

Malaria Intervention Effectiveness and Consistency in Sub-Saharan Africa: Systematic Mapping and Meta-Analysis Across Policy Periods (2011 to 2025)

Eric Aigbogun

eric.aigbogun@solinagroup.com

Solina Centre for International Development and Research (SCIDaR)

Precious Uahomo

Solina Centre for International Development and Research (SCIDaR)

Ibrahim Iya

Solina Centre for International Development and Research (SCIDaR)

Oluwaseun Fadeyi

Solina Centre for International Development and Research (SCIDaR)

Oluwafunmilayo Raheem

Solina Centre for International Development and Research (SCIDaR)

Idowu Akanmu

Solina Centre for International Development and Research (SCIDaR)

Shukrat Yusuff-Lawal

Solina Centre for International Development and Research (SCIDaR)

Osezefe Ehimen

Solina Centre for International Development and Research (SCIDaR)

Miftahu Yahaya

Solina Centre for International Development and Research (SCIDaR)

Saheed Popoola

Solina Centre for International Development and Research (SCIDaR)

Zaharaddeen Babandi

Solina Centre for International Development and Research (SCIDaR)

Ernest Ezeogu

Solina Centre for International Development and Research (SCIDaR)

Chioma Ijah

Solina Centre for International Development and Research (SCIDaR)

Ahmed Mustapha

Solina Centre for International Development and Research (SCIDaR)

Tisan Gugong

Solina Centre for International Development and Research (SCIDaR)

Oluwaleke Jegede

Solina Centre for International Development and Research (SCIDaR)

Uchenna Igbokwe

Solina Centre for International Development and Research (SCIDaR)

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Abstract

Introduction:

This study is a systematic mapping and meta-analysis of comparative malaria intervention studies conducted in SSA across policy periods: pre-SNT (2011–2018) and post-SNT (2019–2025), to assess whether the introduction of SNT had made any significant impact on malaria intervention strategies and outcomes.

Methods

A systematic mapping review with meta-analysis was conducted in accordance with PRISMA 2020 guidelines, with the study protocol registered on the Open Science Framework (<https://osf.io/5rxsp>) and PROSPERO (registration number CRD420261375304). Comparative malaria intervention studies conducted in SSA between 2011 and 2025 were identified from multiple databases. Eligible studies evaluated interventions of epidemiological significance using randomized or quasi-experimental designs and reported quantitative malaria outcomes. Studies were classified into pre-SNT (2011–2018) and post-SNT (2019–2025) periods. Random-effects meta-analyses were conducted across four intervention domains: chemoprevention and treatment, vector control, behavioral and coverage interventions, and epidemiological outcomes. Heterogeneity was assessed using I^2 , τ^2 , and prediction intervals, with subgroup analyses comparing pre- and post-SNT periods.

Results

A total of 108 studies across 34 SSA countries were mapped, with 65 included in the meta-analysis, following strict assessment criteria recommended by PRISMA. The studies had analyzable data for four key domains: chemotherapy and treatment outcomes, vector control outcomes, behavioral and coverage outcomes, and epidemiological outcomes. Across all domains, post-SNT interventions showed substantial reductions in between-study heterogeneity (τ^2 reductions ranging from 87% to 100%) and marked narrowing of prediction intervals. In the pre-SNT period, no intervention domain achieved statistical significance, despite directionally favorable pooled effects. In contrast, post-SNT interventions demonstrated statistically significant effects for behavioral and coverage outcomes ($t_{(2)} = -0.480, p = 0.042$) and epidemiological outcomes ($t_{(15)} = -2.77, p = 0.014$). Average effect sizes did not differ significantly between periods, but consistency and predictability improved markedly after SNT introduction.

Conclusion

Sub-national tailoring was associated with more consistent and reliable malaria intervention outcomes in SSA, rather than larger average effects. These findings support continued investment in SNT, with focus on stratified planning, sub-national data systems, and adaptive implementation to enhance the effectiveness and predictability.

Introduction

Background

Despite decades of intensified control and elimination initiatives, malaria remains one of the most persistent public health challenges in Sub-Saharan Africa (SSA), and this accounts for an overwhelming number of global malaria morbidity and mortality (Oladipo et al., 2022). According to the World Health Organization (WHO), over 90% of global deaths relating to malaria infections occur in SSA. This burden concentration is a reflection of the prevalence of *Plasmodium falciparum*, its complex vector ecology, and substantial heterogeneity in transmission intensity across and within countries (WHO, 2023). Since the early 2000s, the scale up of the already established control strategies which includes long-lasting insecticidal nets (LLINs), indoor residual spraying (IRS), rapid diagnostic tests (RDTs), intermittent preventive treatment (IPT), and artemisinin-based combination therapies (ACTs), has led to a large decline in malaria cases and deaths. However, the initial momentum gained has reduced over time, with some regions experiencing a resurgence in transmission (Bhatt et al., 2015; WHO, 2023).

Overtime, evidence has shown that applying standardized national malaria control strategies across different epidemiological, demographic, and health system contexts has contributed to the uneven and often limited impact of these interventions (Gosling et

al., 2015; WHO, 2018). In October 2018, the WHO formally introduced the Sub-National Tailoring (SNT) approach as a response to this challenge, by advocating for malaria risk to be stratified at subnational levels and for intervention packages to be aligned with local transmission dynamics and contextual factors (WHO, 2018). SNT represents a shift from “one-size-fits-all” programming toward more targeted, data-driven deployment of interventions, with the potential to improve efficiency, effectiveness, and sustainability of malaria control and elimination efforts.

Following the adoption of SNT, the number of studies assessing malaria interventions in SSA has increased substantially, however; this evidence remains fragmented, with variations in intervention types, study designs, geographic settings, and outcome measures. Despite the insights generated by individual trials and quasi-experimental evaluations, the absence of an overarching synthesis means that the broader trajectory of intervention performance cannot be clearly traced. As a result, it is challenging to determine how effectiveness has evolved across different locations and policy phases, particularly when examining shifts between the pre-SNT and post-SNT implementation eras. Moreover, many existing reviews focus on single intervention categories or specific populations, offering limited insight into broader patterns of epidemiological impact and tailoring strategies across the malaria control landscape (Tusting et al., 2013; Eisele et al., 2021).

Meta-analysis/Meta-analysis methods offer a robust framework for integrating findings from comparative studies, enabling quantitative estimation of pooled intervention effects while accounting for heterogeneity across settings and study designs (Higgins et al., 2013). Integrating these methods with systematic mapping makes it possible to pinpoint areas where evidence is lacking, highlight regions where research activity is concentrated, and trace how approaches to intervention tailoring have changed over time. This type of comprehensive analysis is especially critical within the SNT framework, where effective policy and programmatic decisions depend not only on determining whether interventions are successful, but also on clarifying the contexts in which they are effective and the consistency of their impact.

Against this background, the present study aims to systematically map and meta-synthesize comparative malaria intervention studies conducted in SSA between 2011 and 2025, with explicit differentiation between pre-SNT and post-SNT implementation periods. By integrating systematic mapping, and random-effects meta-analysis, this study seeks to (i) characterize the distribution, design, and tailoring approaches of malaria interventions of epidemiological significance; (ii) quantify pooled epidemiological effects across intervention periods; and (iii) assess whether the introduction of SNT is associated with changes in the consistency and magnitude of intervention outcomes. This synthesis provides a comprehensive, policy-relevant assessment of malaria intervention effectiveness in SSA and contributes empirical evidence to ongoing debates on the value of sub-nationally tailored malaria strategies.

Research questions and hypotheses

The questions and hypotheses as listed in the table below are to guide the synthesis and interpretation of findings in the scoping review, offering a structured lens for evaluating evidence and informing future program design.

