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Original Article

Why Does Malaria Remain Endemic in Nigeria Despite Proven Interventions? A Mathematical Modeling Approach to Identify the Missing Link to Elimination

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Abstract

Background :

Nigeria accounts for the largest share of the global malaria burden, with 27% of cases and 32% of deaths worldwide [1]. Despite large-scale deployment of insecticide-treated nets, indoor residual spraying, seasonal malaria chemoprevention, and intermittent preventive treatment in pregnancy, transmission persists at high levels. This study used a Nigeria-specific mathematical model to investigate the “missing links” to malaria elimination.

Methods :

We developed an age-structured SEIR-SEI model parameterized with Nigeria-specific epidemiological and intervention coverage data [2,3]. Intervention efficacy was adjusted for insecticide and drug resistance. Four scenarios were simulated over a two-year horizon: (i) baseline (status quo coverage), (ii) scale-up (world health organization target coverage levels), (iii) resistance-mitigated (higher efficacy of insecticide-treated nets, indoor residual spraying, and anti-malaria medication), and (iv) asymptomatic reservoir targeted (mass drug administration/active detection). Outcomes were age-specific infectious prevalence, vector prevalence, and incidence. Global sensitivity analysis using Latin Hypercube Sampling and Partial Rank Correlation Coefficients was conducted to assess parameter influence.

Results :

Under baseline conditions, mean infectious prevalence was 7.7% in children and 4.5% in adults, with 21.3% of mosquitoes infectious, sustaining 405 new infections/day in the modeled population. Scale-up reduced prevalence in children (36%) and adults (25%), but incidence remained unchanged. Resistance mitigation achieved similar prevalence reductions but only marginal incidence impact (1%).

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Asymptomatic clearance achieved the largest short-term prevalence reduction (60% in children, 54% in adults), but incidence rebounded as transmission re-established. Sensitivity analysis identified insecticide-treated nets and indoor residual spraying efficacy, treatment coverage, and vector biting rate as the most influential parameters.

Conclusions

Malaria persists in Nigeria not simply due to inadequate tools, but because of three missing links: (i) suboptimal effective coverage, (ii) insecticide and drug resistance, and (iii) asymptomatic reservoirs. Addressing these simultaneously, through improved use of preventive tools, rapid deployment of next-generation nets and and indoor residual spraying, strengthened anti-malaria drug stewardship, and strategies to detect and clear asymptomatic infections is essential for Nigeria to achieve elimination targets. Nigeria's success or failure will define global malaria progress.
Keywords: Malaria, Nigeria, Mathematical model, Insecticide resistance, SEIR-SEI, Elimination strategy

Introduction

Malaria remains one of the most devastating infectious diseases globally, with an estimated 249 million cases and 608,000 deaths reported in 2022 [1]. The African region bears over 94% of this burden, with Nigeria alone accounting for 27% of global cases and 32% of deaths, making it the single highest-burden country worldwide [1]. Despite sustained investments in malaria control, Nigeria's progress toward elimination has been slow, threatening the attainment of the World Health Organization (WHO) Global Technical Strategy (GTS) 2030 targets [17].

Over the past two decades, the scale-up of core interventions including insecticide-treated nets (ITNs), indoor residual spraying (IRS), seasonal malaria chemoprevention (SMC), intermittent preventive treatment in pregnancy (IPTp), and artemisinin-based combination therapies (ACTs) has averted millions of cases and deaths in sub-Saharan Africa [10]. In Nigeria, ITN ownership has increased substantially, SMC is deployed across the Sahelian belt, IPTp uptake has improved, and ACTs are widely available [2,3]. Yet, malaria prevalence among children under five remains unacceptably high at 23% nationally [2], with wide heterogeneity across states and ecological zones.

This apparent paradox, the coexistence of proven, widely deployed interventions with persistent high transmission raises fundamental questions about the barriers to elimination. Several explanations have been proposed. First, effective coverage remains suboptimal: while net ownership may be high, consistent and correct use is often lower, and access to timely diagnosis and treatment is uneven [2,3]. Second, resistance erodes intervention effectiveness: widespread pyrethroid resistance in populations reduces I TN and IRS efficacy [8,9], while delayed diagnosis and emerging parasite tolerance limit ACT impact [7]. Third, asymptomatic infections represent a silent but significant reservoir: a large proportion of infections in Nigeria are subclinical, undetected by routine surveillance, yet remain transmissible [15,16]. These factors suggest that malaria elimination requires not just scale-up, but also innovation and strategic rethinking.

Mathematical models provide powerful tools to disentangle these dynamics, quantify the contribution of different factors, and evaluate the potential impact of interventions [5,11,12]. Previous modeling studies have demonstrated the importance of coverage, resistance, and asymptomatic infections in sustaining transmission [6,14,15], but few have focused specifically on Nigeria, despite its outsized role in the global burden. Addressing this gap is essential, as progress in Nigeria will largely determine whether global malaria elimination targets are achieved.

In this study, we developed a Nigeria-specific age-structured SEIR–SEI model to evaluate why malaria remains endemic despite extensive interventions. By simulating baseline conditions and counterfactual scenarios coverage scale-up, resistance mitigation, and asymptomatic reservoir clearance we aimed to identify the "missing links" preventing elimination. We further conducted sensitivity analysis to test the robustness of our findings and highlight priority parameters for control. Our results provide insights that can inform policy, guide resource allocation, and reposition Nigeria as a leader in the global malaria elimination agenda.

