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Trends in Malaria Incidence and Predictive Factors before and after Campaign-Based Distribution of Standard and Next-Generation Insecticide-Treated Nets: An Observational Study Conducted in Kongo Central, Democratic Republic of the Congo

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Abstract

Background: The incidence of malaria has risen globally, including in the DRC, despite repeated LLIN campaigns. In Kongo Central, five distribution cycles occurred from 2010 to 2023. In 2023, standard pyrethroid nets were replaced with next-generation PBO and IG2 nets. Methods: In this observational historical cohort study, we analyzed malaria incidence trends (2010-2024) and projections (2024-2030) across 31 health zones using exhaustive data from the National Health Information System, LLIN distribution records, and ERA5 climatic variables. Bivariate and multivariate panel data models (random effects and STATA v16) identified predictive factors. Results: Incidence rose progressively from 2010 to 2024 (mean, 266 cases/1000 individuals in the population; range, 47 - 765), with projections indicating continuation. Bivariate analyses showed temporary reductions one year post-distribution for both standard (deltamethrin 55 - 80 mg/m^2) and next-generation LLINs, but there was no sustained difference (RR 0.40 [95% CI 0.18 - 0.89] for 2011 for deltamethrin against 2023 PBO/IG2; p = 0.016). Multivariate panel models identified temperature (coef. 10.88, p = 0.02) and deforestation (coef. 7.94, p

= 0.01) as drivers of the increase, and population density (coef. 0.09, $p < 0.001$) was found to be protective. Conclusion: The incidence of malaria is rising in the province, with both standard and next-generation nets providing only short-term reductions. Environmental factors like temperature and deforestation highlight the need for integrated control strategies as opposed to the use of nets alone.

Keywords

Malaria Incidence Rate, New Generation, Kongo Central

1. Introduction

Reducing malaria cases and vector populations represents a major milestone in malaria control efforts [1]. Vector control is a highly effective means of reducing malaria transmission and constitutes a cornerstone of malaria control and elimination strategies [2].

The World Health Organization (WHO) has raised concern by declaring that malaria control is at a crossroads [2]. The "High burden to high impact" response, launched in 2018, is intended to reinvigorate progress in malaria control [2] [3]. Despite remarkable achievements, progress in malaria control worldwide has stalled in recent years, and many high-burden countries have experienced setbacks [1] [3]. While the reduction in malaria cases has stagnated in recent years, incidence may have increased [4]. This alarming trend highlights the need for new tools with which to combat the disease, hence the introduction of next-generation insecticide-treated nets (LLINs) based on combined pyrethroids, either with a synergist such as piperonyl butoxide (PBO) or with other active ingredients such as chlorfenapyr and pyriproxyfen. These compounds are incorporated with pyrethroids during LLIN impregnation—chlorfenapyr combined with alpha-cypermethrin (Interceptor® G2) and pyriproxyfen combined with alphacypermethrin (Royal Guard®)—representing a timely innovation [5]-[8].

Globally, the incidence of malaria declined between 2000 and 2015, remained stable from 2015 to 2019, and showed a slight increase in 2020. Despite a target of 34.8 cases per 1000 individuals, a modest decline was observed in 2021, followed by stabilization through 2022 and a slight increase in 2023 to 60.4 cases per 1000 individuals in the population; this can be compared with the target of 21.3 cases per 1000 individuals in the population [4] [8] [9].

A similar situation has been observed in the Democratic Republic of the Congo (DRC), where malaria incidence trends showed a progressive increase between 2014 and 2020, followed by a slight decrease in 2021. Despite the slight year-to-year variations observed, malaria incidence remained high between 2020 and 2023, reaching 200, 185, 227, and 224 cases per 1000 population, respectively. Notably, incidence rates remained above the targets set by the National Malaria Con-

trol Programme (NMCP) from 2021 to 2023 [10]. These incidence trends suggest a decline in the effectiveness of the primary preventive strategy—campaign-based distribution of LLINs—despite its status as a high-impact intervention for malaria reduction in the DRC [5] [10] [11]. Long-lasting insecticidal nets (LLINs) have nevertheless played a critical role in reducing the incidence of malaria and corresponding vector populations in malaria-endemic countries [12].

The DRC remains among the countries most heavily affected by malaria despite decades of control efforts, including multiple campaign-based programs distributing insecticide-treated nets [13]. Since 2010, there have been between four and six LLIN distribution cycles across provinces, primarily using pyrethroid-treated nets. In 2023, next-generation LLINs (PBO and IG2) were introduced into campaign-based distribution campaigns, beginning in Kongo Central Province [14] [15].

