Malaria Journal

REVIEW

Open Access

# Malaria epidemiology in the Korhogo area, Northern Côte d'Ivoire: baseline assessment prior to a randomized controlled trial

N'cho Bertin Tchiekoi[1,2*], Mahugnon Barnabas Zogo[1,2,3], Ludovic P. Ahoua Alou[1], Anthony Somé[4], Diloma Dieudonné Soma[4], Issa Coulibaly[1], Aboubacar Koné[1], Florence Fournet[2], Paul Taconet[1,4], Amal Dahounto[2,4], Lamine Baba-Moussa[3], Roch K. Dabiré[4], Nicolas Moiroux[2,5], Alphonsine A. Koffi[1†], Cédric Pennetier[1,2,4*†] and Serge Brice Assi[1†]

## Abstract

**Background** Widespread Insecticide resistance among malaria vector populations poses a significant threat to the efficacy of current vector control strategies. This highlights the urgent need for innovative approaches that integrate existing tools with those under development. The primary objective of this study was to characterize the malaria epidemiological profile in the Korhogo region prior to the implementation of complementary vector control tools alongside long-lasting insecticidal nets (LLINs). Both passive and active case detection methods were employed.

**Methods** Passive case detection involved data collection from heath care facilities between July 2016 and July 2017, covering a total of 398,424 person-weeks from 26 villages in the Korhogo health district, northern Côte d'Ivoire. Active case detection was carried out through three cross-sectional surveys (CSS) conducted in September 2016, December 2016 and March 2017. During these surveys, individuals under 21 years of age were invited to attend clinical consultations. Those presenting with fever (> 37,5 °C) were tested for malaria with rapid diagnostic test (RDT), and individuals with a positive result were treated with artemisinin-based combination therapy (ACT). Active case detection during the surveys enabled the estimation of malaria case prevalence, defined as the proportion of population with symptoms and a positive RDT at the time of the survey. Additionally, in a randomly selected sub-sample of six villages, thick blood smears were analysed—regardless of symptoms—to assess the prevalence of malaria infection in the general population during CSS.

**Results** The mean weekly malaria incidence throughout the year in the overall population was 0.25 cases per 100 person-weeks, corresponding to 130 cases per 1000 person-years. During CSS, malaria cases prevalence ranged from 13.4% during the dry season to 43.4% in the late rainy season. The highest malaria cases' prevalence was observed in children under 5 years of age, with significant decline in older age groups. Thick blood smears

†Alphonsine A. Koffi, Cédric Pennetier and Serge Brice Assi have contributed equally to this work.

*Correspondence:
N'cho Bertin Tchiekoi
bertinncho.tchiekoi@ird.fr
Cédric Pennetier
cedric.pennetier@ird.fr
Full list of author information is available at the end of the article

© The Author(s) 2025. **Open Access** This article is licensed under a Creative Commons Attribution-NonCommercial-NoDerivatives 4.0 International License, which permits any non-commercial use, sharing, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if you modified the licensed material. You do not have permission under this licence to share adapted material derived from this article or parts of it. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit http://creativecommons.org/licenses/by-nc-nd/4.0/.

from six villages revealed parasite prevalence between 85.4% and 100%. *Plasmodium falciparum* accounted for 97% of single infection, although mixed infections with *Plasmodium malariae and Plasmodium ovale* were also detected.

**Conclusion** Active case detection conducted through three transversal surveys indicates that the study area exhibits characteristics of malaria transmission hotspot. The region's dense hydrographic network provides a favourable ecological and epidemiological context for assessing additional vector control strategies to supplement universal LLINs coverage in the fight against malaria.

**Keywords** Malaria, Prevalence, Vector control, Korhogo, Côte d'Ivoire

## Background

Despite substantial public health progress achieved between 2000 and 2015 [1], malaria remains the leading cause of morbidity and mortality among children in sub-Saharan Africa. The observed reduction in malaria burden has largely depended on intensified efforts to control malaria vectors, improve diagnostic testing and ensure the availability, accessibility and adherence to antimalarial treatments. In 2017, at the onset of the present study, an estimated 219 million malaria cases and 435,000 malaria-related were reported globally. Africa accounted for 92% of these cases and 93% of deaths [2]. Notably, approximately 80% of global malaria deaths occurred in just only 18 countries, including Côte d'Ivoire [2].

In Côte d'Ivoire, malaria is the leading cause of outpatient consultations in health facilities. In 2017, it accounted for 33% of all medical consultations, with 3,557,891 cases (14 cases per 1000 inhabitants) and 3222 deaths [3]. To combat malaria, the National Malaria Control Programme (NMCP) of Côte d'Ivoire—alongside programmes in other endemic sub-Saharan African countries—has adopted the long-lasting insecticide treated nets (LLINs) as the primary vector control strategy. LLINs primarily target anthropophilic and endophagic mosquitoes, which preferentially bite humans indoors. Since 2012, NMCP has implemented large-scale LLIN distribution campaigns, contributing to a 48% reduction in *Plasmodium* prevalence [1].

Unfortunately, over the last two decades, insecticide resistance mechanisms have rapidly spread across Côte d'Ivoire, mirroring trends observed throughout sub-Saharan Africa [4, 5]. Resistance in malaria vectors is driven by behavioural or physiological mechanisms that reduce or prevent contact between the insecticide and its target site, thereby conferring a selective advantage to mosquitoes carrying such traits. Behavioural resistance enables vectors to avoid insecticide exposure altogether, while physiological resistance involves mechanisms that impair insecticide penetration, enhance its metabolism and excretion, or alter its molecular target. The selective advantages conferred by such mechanisms have led to the rapid spread of pyrethroid resistance among vector populations. Selective pressure is primarily attributed to the widespread use of pyrethroids in agriculture and their extensive deployment in public health interventions such as LLINs and indoor residual spraying (IRS). At present, pyrethroid resistance mechanisms are widespread in nearly all monitored mosquito populations in malaria endemic countries across Sub-Saharan Africa [6], including Côte d'Ivoire [4, 5, 7, 8], posing a serious threat to the effectiveness of current vector control strategies.

Despite a substantial decline in malaria-related morbidity and mortality since 2000, the World Health Organization (WHO) observed a deceleration of this downward trend between 2015 and 2019 [9]. Since 2019, malaria incidence has stagnated or even increased [1], underscoring the urgent need for integrated control strategies that curb the spread of resistance and preserve the efficacy vector control interventions.

To address this issue of insecticide resistance, the WHO recommends the development of complementary vector control strategies targeting malaria vectors that evade LLINs [10]. In this context, a randomized controlled trial (RCT) was conducted in northern Côte d'Ivoire to assess the additional benefit of supplementing universal LLIN coverage with larvicide (LAL), indoor residual spraying (IRS), and an enhanced information, education and communication (IEC) strategy in reducing malaria burden. Prior to village randomization, a one-year entomological and epidemiological monitoring campaign was carried out between 2016 and 2017 to inform the power analysis. Entomological findings were published in Zogo et al. [11]. The present study provides an updated overview of malaria epidemiology in the Korhogo health district, Northern Côte d'Ivoire, prior to the implementation of these complementary interventions.

## Methods

### Study area

The study was conducted in Korhogo health district, located 635 km north of Abidjan. Previous research carried out during the 1990s and 2000s reported malaria transmission rates ranging from 139 to 158 infective bites per person per year, with *Anopheles gambiae* sensu lato (*s.l.*) (84%) and *Anopheles funestus* group (5%) identified as the primary vectors [12, 13]. Between 2003 and 2005,

approximately 80% of individuals screened during cross-sectional surveys were found to be infected, with average parasite densities ranging from 143 to 199 asexual stages of *Plasmodium falciparum* parasites per microlitre of blood [14].

