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Evaluating the effectiveness of insecticide-treated net use in preventing malaria among children under five: a quasi-experimental study

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Abstract

Background Malaria remains a leading cause of morbidity among children under five in Ghana despite widespread deployment of insecticide-treated nets (ITNs). Understanding the effectiveness of ITN use under routine programmatic conditions is essential for guiding national malaria control strategies. This study assessed the impact of ITN use on malaria infection among children under five and explored contextual factors that may influence intervention performance.

Methods We analyzed nationally representative, georeferenced data from surveys in Ghana. Spatial quantile maps were created to describe regional patterns of ITN ownership, ITN use, indoor residual spraying (IRS), and malaria prevalence. Multilevel regression models, estimated using conventional and Bayesian approaches, examined the association between ITN use and malaria infection while accounting for enumeration area and regional clustering. Inverse probability of treatment weighting (IPTW) based on propensity scores was used to balance covariates, and the marginal odds of ITN use were estimated. We further estimated the risk difference (RD) using a linear probability model.

Results This study included a total of 11,481 children. Sleeping under an ITN led to an estimated 13% reduction in the odds of malaria infection (aOR = 0.87; 95% CI 0.81–0.93) and an absolute risk reduction of 2.2% (RD = −0.022; 95% CI −0.037 to −0.006). Spatial analyses revealed misalignment between intervention coverage and malaria burden, while behavioral and contextual factors likely contributed to the modest effect size.

Conclusions ITN use provides meaningful but limited protection against malaria infection among young children in Ghana. Strengthening malaria control will require attention to behavioral and contextual drivers of exposure and improved alignment of interventions with local transmission patterns.

Keywords Malaria, Insecticide-treated net, Quasi-experimental study, Ghana

Background

Malaria continues to be one of the most persistent global public health issues and still hampers socioeconomic progress despite decades of investment and innovative programs. The latest data show a setback from previous progress, with the World Health Organization reporting 263 million cases and 597,000 deaths worldwide in 2023, which is over 11 million more cases than the year

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before [1]. This burden is disproportionately carried by sub-Saharan Africa, responsible for about 95% of global malaria deaths [1]. Malaria is not only a health problem but a cause and result of poverty; historical economic studies reveal that countries with endemic malaria experienced 1.3% lower annual economic growth compared to countries without the disease, highlighting its role as a major obstacle to development [2]. Children under five account for the greatest malaria mortality burden, representing an estimated 76% of global deaths, more than 1000 preventable child deaths every day [3, 4]. The protection of this population, therefore, remains central to global malaria control and elimination efforts.

Insecticide-treated nets (ITNs) are among the most cost-effective malaria prevention tools available and have substantially reduced morbidity and mortality across Africa [5]. Their protection is achieved through a dual mechanism: a physical barrier preventing mosquito–human contact, and an insecticidal component, primarily pyrethroids, that kills or repels vectors [5, 6]. At high coverage levels, ITNs confer both individual and community-wide benefits through the reduction of vector density and survival [6].

However, growing insecticide resistance among Anopheles mosquito populations threatens the long-term efficacy of ITNs. Systematic reviews demonstrate significant attenuation in mosquito mortality and deterrent effect in high-resistance settings, although ITNs remain superior to untreated nets [6]. In response, second-generation nets combining pyrethroids with synergists such as piperonyl butoxide or alternative insecticide classes are increasingly deployed [6]. As resistance increases, the relative contribution of behavioral adherence rather than chemical lethality becomes more crucial, shifting ITNs from a predominantly vector-control tool to a behavior-dependent personal protective intervention.

Evaluating ITN performance under real-world conditions requires distinguishing efficacy effect under ideal controlled conditions from effectiveness, which reflects performance under routine community use [7, 8]. While randomized controlled trials have established biological efficacy, the effectiveness of ITNs depends on consistent household use, correct installation, behavioral acceptability, and environmental context [9, 10]. The persistent gap between ITN ownership and nightly utilization underscores this challenge; although distribution has expanded substantially across Africa, consistent use among children remains uneven [10].

