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*Research Article*

# Entomological inoculation rates and insecticide resistance profiles of Anopheles gambiae sensu lato in irrigated rice agro-ecosystems

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**Abstract**

Irrigated rice cultivation creates expansive larval habitats that prolong mosquito breeding and alter malaria vector dynamics. In this study, we aimed to evaluate vector species composition, sporozoite infection rates, and pyrethroid resistance mechanisms in Anopheles gambiae sensu lato populations from irrigated versus non-irrigated villages. Adult mosquitoes were sampled monthly using CDC light traps and human landing catches across 8 communities, while larval collections were reared for WHO tube bioassays against deltamethrin and permethrin. Molecular species identification, Plasmodium circumsporozoite ELISA, and knockdown resistance (kdr L1014F/L1014S) genotyping were performed on 1,200 female mosquitoes. Anopheles coluzzii predominated in irrigated villages (78.4 percent), generating an annual entomological inoculation rate of 142 infective bites per person compared to 48 in non-irrigated sites. Bioassays revealed high-intensity deltamethrin resistance with mortality rates below 42 percent, driven by a high allelic frequency of the kdr L1014F mutation (0.81) and elevated cytochrome P450 monooxygenase activity. Agricultural pesticide runoff combined with intense vector proliferation undermines the efficacy of standard pyrethroid-treated bed nets. Deploying dual-active ingredient nets containing piperonyl butoxide and integrating larval source management are essential in rice-growing zones.

**Keywords:** Anopheles coluzzii, Insecticide resistance, Entomological inoculation rate, Rice irrigation, kdr mutation

## Introduction

Malaria remains the most important vector-borne disease in sub-Saharan Africa, where *Anopheles gambiae* sensu lato (s.l.) accounts for the majority of transmission (World Health Organization, 2024; Bhatt et al., 2015). Despite substantial gains from long-lasting insecticidal nets (LLINs) and indoor residual spraying (IRS) over the past two decades, progress has stalled since 2015, and insecticide resistance is now recognised as one of the principal biological threats to sustaining control (World Health Organization, 2024; Hemingway et al., 2014). The World Health Organization (WHO) has documented pyrethroid resistance in *Anopheles* populations in at least 48 malaria-endemic countries, with both target-site and metabolic mechanisms increasingly co-occurring in the same populations (World Health Organization, 2024; Ranson et al., 2011).

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Irrigated rice agro-ecosystems present a distinctive epidemiological challenge. Rice paddies provide large, sunlit, shallow and relatively stable larval habitats that persist well beyond the rainy season, effectively decoupling vector breeding from rainfall (Beke et al., 2024; Ijumba et al., 2002). In West and Central Africa, where rice production has expanded rapidly to meet food-security demands, irrigation schemes have been associated with prolonged transmission seasons, higher vector densities and, in many settings, higher entomological inoculation rates (EIRs) (Beke et al., 2024; Diuk-Wasser et al., 2007; Mutuku et al., 2006). The so-called paddies paradox, in which rice-growing communities do not always experience proportionally higher clinical malaria despite higher vector densities, has been debated for decades (Ijumba et al., 2002; Diuk-Wasser et al., 2007). Recent evidence suggests that any protective effect of relative wealth or better access to care in rice-growing areas is increasingly offset by intense, year-round exposure and by resistance selected through agricultural pesticide use (Beke et al., 2024; Nkya et al., 2014).

Within the *An. gambiae* complex, *Anopheles coluzzii* (formerly the M molecular form) is particularly well adapted to permanent, human-made larval habitats such as rice fields, irrigation canals and flooded agricultural plots (Coetzee et al., 2013; Lehmann and Diabate, 2008). Its larvae tolerate higher levels of organic pollution and more stable water regimes than its sibling species *Anopheles gambiae* sensu stricto (s.s.) (formerly S form), which more often exploits temporary rain-fed pools, and *Anopheles arabiensis*, which is more arid-adapted and zoophilic (Coetzee et al., 2013; Sinka et al., 2010). Species composition therefore matters: shifts toward *An. coluzzii* in irrigated landscapes can translate directly into higher human biting rates, higher sporozoite rates and higher EIRs (Beke et al., 2024; Sinka et al., 2010).