The region experiences a tropical Sudanian-Guinean climate, characterized by two seasons: a rainy season from May to October, with two rainfall peaks typically occurring in June and September, and a dry season from November to April. The dry season is further divided into a cooler period from December to February and a hotter period from March to April. Average annual rainfall ranges between 1200 mm and 1400 mm, while average annual temperatures vary from 21 °C to 35 °C [11, 15].

The Bandama watershed drains the region, along with its tributaries, the Naramou and Solomougou rivers, which typically dry up during the dry season. Despite this, the hydrographic network remains relatively dense due to the high numbers of small water reservoirs constructed to support year-round agricultural activities [15]. The economy of Korhogo district is predominantly based on agriculture, with key crops including cotton, cashew nuts, mangoes, rice, maize, millet, groundnuts and vegetables. Rice is primarily cultivated during the rainy season in flooded lowlands, although it is also grown in irrigated areas near dams during the dry season.

A total of 26 villages were randomly selected from six administrative localities within the Korhogo health district—Napié, Kiémou, Dikodougou, Karakoro, Ballekaha and Siolokaha—based on inclusion criteria related to population size (between 100 and 600 inhabitants), accessibility during the rainy season, and a minimum distance of 2 Kms between villages (Fig. 1). Each locality equipped with at least one primary health care centre.

### Data collection

All data were collected using Android tablets equipped with the Open Data Kit (ODK) platform. A complete census of the 26 selected villages was conducted prior to the implementation of one-year baseline epidemiological surveillance system.

All individuals from 26 villages who sought care at the primary health centres were enrolled in the passive surveillance. Data collected included the patient's village of residence, age, sex, reason of consultation (symptoms), temperature, clinical diagnosis, result of RDT (positive or negative or indetermined) and treatment prescribed. Malaria diagnosis was based on the presence of fever (measured or reported, or any fever-related symptoms within the last 48 h) in combination with a positive RDT result, as applied consistently across all primary health centres.

Three cross-sectional surveys (CSS) were conducted in the 26 selected villages during the year preceding the implementation of vector control interventions in September 2017, which aimed to complement universal coverage with LLINs. The first survey took place from 19 September to 14 October 2016, during the minor rainy season; the second from 23 November to 15 December 2016, at the onset of the cool dry season; and the third from 21 February to 15 March 2017, during the hot dry season.

Parasitological and clinical examinations were performed in the 26 villages. During each survey, villages were visited from one to two days, depending on their size and the availability of the population. Prior to each visit, community health worker (CHW) informed the residents of the upcoming survey. Individuals aged between 6-month and 21-year-old were invited to participate, accompanied by a legal guardian in the case of minors. During each CSS, every individual under 21 years of age who presented to the medical team, along with their guardian, received medical care as outlined below. All these participants—or their legal guardians in the case of minors—were informed about the study procedures and objectives, and were invited to provide written informed consent prior to participation.

Three teams—each composed of a nurse and a laboratory technician trained in standard operating procedures (including data collection, obtaining informed consent, performing rapid diagnostic testing, collected blood samples for thick and thin smears, administrating treatment, and more)—visited the villages under the supervision of a physician.

Each participant underwent a clinical examination, which included measurement of axillary temperature, weight, height, age, sex, mid-upper arm circumference, as well as assessment for symptoms as sweating, chills, headache, nausea or vomiting, diarrhoea.

Fever was defined as an axillary temperature $\geq 37.5$ °C. Participants presenting with fever or reporting a history of fever within the previous 48 h were tested for malaria on-site using a rapid diagnostic test (RDT). The RDT used was the CareStart™ Malaria Pf (HRP2) Ag test, the same as that provided by the Ministry of Health through the NMCP to public health centres. Individuals with a positive RDT result were immediately treated with artemisinin-based combination therapy (ACT), in accordance with NMCP guidelines. Febrile illnesses not attributable to malaria were referred to the nearest health facility for appropriate care.

Finger-prick blood samples were collected from all participants for parasitological examination, including preparation of thick and thin blood smears. All slides were analysed by trained microscopists at Institute Pierre

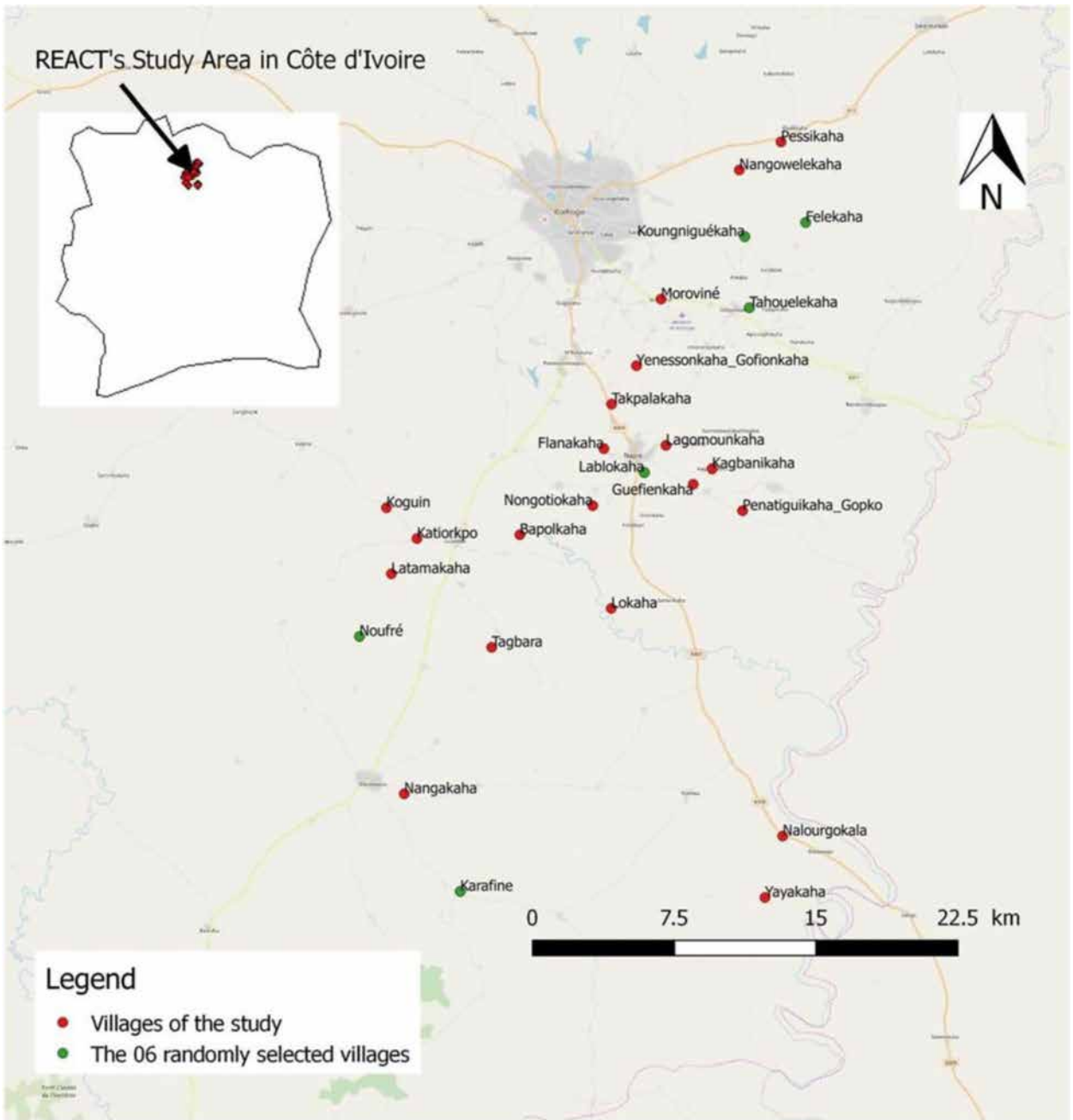


**Fig. 1** Map of the study area. Red dots indicate all villages included in the study, while green dots represent the six villages randomly selected for detailed analysis

Richet (IPR) in Bouaké, Côte d'Ivoire. In the same six randomly selected villages as the entomological baseline study [11], parasite densities were estimated by counting the number of asexual *Plasmodium* parasites observed in 200 high-power microscopic fields on thick smears.