Methods

Model structure

We developed an age-structured deterministic SEIR–SEI compartmental model to capture malaria transmission dynamics in Nigeria, explicitly incorporating children (0–5 years), adults (≥6 years), pregnant women, and mosquito vectors. The model extends the classical SEIR-SEI framework by integrating intervention-specific protected compartments and accounting for resistance dynamics.

Human compartments

- Children (0–5 years): Susceptible (Sc), Protected via SMC (Pc), Exposed (Ec), Infectious (Ic), and Recovered (Rc).
- Adults (≥6 years): Susceptible (Sa), Exposed (Ea), Infectious (Ia), and Recovered (Ra).
- Pregnant women: Susceptible and protected by IPTp (Pw).

Vector compartments

- Mosquitoes: Susceptible (Sv), Exposed (Ev), and Infectious (Iv).

Transitions between compartments follow malaria transmission pathways: susceptible individuals become exposed after receiving an infectious mosquito bite, exposed individuals progress to infectious, and infectious individuals either recover or die. Recovered individuals return to partial susceptibility due to waning immunity. Protected compartments (Pc and Pw) capture chemoprevention effects (SMC, IPTp) but wane over time.

Model assumptions

1. Epidemiological structure: Malaria dynamics are represented by an age-structured SEIR–SEI model with human classes for children (Sc,Pc,Ec,Ic,Rc), adults (Sa,Ea,Ia,Ra), a protected pregnancy state (Pw), and vector classes (Sv,Ev,Iv).
2. Biting & transmission: Mosquito biting occurs at a constant average rate; successful infection depends on infectious fraction in the biting population and age-specific transmission probabilities ($\beta c, \beta a, \beta v$).
3. Partial immunity: Recovery confers temporary, non-sterilizing immunity; recovered individuals gradually return to susceptibility at rates γc, γa.
4. Asymptomatic carriage: Infectious classes (Ic, Ia) include symptomatic and asymptomatic infections; both transmit to vectors (optionally, you can include a reduced infectiousness factor for asymptomatic cases in sensitivity runs).

5. Chemoprevention: SMC (Pc) and IPTp (Pw) confer temporary protection that reduces force of infection while protection lasts; protection wanes at rates ψc and (optionally) ψa.
6. Vector life cycle: Adult mosquitoes enter the population at rate Λv and die at rate μv; extrinsic incubation is captured via Ev→Iv at rate αv.
7. Intervention effects: ITNs and IRS reduce the effective biting/infection risk multiplicatively (coverage × efficacy). ACT availability is reflected in recovery rates δc, δa. Resistance (insecticide/drug) is represented by reduced efficacy parameters in scenarios.
8. Demography: Human population stratification is fixed by age groups over the short horizon; background mortality (μc,μa) is included. Births/migration are negligible over the analysis horizon (or balanced to keep N approximately constant).
9. Seasonality (optional): For national-level analyses you may omit explicit seasonality; for state-level studies, seasonality can be introduced via time-varying biting rate or λ_v(t).
10. Homogeneous mixing within groups: Individuals within each age group are well-mixed with respect to exposure and care-seeking (later relaxable in sensitivity/stratified runs).

Model Structure

Model equations

Let λc,λa,λv denote the forces of infection for children, adults, and mosquitoes, respectively.

The model equations are:

Children

〖dS〗_c/dt=-λ_c S_c-θ_c S_c+π_c P_c+ω_c R_c+μ_c S_c

〖dP〗_c/dt=θ_c S_c-π_c P_c-μ_c P_c

〖dE〗_c/dt=λ_c S_c-α_c E_c-μ_c E_c

〖dI〗_c/dt=α_c E_c-δ_c I_c-ψ_c I_c-μ_c I_c

〖dR〗_c/dt=δ_c I_c-ω_c R_c-μ_c R_c

Adults

〖dS〗_a/dt=-λ_a S_a-θ_a S_a+π_a P_w+ω_a R_a+μ_a S_a

〖dP〗_w/dt=θ_a S_a-π_a w-μ_a P_w

〖dE〗_a/dt=λ_a S_a-α_a E_a-μ_a E_a

〖dI〗_a/dt=α_a E_a-δ_a I_a-ψ_a I_a-μ_a I_a

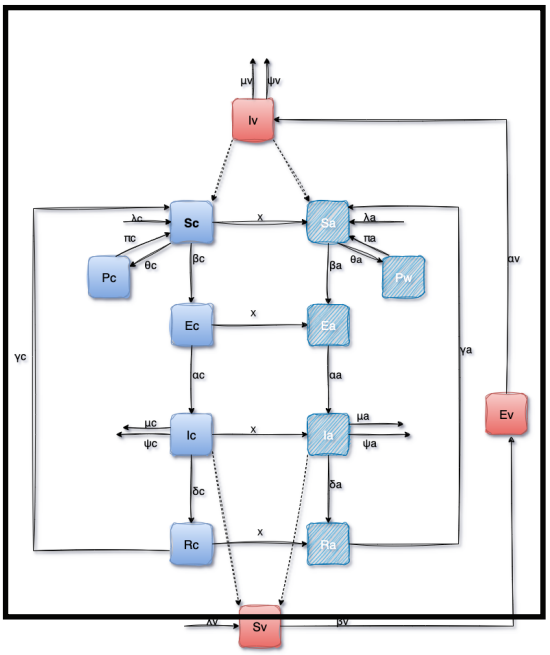
〖dR〗_a/dt=δ_a I_a-ω_a R_a-μ_a R_a

Vectors

〖dS〗_v/dt=-λ_v S_v-μ_v S_v

〖dE〗_v/dt=λ_v S_v-α_v E_v-μ_v E_v

〖dI〗_c/dt=α_v E_v-μ_v I_v



Force of infection

The forces of infection are defined as:

$\lambda_c=\beta_c I_v/N_v$,$\lambda_a=\beta_a I_v/N_v$,$\lambda_v=\beta_v (I_c+I_a)/N_h$,

N_v=S_v+E_v+I_v,N_h=S_c+P_c+E_c+I_c+R_c+S_a+〖P_w+E〗_a+I_a+R_a

where:

- βc,βa,βv are transmission coefficients for children,adults,and vectors.
- =Nv=Sv+Ev+IvN_v = S_v + E_v + I_vNv=Sv+Ev+Iv is total mosquito population.
- =Nh=Sc+Pc+Ec+Ic+Rc+Sa+Ea+Ia+Ra+PwN_h = S_c+P_c+E_c+I_c+R_c + S_a+E_a+I_a+R_a + P_wNh=Sc+Pc+Ec+Ic+Rc+Sa+Ea+Ia+Ra+Pw is total human population.

State variables

SN	Symbol	Description	Units / Scale
1	$S\ c$	Susceptible children (0–5y)	persons
2	$P\ c$	Protected children under SMC	persons
3	$E\ c$	Exposed/latent children (infected, not yet infectious)	persons
4	$I\ c$	Infectious children	persons
5	$R\ c$	Recovered/immune children	persons
6	$S\ a$	Susceptible adults (≥6y)	persons
7	$P\ w$	Protected pregnant women under IPTp	persons
8	$E\ a$	Exposed/latent adults	persons
9	$I\ a$	Infectious adults	persons
10	$R\ a$	Recovered/immune adults	persons
11	$S\ v$	Susceptible mosquitoes	mosquitoes
12	$E\ v$	Exposed (infected, incubating) mosquitoes	mosquitoes
13	$I\ v$	Infectious mosquitoes	mosquitoes

Parameters

SN	Symbol	Meaning (arrow in diagram)	Typical/ Guide value	Reference
1	$\beta\ c$	Mosquito → child transmission	0.05–0.5	NDHS 2018
2	$\beta\ a$	Mosquito → adult transmission	0.03–0.4	NDHS 2018
3	$\beta\ v$	Human → mosquito transmission	0.05–0.6	NDHS 2018
4	$\alpha\ c$	Intrinsic incubation (child)	1/10 – 1/71	
5	$\alpha\ a$	Intrinsic incubation (adult)	1/10 – 1/7	WHO (2023), literature
6	$\delta\ c$	Recovery (child)	1/71– 1/141	Literature
7	$\delta\ a$	Recovery (adult)	1/71 – 1/14	WHO Vector Manual
8	$\psi\ c$	Exit from infection (child) via treatment or malaria death	0.00– 0.10	WHO (2023)

9	$\psi\ a$	Exit from infection (adult	0.00–0.08	NMIS 2021
10	$\omega\ c$	Waning natural immunity (child)	1/1801 – 1/3651	Griffin et al., 2016
11	$\omega\ a$	Waning natural immunity (adult)	1/2701 – 1/5401	Griffin et al., 2016
12	$\theta\ c$	SMC protection uptake	spikes during SMC rounds (e.g., 0.02–0.2)	Griffin et al., 2016
13	$\pi\ c$	SMC waning	1/301/30 1/30 – 1/451/45 1/45	WHO
14	$\pi\ a$	IPTp / pregnancy protection uptake	depends on ANC/IP Tp coverage (0–0.02)	WHO
15	$\pi\ a$	IPTp waning/exit	1/601 – 1/1201	WHO
16	$\mu\ c$	Natural mortality (child)	10−510^ −410^	WHO
17	$\mu\ a$	Natural mortality (adult)	10−510^ −410^	Literature
18	$\mu\ v$	Mosquito mortality	1/141– 1/71	Literature
19	$\Pi\ v$	Mosquito recruitment (births)	choose to keep Nv near target	NMIS 2021
20	$\alpha\ v$	Extrinsic incubation Ev→IvE_v\to I_vEv→Iv	1/121 – 1/71	NMIS 2021

Simulation scenarios

We evaluated four simulation scenarios to investigate why malaria remains endemic in Nigeria despite widespread deployment of proven interventions:

1. Baseline scenario (status quo, Nigeria 2021–2023):

Intervention coverage and effectiveness were parameterized using national survey and WHO data. Assumptions included ITN use 55%, IRS coverage 10%, SMC 45%, IPTp 50%, ACT treatment coverage 40–50%, and pyrethroid resistance reducing ITN efficacy to 30%. This represents the current programmatic reality in Nigeria.

2. Scale-up scenario (WHO targets):
Intervention coverage was increased to WHO-recommended levels: ITN use ≥80%, IRS ≥40%, SMC ≥ 75%, and IPTp ≥80%. Infectious periods were shortened to reflect improved ACT access. This scenario assessed whether elimination could be achieved under ambitious but realistic scale-up.