Kongo Central Province underwent its fifth mass LLIN distribution cycle, occur-ring in three-year intervals, in 2023, following cycles in 2011, 2014, 2017, and 2020. The first four cycles involved pyrethroid-treated LLINs, while next-generation LLINs were employed in the most recent cycle. Notably, during the most recent campaign, 17 health zones distributed pyrethroid-PBO LLINs, whereas 14 health zones distributed pyrethroid-chlorfenapyr (IG2) LLINs [16].

Several studies conducted in the DRC and internationally have identified malaria vectors' increasing resistance to pyrethroids as a major contributor to the rising incidence of malaria. Other studies have identified variations in temperature and relative humidity as predictors of the incidence of malaria, alongside resistance to antimalarial drugs [17]-[20].

To date, no studies have examined the temporal evolution and determinants of the persistent increase in the incidence of malaria in Kongo Central Province within the context of regular LLIN distribution and the transition to next-generation LLINs. Given the continued burden of malaria in terms of cases and deaths, the province remains far from achieving the global targets of a 90% reduction in malaria incidence and corresponding mortality by 2030. This situation underscores the significance of under-standing how next-generation LLINs and other contributing factors influence the incidence of malaria in regard to developing effective strategies for reorienting malaria control efforts in this region [1] [3] [4]. The objective of this study is to assess temporal trends in the incidence of malaria and environmental determinants after the deployment of standard and next-generation LLINs (PBO/IG2) in Kongo Central Province.

2. Materials and Methods

2.1. Study Framework

Kongo Central is one of the 26 provinces of the Democratic Republic of the Congo (DRC) [10]. The province had an estimated population of 4,922,976 inhabitants in 2022 and covers an area of 53,947 km^2, representing approximately 2.3% of the country's total land area, with a population density of 111 inhabitants per km^2 [21] [22]. Kongo Central comprises 10 administrative territories and 31 health

zones, including nine located in forested areas, three in urban zones, two in mangrove and steppe ecosystems, and 17 in savanna areas. In total, the province includes 418 health areas. Geographically, Kongo Central lies between 4˚ and 6˚ south latitude and 12˚ and 16˚ east longitude. It is bordered to the north by the Democratic Republic of the Congo, to the south by Angola, to the east by the city of Kinshasa and the former Bandundu region, and to the west by the Atlantic Ocean and the Angolan enclave of Cabinda. The province has a mean altitude of 471 m, with elevations ranging from −1 m to 1,259 m above sea level [22].

The climate is tropical, being characterized by two main seasons: a rainy season and a dry season. Annual rainfall ranges from 900 to 1500 mm. The dry season extends from May to September, while the long rainy season spans from October to May, interrupted by a short dry period between January and February [22]. The vegetation in Kongo Central comprises three distinct natural formations: the coastal hinterland and Moanda littoral forest characterized by mangroves and steppes; the Mayombe forest, where nine health zones have experienced deforestation; and the remaining areas, covered by wooded and grassy savannas [22] (see **Figure 1**).

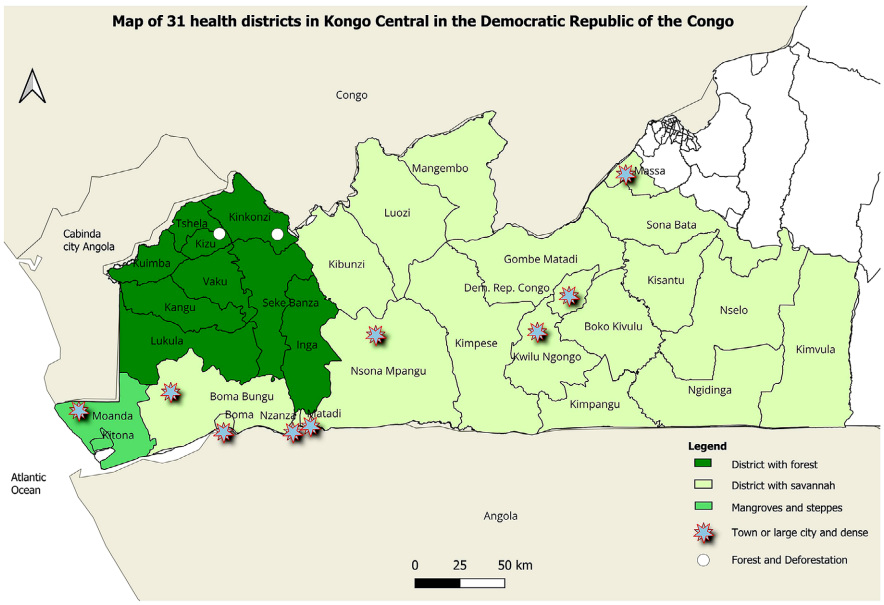

Figure 1. Map of protected areas, indicating types of vegetation.