As part of quality assurance, a randomly selected subset representing 10% of all thick smears were re-examined by a senior technician at IPR.

### Statistical analysis

Data were analysed using R statistical software [16].

The incidence rate was modeled using weekly case counts from passive case detection, stratified by age groups (0–5, 5–18, and > 18 years) and sex. A negative-binomial generalized linear model (GLM) was fitted, with the group size included as an offset. To account for temporal and spatial autocorrelation, a first-order

autoregressive (AR1) covariance structure at the health center level and random intercepts for villages were included.

Models for case prevalence and for infection prevalence were fitted using individual-level data from CSS, applying binomial generalized linear regressions. Explanatory variables included age group, sex, LLIN possession, LLIN use, village and survey round. Case prevalence—defined as the proportion of participants presenting with fever or a history of fever within the past 48 h and a positive rapid diagnostic test (RDT) among the total survey participants—was assessed across all 26 study villages, whereas infection prevalence— defined as the proportion of participants with positive blood smears among the total number of individuals enrolled in the cross-sectional surveys—analysis was restricted to the six villages in which blood-smears were examined. Age categories for these models were derived from age quantiles (0–4, 5–8, 9–12, and 13–21 years), following verification of the linearity assumption of the logit transformation of age as a discrete quantitative variable.

## Results

### Socio-demographic characteristics of the study participants

The passive surveillance recorded data from residents of the 26 censused villages (total population 7662) who attended health centres for malaria episode (Table 1). The total follows up amounted to 398,424 persons-weeks. Between August 31, 2016 and August 31, 2017, a total of 1262 people was tested positive for malaria in the health centres.

Across the three CSS, 9199 participants were enrolled in the 26 villages (Table 2). The sex ratio was balanced, with males representing 50.1% of the participants, and no significant difference in sex distribution was observed between the surveys ($p = 0.982$). Significantly more children aged 0–4 and 5–8 years attended CSS—each age group representing 28.6% of the participants—compared to those aged 9–12 and 13–21 years, which each represented 21.4% of the participants ($p < 0.001$).

The proportion of participants reporting ownership of LLINs varied significantly across the three surveys ($p < 0.001$), with the highest ownership rate of 55% observed during the second survey conducted in November–December 2016. Among LLINs owners, the proportion reporting having slept under a net the night before the survey ranged from 44.3% to 69.2%. LLIN use—defined as the proportion of net owners who reported sleeping under a LLIN the previous night—was significantly higher at the end of the rainy season (69.2% during November–December 2016) compared to other survey periods ($p < 0.01$).

**Table 1** Demographic characteristics of the village populations and participants in the passive surveillance survey

| Features | Observation | |
|---|---|---|
| | **Census population (N = 7662)** | **Consult HC* (N = 2346)** |
| Age groups (years) | | |
| 0–5 | 1478 | 929 |
| 5–18 | 2622 | 379 |
| > 18 | 3562 | 799 |
| Sex | | |
| Female | 4127 | 1204 |
| Male | 3535 | 1141 |
| Villages | | |
| BAP | 183 | 35 |
| FEL | 220 | 53 |
| FLA | 233 | 196 |
| GUE | 171 | 54 |
| KAG | 290 | 130 |
| KAR | 443 | 18 |
| KAT | 300 | 83 |
| KOG | 223 | 20 |
| KON | 391 | 146 |
| LAG | 281 | 144 |
| LAT | 319 | 100 |
| LLO | 393 | 253 |
| LOK | 382 | 122 |
| MOR | 248 | 32 |
| NAK | 99 | 4 |
| NAL | 588 | 178 |
| NOT | 298 | 143 |
| NOU | 414 | 20 |
| NOW | 268 | 85 |
| PEN | 257 | 75 |
| PES | 231 | 122 |
| TAG | 320 | 92 |
| TAH | 147 | 11 |
| TAK | 470 | 182 |
| YAY | 189 | 23 |
| YEN | 304 | 25 |

All individuals from 26 villages who sought care at the primary health centres were enrolled in the passive suvey. NB: Missing data (error by omission): 239 for age and 01 for sex

* Consultations at health centres

### Malaria incidence (passive detection)

The mean weekly malaria incidence over the year for the entire population was 0.30 case per 100 person-weeks, equivalent to 156 cases per 1000 person-years. The incidence exhibited a clear seasonal pattern with two peaks: one occurring in early rainy season (July–August) both in 2016 and 2017, and a second peak

**Table 2** Demographic characteristics of participants to the cross-sectional surveys

| | Surveys | | | Total | *p-value* |
|---|---|---|---|---|---|
| | **Sept-Oct. 2016 (Survey 1)** | **Nov-Dec. 2016 (Survey 2)** | **Feb-Mar. 2017 (Survey 3)** | | |
| Sample size | | | | | |
| N | 3052 | 3234 | 2913 | 9199 | |
| Age groups: n (%) | | | | | |
| [0–4] | 901 (29,5) | 885 (27,4) | 842 (28,9) | 2628 (28,6) | < 0.01 |
| [5–8] | 909 (29,8) | 870 (26,9) | 855 (29,4) | 2634 (28,6) | |
| [9–12] | 622 (20,4) | 728 (22,5) | 617 (21,2) | 1967 (21,4) | |
| [13–21 +] | 620 (20,3) | 751 (23,2) | 599 (20,6) | 1970 (21,4) | |
| Sex: n (%) | | | | | |
| Female | 1522 (49,9) | 1622 (50,2) | 1446 (49,6) | 4590 (49,9) | 0.982 |
| Male | 1530 (50,1) | 1612 (49,8) | 1467 (50,4) | 4609 (50,1) | |
| LLINs possession: n (%) | | | | | |
| Yes | 1291 (42,3) | 1773 (54,8) | 1278 (43,9) | 4342 (47,2) | < 0.001 |
| Sleep under LLIN the night before the survey: n (%) | | | | | |
| Yes | 599 (46,4) | 1227 (69,2) | 566 (44,3) | 2392 (55,1) | < 0.001 |

during the late rainy season (November 2016). Among children under five years of age, malaria incidence exceeded 1 case per 100 person-weeks during these peaks (Fig. 2). In contrast, incidence rates remained below 0.5 cases per 100 person-weeks in the 5–18 and > 18-year-old age groups.