Ghana reports malaria prevalence of 8.6% among children aged 6–59 months, as determined by microscopy, with substantial heterogeneity, from 2.0% in Greater Accra to more than 15% in the Oti Region [11]. National programs have achieved high distribution coverage, with over 90% of eligible pregnant women and children receiving ITNs during routine services [12]. Yet consistent use remains suboptimal and highly seasonal. Regional surveys report year-round child ITN use as low as 38%, with many households deploying nets only during the rainy season [13, 14]. Reported barriers include heat, discomfort, irritation from insecticide, difficulty hanging the net, behavioral fatigue, and sociocultural norms influencing sleeping arrangements and control of household resources [13]. Households opting out of net use are also more likely to live in structurally poor, overcrowded, and poorly ventilated dwellings, conditions that independently elevate mosquito exposure and malaria risk [15]. As a result, simple comparisons between ITN users and non-users risk attributing the effect of structural advantage, not the ITN, to reduced malaria risk.

Since the inception of the Roll Back Malaria initiative in 1999, Ghana has pursued policies to enhance access to insecticide-treated nets (ITNs). In 2002, the government began offering free ITN to pregnant women at their first antenatal check-up, a strategy designed to boost use in homes with children under five [16]. Because ITN allocation in Ghana is universal and ethically cannot be withheld, randomized controlled trials are not feasible. A quasi-experimental design is, therefore, the most appropriate approach for evaluating real-world effectiveness at scale.

The objective is to estimate the effect of ITN use on malaria infection among children under five in Ghana using a robust quasi-experimental design, generating evidence necessary to inform implementation optimization and policy decisions in the evolving malaria control landscape.

Methods

Study design and data sources

This study relied on data from the 2016 and 2019 Ghana Malaria Indicator Surveys (GMIS) and the 2014 and 2022 Ghana Demographic and Health Surveys (GDHS). The GMIS and GDHS were implemented through a partnership involving the Ghana Health Service, the Ghana Statistical Service, and the Ministry of Health, with financial and technical assistance provided by ICF International under the Demographic and Health Survey program. The survey employed a two-stage sampling design: first, 200 enumeration areas (EAs), referred to as clusters nested in administrative regions (Figure S1, Additional File), were selected; second, households were randomly chosen along with eligible women aged 15–49 for interviews and children aged 6–59 months for malaria testing, with parental or caregiver consent. The GMIS and GDHS data sets include geocoded information at the cluster level. We analyzed data on 11,481 children aged 6–59 months whose caregivers (mothers) had consented to malaria testing during the surveys (Figure S2, Additional File). For this study, only observations with complete information across relevant variables were included in the analysis.

Variables

Outcome variable

The outcome variable was malaria infection status among children under 5 years, established through laboratory confirmation using microscopy testing. Children were classified as either positive or negative for malaria infection based on the microscopy results.

Exposure variable

The exposure variable was insecticide-treated net (ITN) use among children under 5 years of age. ITN use was defined by caregiver's report that the child slept under an ITN on the night before the survey and that the child consistently sleeps under an ITN. Children meeting these criteria were classified as the treatment group; all others were classified as the control group.

Covariates

Individual and household covariates were selected based on recent literature [10, 14] and included Age of child (months), sex of child, household wealth index, residence type, region, and indoor residual spraying. A detailed description of the harmonized variables used in this study is shown in Table S1 (Additional File).

Statistical analysis

All analyses were conducted using R version 4.5.1 (R Foundation for Statistical Computing, Vienna, 2025). To appropriately account for the stratified, two-stage cluster sampling design of the GDHS and GMIS, we specified a survey design object incorporating primary sampling units (clusters), sampling strata, and survey weights. Sampling weights were rescaled by dividing by 1,000,000 in accordance with DHS guidelines to ensure correct population-level estimation and variance adjustment.

Baseline characteristics of the study population were described using unweighted frequencies and survey-weighted proportions. Differences between children who slept under an insecticide-treated net (ITN) the night preceding the survey (treatment group) and those who did not (control group) were assessed using survey-adjusted chi-square tests. Covariate balance between groups was evaluated using standardized mean differences (SMDs), with established thresholds applied to assess residual imbalance.

Georeferenced survey data were used to examine spatial variation in malaria infection and malaria prevention indicators. For each indicator, regional-level quantiles were constructed and mapped to visualize geographic heterogeneity in vector-control coverage and disease burden.

