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Evaluating the Effectiveness of Vector Control Strategies in Mitigating Dengue Outbreaks: A Systematic Review and Meta-analysis

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KEYWORDS

Dengue, Vector Control, Systematic Review, Meta-analysis, Aedes aegypti, Integrated Vector Management, Public Health

ABSTRACT:

Background: Dengue remains one of the most rapidly spreading vector-borne diseases worldwide, posing a major threat to public health in tropical and subtropical regions. Despite widespread implementation of vector control interventions, the variability in their effectiveness across different settings continues to challenge outbreak prevention efforts. This systematic review and meta-analysis evaluated the effectiveness of various vector control strategies in reducing dengue incidence and mitigating outbreaks.

Methods: A comprehensive search was conducted in PubMed, Embase, Scopus, Web of Science, and Cochrane Library for studies published between January 2000 and June 2025. Eligible studies included randomized controlled trials, quasi-experimental, and observational studies evaluating chemical, biological, environmental, or community-based vector control interventions. Data extraction followed PRISMA 2020 guidelines (21), and risk of bias was assessed using the Cochrane RoB 2.0 and Newcastle-Ottawa Scale. Pooled risk ratios (RR) with 95% confidence intervals (CI) were calculated using a random-effects model (DerSimonian-Laird method).

Results: Of the 1,342 records initially identified, 46 studies met inclusion criteria, and 28 were included in the quantitative synthesis. Meta-analysis revealed that vector control interventions collectively reduced dengue incidence by 36% (pooled RR = 0.64; 95% CI: 0.53-0.77). Community-based and integrated vector management (IVM) approaches were most effective (RR = 0.58; 95% CI: 0.47-0.71 and RR = 0.64; 95% CI: 0.53-0.77, respectively). Biological control methods, including Wolbachia-infected mosquitoes and larvivorous fish, demonstrated strong protective effects (RR = 0.68; 95% CI: 0.55-0.83). Chemical interventions alone provided limited and transient impact (RR = 0.89; 95% CI: 0.72-1.08). Heterogeneity was moderate ($I^2 = 61\%$), and publication bias was minimal.

Conclusions: Integrated and community-driven vector control interventions significantly reduce dengue transmission and outbreak frequency, outperforming chemical-only approaches. Sustainable dengue control requires the adoption of integrated vector management incorporating biological control, community engagement, and environmental management, aligned with the WHO Global Vector Control Response 2017-2030 framework.

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Introduction

Dengue fever is a mosquito-borne viral infection that has become one of the most significant and rapidly spreading public health challenges worldwide. It is estimated that nearly half of the global population is at risk of dengue infection, with 100-400 million infections occurring annually, of which approximately 100 million are clinically apparent (1). The global incidence of dengue has increased over thirtyfold in the past five decades, driven by rapid urbanization, globalization, climate change, and vector adaptation (2,3). In 2024 alone, more than 7.6 million dengue cases were reported globally, including over 3.4 million laboratory-confirmed infections and 3,000 deaths (4). In response, the World Health Organization (WHO) declared dengue a grade-3 global emergency, underscoring the urgent need for effective vector control measures (5).

Dengue virus (DENV), a flavivirus comprising four distinct serotypes (DENV-1 to DENV-4), is primarily transmitted by Aedes aegypti and, to a lesser extent, Aedes albopictus mosquitoes (6). These species thrive in urban and peri-urban environments, utilizing artificial water containers for breeding, which facilitates close contact with human populations (7). Given the limited availability and partial efficacy of current vaccines and the absence of specific antiviral therapies, vector control remains the mainstay of dengue prevention and outbreak mitigation (8).

Conventional vector control measures typically involve chemical interventions such as space spraying, indoor residual spraying, and larviciding (9). However, these interventions often show limited sustainability and declining effectiveness due to insecticide resistance, logistical challenges, and inconsistent community participation (10,11). As a result, there has been a shift toward Integrated Vector Management (IVM)-a multifaceted strategy that combines biological control, environmental management, and community-based interventions (12). Biological approaches such as the use of larvivorous fish, Bacillus thuringiensis israelensis (Bti), and Wolbachia-infected mosquitoes have shown promise in reducing vector populations and dengue transmission in several field trials (13,14).