The ratio of minimum to maximum village-specific incidence rates ranged from 0.06 to 3.12 relative to the

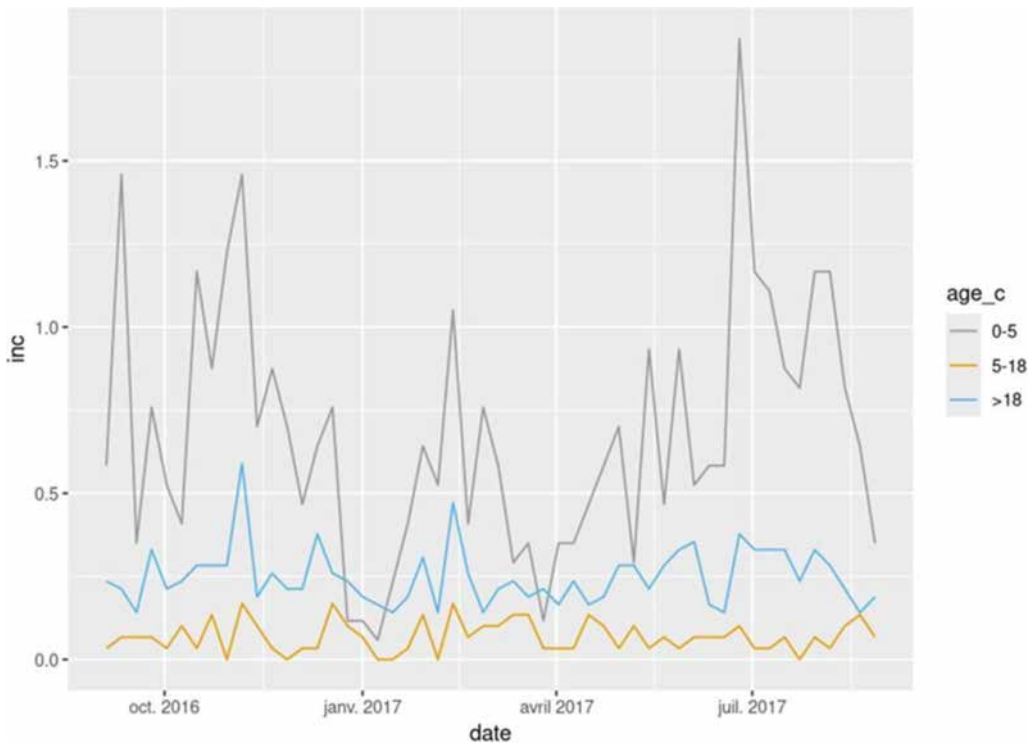


**Fig. 2** Malaria incidence. The curves illustrate the incidence rate dynamics across age groups during the pre-intervention period (August 31, 2016–August 31, 2017). The red line corresponds to children under 5 years, the orange line to individuals aged 5–18 years, and the blue line to those over 18 years

mean incidence (0.30 case per 100 person-weeks), highlighting substantial local scale variability (Fig. 3). Analysis of health centre attendance relative to the mean incidence (0.30 case per 100 person-weeks) revealed that Dikodougou health centre reported a higher number of malaria cases compared to others, whereas Napie health centre reported fewer cases (Fig. 4).

**Malaria burden (active detection)**

The highest malaria cases rates were recorded at the end of the rainy season (November–December 2016) ($p < 0.001$), while no significant differences were observed between the beginning of the rainy season (September–October 2016) and the dry season (February–March 2017) ($p = 0.5$).

Malaria cases rates were highest in the youngest age group (0–4 years old) and declined with increasing age,

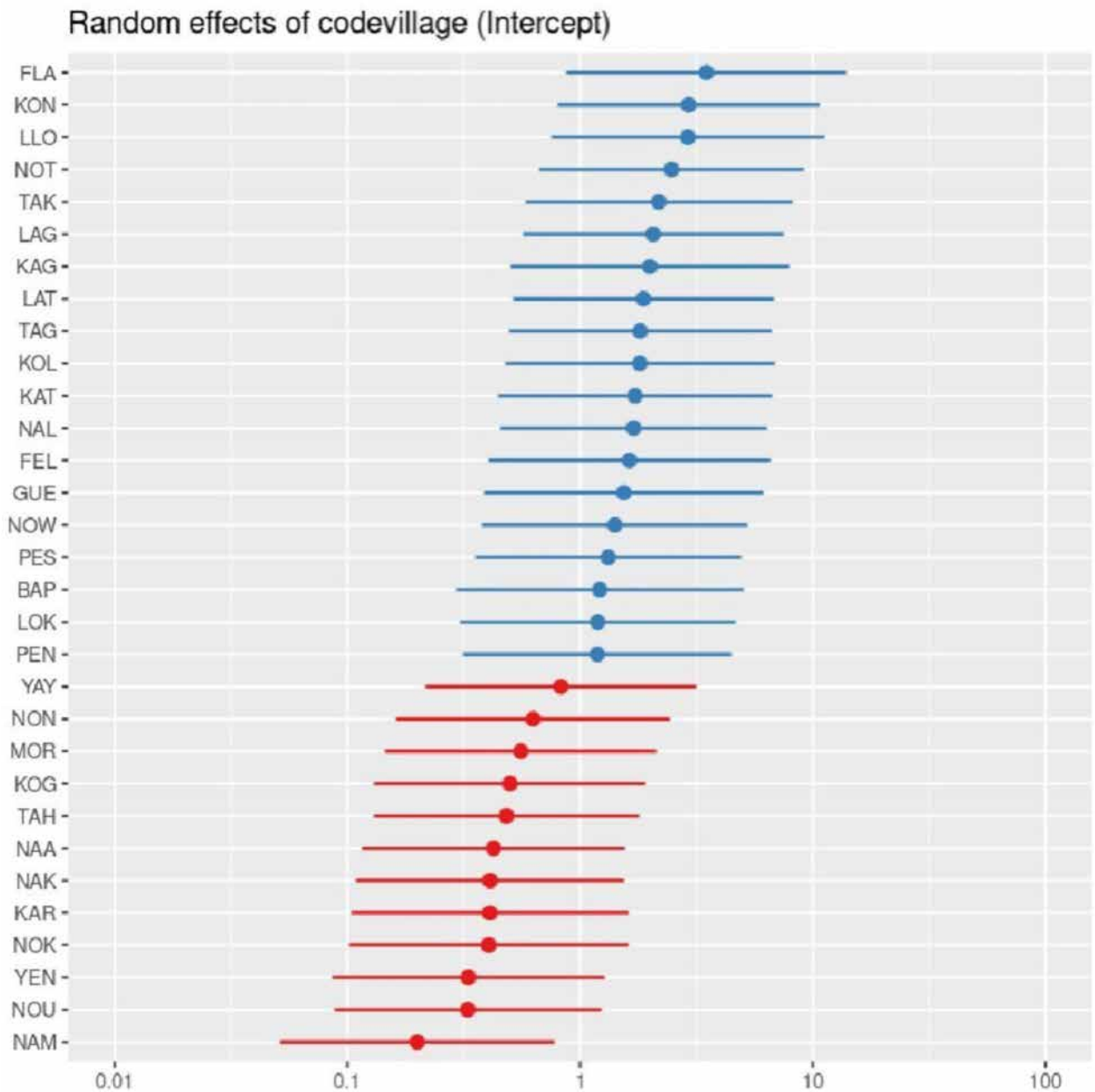


**Fig. 3** Illustration of random village effects. Ratios range from 0.06 to 3.12, shown in blue or red depending on whether they fall below or above the average incidence (0.30 cases per 100 person-weeks), respectively

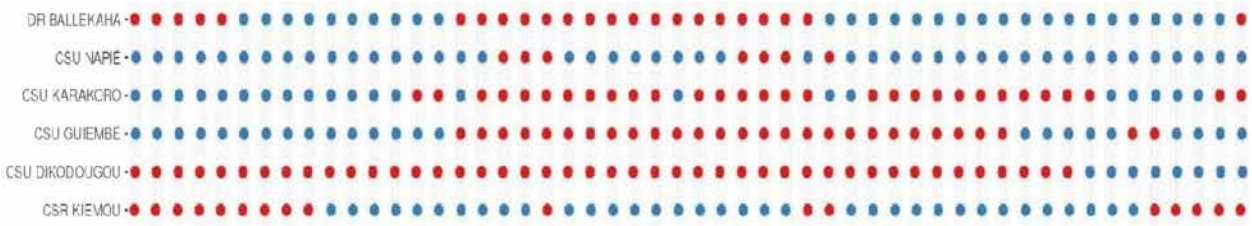


**Fig. 4** Variation in attendance at health centres. Points are coloured blue or red to indicate incidence rates above or below the average incidence (0.30 cases per 100 person-weeks), respectively

reaching the lowest rate in the oldest group (13–21 years) ($p < 0.001$). No significant difference was found between males and females ($p = 0.9$). Interestingly, individuals reporting ownership of LLIN had significantly fewer malaria cases ($p = 0.034$). Conversely, malaria case rates were significantly higher among those who reported having slept under a LLIN the night before the survey ($p = 0.014$).