To identify predictors of malaria infection, we implemented two complementary multilevel modeling approaches. First, we fitted a conventional mixed-effects logistic regression model (Model 1). Second, we estimated a Bayesian hierarchical logistic regression model (Model 2) using weakly informative priors and Markov chain Monte Carlo (MCMC) methods. Both models incorporated random intercepts for clusters nested within regions to account for the hierarchical structure of the survey data. A null (intercept-only) model was initially estimated to compute the intraclass correlation coefficient (ICC), quantifying the proportion of variance attributable to regional- and cluster-level clustering. Employing both conventional and Bayesian frameworks enabled assessment of the robustness of findings: the conventional model produced adjusted odds ratios (aORs) with 95% confidence intervals, whereas the Bayesian model generated exponentiated posterior estimates with corresponding 95% credible intervals, providing a probabilistic quantification of uncertainty.

To estimate the average treatment effect (ATE) of ITN use on malaria infection among children under 5 years, we applied inverse probability of treatment weighting (IPTW) based on propensity scores. Stabilized weights were used to minimize variance inflation and improve numerical stability. After weighting, the marginal effect of ITN use was estimated. In addition, the absolute treatment effect was quantified by estimating the risk difference using a linear probability model with heteroskedasticity-consistent covariance estimator type 3 (HC3) robust standard errors.

All statistical tests were two-sided, and statistical significance was defined at $\alpha = 0.05$.

Model validation and diagnostics

Model diagnostics were conducted to assess the adequacy of both the conventional and Bayesian hierarchical models. For the conventional mixed-effects logistic regression, residual diagnostics were performed using the Diagnostics for Hierarchical Regression Models (DHARMa) framework, evaluating uniformity, dispersion, and outlier patterns to ensure appropriate model fit (Figure S3, Additional File). Bayesian model convergence and stability were assessed through inspection of trace plots (Figure S4, Additional File), effective sample sizes, and $\widehat{R}$ statistics, confirming satisfactory mixing and the absence of divergent transitions. Markov Chain Monte Carlo (MCMC) diagnostics confirmed excellent convergence (all $\widehat{R}$ between 0.9997 and 1.0007, effective sample sizes > 4000).

Kernel density plot (Figure S5, Additional File) of the estimated propensity scores was examined for both treatment and control groups to evaluate overlap and identify potential violations of the positivity assumption. For the IPTW analysis, covariate balance before and after weighting was assessed using a love plot (Figure S6, Additional File), with SMD used to quantify the improvement in balance. A threshold of SMD < 0.1 was applied to indicate acceptable covariate balance following weighting.

Results

Baseline characteristics of the sample population

A total of 11,481 children were included in the analysis (Table 1), comprising 5202 in the control group (did not sleep under an ITN) and 6279 in the treatment group (slept under an ITN). The table reports unweighted sample frequencies alongside survey-weighted proportions for each covariate level, together with standardized mean differences (SMDs) and p values based on the weighted sample, to characterize baseline comparability between exposure groups.

Assessment of baseline imbalance using survey-weighted percentages and SMDs highlighted substantial heterogeneity between groups. The most pronounced imbalances were observed for residence type (SMD = 0.478) and region (SMD = 0.431), reflecting strong structural and geographic patterning of ITN use. Socioeconomic factors, including household wealth and maternal education, also showed notable imbalance (SMDs approximately 0.174–0.382). Health and biological characteristics displayed comparatively smaller differences, although malaria status demonstrated a modest imbalance (SMD = 0.100). Several covariates exceeded accepted thresholds for baseline comparability, underscoring the need for appropriate weighting to account for differential covariate distribution in subsequent analyses.