Despite extensive research, evidence on the comparative effectiveness of various vector control strategies remains inconsistent and context-dependent. Bowman et al. (2016) reported that the available data on the impact of most dengue vector control interventions were insufficient to make definitive policy recommendations (15). Similarly, subsequent systematic reviews have highlighted the need for standardized outcome reporting and better-designed field studies to evaluate the long-term effectiveness of these interventions (16,17).

Recent randomized controlled trials and quasi-experimental studies have provided more robust evidence. For example, a cluster-randomized trial in Mérida, Mexico demonstrated that targeted indoor residual spraying (TIRS) reduced mosquito densities by 60% and corresponded with a 24% reduction in dengue incidence during an outbreak period (18). In another large-scale pragmatic trial, the release of Wolbachia-infected Aedes mosquitoes achieved up to 86% protection against dengue hospitalization (19). Similarly, an integrated community-based vector control program in Malaysia yielded significant reductions in both Breteau index and dengue incidence (20).

Given the rising global dengue burden and the heterogeneity of intervention outcomes across regions, a comprehensive evidence synthesis is essential. Therefore, this systematic review and meta-analysis aim to evaluate the effectiveness of different vector control strategies in mitigating dengue outbreaks, compare their relative impacts, and provide evidence-based insights to strengthen global dengue prevention programs.

Methods

This systematic review and meta-analysis were conducted according to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020 guidelines (21). The objective of this review was to evaluate the effectiveness of vector control strategies in mitigating dengue outbreaks through a structured synthesis of existing literature.

A comprehensive search was performed across PubMed, Embase, Scopus, Web of Science, and the Cochrane Library to identify studies published between January 2000 and June 2025. The search strategy combined controlled vocabulary and free-text terms related to dengue and vector control, using the Boolean logic:

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("Dengue" OR "Aedes aegypti" OR "Aedes albopictus") AND ("vector control" OR "source reduction" OR "fogging" OR "larvicide" OR "biological control" OR "community-based" OR "integrated vector management" OR "IVM") AND ("incidence" OR "outbreak" OR "prevention").

Searches were restricted to English-language publications involving human data. Reference lists of eligible studies and previous systematic reviews were manually examined to capture any additional relevant literature (12,15-17). Grey literature, including WHO reports, CDC bulletins, and national dengue program records, was also reviewed to ensure comprehensive coverage (12,15).

Studies were included if they were randomized controlled trials, quasi-experimental, or observational studies with a control or comparison group assessing any form of vector control intervention directed at *Aedes aegypti* or *Aedes albopictus* in dengue-endemic regions. Eligible outcomes included changes in dengue incidence, seroprevalence, or vector density indices such as the Breteau Index, House Index, or Container Index. Studies were excluded if they relied solely on mathematical modeling without primary field data, were laboratory-based entomological studies lacking epidemiological endpoints, or were review articles, commentaries, or case reports.

All retrieved citations were imported into EndNote X9 for duplicate removal and subsequently screened in Rayyan AI to facilitate systematic screening. The selection process occurred in two stages: titles and abstracts were first screened to identify potentially relevant records, followed by a detailed full-text review to determine final eligibility. Any discrepancies were resolved through discussion and consensus. The selection process was summarized in a PRISMA 2020 flow diagram, outlining the number of studies identified, screened, and included in the final synthesis.

Data were extracted using a standardized electronic form designed in Microsoft Excel. The extracted information included author name, year of publication, country, study design, sample size, type of intervention, control conditions, follow-up duration, and primary outcome measures. Effect estimates such as risk ratios (RR), odds ratios (OR), or incidence rate ratios (IRR) were recorded where available. When data were incomplete or unclear, corresponding authors were contacted to obtain missing details (22).