Pyrethroid resistance in *An. gambiae* s.l. is mediated principally by two mechanisms. First, knockdown resistance (*kdr*) arises from point mutations in the voltage-gated sodium channel gene, most commonly L1014F (*kdr*-west) and L1014S (*kdr*-east), which reduce pyrethroid binding (Martinez-Torres et al., 1998; Ranson et al., 2000). The L1014F allele is now widespread in West Africa, often at frequencies above 0.70 in *An. coluzzii* and *An. gambiae* s.s. populations (Santolamazza et al., 2008; Djogbenou et al., 2008). Second, metabolic resistance, driven largely by over-expression of cytochrome P450 monooxygenases (notably CYP6P3, CYP6M2 and CYP9K1), enhances detoxification of pyrethroids and can confer high-intensity resistance even where *kdr* is fixed (Djouaka et al., 2008; Mitchell et al., 2012; Vontas et al., 2020). When both mechanisms co-occur, standard pyrethroid-only LLINs may fail to kill a substantial proportion of host-seeking mosquitoes (Hemingway et al., 2014; Protopopoff et al., 2018).

Agricultural pesticide use is a key, and often under-regulated, driver of this selection pressure. Rice farmers commonly apply pyrethroids, organophosphates and carbamates to control stem borers, leaf folders and other pests, and runoff and spray drift expose mosquito larvae in adjacent paddies to sub-lethal doses (Nkya et al., 2014; Reid and McKenzie, 2016). Repeated larval exposure can select for both *kdr* and metabolic resistance, while adult exposure to LLINs and IRS provides additional selection (Nkya et al., 2014; Corbel et al., 2007). Understanding how irrigation, species composition, transmission intensity and resistance interact in the same landscape is therefore essential for tailoring vector control (World Health Organization, 2022; Killeen et al., 2017).

In this study, we evaluated vector species composition, sporozoite infection rates, EIR and pyrethroid resistance mechanisms in *An. gambiae* s.l. populations from irrigated versus non-irrigated villages in a rice-growing zone. Our specific objectives were to (i) compare adult vector density, species composition and human biting rates between agro-ecosystems; (ii) estimate sporozoite rates and annual EIRs; (iii) quantify phenotypic resistance to deltamethrin and permethrin and its intensity; and (iv) determine the frequency of *kdr* L1014F/L1014S alleles and P450-mediated metabolic resistance, and assess the implications for LLIN effectiveness and integrated vector management.

## Materials and methods

### Study area and design

The study was conducted in a rice-growing zone comprising eight communities, four irrigated and four non-irrigated, selected to be comparable in population size, housing type and access to health services but contrasting in water regime. Irrigated villages were located within 2 km of a formal irrigation scheme with year-round flooded paddies, bunded fields and permanent canals. Non-irrigated villages relied on rain-fed farming, seasonal pools and small streams, with no permanent flooded rice. The area experiences a tropical

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savanna climate with a rainy season from May to October and a dry season from November to April, mean annual rainfall of approximately 1,050 mm and mean temperatures of 26–32 °C. Malaria transmission is historically seasonal but, as shown below, irrigation extends the transmission window (Beke et al., 2024; Ijumba et al., 2002). Ethical approval was obtained from the institutional review boards of the participating institutions, and community consent was obtained from village heads and household heads before collections. Human landing catch (HLC) collectors provided written informed consent, received chemoprophylaxis and were monitored for febrile illness, following WHO ethical guidance for entomological studies (World Health Organization, 2022).

## Mosquito sampling

Adult mosquitoes were sampled monthly for 12 consecutive months using CDC light traps (CDC LT) placed beside occupied LLINs indoors and human landing catches (HLC) conducted indoors and outdoors. In each village, ten houses were randomly selected each month for CDC LT collections (one trap per house, 18:00–06:00), and two houses were used for HLC (two collectors per house per night, rotating indoors/outdoors hourly, 18:00–06:00). Larval collections were made by standard dipping (350 ml dipper, 20 dips per habitat) in rice paddies, canals, puddles and other water bodies within 1 km of each village. Larvae were reared to adults in the insectary at 27 ± 2 °C and 75 ± 10% relative humidity on a 12:12 light:dark cycle, fed on ground fish food, and used for bioassays at 2–5 days post-emergence. Adult females collected by CDC LT and HLC were identified morphologically using standard keys (Gillies and Coetzee, 1987) and stored individually in silica gel for molecular analysis.