Regional spatial distribution of malaria infection and other covariates

The quantile maps (Fig. 1) show the spatial distribution of malaria-related indicators across Ghana, revealing notable regional disparities and patterns in IRS, household ITN ownership, children's ITN use, and malaria infection rates in children. IRS coverage was highest in the northern belt, Northern, Upper West, and Upper East regions, while lowest in Brong Ahafo, Eastern, and Volta, suggesting targeted spraying in high-transmission zones. In contrast, household ITN ownership peaked in Volta, Brong Ahafo, and Upper West, but was lowest in Northern, Ashanti, and Greater Accra, indicating a mismatch between IRS and ITN distribution strategies. Children's ITN use mirrored ownership trends in some regions, with the highest usage again in Volta, Brong Ahafo, and Upper West, but showed gaps in Greater Accra, Eastern, and Ashanti, where ownership was relatively lower. Interestingly, malaria infection rates in children were highest in Northern, Central, and Western regions with strong IRS coverage but moderate ITN use, while lowest in Upper West, Ashanti, and Greater Accra, despite lower IRS and ITN ownership.

Factors associated with malaria infection in children under the age of five

Both the conventional (Model 1) and Bayesian (Model 2) multilevel models identified similar predictors of malaria infection in children under 5 (Table 2). Sleeping under an ITN was associated with a modest reduction in odds: Model 1 aOR = 0.88 (95% CI 0.78–0.96, $p = 0.028$), while Model 2 estimated $\exp(\beta) = 0.91$ (95% CrI: 0.80–1.04), which was not statistically significant. IRS showed lower odds in the conventional model (aOR = 0.73, 95% CI 0.58–0.92, $p = 0.007$) but greater uncertainty in the Bayesian estimate ($\exp(\beta) = 0.92$, 95% CrI: 0.70–1.20). Age demonstrated a clear, progressive increase in odds (Model 1 aOR 1.33–2.65; Model 2 $\exp(\beta)$ 1.33–2.40). Rural residence markedly increased odds (aOR = 2.66, 95% CI 2.25–3.14; $\exp(\beta) = 2.78$, 95% CrI: 2.31–3.34). Higher maternal education, particularly secondary and tertiary levels, and greater household wealth were consistently associated with lower odds of infection (secondary: aOR = 0.61, 95% CI 0.53–0.71; $\exp(\beta) = 0.64$, 95% CrI: 0.53–0.76; tertiary: aOR = 0.27, 95% CI 0.15–0.48; $\exp(\beta) = 0.18$, 95% CrI: 0.08–0.34). Substantial clustering effects were observed, with the ICC indicating that approximately 27–28% of the variance in malaria infection risk was attributable to contextual differences across primary sampling units (clusters) and regions, beyond individual-level characteristics. The child's sex showed no statistically significant association in both models.

Effect of sleeping under insecticide-treated nets (ITNs) on malaria infection risk in children under the age of 5

Sleeping under insecticide-treated nets (ITNs) was associated with a reduced risk of malaria infection, as shown in Table 3. The relative effect, expressed as a marginal odds ratio, was 0.87 (95% CI 0.81–0.93, $p < 0.001$), corresponding to a 13% decrease in odds compared with children who did not sleep under ITNs. The absolute effect, expressed as a risk difference, was −0.022 (95% CI −0.037 to −0.006, $p = 0.005$), indicating a 2.2 percentage point reduction in risk.

Table 1 Baseline characteristics of the sample population (N = 11,481)

Variable	Child slept under insecticide-treated net				*p* value*	SMD*
	Unweighted (n)		Survey-weighted (%)			
	No	Yes	Control	Treatment		
Malaria status					< 0.001	0.100
Negative	4335	5099	85.4	81.7		
Positive	867	1180	14.6	18.3		
Indoor residual spraying					0.498	0.022
No	4155	5117	87.3	88.0		
Yes	1047	1162	12.7	12.0		
Age group (months**)**					< 0.001	0.105
6–11	554	815	10.5	13.0		
12–23	1231	1572	23.4	25.5		
24–35	1177	1381	23.1	21.8		
36–47	1170	1299	22.3	19.9		
48–59	1070	1212	20.8	19.8		
Sex					0.510	0.017
Male	2645	3218	51.6	50.7		
Female	2557	3061	48.4	49.3		
Residence type					< 0.001	0.478
Urban	2674	1837	57.0	33.8		
Rural	2528	4442	43.0	66.2		
Maternal education level					< 0.001	0.174
No eductaion	1641	2180	23.7	28.2		
Primary	911	1263	17.0	20.2		
Secondary	2310	2593	51.9	46.9		
Tertiary	340	243	7.4	4.7		
Wealth index					< 0.001	0.382
Poorest	1359	2315	17.2	27.0		
Poor	1117	1523	18.4	24.2		
Middle	939	1123	18.2	19.4		
Rich	938	816	22.9	16.5		
Richest	849	502	23.2	12.8		
Anemia					0.004	0.086
Severe	100	125	1.6	1.8		
Moderate	1570	2053	27.1	30.3		
Mild	1453	1731	27.3	27.7		
Not anemic	2079	2370	44.1	40.2		
Region					< 0.001	0.431
Western[†]	521	535	9.3	9.2		
Central	422	482	9.2	10.1		
Greater Accra	552	231	19.8	7.9		
Volta[‡]	396	712	5.6	10.7		
Eastern	418	376	9.3	7.4		
Ashanti	538	490	19.0	17.6		
Brong Ahafo[§]	526	909	7.2	11.9		
Northern[¶]	1065	1319	14.8	16.4		
Upper East	377	638	3.3	5.4		
Upper West	387	587	2.4	3.4		