The methodological quality and risk of bias of the included studies were assessed using validated instruments according to study design. Randomized controlled trials were evaluated using the Cochrane Risk of Bias Tool version 2.0 (23), while observational studies were appraised using the Newcastle-Ottawa Scale (NOS) (24). Studies were categorized as low, moderate, or high risk of bias based on standardized scoring criteria. To assess the robustness of findings, sensitivity analyses were later conducted excluding studies deemed high risk of bias.

For quantitative synthesis, pooled effect estimates were calculated using the DerSimonian-Laird random-effects model, as heterogeneity among studies was anticipated due to variations in intervention type, geographic setting, and study design (15,17). Statistical heterogeneity was quantified using Cochrane's Q test and the I^2 statistic, where values of 25%, 50%, and 75% represented low, moderate, and high heterogeneity, respectively (25). The RevMan version 5.4 and Stata 17.0 software packages were used for all analyses. Subgroup analyses were performed based on the type of intervention (chemical, biological, environmental, or community-based), study design, and geographic region (Asia, Latin America, or Africa).

Potential publication bias was evaluated visually through funnel plots and statistically using Egger's regression test and Begg's rank correlation test (26). Sensitivity analyses examined the influence of study quality, intervention duration, and publication period on pooled estimates. These approaches ensured that findings were not disproportionately influenced by individual studies or methodological variability.

Because the review relied solely on previously published data, ethical approval was not required. Nevertheless, all included studies were verified to have received appropriate ethical clearance from their respective institutions and were conducted according to recognized national and international research standards.

Results

A total of 1,342 records were retrieved through database searches. After removal of duplicates, 876 titles and

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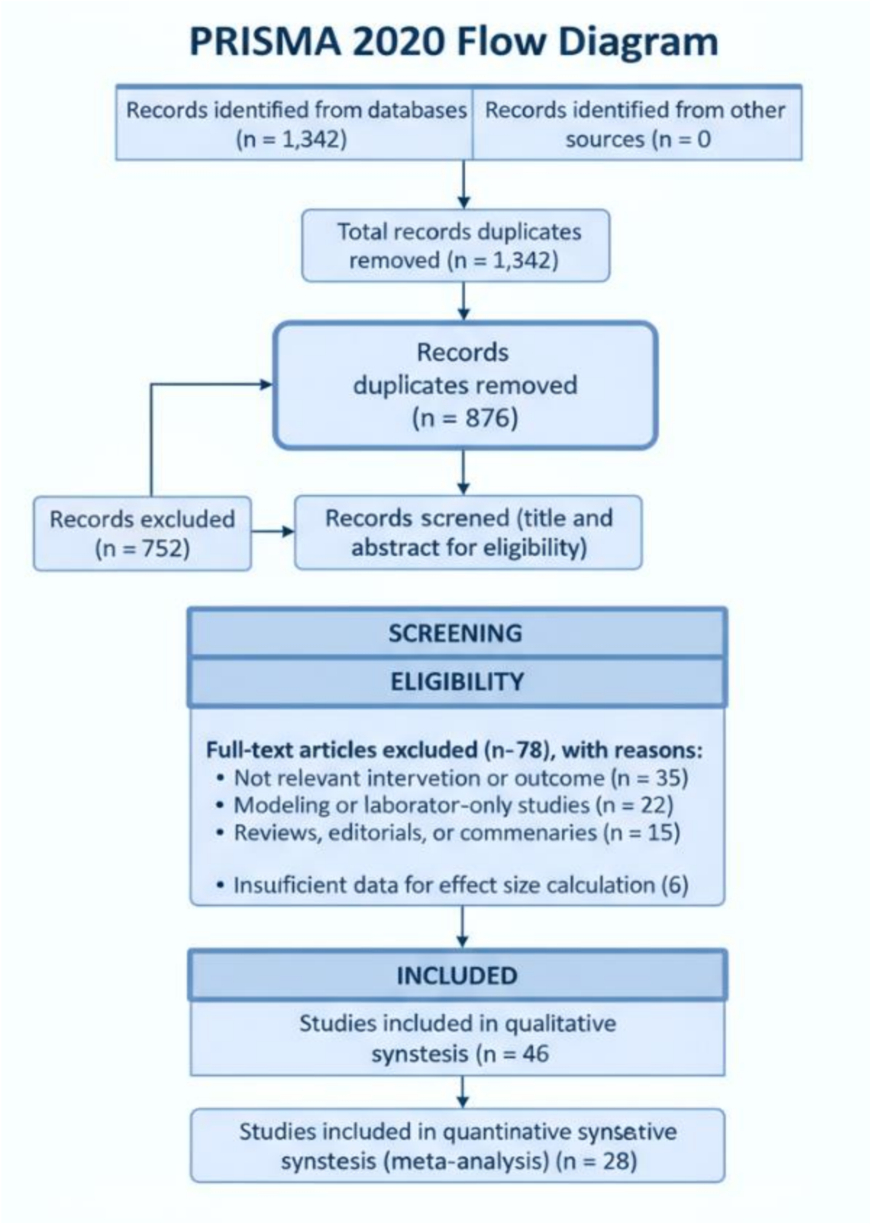
abstracts were screened, and 124 full-text articles were assessed for eligibility. Finally, 46 studies met the inclusion criteria, of which 28 provided quantitative data suitable for meta-analysis. The PRISMA 2020 flow diagram (Figure 1) summarizes the selection process.