The insecticides applied to the LLINs distributed in Kongo Central between 2011 and 2020 included deltamethrin (at 55 mg/m^2) in 2011 and 2014 and deltamethrin (at 80 mg/m^2) in 2017 and 2020. In 2023, next-generation LLINs were introduced, incorporating pyrethroids with a syner-gist—alpha-cypermethrin (6.0 g/kg ± 25%) combined with piperonyl butoxide (2.2 g/kg ± 25%) (PBO LLINs distributed in 17 health zones)—as well as LLINs containing additional active ingredients, namely, chlorfenapyr (200 mg/m^2) combined with alphacypermethrin (100 mg/m^2) (IG2 LLINs distributed in 14 health zones) [23].

2.2. Type and Period of Study

We conducted an observational historical cohort study assessing trends in malaria incidence rates from 2010 to 2024 before and after the distribution of standard insecticide-treated nets (LLINs) and next-generation LLINs (PBO/IG2) and modeling malaria incidence rates from 2024 to 2030 across 31 health zones in Kongo Central Province.

2.3. Sampling

The study included all 31 health zones (HZs) in Kongo Central Province from 2010 to 2024, with confirmed malaria cases recorded before and after the distribution of standard or next-generation LLINs (PBO/IG2), enabling calculation of annual incidence rates (the number of confirmed new malaria cases reported in health facilities, multiplied by 1000 and divided by the total annual population). Areas were considered 'diseased' if they had a high incidence rate (≥231 cases per 1000 population) and 'non-diseased' if they had a low incidence rate (<231 cases per 1000 population) (the RDC 2024 incidence target) [24]. Standard LLINs, for which resistance has been reported in this province, were considered exposed in HZs distributing them before 2023, whereas PBO or IG2 LLINs distributed in 2023 were considered non-exposed due to the absence of reported resistance. In 2023, HZs were further stratified by LLIN type (PBO or IG2). Furthermore, environmental factors were also included as exposure variables.

2.4. Study Variables

The dependent variable was the annual and monthly malaria incidence rate. Independent variables included household coverage with standard LLINs from 2010 to 2022 and PBO/IG2 LLINs from 2023 to 2024, malaria incidence rates by age group, malaria incidence rates by health zone, types of insecticides used in LLINs distributed from 2010 to 2024, vegetation by health zone (savanna, forest, and steppe), mean annual temperature (˚C), cumulative annual rainfall (mm), annual relative humidity (%), primary forest cover(%), deforestation (%), and population density (persons per km^2) .

2.5. Data Sources

We conducted a documentary review of existing and validated data from the National Health Information System (NHIS) for malaria incidence from 2010 to 2024; validated databases of mass LLIN distribution campaigns in 2011, 2014, 2017, 2020, and 2023; and climatic data in the ERA5 dataset, which represents the fifth generation of global atmospheric re-analyses from the European Centre for Medium-Range Weather Forecasts (ECMWF) [25].

2.6. Statistical Analysis

After verifying the consistency of each database, we encoded the data and con-

solidated them into a single database. They were then processed and analyzed using STATA version 16, with a significance threshold of 5%. QGIS software was used to produce maps of the province. Univariate analyses were performed to calculate frequencies and proportions. To assess associations, bivariate analyses were conducted using Student's t-test for independent samples, and the Kolmogorov-Smirnov test was applied to verify normality assumptions. Two groups were defined: high-incidence (diseased), with incidence rates of ≥231 cases per 1000 individuals, and low-incidence (non-diseased), with incidence rates of <231 cases per 1000 individuals. These groups were analyzed against climatic, geographic, intervention-related, and environmental factors [26]. In addition, repeated-measures ANOVA was conducted on malaria incidence rates one year before and one year after the distribution of standard LLINs (2011-2021) and PBO/IG2 LLINs (2023-2024) to assess the impact of mass LLIN distribution on malaria incidence one-year post-distribution. Univariate time-series analyses of monthly malaria incidence rates were performed using multiplicative models after deseasonalization to allow for potential predictions of incidence rates through 2030.