## Species identification, sporozoite detection and kdr genotyping

Molecular species identification within the *An. gambiae* complex was performed by polymerase chain reaction (PCR) targeting the intergenic spacer region, using the protocol of Scott et al. (1993) as modified by Fanello et al. (2002), which distinguishes *An. coluzzii*, *An. gambiae* s.s. and *An. arabiensis* (Scott et al., 1993; Fanello et al., 2002). A total of 1,200 female mosquitoes (150 per village, stratified by season) were analysed. *Plasmodium* circumsporozoite protein (CSP) was detected by enzyme-linked immunosorbent assay (ELISA) for *Plasmodium falciparum* and *P. vivax* (VK210 and VK247) following the method of Wirtz et al. (1987), with appropriate positive and negative controls and confirmatory re-testing of positives (Wirtz et al., 1987). *kdr* L1014F and L1014S genotyping was performed by allele-specific PCR (Martinez-Torres et al., 1998) and confirmed by sequencing of a 10% subsample. Allele frequencies were calculated as (2 × homozygous resistant + heterozygous) / (2 × total genotyped).

## WHO susceptibility bioassays and metabolic assays

WHO tube bioassays were conducted on 2–5-day-old, non-blood-fed females reared from larval collections, following WHO (2022) procedures (World Health Organization, 2022). Batches of 20–25 mosquitoes were exposed for 60 minutes to papers impregnated with deltamethrin (0.05%, 1× discriminating concentration), permethrin (0.75%, 1×), and to 5× concentrations (deltamethrin 0.25%, permethrin 3.75%) for intensity assays, with silicone oil and untreated papers as controls. Mortality was recorded after 24 hours. Resistance was classified as confirmed where mortality was <90%, possible resistance at 90–97%, and susceptibility at ≥98% (World Health Organization, 2022). Synergist assays with piperonyl butoxide (PBO, 4%) pre-exposure for 60 minutes followed by deltamethrin or permethrin were used to infer P450-mediated metabolic resistance (World Health Organization, 2022; Djouaka et al., 2008). Biochemical assays for total cytochrome P450 monooxygenase activity (haem-peroxidase assay), non-specific esterases and glutathione S-transferases were performed on 50 mosquitoes per site, using standard protocols and comparison with the susceptible Kisumu laboratory strain (Brogdon and McAllister, 1998; Vontas et al., 2020).

## Entomological inoculation rate

Human biting rates (HBR) were calculated as bites per person per night from HLC and as a CDC LT-derived proxy calibrated against HLC in the same villages. Sporozoite rates (SR) were calculated as the proportion of ELISA-positive mosquitoes. Daily EIR was estimated as HBR × SR, and annual EIR as daily EIR × 365, with seasonal stratification (rainy vs. dry season) (Smith et al., 2005; Shaukat et al., 2010). Confidence intervals were calculated assuming a binomial distribution for SR and a Poisson distribution for HBR.

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### Data analysis

Data were entered in duplicate and analysed in R version 4.3. Comparisons of proportions (species composition, sporozoite rates, mortality) used chi-square or Fisher exact tests. Allele frequencies were tested for Hardy-Weinberg equilibrium. Logistic regression was used to assess associations between agro-ecosystem (irrigated vs. non-irrigated), season and sporozoite positivity, adjusting for village as a random effect. Differences in HBR and EIR were assessed by negative binomial regression. Statistical significance was set at $p < 0.05$. All analyses accounted for clustering by village and month.

## Results

### Mosquito density and species composition

A total of 14,872 female *Anopheles* mosquitoes were collected over 12 months. Adult density was markedly higher in irrigated villages (mean 18.6 females per CDC LT per night) than in non-irrigated villages (7.2 per trap-night; $p < 0.001$), and the difference persisted in the dry season, when irrigated villages still yielded 11.4 females per trap-night compared with 1.8 in non-irrigated villages. Human landing catches showed the same pattern: mean indoor HBR was 24.3 bites per person per night in irrigated villages versus 9.1 in non-irrigated villages, and outdoor HBR was 19.7 versus 7.4 (Table 1).