Significant variations of malaria case prevalence were observed across villages. Combined results of the three cross-sectional surveys showed mean prevalence rates ranging from 10.9% to 33% ($p < 0.001$) (Table 3).

#### Infection prevalence and parasite density in the 6 villages

The analysis focused on six randomly selected villages where malaria infection was assessed through blood smears examination (Table 4). The overall prevalence of *Plasmodium* infection was 93.1%.

#### Fever and malaria prevalence according to RDTs

Symptomatic infections accounted for 29% (644/2246) of all malaria-positive individuals. This proportion varied significantly across surveys, age groups, LLIN usage and villages. The infection rates ranged from 85.6% to 100% and showed no significant variation across the three surveys ($p > 0.9$). However, the highest prevalence of clinical malaria cases was recorded during the second survey (November–December 2016; $p < 0.001$).

A similar pattern was observed across age groups. Although infection prevalence remained uniformly high (between 91,8% and 95,0%) without significant differences, the prevalence of symptomatic malaria cases decreased significantly with age ($p < 0.001$)(see Table 4).

With respect to spatial variability, symptomatic malaria case prevalence was the highest in Karafine (KAR) ($p < 0.001$), which also exhibited the highest infection prevalence ($p < 0.001$).

*Plasmodium falciparum, Plasmodium malariae* and *Plasmodium ovale* were detected either as mono-infections or mixed infections on blood smears (Table 5). The highest infection probability was associated with *P. falciparum* alone ($p < 0.001$).

## Discussion

This study provides valuable insights into malaria epidemiology—both infection and morbidity—in the Korhogo health district prior to the implementation of complementary vector control strategies alongside universal LLIN coverage.

#### Malaria incidence

The malaria incidence observed in this study (156 cases per 1000 person-years) was markedly lower than the national incidence estimates reported for Côte d'Ivoire in 2016 (243.95 [154.08–366.00] cases per 1000 person-years), 2017 (254.20 [160.21–380.87]), and even 2023 (251.43 [170.09–360.79]) [17].

#### Prevalence of infection and clinical cases

Despite the relatively low incidence, both malaria infections and symptomatic cases prevalence recorded during the CSS were notably higher than those reported in a concurrent study conducted in Bouaké, central Côte d'Ivoire [18]. In Bouaké, symptomatic cases prevalence recorded in August 2016 was 2.42% (66/2725), infection prevalence was 84.88% (2313/2725). In contrast, in Korhogo at the same period, symptomatic cases prevalence ranged from 13.4% to 43.4%, and infection prevalence ranged from 85.4% to 100%, depending of the season.

As expected in such Sudanese Guinean climate, malaria case prevalence showed a clear seasonal variation [11]. Moreover, in line with well-established patterns in endemic regions, symptomatic cases prevalence decreased with age, consistent with the development of acquired immunity [19, 20]. Interestingly, infection prevalence did not vary significantly by seasons or age classes. This lack of variation may be due to extremely high infection prevalence throughout the study population, which could mask any subtle age-related difference.

**Table 3** Prevalence of malaria cases detected by RDTs stratified by socio-demographic characteristics

| | Observation | | Cases (%) | Cases (95%CI) | OR | OR (95%CI) | *p-value* |
|---|---|---|---|---|---|---|---|
| | N | Malaria Cases (n) | | | | | |
| Surveys | | | | | | | < 0.001 |
| Survey 1 | 3052 | 423 | 13,9 | [1, 7–12, 12–15] | 1.00 | – | |
| Survey 2 | 3234 | 1404 | 43,4 | [1, 7–36] | 5.62 | [4.92, 6.41] | < 0.001 |
| Survey 3 | 2913 | 390 | 13,4 | [2–7, 7–12, 12–14] | 0.95 | [0.81, 1.10] | 0.5 |
| Age groups | | | | | | | < 0.001 |
| [13–21 +] | 1970 | 212 | 10,8 | [2, 5–9, 9–12] | 1.00 | – | |
| [9–12] | 1967 | 387 | 19,7 | [18,0–21,5] | 2.22 | 1.83–2.70 | < 0.001 |
| [5–8] | 2634 | 730 | 27,7 | [26,0–29,5] | 4.15 | 3.47–4.96 | < 0.001 |
| [0–4] | 2628 | 888 | 33,8 | [32,0–35,6] | 5.73 | 4.80–6.84 | < 0.001 |
| Sex | | | | | | | > 0.9 |
| Female | 4590 | 1104 | 24,1 | [3, 8–22, 22–25] | 1.00 | – | |
| Male | 4609 | 1113 | 24,1 | [4, 9–22, 22–25] | 1.00 | [0.90, 1.12] | > 0.9 |
| LLINs possession | | | | | | | 0.034 |
| NO | 4857 | 1128 | 23,2 | [1–4, 4–22, 22–24] | 1.00 | – | |
| YES | 4342 | 1089 | 25,1 | [4, 8–23, 23–26] | 0.85 | [0.74, 0.99] | 0.034 |
| Sleep under LLIN the night before the survey | | | | | | | 0.014 |
| No | 1950 | 379 | 19,4 | [3, 7–17, 17–21] | 1.00 | – | |
| Yes | 2392 | 710 | 29,7 | [5, 9–27, 27–30] | 1.22 | [1.04, 1.44] | 0.014 |
| Villages | | | | | | | < 0.001 |
| BAP | 316 | 43 | 13,6 | [3–8, 8–10, 10–17] | 1.00 | – | |
| FEL | 316 | 83 | 26,3 | [4, 7–21, 21–30] | 1.78 | [1.14–2.79] | 0.011 |
| FLA | 301 | 71 | 23,6 | [1–7, 7–19, 19–28] | 1.70 | [1.08–2.68] | 0.021 |
| GUE | 224 | 43 | 19,2 | [6–9, 9–14, 14–24] | 1.19 | [0.72–1.97] | 0.5 |
| KAG | 270 | 85 | 31,5 | [2, 2–26, 26–36] | 2.66 | [1.70–4.16] | < 0.001 |
| KAR | 534 | 176 | 33,0 | [1, 1–29, 29–36] | 3.11 | [2.08–4.63] | < 0.001 |
| KAT | 378 | 101 | 26,7 | [4–22, 22–30] | 1.95 | [1.27–2.99] | 0.002 |
| KOG | 281 | 60 | 21,4 | [17,0–26,5] | 1.45 | [0.91–2.30] | 0.12 |
| KON | 498 | 145 | 29,1 | [3, 3–25, 25–32] | 2.34 | [1.56–3.51] | < 0.001 |
| LAG | 354 | 113 | 31,9 | [3–9, 9–27, 27–35] | 2.57 | [1.68–3.94] | < 0.001 |
| LAT | 365 | 96 | 26,3 | [22,0–31,0] | 2.02 | [1.31–3.11] | 0.001 |
| LLO | 375 | 74 | 19,7 | [16,0–24,1] | 1.28 | [0.82–1.99] | 0.3 |
| LOK | 325 | 84 | 25,8 | [4–9, 9–21, 21–29] | 1.89 | [1.22–2.94] | 0.005 |
| MOR | 340 | 37 | 10,9 | [8,0–14,6] | 0.69 | [0.42–1.14] | 0.14 |
| NAK | 135 | 31 | 23,0 | [7, 7–16, 16–29] | 1.77 | [1.02–3.10] | 0.044 |
| NAL | 678 | 125 | 18,4 | [5, 7–15, 15–21] | 1.06 | [0.70–1.58] | 0.8 |
| NOT | 309 | 60 | 19,4 | [2, 4–15, 15–24] | 1.13 | [0.71–1.80] | 0.6 |
| NOU | 523 | 156 | 29,8 | [1–9, 9–26, 26–32] | 2.53 | [1.69–3.79] | < 0.001 |
| NOW | 358 | 77 | 21,5 | [1, 6–17, 17–26] | 1.79 | [1.15–2.79] | 0.010 |
| PEN | 289 | 77 | 26,6 | [21,9–32,0] | 1.77 | [1.13–2.78] | 0.013 |
| PES | 284 | 54 | 19,0 | [14,9–24,0] | 1.16 | [0.72–1.86] | 0.5 |
| TAG | 482 | 95 | 19,7 | [4, 5, 5–16, 16–23] | 1.28 | [0.84–1.96] | 0.3 |
| TAH | 214 | 47 | 22,0 | [16,9–28,0] | 1.91 | [1.16–3.12] | 0.010 |
| TAK | 426 | 97 | 22,8 | [19,0–27,0] | 1.55 | [1.01–2.37] | 0.045 |
| YAY | 271 | 78 | 28,8 | [4, 7–23, 23–33] | 2.17 | [1.38–3.42] | < 0.001 |
| YEN | 353 | 109 | 30,9 | [3–9, 9–26, 26–34] | 2.44 | [1.59–3.74] | < 0.001 |
| | N = 9199 | Cases: n = 2217 | % = 24,1 | 95%CI | OR | 95%CI | *p-value* |