Research questions

1. How are malaria interventions of epidemiological significance distributed across sub-Saharan Africa in terms of type, design, and sub-national tailoring approaches?
2. What are the pooled effects of malaria interventions on key epidemiological and programmatic outcomes across studies conducted between 2011 and 2025?
3. How does the effectiveness and consistency of malaria interventions differ between the pre-SNT (2011–2018) and post-SNT (2019–2025) periods?
4. To what extent does sub-national tailoring influence the variability and predictability of intervention outcomes across different settings?

Hypotheses

- H1: Malaria interventions implemented in the post-SNT period demonstrate greater consistency (lower heterogeneity) compared to those in the pre-SNT period.
- H2: There is a statistically significant improvement in intervention effectiveness for selected domains (particularly behavioral/coverage and epidemiological outcomes) in the post-SNT period compared to the pre-SNT period.

- H3: Sub-nationally tailored interventions produce more predictable and context-sensitive outcomes than standardized national strategies.

Methods

Study design and approach

This study employed a systematic mapping review with Meta-analysis of comparative malaria intervention studies conducted in SSA, synthesizing evidence from randomized controlled trials, quasi-experimental studies, and other comparative designs implemented pre- and post-introduction of the SNT approach by the WHO (WHO, 2022). This design was adapted with the purpose to achieve two core objectives: (i) map the landscape, typology, and geographic distribution of malaria interventions across SSA, (ii) quantitatively synthesize intervention outcomes using effect measures or estimates. These approaches allowed for an integrated approaches for both causal inference on intervention effectiveness and system-level insight into malaria research and implementation evolution following the SNT policy shift.

Conceptual and analytical framework

The conceptual and analytical framework for the study as depicted in Fig. 1, was adopted from WHO's endorsement of SNT in October 2018 as a defining moment in malaria control and elimination (WHO, 2022; WHO, 2024). This framework reinforces SNT's analogous goal of stratifying malaria burden at sub-national levels and aligning intervention mixes accordingly rather than applying uniform national strategies.

The PICO framework as leveraged by this conceptual framework, serves as a structuring tool to define the scope of the review and ensure methodological rigor, breaking down the analytical path into population, intervention, comparison, and outcome (Table A1).

Search protocol and study selection

In accordance with the Preferred Reporting Items for Systematic Reviews and Meta- Analysis (PRISMA) 2020 recommendations to ensure transparency and reproducibility, the search strategy was systematically documented across all stages of evidence identification (Page et al., 2021). All steps of paper identification and selection are systematically presented in the PRISMA diagram (Figure A1). Similarly, Table A2 provides a structured summary of the databases consulted, search timeframe, concept domains, the search terms, geographic scope, filters applied, and procedures for data management and completeness checks.

Eligibility criteria

Eligibility was restricted to studies conducted in one or more countries within sub-Saharan Africa that evaluated at least one malaria intervention of epidemiological significance. Interventions considered included LLINs, IRS, seasonal malaria chemoprevention (SMC), IPT, case management strategies, surveillance-response systems, or integrated intervention packages implemented at the sub-national level. Only studies employing comparative designs with clearly defined intervention and comparator groups were included. Furthermore, included study requirements were studies who reported quantitative malaria outcomes such as incidence, prevalence, parasitemia, test positivity rate, anemia, entomological indices, malaria-attributable mortality, or coverage or uptake. To ensure consistency and accessibility, the review was limited to publications available in English.

Data extraction, quality assessment, and reproducibility

Data extraction was conducted using a standardized and piloted extraction template to ensure uniformity and completeness across included studies. Variables extracted included bibliographic information; country and sub-national setting; study design; intervention type and comparator; population characteristics; sample size; intervention implementation period; outcome definitions; effect estimates and measures of uncertainty; and indicators of alignment with sub-national stratification principles. Where multiple effect estimates were reported, the most fully adjusted estimate was extracted to minimize confounding, with unadjusted estimates retained only when adjusted estimates were unavailable and this decision was documented. Independent extraction of data was done by four

reviewers (PU, II, EE, and AM) for each study. Discrepancies were reconciled via discussion, with a fifth reviewer (EA) serving as an adjudicator in cases of non-consensus to ensure data integrity and mitigate subjective bias.

Methodological quality and risk of bias were assessed using design-appropriate tools. Randomized controlled trials were evaluated using the Cochrane Risk of Bias tool (Higgins et al., 2011), while non-randomized comparative studies were assessed using the ROBINS-I framework (Sterne et al., 2016), with focus on domains including selection bias, confounding, outcome measurement, and reporting bias. Risk-of-bias assessments were used to inform sensitivity analyses and interpretive weighting of findings rather than as exclusion criteria, in order to preserve the breadth of evidence relevant to malaria intervention effectiveness across heterogeneous settings.

To ensure reproducibility and transparency, all extracted datasets, risk-of-bias assessments, and analytical scripts were archived and version-controlled. The full search strategy, study selection decisions, and rationale for classifying studies into pre- and post-SNT periods were documented in detail to enable independent verification and replication. The individual study characteristics and assessment can be appraised from the supplementary file (S1).

Domain grouping

Inductive classification was adopted to categorize interventions into domains using data-driven approach as informed by the thematic synthesis. Initial intervention categories were extracted from included studies and iteratively grouped based on intervention strategy and outcome implication. This process was guided by established malaria control frameworks, including the WHO malaria intervention pillars (vector control, chemoprevention, case management, and surveillance/response) (WHO, 2025), ensuring the analytical approach was conceptually aligned, while allowing adaptation to the specific evidence base included in this review.

Synthesis and analytical approach

Meta-analytical methods were used to estimate pooled effects of malaria interventions implemented in sub-Saharan Africa, with analyses stratified a priori into pre-sub-national tailoring (pre-SNT; 2011–2018) and post-sub-national tailoring (post-SNT; 2019–2025) periods to enable policy-relevant temporal comparisons. This stratification was defined during protocol development and applied consistently throughout the analysis. All transformation, standardization and analysis were conducted using JASP (version 0.95.4.0. Ink; University of Amsterdam), an open-source statistical software distributed under the GNU Affero General Public License (JASP Team, 2024).

Standardize effect measures

Relative effect measures (odds ratios, incidence rate ratios, and hazard ratios) along with their corresponding 95% confidence intervals and standard errors, were converted to their natural logarithms (for example, logOR, logIRR) using logarithm transformation. This transformation is a statistical requirement to normalize the distribution and stabilize the variance before pooling. After calculating the pooled effect sizes using a random effects model on the log scale the study conducted a back transformation (Borenstein et al., 2004). The final summary estimates and confidence intervals were exponentiated back to their standard ratio scale so they are easily interpretable in our forest plots (Higgins et al., 2022). Following this study's epidemiological outcomes of interest (malaria incidence and prevalence) generally having low baseline occurrence rates within the specific follow-up periods, the odds mathematically approximated the relative risk. Therefore, it is statistically valid to pool these relative measures as generic relative effects (Borenstein et al., 2004; Higgins et al., 2022).

Effect size analysis

Effect size analysis was conducted using random-effects models to reflect anticipated clinical and methodological heterogeneity across intervention types, transmission settings, populations, and study designs. Pooled estimates were reported with 95% confidence intervals. Statistical heterogeneity was assessed using Cochran's Q test and quantified using the I^2 statistic, with interpretation guided by conventional thresholds while emphasizing context-specific variability (Choi and Kang, 2025). Predefining sub-group and stratified analyses were conducted to explore potential sources of heterogeneity, including intervention category, geographic sub-region, transmission intensity, study design, and temporal classification into pre-SNT and post-SNT periods. These analyses were undertaken to assess whether intervention effects differed following the introduction of sub-nationally tailored malaria strategies.