A panel data model was employed to identify predictive factors associated with increased malaria incidence from 2010 to 2024, treating each health zone (31 zones) as an individual over a 15-year series. The dependent variable was malaria incidence, and explanatory variables included various climatic, geographic, intervention-related, and environmental factors. Stationarity was tested using the Levin, Lin, and Chu unit root test: at level I (0), variables included annual malaria incidence, mean annual temperature, household LLIN coverage, proportion of LLINs distributed, and annual precipitation; at level I (1), variables included deforestation, population density, relative humidity, mean temperature, and primary forest cover. The Hausman specification test was conducted to choose between fixed-effect and random-effect estimation; the latter was selected as the consistent model for interpretation ($p < 0.05$). Model validity was assessed through residual diagnostics, including histogram normality, heteroskedasticity, and LM tests for serial correlation, all of which yielded p-values > 5%. Interpretations were based on Z-test p-values and confidence intervals for the estimated coefficients. Notably, each annual mass LLIN distribution campaign in the province was conducted between December 20 and 31; therefore, the year of distribution and the year after were considered "before distribution" and "after distribution", respectively.

3. Results

3.1. The Evolution of the Malaria Incidence Rate from 2010 to 2024 and Projections (2025-2030)

As shown in **Figure 2**, the incidence rate fluctuated, with the lowest value observed in September 2020 and the highest in May 2019. An increasing trend is projected

after 2024 (see Figure 2).

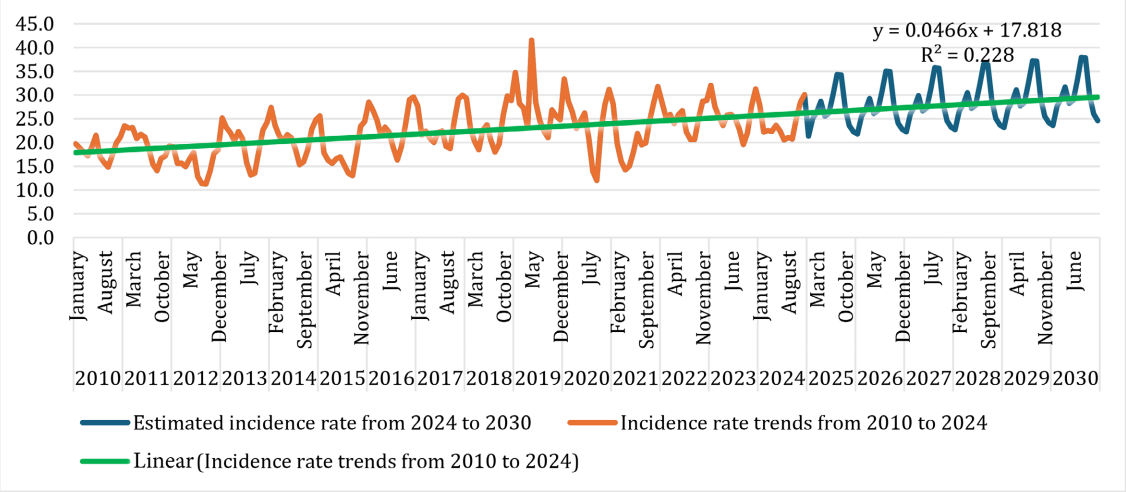

Figure 2. Trends in malaria incidence (2010-2024) and projections (2025-2030).

3.2. Analysis of Incidence Rates by Age, Health Zone, and Statistical Parameter and Before and after PBO/IG2 Distribution by Health Zone

Children under 5 years old had rates much higher than those in the 5-and-over age group; they were between three and four times higher depending on the year (see Figure 3).

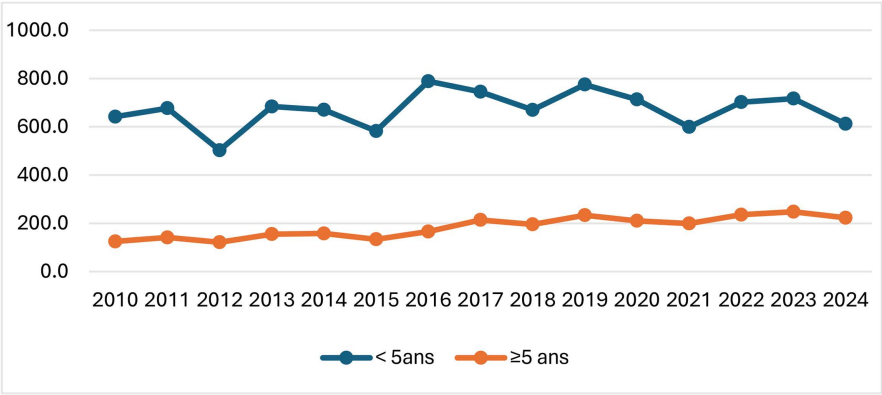

Figure 3. Malaria incidence rates by age group.

As shown in Figure 4, the average incidence rate before and after the distribution of LLINs remained almost the same across the different health zones, except for four Health Zones (KWILU NGONGO, MATADI, NSONA MPANGU, and NZANZA), where incidence rates were significantly higher in 2024, *i.e.*, after the distribution of LLINs PBO/IG2 (see Figure 4).