n (unweighted frequencies); * (survey-weighted); [†] (Western, Western-North); [‡] (Volta, Oti); [§] (Bono, Bono-East, Ahafo); [¶] (Northern, Savanna, North–East)

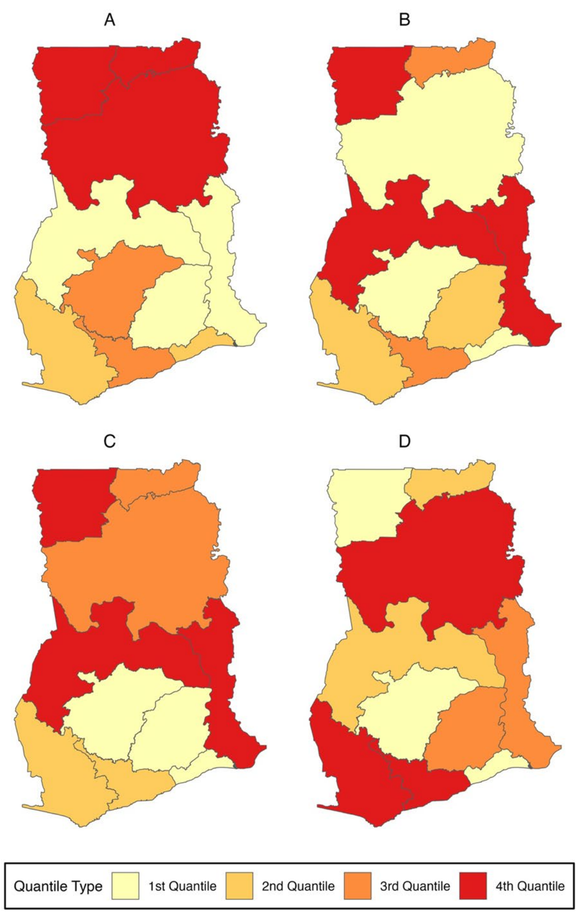

Fig. 1 Spatial distribution of indoor residual spraying (**A**), ITN ownership (**B**), ITN use (**C**), and malaria infection among children under five in Ghana (**D**), by regional quantile classification

Table 2 Factors associated with malaria infection in children under the age of five

Variable	Model 1			Model 2	
	aOR	95% CI	*p* value	exp(*β*)	95% CrI
Child slept under ITN					
No	Ref			Ref	
Yes	0.88	0.78–0.96	0.028	0.91	0.80–1.04
Indoor residual spraying					
No	Ref			Ref	
Yes	0.73	0.58–0.92	0.007	0.92	0.70–1.20
Age group (months)					
6–11	Ref			Ref	
12–23	1.33	1.07–1.64	0.010	1.33	1.06–1.69
24–35	1.83	1.48–2.26	< 0.001	1.58	1.25–2.01
36–47	2.16	1.75–2.67	< 0.001	1.88	1.49–2.38
48–59	2.65	2.14–3.27	< 0.001	2.40	1.90–3.04
Residence type					
Urban	Ref			Ref	
Rural	2.66	2.25–3.14	< 0.001	2.78	2.31–3.34
Maternal education level					
No eductaion	Ref			Ref	
Primary	0.89	0.7–1.04	0.130	1.01	0.84–1.21
Secondary	0.61	0.53–0.71	< 0.001	0.64	0.53–0.76
Tertiary	0.27	0.15–0.48	< 0.001	0.18	0.08–0.34
Sex					
Male					
Female	0.97	0.87–1.07	0.529	1.01	0.89–1.13
Wealth index					
Poorest	Ref			Ref	
Poor	0.71	0.60–0.83	< 0.001	0.71	0.59–0.86
Middle	0.49	0.41–0.60	< 0.001	0.52	0.42–0.65
Rich	0.41	0.32–0.51	< 0.001	0.36	0.28–0.46
Richest	0.19	0.14–0.26	< 0.001	0.21	0.16–0.29