**Table 4** Comparison of malaria case prevalence versus infection prevalence

| | | Infection | | | | | | Cases | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | N | n | % | 95%CI | OR | 95%CI | *p-value* | n | % | 95%CI | OR | 95%CI | *p-value* |
| Surveys | | | | | | | < 0.001 | | | | | | < 0.001 |
| Survey 1 | 732 | 732 | 100,0 | [99–100] | 1.00 | – | | 119 | 16.3 | [1, 8–13, 13–19] | 1.00 | – | |
| Survey 2 | 860 | 814 | 94.7 | [92,9–96,0] | 0.00 | 0.00, Inf | > 0.9 | 385 | 44.8 | [1, 5–36] | 4.97 | 3.83, 6.46 | < 0.001 |
| Survey 3 | 820 | 700 | 85.4 | [6, 8–36] | 0.00 | 0.00, Inf | > 0.9 | 140 | 17.1 | [7, 8, 8–14, 14–19] | 1.14 | 0.86, 1.51 | 0.4 |
| Sex | | | | | | | 0.5 | | | | | | 0.4 |
| Female | 1266 | 1182 | 93.4 | [6, 9–36] | 1.00 | – | | 329 | 26.0 | [5–23, 23–28] | 1.00 | – | |
| Male | 1146 | 1064 | 92.8 | [2, 2–36] | 0.89 | 0.64, 1.24 | 0.5 | 315 | 27.5 | [25,0–30,1] | 1.09 | 0.89, 1.33 | 0.4 |
| LLINs Possession | | | | | | | 0.007 | | | | | | 0.4 |
| NO | 1896 | 1767 | 93.2 | [92,0–94,2] | 1.00 | – | | 457 | 24.1 | [1–22, 22–26] | 1.00 | – | |
| YES | 516 | 479 | 92.8 | [3–8, 8–36] | 0.50 | 0.30, 0.83 | 0.007 | 187 | 36.2 | [2–5, 5–31, 31–36] | 1.12 | 0.86, 1.44 | 0.4 |
| Sleep under LLIN the night before the survey | | | | | | | > 0.9 | | | | | | < 0.001 |
| NO | 481 | 444 | 92.3 | [4, 6–36] | 1.00 | – | | 169 | 35.1 | [31,0–39,5] | 1.00 | – | |
| YES | 35 | 35 | 100,0 | [1–36] | 0,00 | 0.00, Inf | > 0.9 | 18 | 51.4 | [35,6–67,0] | 4.74 | 2.30, 9.78 | < 0.001 |
| Villages | | | | | | | < 0.001 | | | | | | < 0.001 |
| FEL | 310 | 276 | 89.0 | [85,1–93,0] | 1.00 | – | | 75 | 24.2 | [3, 8–19, 19–29] | 1.00 | – | |
| KAR | 521 | 509 | 97.7 | [96,0–98,7] | 5.26 | 2.62, 10.6 | < 0.001 | 176 | 33.8 | [9, 9–29, 29–36] | 2.00 | 1.40, 2.85 | < 0.001 |
| KON | 488 | 463 | 94.9 | [5, 5–36] | 2.37 | 1.35, 4.17 | 0.003 | 137 | 28.1 | [2–24, 24–31] | 1.39 | 0.97, 1.99 | 0.076 |
| LLO | 370 | 339 | 91.6 | [88,4–94,0] | 1.28 | 0.74, 2.20 | 0.4 | 68 | 18.4 | [1, 4–14, 14–22] | 0.69 | 0.46, 1.04 | 0.078 |
| NOU | 519 | 475 | 91.5 | [6, 8–36] | 1.25 | 0.75, 2.09 | 0.4 | 141 | 27.2 | [2, 5–23, 23–30] | 1.46 | 1.01, 2.10 | 0.044 |
| TAH | 204 | 184 | 90.2 | [3–6, 6–36] | 1.40 | 0.75, 2.63 | 0.3 | 47 | 23.0 | [3, 8–17, 17–29] | 1.15 | 0.73, 1.83 | 0.5 |
| Age groups | | | | | | | 0.4 | | | | | | < 0.001 |
| [13–21 +] | 462 | 439 | 95.0 | [6, 7, 7–36] | 1.00 | – | | 65 | 14.1 | [2–5, 5–11, 11–17] | 1.00 | – | |
| [9–12] | 641 | 595 | 92.8 | [6, 6–36] | 0.81 | 0.47, 1.40 | 0.5 | 146 | 22.8 | [2, 7–19, 19–26] | 1.98 | 1.40, 2.79 | < 0.001 |
| [5–8] | 650 | 597 | 91.8 | [5–7, 7–36] | 0.68 | 0.40, 1.15 | 0.15 | 179 | 27.5 | [1–24, 24–30] | 2.82 | 2.01, 3.95 | < 0.001 |
| [0–4] | 659 | 615 | 93.3 | [91,2–95,0] | 0.91 | 0.53, 1.57 | 0.7 | 254 | 38.5 | [3, 9–33, 33–36] | 5.28 | 3.79, 7.36 | < 0.001 |

Infection prevalence was defined as the proportion of participants with positive blood smears among the total number of individuals enrolled in the cross-sectional surveys

Case prevalence was defined as the proportion of participants presenting with fever or a history of fever within the past 48 h and a positive rapid diagnostic test (RDT) among the total survey participants

### Importance of a micro spatial approach

The high prevalence of both infections and symptomatic cases, supported by the entomological data from Zogo et al. [11, 21] suggests that the Korhogo district represents a hyper-endemic area according to the Yaoundé classification (1962) [22, 23], and may even constitute a transmission hotspot [24]. Understanding the drivers of such hotspots is essential for optimizing malaria surveillance and evaluating novel vector control tools [24, 25]. To achieve this, fine-scale spatial and temporal analysis are needed to model both epidemiological and entomological dynamics. While environmental and socio-economic studies have been conducted in various settings [26, 27], predictive tools remain under development [28]. Nevertheless, the present study confirms that the Korhogo area is highly endemic, underline the urgent need for additional interventions beyond LLIN distribution.