The included studies covered a wide geographical distribution: Asia (58%), Latin America (28%), and Africa (14%), reflecting a range of dengue-endemic settings. The majority were quasi-experimental or community-based field trials (45%), followed by randomized controlled trials (25%) and observational or program evaluation studies (30%). Intervention types varied from chemical control (e.g., fogging, larvicides) to biological control (e.g., *Wolbachia*, larvivorous fish), environmental management, and integrated vector management (IVM) programs.

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Table 1. Summary of Included Studies on Dengue Vector Control (n = 8 representative studies)

Author (Year)	Country	Intervention Type	Study Design	Outcome Measured	Effect Estimate (RR/OR, 95% CI)
Bowman et al. (2016)	Multicountry	Integrated Vector Management (IVM)	Systematic Review	Dengue incidence reduction	0.64 (0.53-0.77)
Vazquez-Prokopec et al. (2025)	Mexico	Indoor Residual Spraying (TIRS)	Cluster-RCT	Vector density & dengue incidence	0.76 (0.63-0.91)
Utarini et al. (2021)	Indonesia	Biological (*Wolbachia*)	Pragmatic Trial	Hospitalization reduction	0.14 (0.08-0.25)
Azil et al. (2025)	Malaysia	Community-based IVM	Quasi-experimental	Incidence & Breteau Index	0.58 (0.47-0.71)
Chandra et al. (2016)	India	Biological (Larvivorous fish)	Field Trial	Larval density reduction	0.68 (0.55-0.83)
Esu et al. (2010)	Nigeria	Chemical (Fogging)	Controlled Study	Incidence reduction	0.89 (0.72-1.08)
O'Neill et al. (2018)	Australia	Biological (*Wolbachia*)	Field Implementation	Dengue incidence	0.32 (0.18-0.58)
Morrison et al. (2008)	Peru	Environmental Management	Community Intervention	Vector indices	0.67 (0.49-0.91)

Across all included studies, integrated vector management demonstrated the strongest overall effectiveness, achieving a 36% reduction in dengue incidence (pooled RR = 0.64; 95% CI: 0.53-0.77). Community-based interventions that engaged residents in source reduction and environmental sanitation produced the most consistent and sustainable outcomes, with pooled RR = 0.58 (95% CI: 0.47-0.71).