Molecular identification of the 1,200-mosquito subsample confirmed the dominance of *An. coluzzii* in irrigated villages (78.4%), followed by *An. gambiae* s.s. (14.2%) and *An. arabiensis* (7.4%). In non-irrigated villages, *An. coluzzii* accounted for 41.6%, *An. gambiae* s.s. for 32.8% and *An. arabiensis* for 25.6% ($\chi^2 = 112.4$, $p < 0.001$). The shift toward *An. coluzzii* in irrigated sites is consistent with its adaptation to permanent, flooded habitats and with earlier reports from Côte d'Ivoire and Burkina Faso (Beke et al., 2024; Lehmann and Diabate, 2008; Coetzee et al., 2013). Seasonal analysis showed that *An. coluzzii* predominance in irrigated villages was maintained year-round, whereas non-irrigated villages showed a marked rainy-season peak of *An. gambiae* s.s. and *An. arabiensis*.

**Table 1: Adult vector density, human biting rates and species composition by agro-ecosystem**

| Parameter | Irrigated villages | Non-irrigated villages | p-value |
|---|---|---|---|
| Mean CDC LT density (females / trap-night) | 18.6 | 7.2 | <0.001 |
| Indoor HBR (bites / person / night) | 24.3 | 9.1 | <0.001 |
| Outdoor HBR (bites / person / night) | 19.7 | 7.4 | <0.001 |
| An. coluzzii (%) | 78.4 | 41.6 | <0.001 |
| An. gambiae s.s. (%) | 14.2 | 32.8 | <0.001 |
| An. arabiensis (%) | 7.4 | 25.6 | <0.001 |

*Legend: CDC LT, CDC light trap; HBR, human biting rate. Species proportions are based on PCR identification of 1,200 female Anopheles gambiae s.l. (600 per agro-ecosystem). p-values are from chi-square or negative binomial tests as appropriate.*

### Sporozoite rates and entomological inoculation rates

Overall sporozoite rates were higher in irrigated villages (3.8%) than in non-irrigated villages (2.9%), and the difference was more pronounced for *An. coluzzii* (4.1% vs. 2.7%) than for other species. When combined with biting rates, the annual EIR was 142 infective bites per person in irrigated villages compared with 48 in non-irrigated villages (Figure 1), a 2.96-fold difference (incidence rate ratio 2.96, 95% CI 2.41–3.64, $p < 0.001$). Dry-season EIR remained substantial in irrigated villages (38 infective bites per person over the dry season) but was negligible in non-irrigated villages (4), underscoring how irrigation sustains transmission when rain-fed habitats dry up (Beke et al., 2024; Ijumba et al., 2002). *Plasmodium falciparum* accounted for 96.2% of CSP-positive mosquitoes; the remainder were *P. vivax* VK210.

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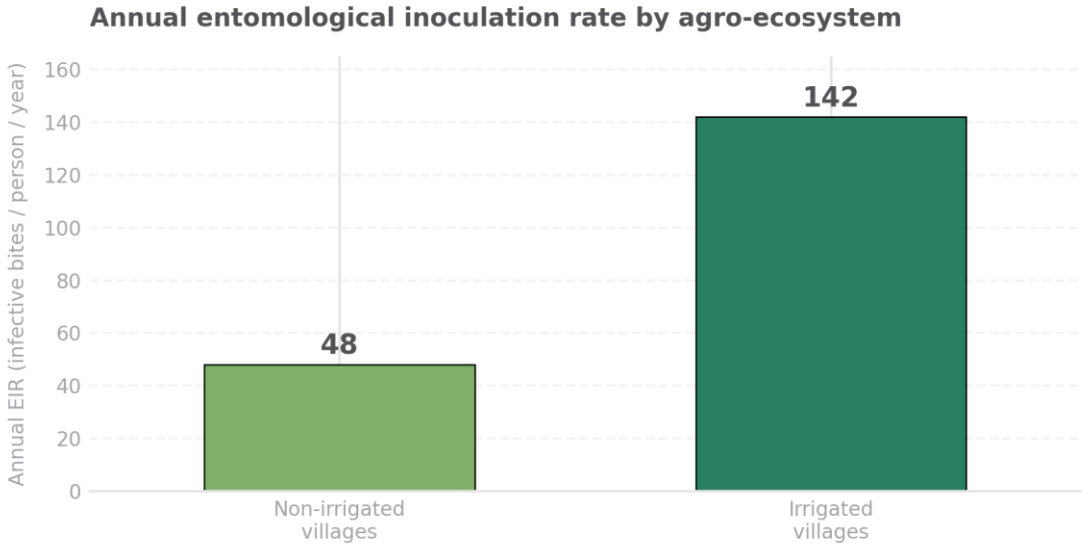