Publication bias sensitivity analysis

Sensitivity analyses assessed the robustness of pooled estimates by excluding studies assessed as high risk of bias (previously defined), restricting analyses to randomized controlled trials, and varying assumptions related to effect measure selection. Potential publication bias was assessed visually using funnel plots. To formally test for funnel plot asymmetry, Egger's regression test was applied, with statistical significance indicating the presence of publication bias. Where evidence of asymmetry was detected, the trim-and-fill method was employed to estimate the number of potentially missing studies and to generate an adjusted pooled effect size that accounts for unpublished or underreported results, and where appropriate, formally evaluated using tests for small-study effects (Sterne & Egger, 2001).

Protocol registration

This systematic review and meta-synthesis was conducted in accordance with a predefined protocol, which was registered on the Open Science Framework (<https://osf.io/5rxsp>) and PROSPERO available at <https://www.crd.york.ac.uk/PROSPERO/view/CRD420261375304>.

Results

Mapping of malaria intervention studies in SSA

The analysis synthesizes evidence from 108 experimental studies across 34 countries, capturing both pre-SNT and post-SNT implementation periods. The descriptive component characterizes trends in publication volume, geographic distribution, and the types of tailoring applied across intervention categories. The most common study design was the cluster randomized controlled trial, and the average intervention group sample size was approximately 3,041 participants. Of the 108 studies, 96 were single-country, while 12 were multi-country. From the studies, 107 unique interventions were identified, with geographic tailoring being the most frequently applied (Fig. 3).

From the graph, Nigeria led with 18 studies, the highest in the region, followed by Burkina Faso (12 studies), then Tanzania (10 studies). Ghana, Kenya, Malawi, and Mozambique contributed 9 studies each, a substantial amount of research in these regions. Mali has 8 studies, while 6 studies originated from DR Congo. 5 studies each, were contributed by Benin, Madagascar, and Uganda, and Côte d'Ivoire, Ethiopia, and Senegal accounted for 3 studies each. This observed distribution indicates that Nigeria plays a central role for malaria research in the SSA region (Fig. 3).

The result in Fig. 4 shows fluctuations in malaria intervention research activity from 2011 to 2025. The number of experimental, evidence-based studies was relatively low between 2011 and 2017, ranging from 3 to 8 per year. The highest publication was in 2019 with 14 studies, and fluctuating publications ranging between 6 and 12 annually through 2025. This pattern suggests a peak in research activity around 2019–2021, which coincides with the switch to SNT approaches. The tailoring approaches over time indicate a diversity and frequency of tailoring types used in various studies. Geographic tailoring (green) appears consistently across all years, often occupying the largest portion of each bar. Demographic, epidemiological, and logistical tailoring types also show regular presence, while cultural and biological tailoring are less frequent.

The heatmap as illustrated in Fig. 5 reveals that malaria intervention strategies are most tailored from geographic and demographic perspectives, with geographic tailoring being especially dominant in vaccine (36.8%), diagnostic (33.3%), and larval control (33.3%) interventions. Epidemiological tailoring is also prominent, particularly in vaccine (26.3%) and chemoprevention (18.1%) efforts, indicating a strong reliance on disease patterns and transmission data. Behavioral interventions show notable use of behavioral (20.6%) and cultural (13.2%) tailoring, while biological tailoring is more relevant for drug efficacy (12.7%) and vector control (18.6%). However, cultural tailoring remains underutilized across most intervention types, suggesting a potential gap in integrating local cultural contexts into malaria control strategies.

Meta-analysis of malaria intervention studies in SSA

Overview of temporal patterns

The comparison of intervention effectiveness across the four domains revealed consistent patterns of reduced heterogeneity accompanied by mixed changes in average effect sizes (τ^2 ; ranging from 87% to 100%). The pattern of statistical significance

changed remarkably between periods. In the pre-SNT period, none of the four domains achieved statistical significance (p -values ranging from 0.12 to 0.43). Although when compared to the post-SNT period, was indicative of domains with statistically significant results: Behavioral & Coverage ($p = 0.042$) and Epidemiological ($p = 0.014$). The prediction intervals across the four domains narrowed substantially for the post-SNT period, with reductions in width ranging from 65% (Vector Control) to 96% (Behavioral & Coverage) (Table 1).

Intervention effect

Chemoprevention and treatment intervention outcomes: In the pre-SNT period, chemoprevention and treatment interventions showed a positive but non-significant pooled effect (1.34; 95% CI: -0.80 to 3.49; $p = 0.168$), with extreme heterogeneity ($I^2 = 99.82\%$; $\tau^2 = 4.12$) and a wide prediction interval (-4.30 to 6.99), indicating substantial variability. In the post-SNT period, the pooled effect shifted to -0.35 (95% CI: -0.93 to 0.24; $p = 0.196$) and remained non-significant. However, heterogeneity reduced ($I^2 = 96.31\%$; $\tau^2 = 0.29$; 93% reduction), and the prediction interval narrowed (-1.80 to 1.10), suggesting improved precision. The subgroup difference was marginally non-significant ($Q(1) = 3.80$; $p = 0.051$), indicating a borderline difference between periods.

Vector control intervention outcomes: Pre-SNT vector control interventions yielded a non-significant pooled effect of -0.48 (95% CI: -1.78 to 0.82; $p = 0.426$), with extreme heterogeneity ($I^2 = 99.82\%$; $\tau^2 = 3.17$) and a wide prediction interval (-4.71 to 3.75). Post-SNT, the pooled effect was -0.27 (95% CI: -0.77 to 0.24; $p = 0.256$), with minimal change in I^2 (99.35%) but a substantial reduction in τ^2 (0.29; 91% reduction). The prediction interval narrowed to -1.64 to 1.11. The subgroup difference was not statistically significant ($Q(1) = 0.12$; $p = 0.727$), indicating no meaningful difference between periods.

Behavioral and coverage intervention outcomes: Pre-SNT, behavioral and coverage interventions showed a large but non-significant pooled effect (3.26; 95% CI: -1.30 to 7.82; $p = 0.118$), with extreme heterogeneity ($I^2 = 99.96\%$; $\tau^2 = 13.19$) and a very wide prediction interval (-7.81 to 14.33). Post-SNT, the pooled effect was smaller but statistically significant (0.46; 95% CI: 0.04 to 0.88; $p = 0.042$), with no heterogeneity ($I^2 = 0.00\%$; $\tau^2 = 0.00$) and a narrow prediction interval identical to the confidence interval. The subgroup difference was marginally non-significant ($Q(1) = 2.89$; $p = 0.089$), despite substantial reductions in τ^2 and prediction interval width.

Epidemiological intervention outcomes: Pre-SNT epidemiological outcomes showed a non-significant pooled effect (-0.72; 95% CI: -2.05 to 0.61; $p = 0.250$), with extreme heterogeneity ($I^2 = 99.68\%$; $\tau^2 = 3.34$) and a wide prediction interval (-5.06 to 3.62). Post-SNT, the pooled effect was statistically significant (-0.48; 95% CI: -0.85 to -0.11; $p = 0.014$), with a modest reduction in I^2 (99.17%) but a substantial decrease in τ^2 (0.43; 87% reduction). The prediction interval narrowed to -1.92 to 0.96. The subgroup difference was not statistically significant ($Q(1) = 0.16$; $p = 0.692$), indicating no significant difference in average effects between periods.