Model 1: Conventional mixed-effects model; Model 2: Bayesian multilevel logistic regression ref: reference category; aOR: Adjusted Odds Ratio; exp(*β*): posterior mean (odds ratio); CI: Confidence Interval; CrI: Credible Interval

Table 3 Effect of sleeping under insecticide-treated nets (ITNs) on malaria infection risk in children under the age of 5

	Relative effect	Absolute effect
Measure	Marginal odds ratio	Risk difference
Estimate	0.87	−0.022
95% CI [lower, higher]	[0.81, 0.93]	[−0.037, −0.006]
% effect	−13	−2.2
p value	< 0.001	0.005

Discussion

In this quasi-experimental analysis leveraging nationally representative survey data from Ghana, sleeping under an insecticide-treated net was associated with a modest but measurable reduction in malaria infection among children under five. Both the relative effect and the absolute effect indicate that ITNs continue to provide protective benefits in routine programmatic settings. Although the effect size is smaller than that reported in early randomized trials [17–19], it is broadly consistent with findings from contemporary operational research in high-transmission settings, where ITN effectiveness is attenuated by increasing pyrethroid resistance and behavioral adaptations in vector populations [20, 21]. Similarly, large observational studies in sub-Saharan Africa have reported that insecticide-treated net use is associated with an approximately 15–16% reduction in the odds of malaria infection compared with non-use [22]. Several behavioral and contextual factors may help explain the modest protective effect of ITN use observed in this study. In many households, intermittent net use, driven by heat, discomfort, or variable sleeping arrangements, reduces effective coverage despite high reported ownership [23]. Early evening and outdoor biting by malaria vectors, combined with children's outdoor activities before bedtime, creates substantial exposure during hours when nets are not yet deployed; this behavioral pattern is consistent with the clear age gradient observed in our findings, where older children had progressively higher odds and posterior means of malaria infection. These behavioral dynamics, together with the physical deterioration of nets and suboptimal hanging practices, likely constrain the real-world impact of ITNs and contribute to the modest effect size observed.

Several field studies conducted in settings with high ITN coverage have reported little or no additional personal protection from nets. In Haiti, where the predominant vector, *Anopheles albimanus*, primarily bites outdoors, a case–control study found no significant reduction in clinical malaria among ITN users [24]. Similarly, a case–control study in rural Malawi observed no measurable personal benefit for children, likely reflecting herd protection arising from very high community coverage [25].

Contextual factors offer further insights. The spatial analyses revealed a notable misalignment between intervention coverage and malaria burden. Regions with the highest indoor residual spraying (IRS) coverage, particularly in northern Ghana, continued to experience elevated malaria prevalence. This pattern reflects evidence of persistent malaria transmission in high-coverage IRS districts of northern Ghana, likely sustained by vector resistance, ecological suitability, and household structural vulnerabilities [26]. Malaria elimination program operational constraints, regional climatic suitability, and differences in program targeting may contribute to the observed discordance between coverage and impact. Conversely, regions with comparatively lower ITN use, such as Greater Accra, exhibited some of the lowest infection rates, reflecting structural, climatic, and urbanization-related reductions in receptivity rather than intervention effect per se.