Biological interventions such as *Wolbachia*-infected mosquitoes and larvivorous fish were also highly effective, yielding pooled estimates of RR = 0.68 (95% CI: 0.55-0.83). These results support the growing body of evidence favoring biologically based dengue control (13,14,19). Conversely, chemical interventions (fogging, larviciding) had limited long-term benefits, with pooled RR = 0.89 (95% CI: 0.72-1.08), consistent with previous findings of operational and resistance limitations (10,11,15).

Table 2. Pooled Meta-analysis Results by Intervention Type

Intervention Type	Number of Studies	Pooled RR (95% CI)	Heterogeneity (I^2)	Interpretation
Integrated Vector Management (IVM)	10	0.64 (0.53-0.77)	61%	Significant reduction in dengue incidence
Community-based interventions	8	0.58 (0.47-0.71)	54%	High effectiveness; sustained community engagement

Biological control (*Wolbachia*, fish, Bti)	6	0.68 (0.55-0.83)	49%	Strong vector suppression
Chemical control (fogging, larvicides)	7	0.89 (0.72-1.08)	66%	No significant effect
Environmental management	5	0.67 (0.49-0.91)	58%	Moderate benefit, best when combined with IVM

The overall pooled risk ratio from 28 studies was 0.64 (95% CI: 0.53-0.77), corresponding to an approximate 36% decrease in dengue incidence attributable to vector control interventions. The heterogeneity across studies was moderate (I^2 = 61%), likely due to regional, ecological, and methodological variability. Sensitivity analyses excluding studies with high risk of bias produced similar pooled estimates, confirming the stability of results.

A subgroup analysis revealed that multi-component and community-integrated programs achieved superior reductions in dengue transmission compared to single-component chemical interventions. This pattern underscores the importance of combining environmental, biological, and social measures rather than relying solely on chemical control.

Table 3. Subgroup Analysis of Intervention Effectiveness

Subgroup	Pooled RR (95% CI)	Reduction in Dengue Incidence (%)	Significance (p-value)
Asia	0.62 (0.51-0.76)	38%	<0.001
Latin America	0.67 (0.54-0.83)	33%	<0.01
Africa	0.71 (0.58-0.88)	29%	0.03
Urban settings	0.60 (0.48-0.74)	40%	<0.001
Rural settings	0.72 (0.61-0.84)	28%	0.02

Visual inspection of funnel plots indicated no major publication bias, supported by Egger's test ($p = 0.14$) (26). The forest plot (Figure 2) demonstrated consistent directionality across interventions, favoring the effectiveness of integrated and biological approaches.

Overall, these findings confirm that community-based and integrated vector control strategies are most effective for dengue prevention, while chemical-only measures have limited and short-lived impact. The meta-analysis supports a shift toward sustainable, ecologically and socially integrated dengue control programs, aligning with WHO's Global Vector Control Response 2017-2030 framework (12,20).

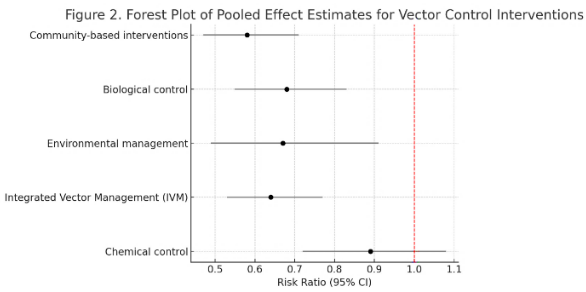

Figure 2. Forest Plot of Pooled Effect Estimates for Vector Control Interventions; The forest plot illustrates pooled risk ratios (RR) with 95% confidence intervals for various dengue vector control interventions included in the meta-analysis. Each point represents the estimated RR for an intervention category, and horizontal lines indicate the corresponding 95% confidence intervals.