As shown in Figure 5, from 2010 to 2024, malaria incidence rates ranged from 47.1 cases per 1000 people to 765 cases per 1000 people. The mean was 265.6 ± 102.5 cases per 1000 people, with a median of 253.7 cases per 1000 people (see

Figure 5).

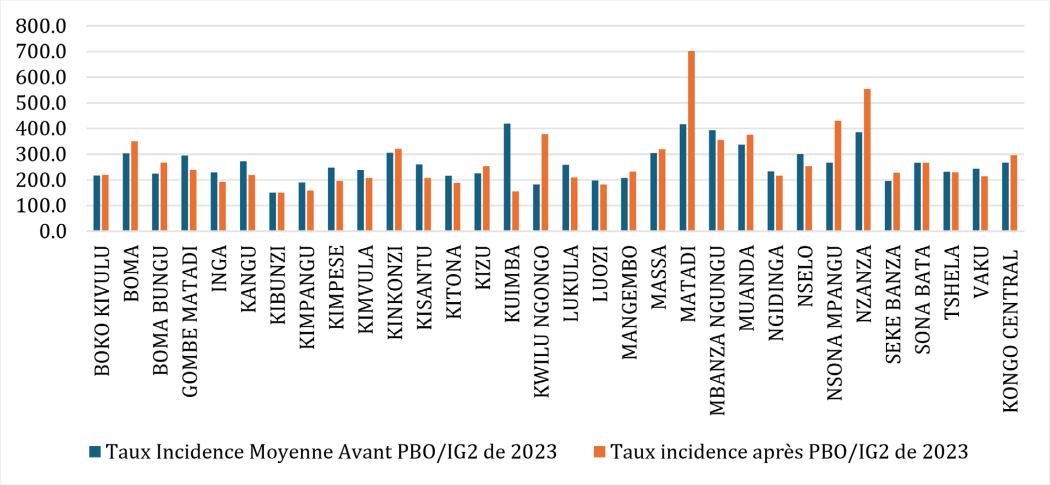

Figure 4. Malaria incidence rates by health zone before and after PBO/IG2.

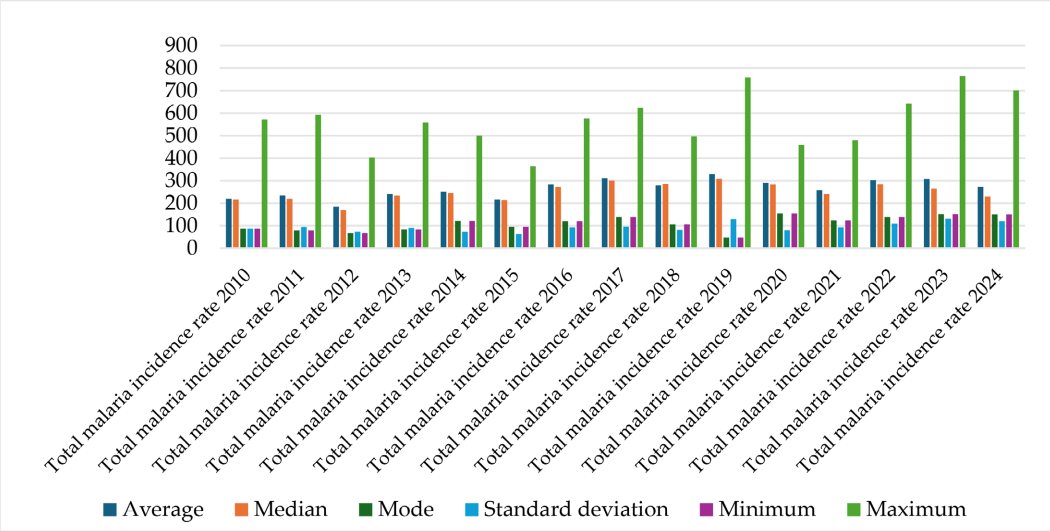

Figure 5. Summary statistics regarding annual malaria incidence rates.

3.3. Bivariate Analysis of the Incidence Rate of Malaria One Year after the Distribution of LLINs

Bivariate analysis of the incidence rate considering the target of 231 malaria cases per 1000 people in 2024, stratified by the type of insecticide used, and compared to the malaria incidence rate one year after the distribution of LLINs PBO/IG2 used in 2023 showed that standard LLINs (Deltamethrin (55 mg/m^2)) had a protective link to malaria incidence in 2011 and then an exposure link in 2017 with Deltamethrin (80 mg/m^2) (see Table 1).