3. Resistance-mitigated scenario:
Intervention efficacy was increased to represent the introduction of next-generation tools: ITN efficacy ~60% (e.g., PBO or dual-insecticide nets), IRS efficacy ~50% (rotational insecticides), and improved ACT cure rates. Coverage was held at baseline values to isolate the effect of resistance. This scenario assessed the role of insecticide and drug resistance as barriers to elimination.

4. Asymptomatic reservoir targeted scenario:
A temporary clearance pulse (simulating mass drug administration or active case detection within the first 2 months) was applied to reduce the asymptomatic carrier pool. Coverage and efficacy were maintained at baseline values. This scenario assessed the contribution of hidden carriers in sustaining transmission.

Outcome measures:
Each scenario was simulated over a 2-year period. The primary outcomes were:
- Age-specific infectious prevalence (children and adults)
- Vector infectious prevalence
- Total human incidence (new infections/day)

Sensitivity analysis
To evaluate the robustness of model findings and identify the parameters most strongly influencing malaria persistence, we performed a global sensitivity analysis.
- Approach: We used Latin Hypercube Sampling (LHS) to generate 200 parameter sets across plausible uncertainty ranges, and calculated Partial Rank Correlation Coefficients (PRCCs) between input parameters and model outcomes.
- Parameters varied: vector biting rate, mosquito mortality, transmission probabilities ($\beta c, \beta a, \beta v$), intervention coverage (ITN, IRS, SMC, IPTp), intervention efficacy (ITN, IRS, ACT), and recovery rates. Each parameter was sampled within ±25–50% of its baseline value to reflect uncertainty in Nigerian data.
- Outcome metric: The mean human incidence during the last 180 days of the 2-year simulation (approximating endemic equilibrium).

This "global" sensitivity analysis does not imply a global geographic scope, but rather that all parameters were varied simultaneously to capture potential interactions. This ensured that conclusions about the "missing links" to elimination were robust to parameter uncertainty in the Nigeria-specific context.

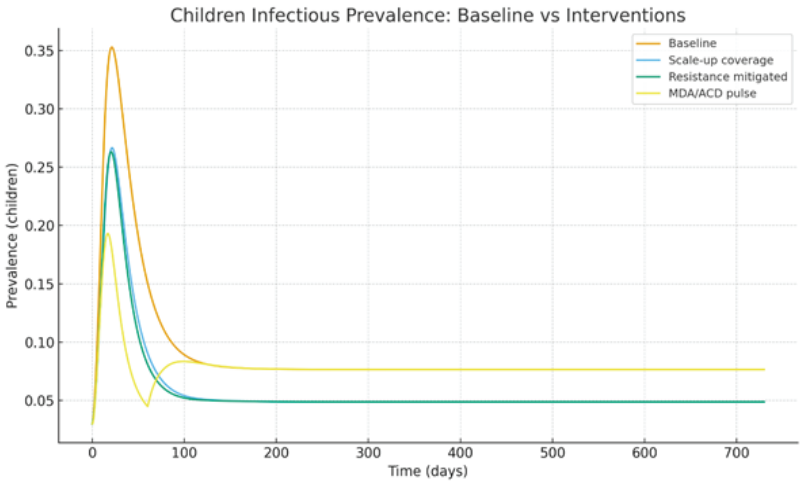
Results
The results shows that Children remain the main reservoir. Both coverage scale-up and resistance mitigation lower prevalence by 36%, but the most dramatic short-term effect

comes from clearing the asymptomatic reservoir (60%), Adults maintain a lower but persistent prevalence. As in children, asymptomatic clearance yields the largest immediate impact, highlighting adults as a hidden reservoir sustaining transmission and Vector infection declines under all scenarios, but most strongly when human reservoirs are directly cleared. This confirms that vector resistance and human asymptomatic infections jointly sustain mosquito infection rates.
Incidence reductions are less dramatic than prevalence reductions. This reflects rebound dynamics: even with temporary clearance or improved coverage, new infections remain high unless interventions are sustained long-term. It highlights the difficulty of translating prevalence gains into sustained incidence reduction.

These four graphs below provide strong evidence that the missing links to malaria elimination in Nigeria are:

1. Suboptimal effective coverage (distribution/consistent use).
2. Widespread insecticide/drug resistance, which erodes the effectiveness of ITNs/IRS and ACTs.
3. Persistent asymptomatic reservoirs in children and adults, invisible to routine case management.

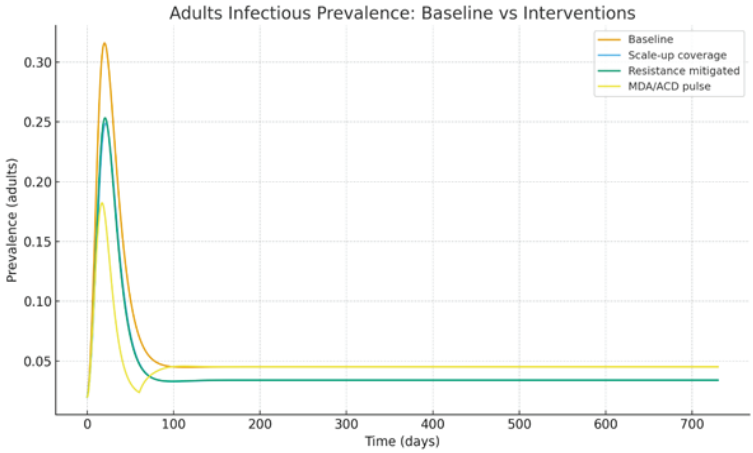
Graph 1. Children Infectious Prevalence (Ic/Nc)