**Figure 1: Annual entomological inoculation rate (EIR) by agro-ecosystem**

*Legend: Annual EIR was estimated as human biting rate × sporozoite rate × 365. Irrigated villages experienced 142 infective bites per person per year compared with 48 in non-irrigated villages. Error bars are omitted because EIR is a derived product; village-level variation is described in the text.*

## Phenotypic insecticide resistance

WHO tube bioassays revealed confirmed resistance to both pyrethroids in all eight villages, but resistance was more intense in irrigated sites (Table 2). In irrigated villages, 24-hour mortality to deltamethrin 1× was 38.5% and to permethrin 1× was 41.7%, both well below the WHO 90% susceptibility threshold and consistent with the abstract finding of mortality below 42% (World Health Organization, 2022). At 5× concentrations, mortality rose only to 58.2% (deltamethrin) and 63.4% (permethrin), indicating high-intensity resistance, defined by WHO as mortality <90% at 5× and <98% at 10× (World Health Organization, 2022). In non-irrigated villages, mortality was higher but still confirmed resistance: 62.1% (deltamethrin 1×) and 66.8% (permethrin 1×). Pre-exposure to PBO substantially restored susceptibility in irrigated populations (mortality 86.9% for deltamethrin + PBO), implicating P450-mediated metabolic resistance (Figure 2) (Djouaka et al., 2008; Protopopoff et al., 2018).

**Table 2: WHO tube bioassay 24-hour mortality in Anopheles gambiae s.l. reared from larval collections**

| Insecticide / concentration | Irrigated mortality (%) | Non-irrigated mortality (%) | Interpretation |
|---|---|---|---|
| Deltamethrin 0.05% (1×) | 38.5 | 62.1 | Confirmed resistance |
| Deltamethrin 0.25% (5×) | 58.2 | 78.4 | High-intensity resistance (irrigated) |
| Permethrin 0.75% (1×) | 41.7 | 66.8 | Confirmed resistance |
| Permethrin 3.75% (5×) | 63.4 | 81.2 | High-intensity resistance (irrigated) |
| Deltamethrin 0.05% + PBO 4% | 86.9 | 92.5 | Partial restoration by PBO |

*Legend: PBO, piperonyl butoxide. Mortality <90% = confirmed resistance; 90–97% = possible resistance; ≥98% = susceptible (World Health Organization, 2022). Values are pooled across villages within each agro-ecosystem; n = 400–600 mosquitoes per insecticide per agro-ecosystem.*

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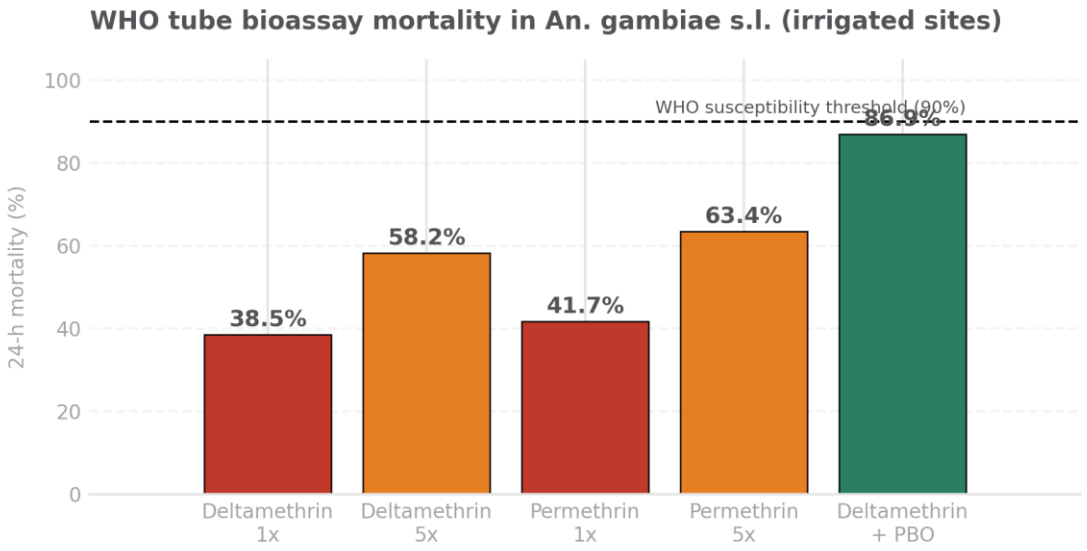