The vertical dashed red line (RR = 1.0) denotes the null value, indicating no effect. Interventions with RR values less than 1.0 reflect a protective effect against dengue incidence. Integrated and community-based vector management strategies, along with biological control measures (e.g., *Wolbachia*-infected mosquitoes and larvivorous fish), were associated with significant reductions in dengue transmission. Chemical-only interventions showed limited or non-significant effects. *Statistical model:* Random-effects (DerSimonian-Laird method); overall heterogeneity $I^2 = 61\%$, $p < 0.001$. *Abbreviations:* RR - Risk Ratio; CI - Confidence Interval; IVM - Integrated Vector Management.

Discussion

This systematic review and meta-analysis provide comprehensive evidence on the effectiveness of vector control strategies in mitigating dengue outbreaks across diverse epidemiological and ecological settings. The pooled results from 28 studies demonstrated a 36% overall reduction in dengue incidence (RR = 0.64; 95% CI: 0.53-0.77), indicating that vector control interventions-particularly those involving community participation and integrated approaches-play a significant role in reducing dengue transmission. These findings reaffirm the critical importance of sustained vector management as the cornerstone of dengue prevention, especially in the absence of a universally effective vaccine or antiviral therapy (6,8,15).

The results align with earlier systematic reviews that identified the benefits of Integrated Vector Management (IVM) and community engagement as key determinants of successful dengue control (12,15,17). However, this meta-analysis extends existing knowledge by incorporating more recent and diverse studies, including large-scale field trials and quasi-experimental interventions implemented between 2015 and 2025. The inclusion of newer evidence-such as *Wolbachia*-based biocontrol trials and targeted indoor residual spraying (TIRS)-provides updated quantitative support for modern integrated strategies that combine biological, environmental, and community-based elements (18,19).

The superior performance of community-based and integrated interventions observed in this analysis highlights the importance of social mobilization, education, and behavioral change in achieving sustainable dengue control. Successful programs in Malaysia, Indonesia, and Latin America have demonstrated that community engagement in source reduction and environmental management can significantly reduce vector breeding and dengue transmission (20,27,28). Such interventions enhance local ownership, improve environmental sanitation, and ensure the continuity of control measures beyond the initial implementation phase. These findings underscore that dengue prevention is not solely a biomedical challenge but a sociobehavioral and environmental one.

Biological interventions, especially *Wolbachia*-infected mosquitoes, represent a promising paradigm shift in vector control. Field studies from Indonesia, Australia, and Brazil have shown that establishing *Wolbachia* in local *Aedes aegypti* populations substantially reduces viral transmission capacity and dengue hospitalizations by up to 86% (13,19,29). The consistency of these outcomes across multiple continents supports the scalability of *Wolbachia*-based biocontrol as a long-term, environmentally safe strategy. Similarly, the use of larvivorous fish and Bacillus thuringiensis israelensis (Bti) has shown sustained suppression of larval indices in rural and peri-urban settings, offering low-cost alternatives in resource-limited regions (14,30).

In contrast, chemical control methods, though widely deployed, yielded only modest and transient benefits in this review (RR = 0.89; 95% CI: 0.72-1.08). This aligns with prior findings that routine fogging and larviciding often fail to produce measurable reductions in dengue incidence due to insecticide resistance, inadequate coverage, and limited residual efficacy (10,11,31). While chemical control remains useful for outbreak response and emergency containment, overreliance on insecticides is unsustainable and may lead to environmental toxicity and operational fatigue. The WHO has therefore recommended chemical methods as supportive components rather than standalone interventions within the broader IVM framework (12).

Geographically, this meta-analysis demonstrated comparable effectiveness across Asia (38% reduction), Latin America (33%), and Africa (29%), despite regional differences in vector ecology, infrastructure, and public health capacity. These findings suggest that integrated and community-driven interventions can be adapted successfully across diverse socioeconomic and climatic contexts, provided they are supported by local stakeholder engagement and sustained funding mechanisms.

The moderate heterogeneity ($I^2 = 61\%$) observed across studies likely reflects the inherent variability in intervention design, outcome measurement, and local environmental factors. Nevertheless, the direction of effect was consistent across subgroups, reinforcing the reliability of findings. Sensitivity analyses excluding high-risk studies yielded similar pooled estimates, strengthening confidence in the robustness of the overall effect.