The study also documented the presence of both permanent and temporary mosquito breeding sites—such as inland valleys, rice paddies, swamps, and freshwater ponds— across the dense hydrographic network [15,

**Table 5** Distribution of *Plasmodium* species identified in positive blood smears

| ***Plasmodium* species** | **Number of species** | |
|---|---|---|
| | **N = 2246** | **%** |
| *P.f* | 2182 | 97.15 |
| *P.m* | 0 | 0.00 |
| *P.o* | 0 | 0.00 |
| *P.f* + *P.m* | 28 | 1.24 |
| *P.f* + *P.o* | 33 | 1.50 |
| *P.f* + *P.m* + *P.o* | 3 | 0.13 |

N: Number of occurrences; %: Percentage of occurrences; *P.f.: Plasmodium falciparum; P.m.: P. malariae; P.o.: P. ovale; P.f. + P.m.: P. falciparum + P. malariae; P.f. + P.o.: P. falciparum + P. malariae; P.f. + P.m. + P.o.: P. falciparum + P. ovale + P. falciparum + P. malariae + P. ovale*

29], laying the groundwork for evaluating larval source management strategies as a complement to LLIN use.

#### Local socio-economic factors

However, spatial heterogeneity in malaria case prevalence is not solely driven by ecological factors [29]. Socio-economic determinants may also contribute significantly. This may include household income, woman's economic autonomy, the presence and practices of traditional healers, and variability in the availability and activities of CHWs. Although detailed socio-economic data were not collected, future investigations should address these aspects to better understand the local epidemiology and inform the evaluation of RCTs.

#### LLIN ownership and use

Mass LLIN distribution remains the cornerstone of vector control in Côte d'Ivoire and other sub-Saharan countries [2]. LLINs ownership and use the night before the survey were recorded during the cross-sectional assessments. Overall, ownership was 47,2% and use was 55,1%, with both coverage (54,8%) and utilization (69,2%) being significantly higher during the dry-cold season. Although these rates were lower than those reported in a 2019 national study (ownership: 65.5%; use: 71.8%) [30], they were comparable to WHO-reported averages for sub-Saharan Africa in 2017 (ownership: 56%; use: 50%) [2].

Some studies have suggested that in absence of mosquito nuisance or during hot weather, discomfort (e.g. heat or unpleasant smell of insecticide) can deter LLIN use [31]. Surprisingly, malaria case prevalence was higher among individuals who reported sleeping under a LLIN the previous night. This contradicts numerous studies that demonstrate the protective effect of LLIN use [32], although some studies have found no association [33, 34]. This discrepancy could reflect limitations of self-reported data, which are subject to recall or desirability bias, especially when focused on a single night. Additional indicators and more objective measures of LLIN use should be considered in future studies.

#### Passive *vs* active case detection: contrasting even inconsistent results

The incidence captured through passive surveillance (156 cases per 1,000 person-years) appeared inconsistent with the high malaria case prevalence identified through cross-sectional surveys, which was higher than in comparable region [18]. This discrepancy underscores key methodological and contextual differences between passive and active case detection approaches. Recent studies have compared the two methods directly [35, 36]. For instance, Tiono et al. found that active detection identified significantly more cases, with a rate ratio of 1.32 [95% CI 1.13–1.54]. They concluded that passive surveillance would require a 30%–40% larger sample size in vaccine trials compared to achieve equivalent statistical power. Their study design ensured community awareness and involvement, potentially influencing health-seeking behaviour.

In contrast, passive case detection relied on routine health centre attendance without any awareness campaign in the control villages that could bias the population behaviour, while active case detection was conducted independently during CSS. Nevertheless, methodological differences in the data—incidence (count) vs prevalence (proportion)—make direct comparisons challenging. Addressing this gap is essential to accurately classify transmission intensity and to determine wether an area should be considered hyperendemic or holoendemic depending on the case detection strategy.

## Conclusion

Active case detection through three cross-sectional surveys revealed that Korhogo health district constitutes a malaria transmission hotspot. With its dense hydrographic network and high infection prevalence, the area presents an optimal setting for the implementation and evaluation of implement the complementary vector control strategies to enhance the impact of universal LLIN coverage and reduce malaria transmission.

#### Acknowledgements

We sincerely thank the residents of the villages for their participation in this study, as well as the nurses and laboratory technicians who contributed to data collection. We thank also the administration of the Korhogo health district for their strong collaboration. Special thanks to Mr. Koffi Laurent for his assistance with data cleaning and archiving, to the REACT administrative team (Mr. Zoumenou Félix and Ms. Soro Awa) and to the Korhogo AIP team for their vital contribution to the smooth execution of the project. We also acknowledge the support of various institutions and organizations involved in the project in Côte d'Ivoire and Burkina Faso including Institute Pierre Richet, IRSS, IRD).

#### Author contributions

CP, LPAA, RKD, NM and FF conceptualized the study and coordinated its implementation. NBT supervised and conducted the field and laboratory activities alongside LPAA and SBA, performed the statistical analysis with support of NM and CP, and drafted the manuscript with CP and FF. MBZ, AK, IC, DDS and AS contributed to the field and laboratory work. AD managed the study database. PT oversaw data management, created the study map, and contributed to manuscript revision. LB-M and RKD reviewed and revised the manuscript. All authors read and approved the final version of the manuscript.

#### Funding

This study was conducted as part of the REACT project, supported by the French Initiative 5% (Grant No. 15SANIN213).

**Data availability**
All data generated or analysed during this study are included within this published article.

## Declarations

**Ethics approval and consent to participate**
Ethical clearance for the study was obtained from the national ethical committee (N/Réf: 063/MSHP/CNER-kp, dated July 21, 2016). All symptomatic participants who tested positive by the rapid diagnostic test (RDT) during the study, received free and appropriate treatment. Participants were also informed of their right to withdraw from the study at any time without any consequences.

**Competing interests**
The authors declare no competing interests.

**Author details**
[1]Institut Pierre Richet (IPR), Institut National de Santé Publique (INSP), Bouaké, Côte d'Ivoire. [2]MIVEGEC (Montpellier University, IRD, CNRS), Montpellier, France. [3]Faculté des Sciences et Techniques, Université d'Abomey Calavi (UAC), Abomey-Calavi, Bénin. [4]Institut de Recherche en Sciences de La Santé (IRSS), Bobo Dioulasso, Burkina Faso. [5]Medical Zoology Center, Institut Pasteur Dakar, Dakar, Sénégal.

Received: 30 June 2025 Accepted: 5 September 2025
Published online: 01 October 2025