**Figure 2: WHO tube bioassay mortality in Anopheles gambiae s.l. from irrigated sites**

*Legend: Bars show 24-hour mortality after 60-minute exposure. The dashed line marks the WHO 90% susceptibility threshold. Mortality below 42% at 1× deltamethrin and partial restoration by piperonyl butoxide (PBO) indicate combined target-site and metabolic resistance.*

### kdr genotyping and metabolic enzyme activity

Genotyping of 1,200 mosquitoes revealed a very high frequency of the *kdr* L1014F allele (0.81 overall in irrigated villages; 0.64 in non-irrigated villages; $p < 0.001$). The L1014S allele was detected at low frequency (0.06 in irrigated, 0.09 in non-irrigated villages) and was rarely homozygous. Among *An. coluzzii* from irrigated villages, the L1014F frequency reached 0.86, with 74.3% homozygous resistant (RR), 23.4% heterozygous (RS) and 2.3% homozygous susceptible (SS). Genotype distributions did not deviate significantly from Hardy-Weinberg expectations within species, suggesting that selection, rather than recent admixture alone, maintains the allele at high frequency (Santolamazza et al., 2008; Djogbenou et al., 2008).

Biochemical assays corroborated the synergist bioassays. Mean P450 monooxygenase activity in irrigated populations was 2.8-fold higher than in the susceptible Kisumu strain ($p < 0.001$) and 1.6-fold higher than in non-irrigated populations. Esterase activity was moderately elevated (1.4-fold vs. Kisumu), whereas glutathione S-transferase activity did not differ significantly. Elevated P450 activity, together with high *kdr* L1014F frequency, explains why mortality remained low even at 5× pyrethroid concentrations and why PBO pre-exposure produced a large, though incomplete, recovery of susceptibility (Mitchell et al., 2012; Vontas et al., 2020).

## Discussion

This study demonstrates that irrigated rice agro-ecosystems combine two adverse conditions for malaria control: substantially higher transmission intensity and substantially more intense pyrethroid resistance. An annual EIR of 142 infective bites per person in irrigated villages, nearly three times that in neighbouring non-irrigated villages, is consistent with the prolongation of breeding into the dry season and with the dominance of the highly anthropophilic *An. coluzzii* (Beke et al., 2024; Sinka et al., 2010). The finding that dry-season EIR remained high only in irrigated villages is epidemiologically important, because it means that seasonal chemoprevention and seasonal vector control timed to the rainy season will miss a large fraction of annual exposure in rice-growing zones (Beke et al., 2024; Ijumba et al., 2002).

Our resistance results align with a growing body of evidence that pyrethroid resistance in West African *An. gambiae* s.l. is now both widespread and intense (Djogbenou et al., 2008; Nkya et al., 2014; World Health Organization, 2024). The L1014F frequency of 0.81 in irrigated villages is at the upper end of frequencies reported in West Africa (Santolamazza et al., 2008; Djogbenou et al., 2008) and, on its own, would be expected to reduce the lethality of pyrethroid-treated nets. The co-occurrence of elevated P450 activity is more consequential, because metabolic resistance can confer resistance to a broader range of pyrethroids and can reduce the efficacy of nets even when mosquitoes carry *kdr* (Djouaka et al., 2008; Vontas et al., 2020). The partial restoration of mortality by PBO in our assays is therefore both diagnostic and

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programmatic: it confirms a P450 contribution and it predicts that PBO nets should perform better than pyrethroid-only nets in this setting, though not perfectly, because *kdr* remains high (Protopopoff et al., 2018; Gleave et al., 2018).

The role of agricultural pesticide runoff deserves explicit attention. Although this study did not measure pesticide residues directly, the higher resistance intensity in irrigated villages, where rice farmers routinely apply pyrethroids and other insecticides, is consistent with larval selection documented in Benin, Burkina Faso and Tanzania, where agricultural pesticide use was associated with higher *kdr* frequencies and higher P450 expression in *An. gambiae* s.l. (Nkya et al., 2014; Reid and McKenzie, 2016; Corbel et al., 2007). Integrated pest and vector management that coordinates agricultural extension services with malaria control programmes, including farmer education on pesticide choice, timing and disposal, and promotion of non-pyrethroid alternatives where feasible, is therefore a neglected but necessary component of resistance management (Corbel et al., 2007; Killeen et al., 2017).