Bivariate analysis of geographical and environmental factors showed no notable influence of the 6 factors studied on the malaria incidence rate in the 31 health zones (see Table 2).

Table 1. Malaria incidence rates one year after the distribution of standard LLINs according to the types of insecticides used in LLINs and one year after LLINs PBO/IG2 distributed in 2023.

VARIABLES	Incidence rate		RR (95% CI)	p
	≥231	<231		
Type of insecticide used in LLINs 2011				
Deltamethrin (55 mg/m²) 2011	6 (28.6)	25 (61.0)	0.40 (0.18 - 0.89)	0.016
PBO/IG2 in 2023	15 (71.4)	16 (39.0)	1	
Type of insecticide used in LLINs 2014				
Deltamethrin (55 mg/m²) 2014	14 (48.3)	17 (51.5)	0.93 (0.55 - 1.59)	0.799
PBO/IG2 in 2023	15 (51.7)	16 (48.5)	1	
Type of insecticide used in LLINs 2017				
Deltamethrin (80 mg/m²) 2017	23 (60.5)	8 (33.3)	1.53 (1.01 - 2.33)	0.037
PBO/IG2 in 2023	15 (39.5)	16 (66.7)	1	
Type of insecticide used in LLINs 2020				
Deltamethrin (80 mg/m²) 2020	17 (53.1)	14 (46.7)	1.13 (0.69 - 1.84)	0.611
PBO/IG2 in 2023	15 (46.9)	16 (53.3)	1	

Table 2. Analysis of the factors influencing the incidence rate of malaria one year after the distribution of LLINs PBO/IG2 in December 2023.

VARIABLES	Incidence rate		RR (95% CI)	p
	≥231	<231		
Type of insecticide used in LLINs 2023				
PBO	8 (53.3)	9 (56.3)	0.94 (0.43 - 2.04)	0.87
IG2	7 (46.7)	7 (43.7)	1	
Vegetation				
Forest	2 (13.3)	5 (31.3)	0.28 (0.08 - 1.10)	0.341
Wooded and grassy savannah	4 (26.7)	6 (37.4)	0.40 (0.18 - 1.20)	
Grassy savannah	8 (53.3)	5 (31.3)	0.62 (0.40 - 1.11)	
Mangrove	1 (6.7)	0 (0)	1	
Household coverage regarding LLINs during campaign-based distribution, December 2023				
<80%	0 (0)	1 (6.3)	0.00 (0.00 - α)	0.325
≥80%	15 (100.0)	15 (93.7)	1	

Continued

Average annual temperature				
<25˚C	13 (86.7)	15 (96.7)	0.69 (0.28 - 1.70)	0.505
≥25˚C	2 (13.3)	1 (6.3)	1	
Average annual precipitation				
<100 mm	14 (93.3)	15 (93.7)	0.96 (0.23 - 4.06)	0.962
≥100 mm	1 (6.7)	1 (6.3)	1	
Annual relative humidity				
<80%	12 (80.0)	14 (87.5)	0.76 (0.33 - 1.76)	0.570
≥80%	3 (20.0)	2 (12.5)	1	

3.4. Comparative Analysis of the Incidence of Malaria Post-Distribution of LLINs from 2010 to 2024

The results of the repeated-measures ANOVA (p = 0.001) generally show a significant association between the decrease in malaria incidence in the year LLINs were distributed and the year immediately following the distribution of standard or next-generation LLINs. However, starting in the second year after distribution, the incidence increases, except following the distribution of Deltamethrin (55 mg/m^2) for the second time in 2014, for which the significant decreases in incidence persisted for at least three years (see Table 3).

Table 3. Comparison of incidence rates before and after the distribution of LLINs from 2010 to 2024.

Incidence rate		Statistical	p	Kind	Type of insecticide
2011	2012	3.43	0.00	Standard	Deltamethrin (55 mg/m^2)
2011	2013	0.44	0.66	Standard	Deltamethrin (55 mg/m^2)
2011	2014	2.00	0.05	Standard	Deltamethrin (55 mg/m^2)
2014	2015	3.55	0.00	Standard	Deltamethrin (55 mg/m^2)
2014	2016	2.55	0.01	Standard	Deltamethrin (55 mg/m^2)
2014	2017	5.13	0.00	Standard	Deltamethrin (55 mg/m^2)
2017	2018	3.21	0.00	Standard	Deltamethrin (80 mg/m^2)
2017	2019	0.40	0.69	Standard	Deltamethrin (80 mg/m^2)
2017	2020	1.82	0.07	Standard	Deltamethrin (80 mg/m^2)
2020	2021	4.10	0.00	Standard	Deltamethrin (80 mg/m^2)
2020	2022	0.08	0.94	Standard	Deltamethrin (80 mg/m^2)
2020	2023	0.12	0.91	Standard	Deltamethrin (80 mg/m^2)
2023	2024	3.10	0.00	PBO/IG2	Alpha cypermethrin 6.0 g/kg ±25% & piperonyl Butoxide 2.2 g/kg ±25%