Table 1
Random-effects meta-analysis with pre- and post-SNT comparison across intervention domains

Domain	Period	Studies (k)	Pooled Effect (95% CI)	p-value	Heterogeneity Q (p)	I^2 (95% CI)	τ^2 (95% CI)	95% Prediction Interval	Subgroup Difference Q_{sub} (p)
Chemoprevention & Treatment	Pre-SNT	6	1.34 (-0.80 to 3.49)	0.168	$Q(5) = 6809.42$ (p < 0.001)	99.82% (99.52–99.97%)	4.12 (1.57–24.98)	-4.30 to 6.99	$Q_{\text{sub}}(1) = 3.80$ (p = 0.051)
	Post-SNT	7	-0.35 (-0.93 to 0.24)	0.196	$Q(6) = 162.05$ (p < 0.001)	96.31% (89.10–99.49%)	0.29 (0.09–2.17)	-1.80 to 1.10	
	Change		$\Delta = -1.69$	ns		$\Delta I^2 = -3.5\%$	$\Delta \tau^2 = -93\%$	$\Delta \text{width} = -70\%$	
Vector Control	Pre-SNT	10	-0.48 (-1.78 to 0.82)	0.426	$Q(9) = 837.68$ (p < 0.001)	99.82% (99.61–99.95%)	3.168 (1.48–11.25)	-4.71 to 3.75	$Q_{\text{sub}}(1) = 0.12$ (p = 0.727)
	Post-SNT	8	-0.27 (-0.77 to 0.24)	0.256	$Q(7) = 115.82$ (p < 0.001)	99.35% (98.24–99.88%)	0.293 (0.11–1.65)	-1.64 to 1.11	
	Change		$\Delta = +0.21$	ns		$\Delta I^2 = -0.5\%$	$\Delta \tau^2 = -91\%$	$\Delta \text{width} = -65\%$	
Behavioral & Coverage	Pre-SNT	5	3.26 (-1.30 to 7.82)	0.118	$Q(4) = 5571.95$ (p < 0.001)	99.96% (99.89–100%)	13.19 (4.61–113.01)	-7.81 to 14.33	$Q_{\text{sub}}(1) = 2.89$ (p = 0.089)
	Post-SNT	3	0.46 (0.04 to 0.88)	0.042*	$Q(2) = 0.00$ (p = 0.998)	0.00% (0.00–0.0%)	0.000 (0.00–0.00)	0.04 to 0.88	
	Change		$\Delta = -2.80$	s		$\Delta I^2 = -100\%$	$\Delta \tau^2 = -100\%$	$\Delta \text{width} = -96\%$	
Epidemiological	Pre-SNT	10	-0.72 (-2.05 to 0.61)	0.250	$Q(9) = 747.52$ (p < 0.001)	99.68% (99.23–99.90%)	3.339 (1.38–10.59)	-5.06 to 3.62	$Q_{\text{sub}}(1) = 0.16$ (p = 0.692)
	Post-SNT	16	-0.48 (-0.85 to -0.11)	0.014*	$Q(15) = 2237.23$ (p < 0.001)	99.171% (98.282–99.670%)	0.426 (0.204–1.075)	-1.92 to 0.96	
	Change		$\Delta = +0.242$	s		$\Delta I^2 = -0.5\%$	$\Delta \tau^2 = -87\%$	$\Delta \text{width} = -68\%$	

Note: Expected effect directions: Chemoprevention (+ ve), Vector Control (-ve), Behavioral & Coverage (+ ve), Epidemiological (-ve)

Bold p-values indicate statistical significance (p < 0.05), ns (not significant), s (significant)

Δ = Change from Pre-SNT to Post-SNT

Intervention interpretation

Table 2 summarizes the meta-analysis results across four intervention domains before and after the introduction of SNT. For each period, we report the pooled effect, prediction interval (in natural units), and a summary of changes in consistency. The prediction

interval, rather than I^2 alone, is emphasized because it describes the range of plausible effects a future intervention might achieve in a new setting, which is directly relevant to policy and program planning.

Chemoprevention and treatment intervention

After the introduction of SNT, chemoprevention and treatment interventions became far more predictable. A future tailored intervention is likely to produce effects within a much narrower range, from strong protection (83% reduction) to modest harm (3-fold increase). Although the average effect did not become statistically significant, the reduction in uncertainty represents a meaningful improvement for program planning.

Tailored vector control interventions (for example, stratified IRS or LLIN distribution) did not, on average, outperform non-tailored approaches in terms of effect magnitude. However, they became substantially more consistent. A future tailored vector control program is now likely to achieve somewhere between an 81% reduction and a 3-fold increase, which can be regarded as likely variable, but far less extreme than the pre-SNT range. This improved predictability supports the continued use of sub-national stratification for vector control, especially in areas with heterogeneous transmission and resistance profiles.

Tailored behavioral and coverage interventions (for example, culturally adapted community engagement, targeted health promotion) consistently produced beneficial effects, with a future intervention guaranteed to improve coverage or behavior by between 4% and 141% (that is, always positive). This stands in stark contrast to the pre-SNT era, where large but unpredictable effects were the norm. SNT appears particularly valuable for context-dependent outcomes like care-seeking, treatment adherence, and net use.

Tailored malaria interventions aimed at epidemiological endpoints now produce a statistically significant pooled protective effect. More importantly, a future tailored intervention is likely to achieve an effect between an 85% reduction and a 2.6-fold increase. While the upper bound still includes potential harm, the range is substantially more concentrated on protection compared to the pre-SNT period. This suggests that SNT has moved epidemiological outcomes from highly unpredictable to moderately predictable, with a clear average benefit.

Table A2

Intervention implication of prediction intervals of malaria intervention effects before (2011–2018) and after (2019–2025)
Sub-National Tailoring (SNT)

Domain & Period	Studies (k)	Pooled effect (95% CI)	p-value	Prediction interval (natural units)	Clinical interpretation	Change in consistency (post-SNT vs pre-SNT)
Chemoprevention & Treatment						
Pre-SNT	6	1.34 (–0.80 to 3.49)	0.168	RR 0.01 to 1,089	In a future SSA setting, the true effect could range from a 99% reduction to a > 1000-fold increase in malaria outcomes.	–
Post-SNT	7	–0.35 (–0.93 to 0.24)	0.196	RR 0.17 to 2.99	In a future SSA setting, the true effect could range from an 83% reduction to a 3-fold increase.	Prediction interval width ↓70%; τ^2 ↓93% (4.12 → 0.29). Effects more predictable.
Vector Control						
Pre-SNT	10	–0.48 (–1.78 to 0.82)	0.426	RR 0.01 to 42.6	In a future SSA setting, the true effect could range from a 99% reduction to a 42-fold increase in vector density or transmission.	–
Post-SNT	8	–0.27 (–0.77 to 0.24)	0.256	RR 0.19 to 3.03	In a future SSA setting, the true effect could range from an 81% reduction to a 3-fold increase.	Prediction interval width ↓65%; τ^2 ↓91% (3.17 → 0.29). Consistency improved.
Behavioral & Coverage						
Pre-SNT	5	3.26 (–1.30 to 7.82)	0.118	OR 0.0004 to 1,674	In a future SSA setting, the true effect could range from near-zero odds to > 1600-fold higher odds of improved coverage/behaviour.	–
Post-SNT	3	0.46 (0.04 to 0.88)	0.042	OR 1.04 to 2.41	In a future SSA setting, the true effect could range from a 4% to a 141% relative increase in coverage/behaviour (always beneficial).	Prediction interval width ↓96%; τ^2 ↓100% (13.19 → 0.00). Highly consistent, always positive.
Epidemiological						
Pre-SNT	10	–0.72 (–2.05 to 0.61)	0.250	RR 0.006 to 37.4	In a future SSA setting, the true effect could range from a 99.4% reduction to a 37-fold increase in malaria incidence/prevalence.	–
Post-SNT	16	–0.48 (–0.85 to –0.11)	0.014	RR 0.15 to 2.62	In a future SSA setting, the true effect could range from an 85% reduction to a 2.6-fold increase (mostly protective; upper bound only modestly harmful).	Prediction interval width ↓68%; τ^2 ↓87% (3.34 → 0.43). Future effects substantially more predictable.
Note: Pooled effects and prediction intervals are presented on the log scale in the original analysis (risk ratios / odds ratios). For clinical interpretation, we exponentiated the 95% prediction interval limits to natural units (RR or OR).						

Expected beneficial direction: Chemoprevention (+), Vector Control (–), Behavioral & Coverage (+), Epidemiological (–).