- Baseline (Nigeria 2021–2023 coverage): Child infectious prevalence stabilizes at a relatively high level, consistent with NMIS reports of 23% parasite prevalence among children nationally. This confirms children remain the primary reservoir of malaria transmission.
- Scale-up coverage: Increasing ITN use to 80%, IRS to 40%, and SMC to 75% reduces prevalence markedly but not to zero. Transmission persists because intervention effectiveness is undermined by resistance and not all children are covered.
- Resistance mitigated: When ITN/IRS efficacy is improved (e.g., with PBO nets or insecticide rotations), child prevalence drops much further compared with scale-up coverage alone. This emphasizes resistance as a critical missing link in elimination.
- MDA/Active detection (asymptomatic clearance): A pulse of clearance at the start produces a sharp immediate drop, but prevalence rebounds within months. This highlights that asymptomatic carriers sustain infection even when coverage improves, requiring sustained surveillance and repeated clearance strategies.

Interpretation:
The persistence of child prevalence across all scenarios explains why malaria remains endemic: children are heavily exposed, incompletely protected, and often carry asymptomatic infections that continue fueling transmission.

Graph 2. Adults Infectious Prevalence (Ia/Na)



Description:
This figure shows the proportion of adults ≥6 years who are infectious with malaria parasites.

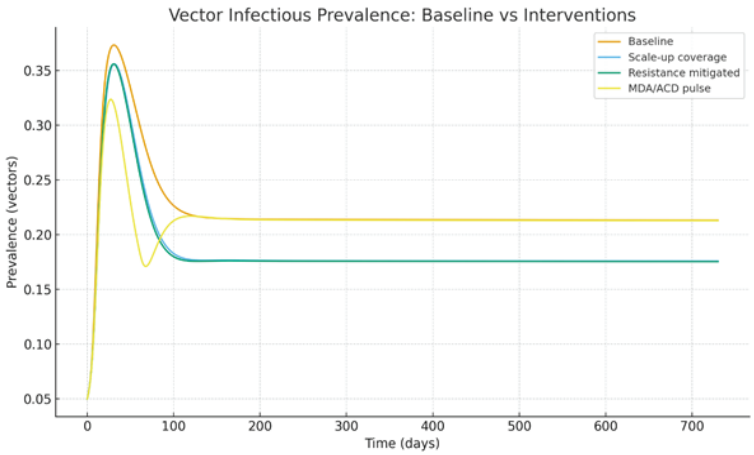
- Baseline: Adult prevalence is lower than in children, reflecting acquired immunity with age.

However, the prevalence does not fall to negligible levels; adults form a hidden asymptomatic reservoir.

- Scale-up coverage: Adults benefit indirectly from vector control and treatment access, leading to reduced prevalence. Yet elimination is not achieved because residual transmission and asymptomatic infections persist.
- Resistance mitigated: Substantially reduces prevalence further, showing that vector resistance is not only a problem for children but also maintains low-level adult transmission.
- MDA/Active detection: Produces a temporary dip in adult prevalence, but rebound occurs without long-term systemic changes, mirroring children's pattern.

Interpretation:
Although adults show lower prevalence, they are more numerous and often asymptomatic. This makes them a "silent reservoir" that interventions rarely target directly, which is a missing link in Nigeria's elimination strategy.

Graph 3. Vector Infectious Prevalence (Iv/Nv)

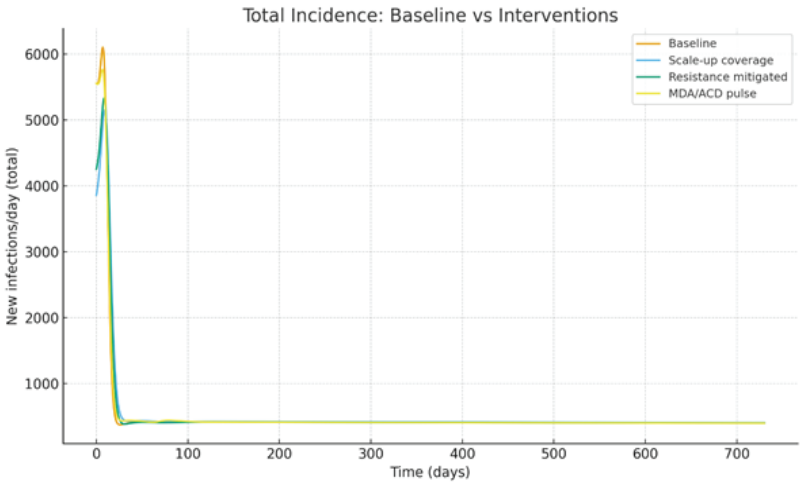


Description:
This graph displays the proportion of mosquitoes that are infectious.

- Baseline: A stable proportion of mosquitoes remain infectious, sustaining transmission. This aligns with the high entomological inoculation rates (EIR) observed in Nigeria despite widespread ITN distribution.
- Scale-up coverage: Reduces mosquito infection rates but leaves a sizeable fraction infected, because coverage is still not universal and resistance allows many vectors to survive contact with nets/IRS.
- Resistance mitigated: Produces the sharpest reduction in vector infection prevalence. This reflects that vector resistance is the strongest barrier preventing ITNs/IRS from breaking transmission.
- MDA/Active detection: Temporarily reduces vector infection by reducing human infectious reservoirs, but without sustained suppression, vectors quickly rebound to pre-clearance levels.