3.5. Time Series Analysis of Predictive Factors of Malaria Incidence in Central Kongo

In this random-effects panel data model, deforestation and temperature are associated with an annual increase in the incidence of malaria. However, population density is associated with a decrease in the incidence of malaria. On the other hand, household coverage regarding LLINs, the proportion of LLINs distributed, primary forest, precipitation, and relative humidity were not associated with the incidence rate (see Table 4).

Table 4. Multivariate time series analysis of predictive factors of the annual malaria incidence rate from 2010 to 2024 using the PANEL model.

Variables	Coefficient	Z-Test	p-value	95% confidence
Coverage provided in terms of LLINs	0.062	0.08	0.94	−1.55 - 1.68
Proportion of LLINs distributed	0.19	0.21	0.83	−1.59 - 1.97
Primary Forest	−0.40	−0.07	0.94	−11.35 - 10.56
Deforestation	7.94	2.45	0.01	1.59 - 14.29
Temperature	10.88	2.25	0.02	1.42 - 20.34
Precipitation	0.30	1.43	0.15	−0.11 - 0.71
Population density	0.09	6.49	0.00	0.06 - 0.12
Relative humidity	−3.13	−1.10	0.27	−8.69 - 2.43
Constant	146.21	0.55	0.58	−376.22 - 668.64

4. Discussion

The first four campaign-based distribution cycles of LLINs were conducted using standard LLINs (2011-2020), while the most recent cycle in 2023 involved PBO/IG2 LLINs. Overall, the trend of malaria incidence remained largely the same in this period, showing a continued increase [9]. This pattern is consistent with trends observed in Angola, Burundi, and Madagascar in 2022 relative to 2015 [26]. In contrast, studies conducted in other regions have demonstrated that mass LLIN distribution significantly reduce malaria incidence, including in Kenya, India, and in M'bé, central Côte d'Ivoire (with PBO LLINs) [20] [27] [28]. This is further evidenced by the 2024 target for the DRC, which aimed to reduce malaria incidence below 231 cases per 1000 individuals; however, Kongo Central exceeded this target with 296 cases per 1000 individuals [15] [24].

Modeling of malaria incidence from 2024 to 2030, within the context of PBO/IG2 LLINs, showed similar temporal patterns of monthly incidence. In addition, a declining trend in the incidence rate was often observed between August and September each year, reflecting the influence of the dry season following the disappearance of temporary Anopheles breeding sites [22]. Incidence was higher among children under five years of age compared to those over five, aligning with na-

tional trends that suggest older individuals are more aware of and more likely to use LLINs [29]. Conversely, a study on Mali reported higher incidence among individuals over five years of age [15] [30]. Furthermore, incidence was higher in urban health zones one year after PBO/IG2 LLIN distribution, likely due to improved case reporting in urban areas [15].

Bivariate analysis of the incidence of malaria from 2011 to 2020 according to the type of standard LLIN used, compared to PBO/IG2 LLINs in 2023, indicated that standard LLINs initially provided protective effects by reducing the incidence or number of malaria episodes relative to PBO/IG2 LLINs (especially in 2011 with deltamethrin 55 mg/m^2). However, no protective effects were observed during the second distribution, and in 2017, the higher insecticide dose in LLINs (deltamethrin 80 mg/m^2) was associated with exposure, likely due to pyrethroid resistance [31]. In contrast, in Tanzania in 2023, IG2 LLINs were more effective than PBO or standard LLINs, while pyrethroid-PBO nets were superior to pyrethroid-only nets [32] [33].

Repeated measures ANOVA revealed that one year after each mass LLIN distribution (conducted in December), malaria incidence significantly decreased for both PBO/IG2 and standard LLINs, but this reduction was not significant in the second-year post-distribution. These findings are consistent with observations made in Rwanda in 2023 and the Amhara region of Ethiopia from 2019 to 2023, where PBO and standard LLINs had similar effects [34] [35]. Studies of other areas, such as in Ebonyi State, Nigeria, in 2023, showed that PBO LLINs remained effective for up to two years [36].

