambiae* mosquitoes are recognized as the most prevalent malaria vectors in Central Africa, with exceptional capacity for transmitting human malaria. These species also adapt well to both natural and human-made water collections (Sinka et al., 2020).

Figure 4:
Proportion of ***Anopheles*** Resistance to Insecticides (LLINs and IRS)

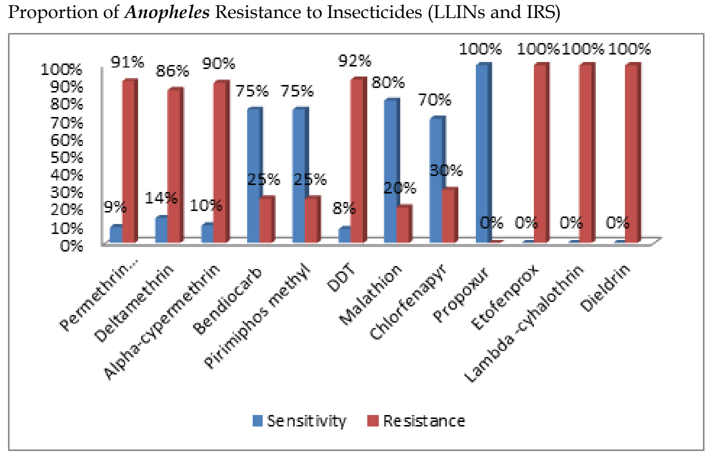


Figure 4 summarizes the resistance status of *Anopheles* mosquitoes to insecticides used in vector control in the DRC. Resistance is widespread, except for a few insecticides such as propoxur, pirimiphos-methyl,

chlorfenapyr, malathion, and bendiocarb, used primarily in indoor residual spraying (IRS) (PNLP, 2022).

As noted, the development of insecticide resistance is influenced by various factors beyond the use of LLINs. Environmental conditions, particularly pollution, significantly contribute to the selection pressure on resistance genes. In the DRC, IRS is practiced mainly by private sector organizations, including mining companies such as Tenke Fungurume Mining Company (TFM), Namoya Mining SARL (BANRO Resources Corporation), Kibali Gold Mining Company, Cimenterie de Kimpese, and the NGO Médecins Sans Frontières (PNLP, 2022).

INSECTICIDES RECOMMENDED FOR AGRICULTURAL USE IN THE DRC

The DRC Ministry of Agriculture has approved certain insecticides for controlling crop pests, many of which belong to the pyrethroid family (PNLP, 2022). These insecticides are also used in public health to control malaria vectors. However, their intensive agricultural application, often at sublethal doses, is thought to contribute to the growing resistance of malaria vectors and other vector-borne disease vectors to insecticides (PNLP, 2022).

Table 11:
List of insecticides used in agriculture in the DRC (source: PNLP, 2022)

Commercial brand	Active ingredient
ACHA 25 EC	Acetamiprid 10g/l +Lambanda-cyhalothrin 25g/l
BLINDE 25EC	Acetamiprid 10g/l +Lambanda-cyhalothrin 15g/l
DELTA 25 EC	Deltamethrin 25g/l
CYPERMETHRIN 50 EC	Cypermethrin 50g/l
DELTAL 25 EC	Deltamethrin 25g/l
VERSO 480 EC	Chlorpyriphos-ethyl 480g/l
TONYSHENZEN 10 EC	Bifenthrin 10g/l
CYGA 50 EC	Cypermethrin 50g/l
ZALANG 50 EC	Lambanda-cyhalothrin 50g/l
TAMEGA 25 EC	Deltamethrin 25g/l
PYRIGA 480 EC	Chlorpyriphos-ethyl 480g/l
PACHA 25 EC	Lambanda-cyhalothrin 15g/l + Acetamiprid 10g/l
PROTEC DP 1.6 EC	Deltamethrin 1g/l + Pyrimiphos 15g/kg
ACTEGO 20 EC	Pyrimiphos-methyl 200g/L
PYRIFORCE	Chlorpyriphos-methyl 480g/l
FORCE GOLD	D-trans-tetrametrin 30g/l+ Cypermethrin 100g/l
CYPERBIO 100 EW	Cypermethrin 100g/l
CYPERCAL 50 EC	Cypermethrin 50g/l

The use of insecticides in the agricultural sector has a significant impact on the selection pressure of resistance genes (Sonhafouo-Chiana et al., 2022; Wipf et al., 2022). Research suggests that additional environmental factors, such as the application of insecticides/pesticides in agriculture, the presence of natural or anthropogenic xenobiotics, and interactions between vectors and other organisms, influence mosquito responses to pyrethroids and the selection of resistance mechanisms (Sadia et al., 2024). Moreover, agricultural practices have been directly linked to insecticide resistance profiles in *Anopheles gambiae* s.l. Studies in Côte d'Ivoire, for instance, reveal that the use of pesticides for crop protection contributes significantly to resistance in malaria vectors (Kouadio et al., 2023).

The predominance of agriculture in the Democratic Republic of the Congo (DRC), where over 70% of the population resides in rural areas, underscores the extensive use of phytosanitary products, often without regulation (Karume et al., 2022). This intensifies the selection pressure on resistance genes. These findings emphasise the need for integrated resistance management strategies that account for agricultural practices.

CHALLENGES AND RECOMMENDATIONS

Studies on *Anopheles* susceptibility to insecticides reveal a widespread resistance to commonly used insecticides for vector control across almost all provinces of the DRC. This highlights the necessity of introducing innovative control strategies to preserve the effectiveness of current interventions. Monitoring mosquito susceptibility through bioassays and genomic analysis is critical for designing resistance management strategies (Wipf et al., 2022). One promising strategy involves the rotation of insecticides with distinct modes of action to delay resistance development (Yamamura, 2021). However, the implementation of such strategies faces significant financial hurdles.

Nanoparticle-based approaches to vector control, which have shown preliminary success in targeting *Anopheles* larvae in Kinshasa, present an innovative alternative. Future research should focus on verifying the non-toxicity of nanoparticles in aquatic organisms and assessing their impact on adult mosquitoes (Basosila et al., 2023; Prakash et al., 2022).

CONCLUSION

The bibliographic review underscores the critical challenge posed by *Anopheles* resistance to insecticides in the DRC. With widespread resistance threatening the effectiveness of vector control strategies, innovative alternatives, such as nanoparticle-based interventions, are imperative. Decision-makers must prioritise sustainable approaches that integrate advanced methodologies to combat malaria vectors effectively.

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