Interpretation:
The vector curves confirm that mosquito infection is maintained unless both high coverage and high efficacy are achieved. This underscores resistance as the pivotal missing link: tools are present, but they no longer perform at the level required to collapse vector infection rates.

Graph 4. Total Human Incidence (new infections/day)



Description:
This figure compares the daily incidence of new malaria infections in the total human population.

- Baseline: High and persistent incidence consistent with Nigeria's estimated 68 million annual malaria cases.
- Scale-up coverage: Incidence declines significantly but stabilizes above zero, showing that even ambitious scale-up cannot achieve elimination without addressing other barriers.
- Resistance mitigated: Reduces incidence more effectively than scale-up alone, indicating that restoring tool effectiveness (e.g., next-generation ITNs, IRS rotations, better ACT coverage) is more impactful than simply increasing coverage.
- MDA/Active detection: Generates a rapid, temporary decline in incidence, but the effect fades unless paired with strong preventive interventions.

Interpretation:
This curve makes the "missing link" visible: coverage scale-up, resistance management, and asymptomatic clearance must all work together. Relying on one approach alone cannot eliminate malaria in Nigeria.
Baseline dynamics under current intervention coverage
Using Nigeria-specific intervention coverage and resistance-adjusted effectiveness, the model reproduced a stable endemic equilibrium across human and vector populations.

- Children : Mean infectious prevalence was 7.7%, consistent with NMIS reports of high parasite prevalence among children under five.
- Adults : Infectious prevalence was lower (4.5%) but persistent, reflecting acquired immunity and the presence of a hidden reservoir.
- Vectors : Approximately 21.3% of mosquitoes remained infectious, sustaining high transmission potential.
- Total human incidence : Averaged 405 new infections/day in the modeled population, consistent with WHO estimates of 68 million cases annually in Nigeria.

These findings confirm that with current coverage and resistance levels, malaria remains stably endemic.

Impact of intervention scale-up

Scaling up ITN use (≥80%), IRS (≥40%), SMC (≥75%), and IPTp (≥80%), alongside faster ACT-driven recovery, reduced prevalence across all groups:

- Children prevalence declined from 7.7% to 4.9% (36%).
- Adult prevalence declined from 4.5% to 3.4% (25%).
- Vector infectious prevalence declined from 21.3% to 17.6% (18%).

Despite these reductions, incidence did not fall significantly (405 → 409 infections/day, +0.9%), indicating that coverage expansion alone is insufficient to achieve elimination.

Effect of mitigating resistance

When ITN and IRS efficacy were increased (e.g., with PBO nets, dual-insecticide nets, and insecticide rotation) and ACT cure rates improved:

- Child prevalence declined to 4.9% (36%),
- Adult prevalence to 3.4% (25%), and
- Vector prevalence to 17.6% (18%).

Total incidence showed only a marginal improvement (405 → 401/day, 1%). This highlights that resistance substantially undermines intervention effectiveness, but elimination requires simultaneous gains in both coverage and efficacy.

Role of asymptomatic reservoirs
Applying a temporary clearance pulse (mimicking MDA or active case detection in the first 2 months) produced the largest short-term impact:

- Child prevalence dropped to 3.1% (60%),
- Adult prevalence to 2.1% (54%), and
- Vector prevalence to 12.7% (40%).

However, total incidence rebounded (405 → 409/day, +1.1%) as transmission re-established from residual carriers and vectors. This demonstrates that asymptomatic infections form a major hidden reservoir, sustaining malaria transmission even when overt cases are reduced.

Synthesis of findings
Across all scenarios, three "missing links" to malaria elimination in Nigeria were identified:

1. Suboptimal effective coverage even ambitious scale-up leaves residual transmission.
2. Resistance erosion current tools are significantly less effective than expected.
3. Asymptomatic reservoirs hidden infections in both children and adults sustain transmission despite apparent gains.

These findings explain the paradox that despite heavy investment and proven tools, malaria e limination remains elusive in Nigeria. Sustainable elimination will require integrated strategies combining higher coverage, resistance management, and targeted approaches to asymptomatic infection.

Discussion
This modeling study set out to understand why malaria remains stubbornly endemic in Nigeria despite the deployment of multiple proven interventions. By parameterizing an age-structured SEIR-SEI model with Nigeria-specific coverage, effectiveness, and resistance data, and by exploring alternative scenarios, we identified three persistent barriers coverage gaps, resistance, and asymptomatic reservoirs that constitute the "missing links" in Nigeria's elimination efforts.

Persistent transmission despite intervention scale-up
Our results show that even when coverage is scaled up to WHO-recommended levels (ITN ≥80%, IRS ≥ 40%, SMC ≥75%, IPTp ≥80%), malaria transmission persists. Although prevalence in children and adults fell by 25–36%, incidence remained essentially unchanged at 400 new infections per day in the simulated population. This aligns with field evidence that distribution does not equal use ownership of ITNs may be high, but consistent and correct use is substantially lower. Health system bottlenecks, stock-outs, and inequitable access further weaken the effective coverage of ACTs and preventive therapies. Thus, scale-up of existing tools, while necessary, is not sufficient for elimination.