τ^2 = between-study variance; I^2 values (not shown) remained high in all periods, confirming that I^2 alone is a poor indicator of practical consistency. Prediction intervals and τ^2 reductions better reflect improved predictability after SNT.

Width reduction compared to the pre-SNT prediction interval for the same domain (Bold p-values indicate significance).

Publication bias analysis

Funnel plot inspection indicated asymmetry across outcome domains, suggesting potential publication bias and small-study effects, although interpretation is constrained by substantial heterogeneity (Figure A3). For chemoprevention and treatment, mild asymmetry

was observed, but given the extremely high heterogeneity ($I^2 = 99.73\%$, $Q(12) = 10461.65$, $p < 0.001$) and non-significant pooled effect ($t(12) = 0.91$, $p = 0.382$), this likely reflects between-study variability rather than systematic bias. For vector control, the funnel plot was relatively symmetric, with high dispersion ($I^2 = 99.85\%$, $Q(17) = 1008.64$, $p < 0.001$) and a non-significant pooled estimate ($t(17) = -1.20$, $p = 0.247$), indicating limited evidence of publication bias. In contrast, behavioral and coverage outcomes demonstrated clear asymmetry, particularly in the pre-SNT subgroup ($I^2 = 99.96\%$, $Q(4) = 5571.95$, $p < 0.001$), consistent with small-study effects. The post-SNT subgroup showed no heterogeneity ($I^2 = 0.00\%$, $Q(2) = 0.00$, $p = 0.998$) but a significant pooled effect ($t(2) = 4.71$, $p = 0.042$), suggesting possible overestimation due to selective reporting. For epidemiological outcomes, funnel plot asymmetry was evident, with high heterogeneity across pre-SNT ($I^2 = 99.68\%$, $Q(9) = 747.52$, $p < 0.001$), post-SNT ($I^2 = 99.17\%$, $Q(15) = 2237.23$, $p < 0.001$), and full dataset ($I^2 = 99.67\%$, $Q(25) = 3123.84$, $p < 0.001$). Significant pooled effects in the post-SNT ($t(15) = -2.77$, $p = 0.014$) and full dataset ($t(25) = -2.40$, $p = 0.024$) analyses should therefore be interpreted with caution.

Sensitivity analysis

This analysis evaluated the overall effectiveness of malaria interventions using a random-effects meta-analysis, while explicitly testing for and adjusting publication bias using Egger's regression and trim-and-fill methods. Funnel plot inspection indicated asymmetry across outcome domains, suggesting potential publication bias and small-study effects, although interpretation is constrained by substantial heterogeneity (Table A3 and Figure A4).

The initial pooled effect (REML) shows a modest, non-statistically significant reduction in malaria incidence (LogRR = -0.17 , 95% CI: -0.38 to 0.03 , $p = 0.095$), indicating that, on average, interventions tend to reduce malaria burden, but with uncertainty around the true effect. This is further complicated by extreme heterogeneity ($I^2 = 99.4\%$, $\tau^2 = 0.60$), suggesting that intervention effects vary widely across settings. Egger's regression test provides strong evidence of funnel plot asymmetry ($t = 3.87$, $p = 0.0003$), indicating the presence of publication bias and small-study effects, where studies with stronger or more favorable results are more likely to be reported. After adjusting for this bias using the trim-and-fill method, the pooled effect becomes larger and statistically significant (LogRR = -0.32 , 95% CI: -0.54 to -0.10 , $p = 0.004$), with seven studies imputed to correct for missing evidence. This suggests that the true effect of interventions may be stronger than initially estimated, and that the observed non-significance in the unadjusted model may be partly due to missing or suppressed studies (Table A3). The Forest Plot can be visualized from Figure A3 of the supplementary file.

Discussion

This meta-analysis provides important insights into how SNT has shaped the effectiveness, consistency, and predictability of malaria interventions in sub-Saharan Africa. While the findings demonstrate that the introduction of SNT is associated with improved consistency of intervention effects, interpretation of these results should be situated within the context of observed publication bias, small-study effects, and results from bias-adjusted sensitivity analyses.

Across the four intervention domains, funnel plot asymmetry suggests that studies reporting stronger or statistically significant effects may be overrepresented, particularly within the behavioral/coverage and epidemiological domains. This has important implications for interpreting pooled estimates, especially in the post-SNT period where statistically significant findings were observed. However, formal assessment using Egger's regression indicated significant asymmetry, and subsequent trim-and-fill adjustment yielded a larger and statistically significant pooled effect compared to the primary model. This suggests that, in aggregate, the overall intervention effect may be underestimated rather than inflated due to missing or unpublished studies, highlighting the complex and bidirectional influence of publication bias (Egger et al., 1997; Sterne et al., 2011).

Notwithstanding these dynamics, the central finding of this study, the marked reduction in between-study heterogeneity and narrowing of prediction intervals following SNT introduction, remains sufficient to concerns of publication bias. Unlike effect size magnitude, which is more sensitive to selective reporting, improvements in consistency are less likely to be artifacts of bias. This reinforces the interpretation that SNT's primary contribution lies in stabilizing intervention performance across heterogeneous contexts, rather than simply increasing average effectiveness (WHO, 2025; Onyango et al., 2025).

The extreme heterogeneity observed in the pre-SNT period, coupled with funnel plot asymmetry, indicates that earlier evidence was characterized not only by contextual variability but also by selective visibility of successful interventions. This may partly explain the wide range of reported effects, from strongly beneficial to null or adverse outcomes across similar intervention types (Konaté et al.,

2011; Dicko et al., 2011a; b). Similar variability has been documented in earlier evaluations of malaria interventions, where effectiveness was highly sensitive to local conditions and implementation fidelity (Bachan et al., 2025; Zhuo et al., 2024).

In contrast, the post-SNT period shows both reduced heterogeneity and, in some domains, more coherent distributions of effect sizes, suggesting improved alignment between intervention design and contextual realities. This shift aligns with growing evidence that context-tailored, sub-national strategies enhance implementation efficiency and reduce outcome variability (Gosling et al., 2020; Onyango et al., 2025; WHO, 2025).

The behavioral and coverage domain emphasizes this dynamic most clearly. Whereas post-SNT results indicate consistent positive effects with minimal heterogeneity, funnel plot asymmetry suggests the presence of small-study effects. When interpreted alongside the sensitivity analysis, this indicates that while some domain-specific effects may appear inflated, the broader evidence base may still underrepresent the full magnitude of impact. Nonetheless, the near elimination of heterogeneity points to meaningful gains in intervention standardization and contextual adaptation. Behavioral outcomes, including care-seeking, treatment adherence, and uptake of preventive services, are inherently context-dependent, and tailored interventions have been shown to improve both uptake and consistency (Anthonj et al., 2022; Asante, 2024; Diallo et al., 2025).

Similarly for epidemiological outcomes, while statistically significant reductions in malaria burden are observed post-SNT, the presence of publication bias and sensitivity-adjusted estimates suggests that the true effect may be stronger than initially observed, even as caution is warranted in interpreting domain-specific magnitudes. Importantly, the reduction in variability supports the conclusion that SNT enhances the predictability and reliability of intervention impact, which is critical for programmatic planning and resource allocation (Pierson & Verguet, 2023; WHO, 2025).

In contrast, the chemoprevention/treatment and vector control domains show weaker evidence of publication bias, with non-significant pooled effects and persistent high heterogeneity. This reinforces the interpretation that biological and ecological constraints, such as drug and insecticide resistance, may limit the extent to which SNT alone can enhance effectiveness, independent of innovation in intervention tools (Onyango et al., 2025; Dicko et al., 2011).

Ultimately, while moderate to strong evidence of publication bias is present, particularly in domains driven by behavioral and system-level changes, the sensitivity analysis demonstrates that its impact is not unidirectional. Rather than simply inflating observed effects, publication bias may also obscure the full magnitude of intervention benefits. These findings refine the study's central conclusion: SNT should not be viewed primarily as a mechanism for increasing effect size, but as a strategy for reducing uncertainty, improving consistency, and enhancing the reliability of intervention outcomes across diverse settings, even in the presence of incomplete or selectively reported evidence.