Multivariate panel analysis identified two factors—rising temperature and deforestation—as major contributors to increased malaria incidence. Specifically, a 1˚C increase in temperature was associated with an increase of 10.8 cases per 1000 individuals, at a mean temperature of 25.00˚C and a median of 25.32˚C. These results are consistent with studies reporting that higher temperatures shorten the sporogonic cycle of Anopheles mosquitoes, thereby increasing malaria transmission risk, as observed in studies conducted in Lubumbashi and ecological analyses conducted in Burkina Faso [37]-[40]. Most health zones are at low altitudes, experiencing high temperatures ranging from 20.0˚C to 30.0˚C [37].

A 1% increase in deforestation was associated with an increase of 7.9 cases per 1000 individuals. Approximately one-third of health zones are forested, while nearly two-thirds are covered by wooded and grassy savannas, both of which are subjected to ongoing deforestation (e.g., for timber and charcoal production), creating stagnant water habitats that facilitate Anopheles breeding and increases in malaria incidence. Similar observations have been reported in the Lao People's Democratic Republic and in the Brazilian Amazon [41]-[43]. However, studies conducted on Colombia, Latin America, and the Caribbean have reported both positive and negative correlations between deforestation and malaria incidence [44].

An increase of one inhabitant per km^2 was associated with a decrease of 0.09 cases per 1000 inhabitants, likely because greater population density, typical of

urban areas, reduces vegetation and mosquito breeding sites, thereby limiting malaria transmission [45]. Conversely, in rural areas, a reduction in forest edges may lower chronic malaria exposure, leading to faster acquisition of temporary partial immunity [41].

Relative humidity, precipitation, and primary forest cover were not associated with reductions in malaria incidence. The same was observed for household LLIN coverage and the proportion of LLINs distributed, for both standard and next-generation LLINs, a result consistent with findings from Burkina Faso, where precipitation was not associated with malaria incidence [39]. Some studies, however, have found associations between malaria cases and minimum/maximum temperatures and relative humidity, too [27] [28] [39].

Study limitations: Secondary data from two sources were used instead of a single source: the national Excel database (2010-2016) and DHIS2 (2017-2024). Consequently, some variables, such as the number of reporting health facilities, were missing, pre-venting assessment of their influence on malaria case increases. Additionally, monthly data on deforestation, household LLIN coverage post-campaign, and the proportion of LLINs distributed were unavailable, limiting our ability to conduct monthly panel analyses across the 31 health zones.

5. Conclusions

This study identified a persistent upward trend in malaria incidence, driven primarily by environmental changes. Subsequently, incidence increased after each distribution cycle. Among all predictive factors analyzed using the developed panel model, only rising temperature and deforestation were associated with an increase in malaria incidence.

LLIN distribution should be guided by integrated findings from studies on Anopheles vector behavior and insecticide resistance to stratify health zones and in-form the choice of LLIN type. Consequently, qualitative studies on LLIN usage, as well as controlled comparative trials, could provide further insights into unidentified factors. Malaria control, beyond LLIN distribution, should rely on a combination of interventions across the health sector, as well as other sectors, including environmental management.

Abbreviations and Acronyms

ECMWF: European Centre for Medium-Range Weather Forecasts, ERA5: Fifth generation atmospheric reanalysis, IG2: Second generation interceptor, LLINs: long-lasting insecticidal nets, WHO: World Health Organization, NMCP: National Malaria Control Program, PBO: Piperonyl butoxide, DRC: Democratic Republic of the Congo, NHIS: National Health Information System, UNILU: University of Lubumbashi; HZ: Health Zone.

Units

Coverage of long-lasting insecticidal nets (LLINs) (%), proportion of LLINs dis-

tributed (%), deforestation rate (%), primary forest cover (%), temperature (˚C), precipitation (mm), population density (persons/km²), and relative humidity (%).

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Author's Contributions

Conceptualization, NKN and EMS; methodology, NKN, ANK, and EMS; software, NKN; validation, NKN, EMS, ANK, NMM, TBL, GMN, and TBL; formal analysis, NKN, ANK, and EMS; resources, NKN; data curation, NKN; writing—original draft preparation, NKN; writing—review and editing, NKN, EMS, ANK, NMM, TBL, GMN, and TBL; visualization, NKN; supervision, EMS; project administration, NKN and EMS; funding acquisition, NKN. All authors have read and agreed to the published version of the manuscript.

Data Availability

We used DHIS2, District Health Information Software 2, and the ERA5 dataset, which represents the fifth generation of global atmospheric re-analyses from the European Centre for Medium-Range Weather Forecasts (ECMWF).

Ethical Considerations

We obtained approval from the Medical Ethics Committee No. UNILU/CEM/013/2024, and then authorization from the Kongo Central provincial division for the use of malaria control data.

Conflicts of Interest

The authors declare that they have no competing interests.

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