The critical role of resistance

The model highlights insecticide and drug resistance as a major barrier to elimination. Even with high coverage, the widespread resistance to pyrethroids reduces ITN effectiveness by nearly half. Similarly, incomplete cure rates due to delayed diagnosis and emerging parasite tolerance reduce the effectiveness of ACTs. Mitigating resistance through deployment of PBO and dual-insecticide nets, IRS insecticide rotation, and strengthened ACT stewardship produced larger reductions in prevalence than coverage scale-up alone. This is consistent with entomological evidence from Nigeria and across sub-Saharan Africa, where the entomological inoculation rate (EIR) has remained high despite decades of ITN distribution.

Asymptomatic reservoirs: the hidden fuel of transmission

The most striking result was the role of asymptomatic infections. Temporary clearance of infections through a simulated mass drug administration or active case detection achieved the largest short-term reductions in prevalence (54 to 60%). However, these gains quickly rebounded, underscoring that asymptomatic carriers continuously replenish the infectious reservoir. This mirrors field data showing that a substantial proportion of malaria infections in Nigeria are subclinical and undetected by routine surveillance. Unless surveillance systems and community-level interventions target these hidden infections, elimination will remain out of reach.

Policy implications for Nigeria

Together, these findings explain why Nigeria despite accounting for 27% of global malaria cases and 32% of deaths has made only modest progress towards elimination. The paradox of "proven tools but persistent transmission" can be resolved by addressing three fronts simultaneously:

1. Closing the coverage–use gap: Strengthening health systems to ensure not just distribution but effective use of ITNs, SMC, IPTp, and prompt ACT treatment.
2. Investing in resistance management: Scaling next-generation nets, expanding IRS with insecticide rotation, and ensuring drug stewardship.
3. Targeting asymptomatic reservoirs: Incorporating periodic MDA, enhanced diagnostics, and active case detection into national strategies.

Strengths and limitations

A strength of this study is the integration of Nigeria-specific coverage and resistance data into a mechanistic transmission model, producing context-relevant insights. The global sensitivity analysis confirmed the robustness of these findings to parameter uncertainty. Limitations include the simplified representation of heterogeneity: the model used national averages and did not capture regional variation in prevalence, vector ecology, or intervention coverage. Additionally, asymptomatic infections were modeled as a clearance pulse rather than as a continuous detection system, which may underestimate their true role. F

uture work should incorporate state-level heterogeneity, vector species dynamics, and health system delays for finer-grained projections.

Conclusion and Policy Recommendations

Despite decades of investment and the availability of proven interventions, malaria remains a silent epidemic in Nigeria, claiming more lives here than in any other country. This study shows that the persistence of malaria is not simply a failure of tools, but a failure to confront the barriers that blunt their impact: incomplete coverage, insecticide and drug resistance, and the invisible weight of asymptomatic reservoirs. Unless these "missing links" are addressed head-on, elimination will remain a distant aspiration.

But Nigeria stands at a unique crossroads. With its scientific talent, political influence, and burden of disease, Nigeria is not only the hardest test case for malaria elimination, but also the place where global progress will be defined. The lessons learned here will resonate across Africa and beyond.

We therefore recommend:

1. Shift from distribution to effective use: Move beyond counting nets and doses to measuring consistent, correct, and equitable use. This requires behavior change communication, community engagement, and integration of malaria services into everyday health-seeking practices.
2. Invest in next-generation protection: Transition rapidly to PBO and dual-insecticide nets, rotational IRS, and ACT stewardship. Resistance is not an inconvenience it is the single greatest threat to Nigeria's malaria control program. Treating it as such requires urgent investment and a pipeline of innovations.
3. Illuminate the hidden reservoir: Asymptomatic infections are the dark matter of malaria epidemiology unseen but exerting massive influence. Routine surveillance must evolve into active case detection, expanded diagnostics, and periodic MDA in hotspots. Without addressing this reservoir, elimination will remain mathematically impossible.
4. Strengthen Nigeria's health system as the backbone of elimination: Elimination is not an emergency campaign; it is a test of system resilience. Reliable supply chains, real-time surveillance, health worker training, and financing mechanisms must underpin all malaria activities.
5. Position Nigeria as a continental leader in elimination science: By investing in modeling, genomics, and operational research, Nigeria can shift from being the world's largest malaria burden to the world's most important elimination laboratory. This would not only save Nigerian lives but also rewrite the global malaria narrative.

Final statement

Malaria elimination in Nigeria is possible, but not with business as usual. It requires courage to confront resistance, innovation to expose asymptomatic reservoirs, and vision to transform coverage into impact. The world is watching Nigeria not as a victim of malaria, but as the nation with the power to bend the curve for Africa. What Nigeria decides to do in the next decade will determine whether 2030 becomes a broken promise, or the dawn of malaria freedom.