**References**

1. WHO. World malaria report 2024: addressing inequity in the global malaria response. Geneva: World Health Organization; 2024. https://iris.who.int/. Accessed 27 Jan 2025.
2. WHO. World malaria report 2018. Geneva: World Health Organization; 2018. https://iris.who.int/handle/10665/275867. Accessed 29 Jan 2025.
3. Ministère de la Santé et de l'Hygiène Publique. Rapport annuel sur la situation sanitaire (RASS) 2017. Abidjan, Côte d'Ivoire; 2017.
4. Camara S, Koffi AA, Ahoua Alou LP, Koffi K, Kabran J-PK, Koné A, et al. Mapping insecticide resistance in *Anopheles gambiae* (s.l.) from Côte d'Ivoire. Parasit Vectors. 2018;11:19.
5. Edi CV, Djogbénou L, Jenkins AM, Regna K, Muskavitch MAT, Poupardin R, et al. CYP6 P450 enzymes and ACE-1 duplication produce extreme and multiple insecticide resistance in the malaria mosquito *Anopheles gambiae*. PLoS Genet. 2014;10:e1004236.
6. Ranson H, N'Guessan R, Lines J, Moiroux N, Nkuni Z, Corbel V. Pyrethroid resistance in African anopheline mosquitoes: what are the implications for malaria control? Trends Parasitol. 2011;27:91–8.
7. Koffi AA, Ahoua Alou LP, Adja MA, Chandre F, Pennetier C. Insecticide resistance status of *Anopheles gambiae s.s* population from M'Bé: a WHOPES-labelled experimental hut station, 10 years after the political crisis in Côte d'Ivoire. Malar J. 2013;12:151.
8. Edi CVA, Koudou BG, Jones CM, Weetman D, Ranson H. Multiple-insecticide resistance in *Anopheles gambiae* mosquitoes, Southern Côte d'Ivoire. Emerg Infect Dis. 2012;18:1508–11.
9. WHO. World-malaria-report-2020: 20 years of global progress and challenges.. Geneva: World Health Organization; 2020. https://www.who.int/teamsglobal-malariaprogrammereportsworld-malaria-report-2020.
10. WHO. World malaria report 2013. Geneva: World Health Organization; 2013. https://iris.who.int/handle/10665/97008. Accessed on 29 Jan 2025.
11. Zogo B, Soma DD, Tchiekoi BN, Somé A, Ahoua Alou LP, Koffi AA, et al. *Anopheles* bionomics, insecticide resistance mechanisms, and malaria transmission in the Korhogo area, northern Côte d'Ivoire: a pre-intervention study. Parasite. 2019;26:40.
12. Dossou-Yovo J, Diarrassouba S, Doannio J, Darriet F, Carnevale P. Le cycle d'agressivité d'*Anopheles gambiae s.s.* à l'intérieur des maisons et la transmission du paludisme dans la région de Bouaké (Côte d'Ivoire) : intérêt de l'utilisation de la moustiquaire imprégnée. Bull Soc Pathol Exot. 1999;92:198–200.
13. Doannio JMC, Dossou-Yovo J, Diarrassouba S, Chauvancy G, Darriet F, Chandre F, et al. Efficacité des moustiquaires pré-imprègnées de permethrine Olyset net en zone de résistance des vecteurs aux pethrenoïdes. I. Evaluation entomologique. Med Trop (Mars). 1999;59:349–54.
14. Henry M-C, Assi S-B, Rogier C, Dossou-Yovo J, Chandre F, Guillet P, et al. Protective efficacy of lambda-cyhalothrin treated nets in *Anopheles gambiae* pyrethroid resistance areas of Côte d'Ivoire. Am J Trop Med Hyg. 2005;73:859–64.
15. Cecchi P. L'eau en partage: les petits barrages de Côte d'Ivoire. Paris: IRD éd; 2007.
16. R version 3.2.3. Copyright (C) 2015.The R Foundation for Statistical Computing Platform: i386 w61 mingw32/i386.
17. Link to OMS_Incidence_Malaria_CI. https://www.who.int/data/gho/data/indicators/indicator-details/GHO/malaria-incidence-(per-1-000population-at-risk.
18. Sagna AB, Gebre Y, Vera-Arias CA, Traoré DF, Tchekoi BN, Assi SB, et al. High prevalence of asymptomatic and subpatent *Plasmodium falciparum* infections but no histidine-rich protein 2 gene deletion in Bouaké, Côte d'Ivoire. Sci Rep. 2024;14:19060.
19. Bloland PB, Boriga DA, Ruebush TK, McCormick JB, Roberts JM, Oloo AJ, et al. Longitudinal cohort study of the epidemiology of malaria infections in an area of intense malaria transmission part II. Descriptive epidemiology of malaria infection and disease among children. Am J Trop Med Hyg. 1999;60:641–8.
20. Rogier C, Commenges D, Trape JF. Evidence for an age-dependent pyrogenic threshold of *Plasmodium falciparum* parasitemia in highly endemic populations. Am J Trop Med Hyg. 1996;54:613–9.
21. Taconet P, Zogo B, Soma DD, Alou LPA, Mouline K, Dabiré RK, et al. *Anopheles* sampling collections in the health districts of Korhogo (Côte d'Ivoire) and Diébougou (Burkina Faso) between 2016 and 2018. GigaByte. 2023;2023:gigabyte83.
22. Rogier C, Henry MC, Trape J-F. Evaluation épidémiologique du paludisme en zone d'endémie. Med Trop. 2009;69(Mars):123–42.
23. Carnevale P, Baudon D, Molez J-F, Boudin C, Robert V, Gazin P. Evaluation épidémiologique des paludismes. Etudes Méd. 1984;91:15.
24. Stresman G, Bousema T, Cook J. Malaria hotspots: is there epidemiological evidence for fine-scale spatial targeting of interventions? Trends Parasitol. 2019;35:822–34.
25. Taconet P, Zogo B, Ahoua Alou LP, Amanan Koffi A, Dabiré RK, Pennetier C, et al. Landscape and meteorological determinants of malaria vectors' presence and abundance in the rural health district of Korhogo, Côte d'Ivoire, 2016–2018, and comparison with the less anthropized area of Diébougou, Burkina Faso. PLoS ONE. 2024;19:e0312132.
26. Taconet P, Soma DD, Zogo B, Mouline K, Simard F, Koffi AA, et al. Insecticide resistance and biting behaviour of malaria vectors in rural West-Africa : a data mining study to adress their fine-scale spatiotemporal heterogeneity, drivers, and predictability. BioRxiv. 2024. https://doi.org/10.1101/2022.08.20.504631.
27. Bationo CS, Gaudart J, Dieng S, Cissoko M, Taconet P, Ouedraogo B, et al. Spatio-temporal analysis and prediction of malaria cases using remote sensing meteorological data in Diébougou health district, Burkina Faso, 2016–2017. Sci Rep. 2021;11:20027.
28. Hussain-Alkhateeb L, Rivera Ramírez T, Kroeger A, Gozzer E, Runge-Ranzinger S. Early warning systems (EWSs) for chikungunya, dengue, malaria, yellow fever, and Zika outbreaks: what is the evidence? A scoping review. PLoS Negl Trop Dis. 2021;15:e0009686.
29. Zogo B, Koffi AA, Alou LPA, Fournet F, Dahounto A, Dabiré RK, et al. Identification and characterization of *Anopheles* spp. breeding habitats in the Korhogo area in northern Côte d'ivoire: a study prior to a Bti-based larviciding intervention. Parasit Vectors. 2019;12:146.
30. Breakthrough Action. Enquête sur les déterminants des comportements liés au paludisme en Côte d'Ivoire, 2018. Baltimore: Johns Hopkins Center for Communication Programs; 2019.
31. Moiroux N, Boussari O, Djènontin A, Damien G, Cottrell G, Henry M-C, et al. Dry season determinants of malaria disease and net use in Benin, West Africa. PLoS ONE. 2012;7:e30558.
32. Okebe J, Mwesigwa J, Kama EL, Ceesay SJ, Njie F, Correa S, et al. A comparative case control study of the determinants of clinical malaria in The Gambia. Malar J. 2014;13:306.
33. Nahum A, Erhart A, Mayé A, Ahounou D, Van Overmeir C, Menten J, et al. Malaria incidence and prevalence among children living in a peri-urban

area on the coast of Benin, West Africa: a longitudinal study. Am J Trop Med Hyg. 2010;83:465–73.
34. Krefis AC, Schwarz NG, Nkrumah B, Acquah S, Loag W, Sarpong N, et al. Principal component analysis of socioeconomic factors and their association with malaria in children from the Ashanti Region, Ghana. Malar J. 2010;9:201.
35. Tiono AB, Kangoye DT, Rehman AM, Kargougou DG, Kaboré Y, Diarra A, et al. Malaria incidence in children in south-west Burkina Faso: comparison of active and passive case detection methods. PLoS ONE. 2014;9:e86936.
36. Searle KM, Katowa B, Kobayashi T, Siame MNS, Mharakurwa S, Carpi G, et al. Distinct parasite populations infect individuals identified through passive and active case detection in a region of declining malaria transmission in southern Zambia. Malar J. 2017;16:154.

## Publisher's Note

Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.