Implication for policy and practice

From a policy perspective, these findings provide empirical support for the World Health Organization's endorsement of sub-national tailoring as a core malaria control strategy (WHO, 2018; WHO, 2024). The reduction in heterogeneity observed across domains suggests that SNT can improve the efficiency of resource use by minimizing mismatches between intervention strategies and local needs. For national malaria control programs, this implies a drifting from uniform coverage targets toward stratified planning, differentiated intervention mixes, and adaptive implementation informed by routine hyperlocal data.

For practice, these results highlight the importance of investing in sub-national data systems, analytic capacity, and decentralized decision-making. Tailoring is not a single process exercise but an iterative process that depends on timely surveillance, feedback loops, and local ownership. Programs that lack the capacity to generate and use sub-national data may struggle to realize the full benefits of SNT, even when the policy framework is in place and seems good.

Finally, the findings point to several priorities for future research. Further subgroup analyses by transmission intensity, intervention type, and geographic region are needed to identify contexts in which tailoring yields the greatest marginal benefit. In addition, more rigorous reporting of implementation processes and contextual factors would strengthen future meta-syntheses and support cross-country learning. As malaria programs increasingly operate in low-transmission, fragile, and hard-to-reach settings, understanding how SNT interacts with health system constraints and sociopolitical instability remains critical.

Conclusion

This synthesis indicates that the introduction of SNT is associated with reduced heterogeneity and improved consistency of intervention effects across sub-Saharan Africa. Although these improvements were not observed uniformly across all domains, and there was no statistically significant difference in average effect sizes between pre- and post-SNT periods, the findings suggest a meaningful shift toward more predictable and reliable intervention performance. These results align with the core objectives of SNT and provide quantitative support for its continued use and refinement in malaria control strategies.

Abbreviations

BMGF
Bill & Melinda Gates Foundation (mentioned in funding)
CI
Confidence interval
 I^2
Heterogeneity statistic
MLE
Monitoring, Learning and Evaluation (mentioned in funding)
OSF
Open Science Framework
PICO
Population, Intervention, Comparison, Outcome (mentioned in methods)
PRISMA
Preferred Reporting Items for Systematic Reviews and Meta-Analysis
 Q
Subgroup difference test statistic
RDTs
Rapid diagnostic tests
ROBINS-I
Risk of Bias in Non-randomized Studies of Interventions (mentioned in quality assessment)
SMC
Seasonal malaria chemoprevention (mentioned in eligibility criteria)
SNT
Sub-National Tailoring
SSA
Sub-Saharan Africa
WHO
World Health Organization
 τ^2
Between-study variance

Declarations

Authors' contributions

Conceptualization: UI, EA, PU, OF; Methodology: EA, OF, PU, II; Software: II, EA, PU, SP; Validation: EA, PU, II; Formal Analysis: II, EA, PU; Investigation: PU, OF, AM, EE; Resources: UI, EA, PU, II; Data Curation: PU, OF, II, EA, AM; Writing – Original Draft: PU, OR, EA; Writing – Review & Editing: UI, IA, ZB, SY-L, OE, OF; Visualization: II, EA, PU; Supervision: UI, EA, OE; Project Administration: EA, OE, PU; Funding Acquisition: UI.

Ethical considerations

Not applicable

Consent for publication

Not applicable

Data availability statement

All additional analysis relevant to the study has been included as a supplementary material. The data supporting the findings of this study are derived from publicly available sources and published literature included in the systematic review and meta-analysis. Extracted datasets and analytical code used for the meta-analysis, including publication bias and sensitivity analyses, are available from the Harvard Dataverse repository at <https://dataverse.harvard.edu/dataset.xhtml?persistentId=doi:10.7910/DVN/ODZ1TU>

Competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Figures

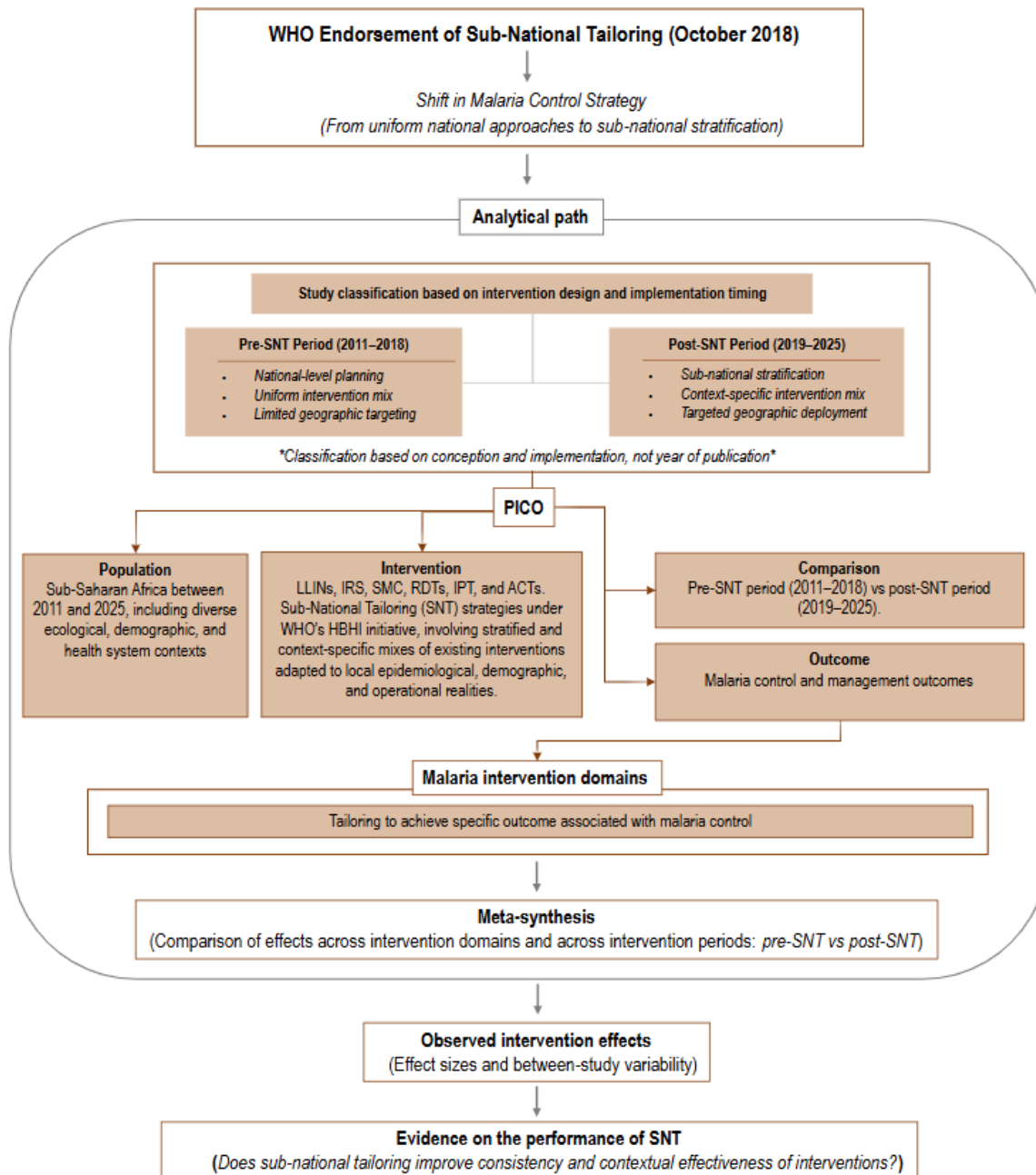


Figure 1

The conceptual and analytical framework

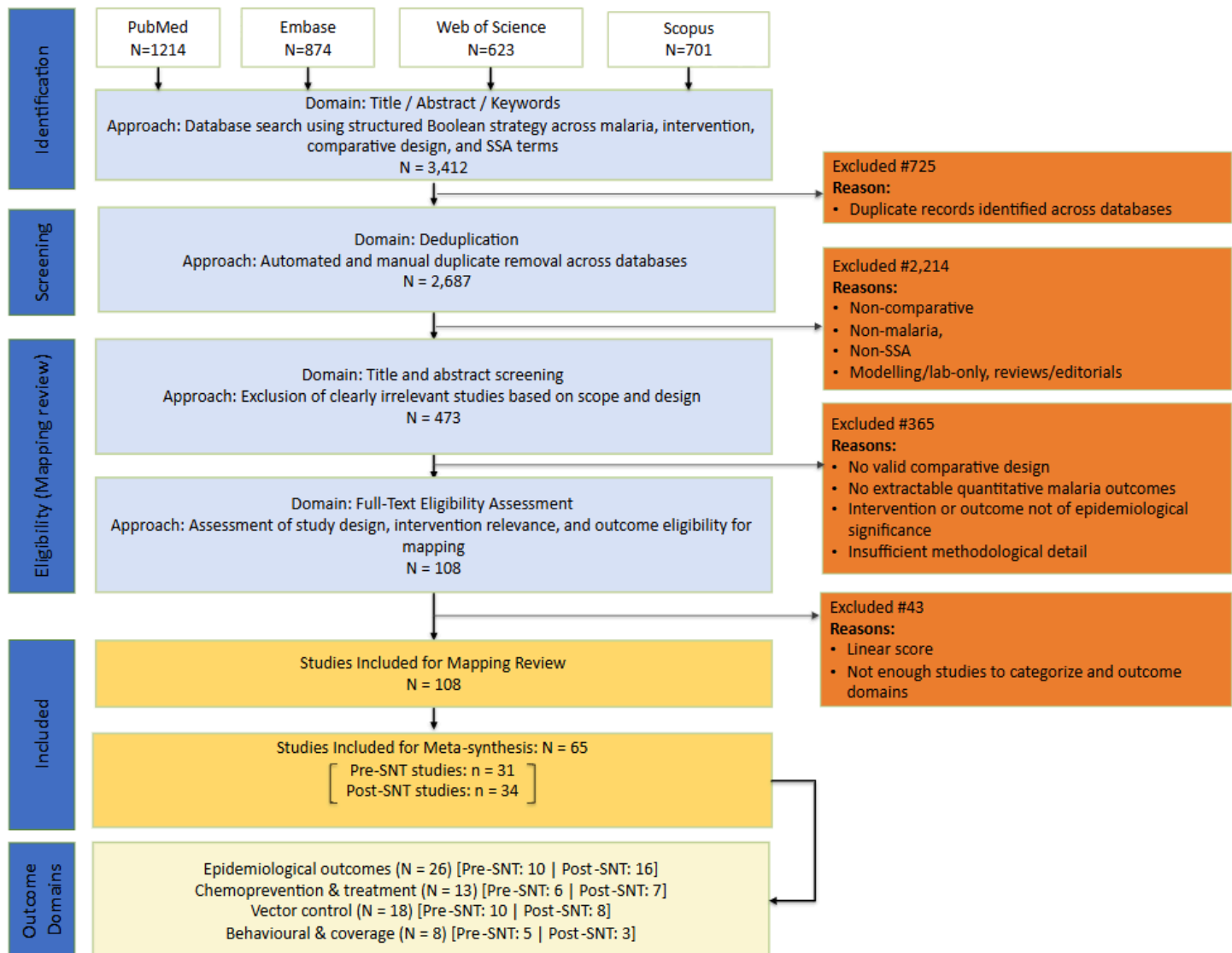


Figure 2

The flow diagram for the database search of publications for the mapping and Meta-analysis.