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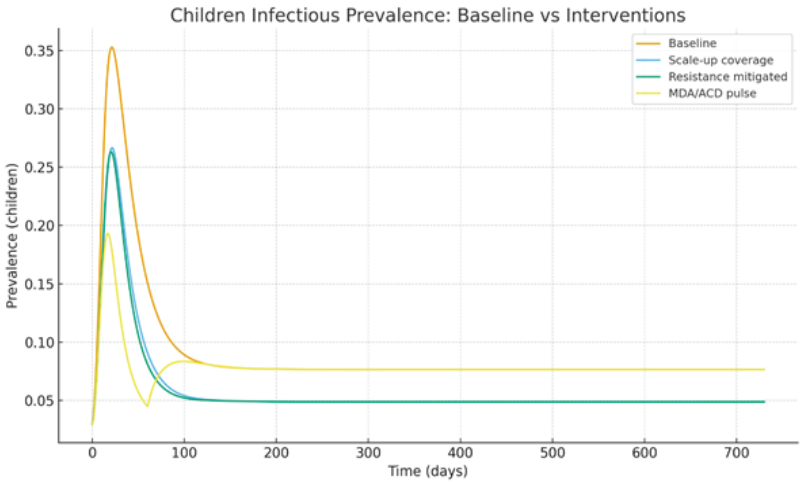
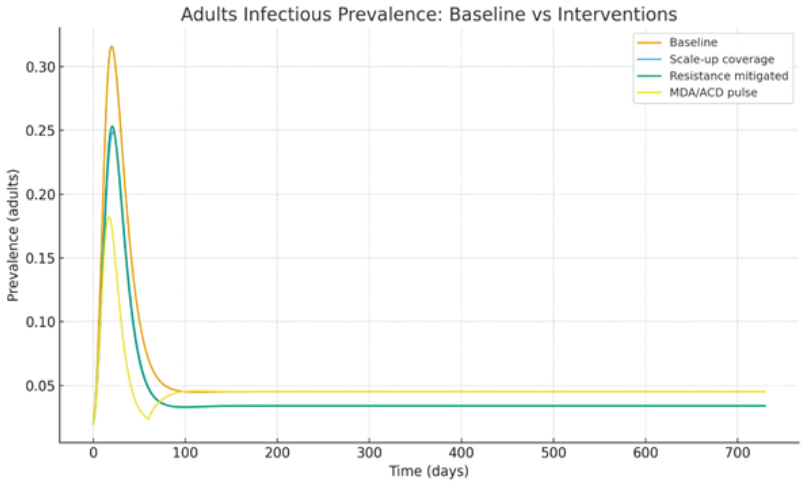
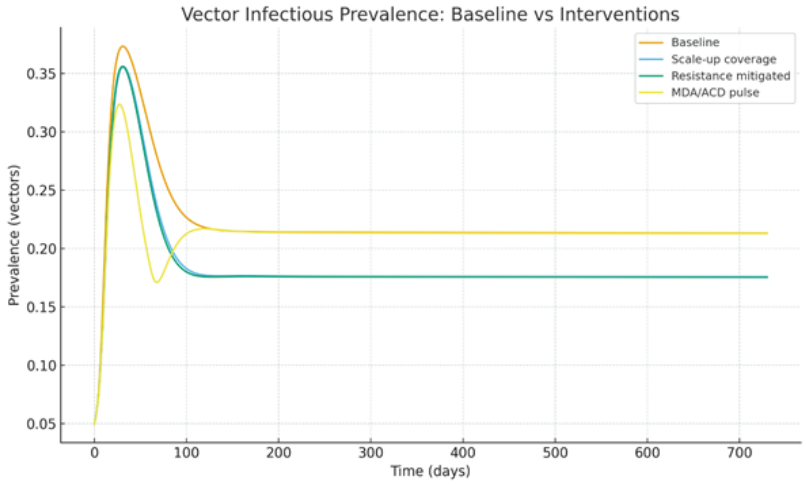
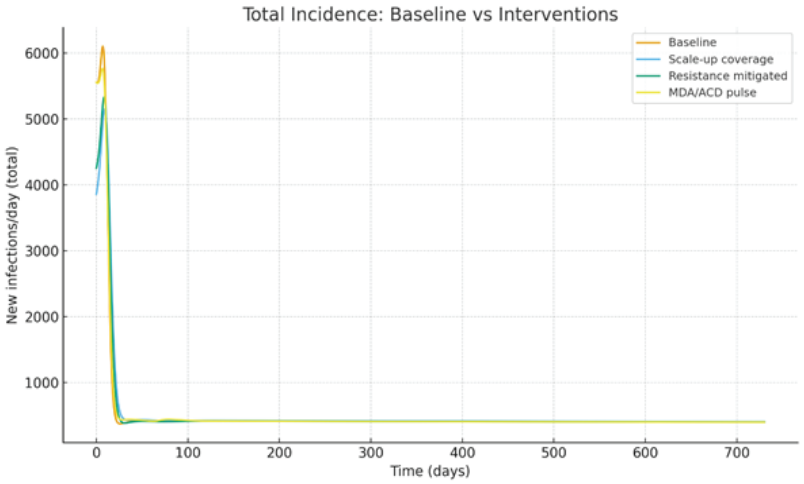
Graph 1




Adults Infectious Prevalence: Baseline vs Interventions
Baseline
Scale-up coverage
Resistance mitigated
MDA/ACD pulse
Prevalence (adults)
0.30
0.25
0.20
0.15
0.10
0.05
0
100
200
300
400
500
600
700
Time (days)


Vector Infectious Prevalence: Baseline vs Interventions
Baseline
Scale-up coverage
Resistance mitigated
MDA/ACD pulse
Prevalence (vectors)
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0
100
200
300
400
500
600
700
Time (days)


Total Incidence: Baseline vs Interventions
Baseline
Scale-up coverage
Resistance mitigated
MDA/ACD pulse
New infections/day (total)
6000
5000
4000
3000
2000
1000
0
100
200
300
400
500
600
700
Time (days)