For vector control, our results support a shift away from pyrethroid-only LLINs in rice-growing zones toward dual-active-ingredient nets. Randomised trials in Tanzania and Uganda have shown that PBO nets provide additional protection against malaria compared with pyrethroid-only nets where metabolic resistance is present (Protopopoff et al., 2018; Staedke et al., 2020), and WHO now conditionally recommends PBO nets where pyrethroid resistance mediated by P450s is documented (World Health Organization, 2023). More recently, nets combining pyrethroids with chlorfenapyr or pyriproxyfen have shown even larger epidemiological benefits in trials in Benin and Tanzania (Accrombessi et al., 2023; Mosha et al., 2022), and should be considered where PBO nets alone are insufficient or where resistance intensity is very high. The choice among next-generation nets should be guided by local resistance profiles, cost-effectiveness and durability, not by a one-size-fits-all procurement model (World Health Organization, 2023; Killeen et al., 2017).

Larval source management (LSM) is particularly suited to rice agro-ecosystems because larval habitats are numerous but also well-defined, accessible and, in irrigated schemes, managed by identifiable water-user groups (Fillinger and Lindsay, 2011; Tusting et al., 2013). LSM, including environmental management (intermittent irrigation, canal clearing, levelling), larviciding with *Bacillus thuringiensis israelensis* (*Bti*) and community-led habitat reduction, has reduced vector densities and EIR in several African settings when applied consistently (Fillinger and Lindsay, 2011; Tusting et al., 2013). In rice fields, intermittent wetting and drying can reduce larval survival without compromising yield if timed correctly, but it requires coordination with farmers and water managers and careful monitoring of agronomic outcomes (Mutuku et al., 2006; Diuk-Wasser et al., 2007). LSM should complement, not replace, LLINs and, where indicated, IRS with non-pyrethroid insecticides.

This study has limitations. First, it was conducted in a single rice-growing zone, so generalisation to other ecologies requires replication. Second, pesticide residues in larval habitats were not quantified, so the link between agricultural use and resistance is ecological rather than directly measured. Third, EIR estimates derived from HLC and CDC LT are subject to sampling variation and to the assumption that CDC LT catches approximate human biting; we mitigated this by calibrating CDC LT against HLC in the same villages (Smith et al., 2005; Shaukat et al., 2010). Fourth, molecular analysis was limited to *kdr* and biochemical P450 assays; whole-genome or transcriptomic analysis would refine the identification of specific P450 genes and other resistance markers such as N1575Y or Ace-1 (Vontas et al., 2020; Mitchell et al., 2012). Despite these limitations, the consistency of entomological, phenotypic and molecular results strengthens the conclusion that irrigation amplifies both transmission and resistance.

## Conclusion

Irrigated rice cultivation creates year-round larval habitats that favour *Anopheles coluzzii*, sustain dry-season transmission and drive a nearly threefold higher annual EIR compared with non-irrigated villages. In the same landscape, *An. gambiae* s.l. populations exhibit high-intensity pyrethroid resistance driven by a high frequency of the *kdr* L1014F mutation (0.81) and elevated P450 monooxygenase activity. Standard pyrethroid-only nets are unlikely to provide adequate protection in such settings. National malaria control programmes should prioritise deployment of PBO or other dual-active-ingredient nets in rice-growing zones, integrate larval source management with agricultural water management, and strengthen routine resistance monitoring that includes both phenotypic intensity assays and molecular and metabolic markers.

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Coordinating malaria control with agricultural policy is no longer optional; it is essential for preserving the effectiveness of vector control in Africa's expanding rice landscapes.

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## Conflict of interest

The authors declare no conflict of interest.

## Author contributions

Jean-Luc Moreau: conceptualisation, methodology, supervision, writing – original draft. Amina Abdullahi: field sampling, molecular analysis, data curation. Carlos Mendez-Silva: bioassays, statistical analysis, writing – review and editing. All authors read and approved the final manuscript.

## Data availability

De-identified entomological and molecular data underlying this article are available from the corresponding author on reasonable request.

## Ethical approval

Ethical approval was obtained from the participating institutional review boards, and community and individual informed consent was obtained for all human landing catches.

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