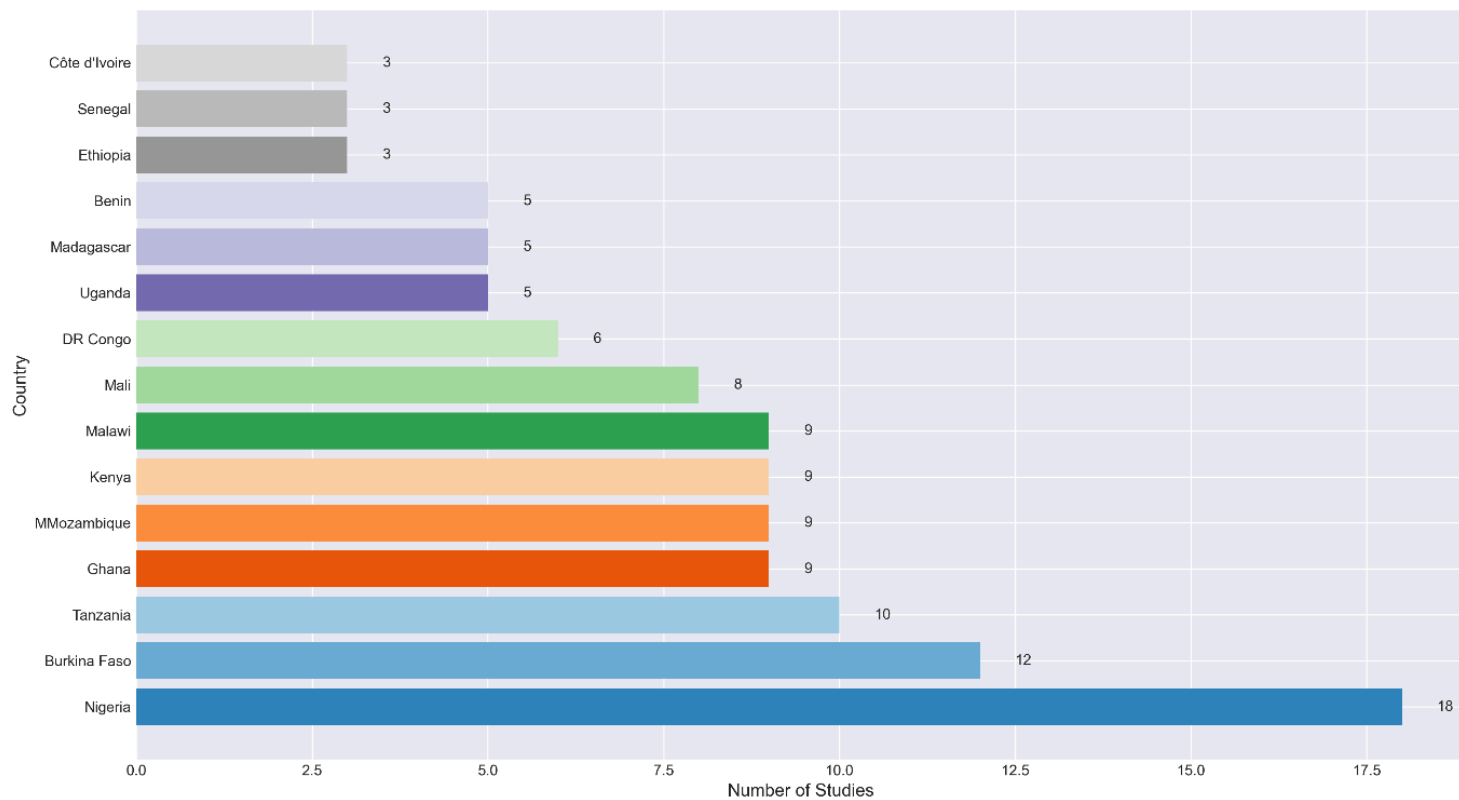


Figure 3

Top 15 countries and their publications spread across SSA

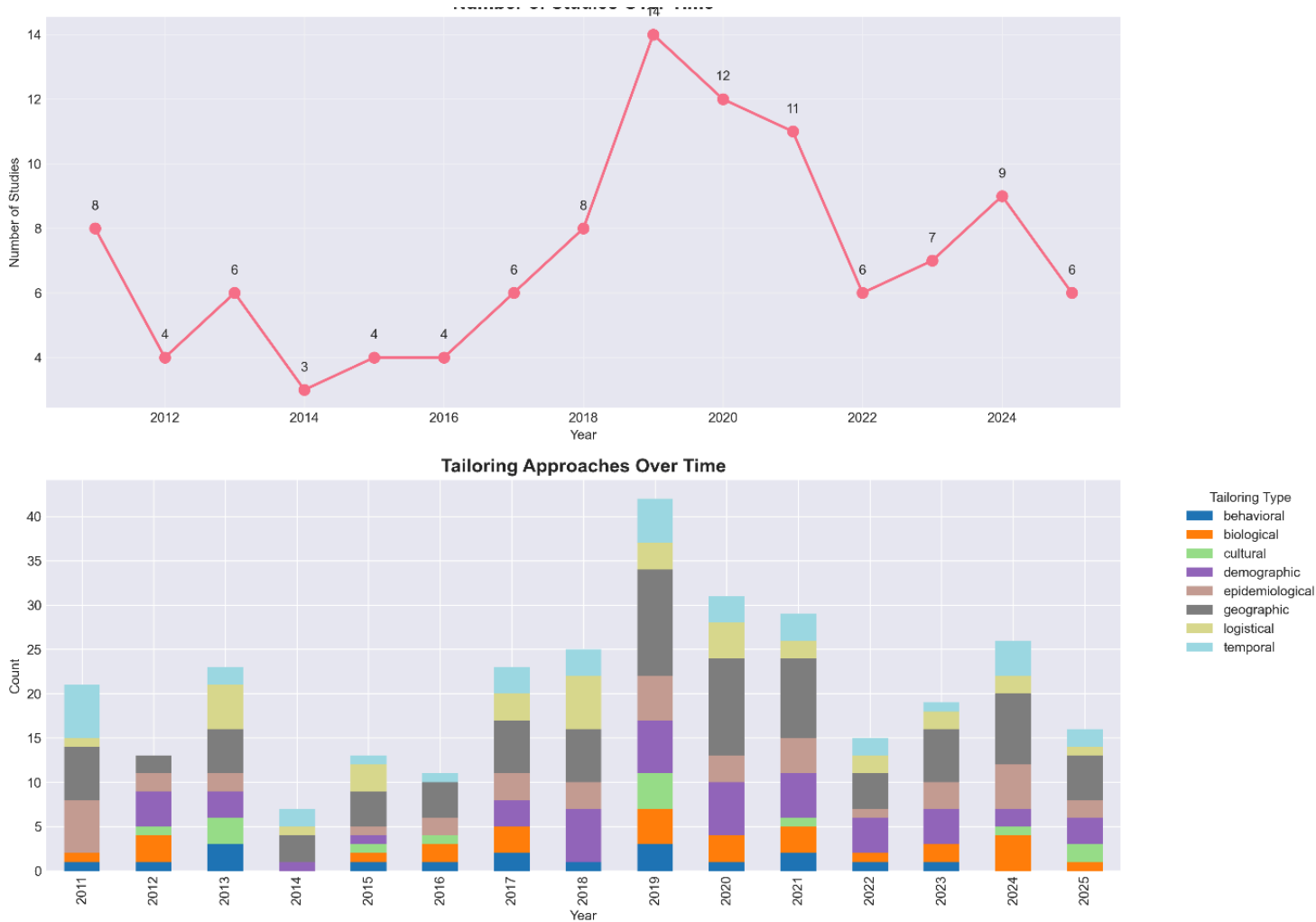


Figure 4

Publication trend and the malaria intervention approaches

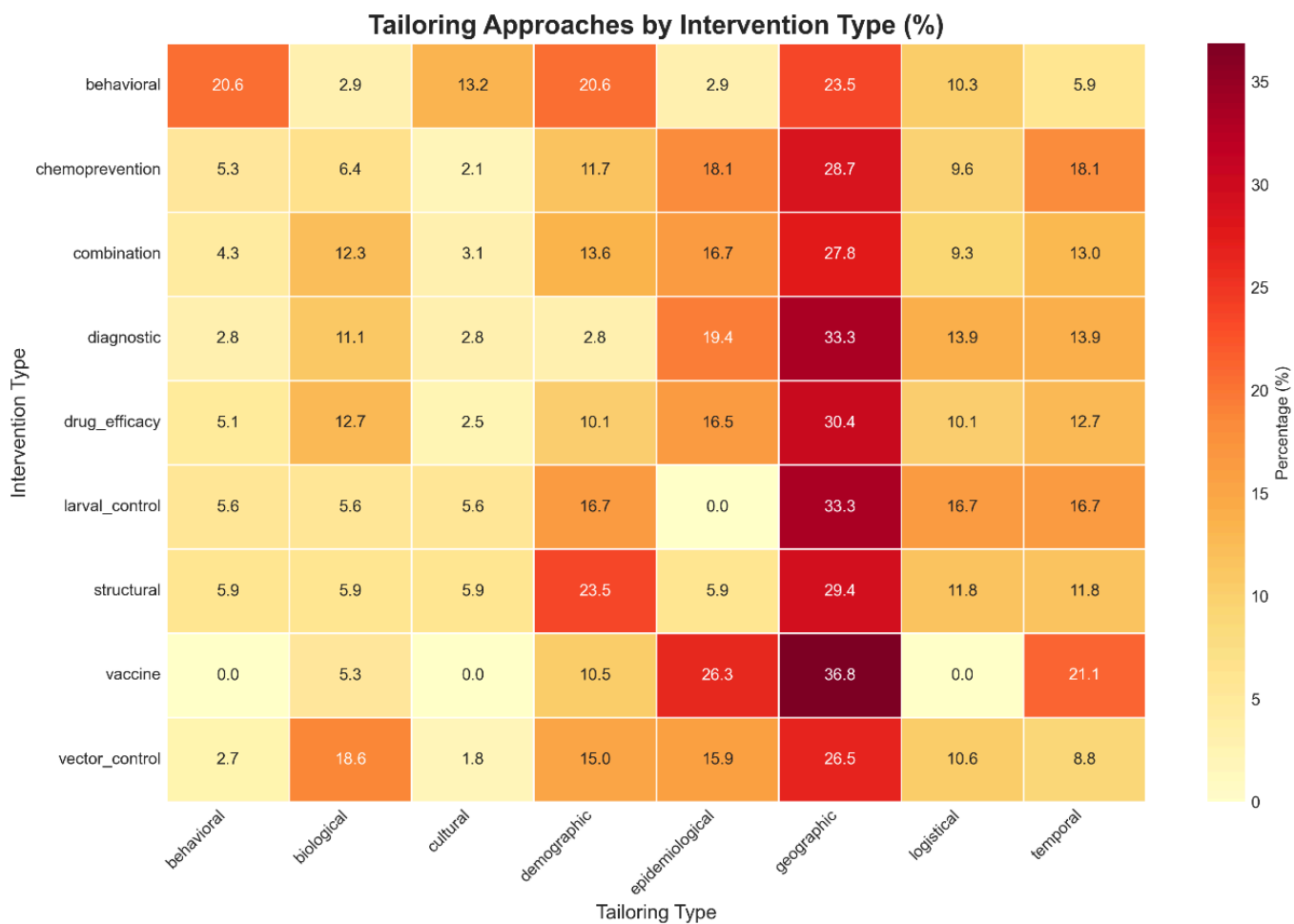


Figure 5

Heatmap of the different tailoring approaches applied across various malaria intervention types

Supplementary Files

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