This study revealed sociodemographic gradients in malaria outcomes, with higher maternal education and greater household wealth serving as protective factors consistently linked to lower odds of infection. These gradients likely reflect differences in housing quality, care-seeking behavior, health literacy, and broader socioeconomic determinants. Maternal education appears to strengthen the protective effect of ITN use by shaping knowledge and practices around malaria prevention. Educated mothers are more likely to ensure that children consistently sleep under nets and to maintain nets in good condition. They are also better equipped to interpret public health messages and adopt complementary preventive measures within the household [27]. These pathways suggest that maternal education enhances the effectiveness of ITNs, contributing to lower odds of malaria infection in households, where mothers have higher levels of schooling. The strong association between rural residence and heightened infection risk is also well-established and highlights the need for tailored strategies sensitive to environmental and infrastructural differences.

Although ITNs remain a cornerstone of Ghana's malaria prevention program, the relatively small magnitude of effect observed here underscores the need to integrate and sustain complementary interventions. Recent data on the RTS, S/AS01$_E$ malaria vaccine demonstrate substantial reductions in clinical malaria incidence when combined with vector control, particularly among highly exposed populations [28]. Emerging evidence from pilot implementation suggests additive benefits when ITNs, IRS, and vaccination are delivered together, a combination approach now reflected in WHO guidance. Strengthening environmental management, promoting improved housing, and addressing residual outdoor and early evening transmission will also be critical as Ghana transitions towards more integrated vector-management strategies.

This study benefits from the use of nationally representative, georeferenced data, allowing findings to reflect the full ecological and epidemiological diversity of malaria risk in Ghana. The analytic framework combining multilevel modeling, spatial assessment, and weighting approaches enhanced the robustness of estimates by improving comparability between exposure groups and accounting for clustering and contextual variation. These design elements strengthen confidence in the observed associations despite the inherent constraints of survey data.

Several limitations should be acknowledged, though the study's methodological choices helped mitigate many of them. ITN use was based on caregiver report and may be subject to misclassification, but adjustment for key demographic and socioeconomic correlates helped reduce associated bias. The cross-sectional design limits causal interpretation and cannot capture seasonal variability in malaria transmission; however, controlling for household and regional clustering attenuates some confounding related to unmeasured environmental factors. ITN condition and entomological indicators, such as insecticide resistance or outdoor biting, were not directly measured, yet spatial comparisons provided indirect contextual insight into regions, where these factors may diminish ITN effectiveness. Although residual confounding remains possible, the overall approach supports the credibility and policy relevance of the study's findings. Malaria transmission follows a clearly defined biological pathway, occurring only through bites from infected Anopheles mosquitoes, which substantially constrains the set of plausible unmeasured confounders. Combined with adjustment for other vector-control measures and relevant household and contextual characteristics, this enhances confidence that the estimated effects largely capture differences in mosquito exposure rather than residual or unrelated sources of bias.

Findings from this study showed that ITN use was associated with a modest reduction in malaria infection among children under five in Ghana, indicating that nets continue to provide important but limited protection. The modest effect likely reflects behavioral patterns, environmental exposure, and vector resistance that reduce the consistency and extent of protection ITNs can offer. Strengthening malaria control efforts will require attention to these contextual factors and better alignment of prevention strategies with local transmission dynamics. Continued monitoring and targeted support in high-risk areas will be essential to maximize the impact of existing interventions and reduce the burden of malaria among young children.

Abbreviations

ITN	Insecticide-treated nets
IRS	Indoor residual spraying
IPTW	Inverse probability of treatment weighting
GMIS	Ghana Malaria Indicator Survey
GDHS	Ghana Demographic and Health Survey
SMD	Standardized mean difference
ICC	Intraclass correlation coefficient

Supplementary Information

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Supplementary Material 1.

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Author contributions
KMO: conceptualization, data curation, formal analysis, visualization, manuscript writing—original draft, and manuscript writing—review and editing. AAA: data curation and manuscript writing—review and editing. WH: supervision, validation, and manuscript writing—review and editing.

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Data availability
The data sets used in this study are publicly available by registering the abstract and analysis plan at http://www.dhsprogram.com/data

Declarations

Ethics approval and consent to participate
The DHS protocol is approved by the Ethics Committee of ORC Macro Inc. This study used anonymized secondary data from the DHS available in the public domain.

Competing interest
The authors declare no competing interest.

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