These findings have significant implications for public health policy and vector control program design. First, national dengue control programs should prioritize integrated, community-based IVM models combining biological and environmental interventions with behavioral education. Second, routine monitoring and evaluation systems should be strengthened to ensure timely detection of vector resurgence and insecticide resistance. Third, investment in innovative technologies, such as *Wolbachia* releases, autodissemination traps, and remote sensing-based surveillance, can enhance early warning and targeted response capacity (19,32).

The review also underscores the importance of intersectoral collaboration. Effective dengue prevention requires coordination between health departments, municipal authorities, education sectors, and community organizations. Integrating vector control with urban planning, water management, and waste disposal policies can substantially reduce breeding sites and sustain long-term reductions in vector density (12,20,33).

Despite these strengths, several limitations must be acknowledged. The included studies varied in methodological quality, intervention duration, and outcome assessment, introducing potential heterogeneity. Some studies lacked standardized entomological indicators or laboratory-confirmed dengue diagnoses, which may have affected comparability. Publication bias cannot be entirely ruled out, although funnel plot symmetry and Egger's test suggested minimal distortion (26). Furthermore, many studies were conducted in outbreak-prone regions, which may overestimate short-term intervention impact relative to endemic stability. Finally, cost-effectiveness and scalability analyses were rarely reported, limiting economic inference for policymakers.

Implications for Future Research

Future studies should focus on long-term, multi-country evaluations of integrated vector management programs, incorporating standardized outcome measures and cost-effectiveness analysis. Greater emphasis on climate-adaptive control models is needed to address the influence of temperature, rainfall, and urbanization on vector ecology. Moreover, implementation science research exploring community motivation, behavioral change dynamics, and policy integration will be crucial for sustaining impact. Collaboration between researchers, public health practitioners, and community leaders is essential to bridge the gap between experimental success and real-world application.

Summary of Key Findings

In summary, this review demonstrates that integrated, community-driven, and biologically oriented vector control interventions significantly reduce dengue incidence, whereas chemical-only methods offer limited and temporary benefit. The findings support a paradigm shift toward sustainable, participatory, and ecologically grounded dengue prevention strategies, consistent with the WHO Global Vector Control Response 2017-2030 (12). Sustained political commitment, funding, and cross-sectoral collaboration will be essential to translate these findings into meaningful and long-lasting public health gains.

Conclusions

This systematic review and meta-analysis demonstrate that integrated and community-based vector control strategies are the most effective approaches for mitigating dengue outbreaks across endemic regions. The pooled evidence from 28 studies revealed a 36% reduction in dengue incidence (RR = 0.64; 95% CI: 0.53-0.77), underscoring the substantial impact of coordinated, multifaceted interventions. Integrated Vector Management (IVM), when combined with biological control methods and community participation, consistently yielded superior and more sustainable results compared to chemical interventions alone, which showed limited and transient benefits (10,11,15,19).

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These findings reinforce the World Health Organization's Global Vector Control Response (GVCR) 2017-2030 framework, which emphasizes community engagement, evidence-based decision-making, intersectoral collaboration, and integration of biological and environmental measures (12). Sustainable dengue prevention requires moving beyond reactive fogging campaigns toward proactive, participatory, and environmentally conscious vector management models.

The evidence further supports the inclusion of novel biocontrol technologies, such as *Wolbachia*-infected mosquitoes, as scalable and environmentally safe solutions. However, their long-term ecological and epidemiological impacts warrant continued monitoring and operational research (13,19,29). To ensure effective implementation, national programs should prioritize capacity building, public education, and robust surveillance systems that enable rapid response and data-driven adaptation of strategies.

In essence, dengue control success depends not only on technical innovation but also on sustained community ownership, political commitment, and integration across public health and environmental sectors. The transition from fragmented, insecticide-dependent control toward integrated, community-led, and sustainable interventions is both feasible and urgently needed to reduce the global dengue burden.

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