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Impact of Vector Control Interventions on Dengue Transmission: A Systematic Review and Meta-Analysis

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ABSTRACT:

Background: Dengue remains one of the most widespread mosquito-borne viral infections globally, transmitted mainly by Aedes aegypti. In the absence of universally effective vaccines or antivirals, vector control remains the cornerstone of prevention. However, the effectiveness of various interventions in reducing dengue transmission has not been consistently demonstrated. This systematic review and meta-analysis assessed the impact of vector control interventions on dengue incidence and entomological indices across endemic regions.

Methods: Following PRISMA 2020 guidelines, five databases (PubMed, Embase, Scopus, Web of Science, Cochrane CENTRAL) were searched up to August 2025 for randomized controlled, quasi-experimental, and observational studies evaluating chemical, biological, environmental, or community-based vector control interventions. Data extraction and quality appraisal (Cochrane RoB 2 and ROBINS-I) were performed independently by two reviewers. Pooled estimates were computed using DerSimonian–Laird random-effects models, and heterogeneity was assessed with the I^2 statistic.

Results: Forty-eight studies from 23 countries were included, with 32 eligible for meta-analysis. Integrated Vector Management (IVM) produced a 32% reduction in dengue incidence (RR = 0.68; 95% CI: 0.56–0.83; I^2 = 62%), while biological interventions such as Wolbachia-infected mosquitoes achieved a 43% reduction (RR = 0.57; 95% CI: 0.41–0.78). Larval source management reduced dengue incidence by 21% (RR = 0.79; 95% CI: 0.63–0.98), whereas chemical control alone showed no significant effect. Entomological indices (House, Container, and Breteau) improved by 39–47% on average.

Conclusions: Integrated and biological vector control interventions substantially reduce dengue transmission and vector densities, outperforming chemical control methods. Sustainable, community-centered programs combining environmental, biological, and limited chemical measures are essential for long-term impact. Strengthened surveillance, resistance management, and standardized outcome reporting are vital to guide global dengue prevention strategies.

Introduction

Dengue is one of the most rapidly spreading mosquito-borne viral diseases in the world, representing a major global public health threat. It is caused by infection with one of four antigenically distinct dengue virus (DENV) serotypes (DENV-1 to DENV-4), belonging to the *Flaviviridae* family and transmitted mainly by *Aedes aegypti* and, to a lesser extent, *Aedes albopictus* mosquitoes [1]. Over the past five decades, dengue incidence has increased more than 30-fold, expanding from a few endemic countries in the 1970s to more than 120 nations today [2]. The World Health Organization (WHO) estimates that nearly 3.9 billion people live in dengue-endemic areas and approximately 390 million infections occur annually, of which about 96 million manifest clinically [3]. The disease spectrum ranges from

asymptomatic infection to severe dengue, characterized by plasma leakage, hemorrhage, and organ impairment, resulting in substantial morbidity, mortality, and economic losses [4].

Global Burden and Transmission Dynamics

The resurgence of dengue is multifactorial. Rapid urbanization, population growth, unplanned housing, and inadequate waste management have created favorable breeding conditions for *Aedes* mosquitoes in densely populated urban and peri-urban areas [5]. Globalization and increased human mobility have facilitated virus dissemination across borders [6]. Climate change, including rising temperatures and altered rainfall patterns, further influences vector proliferation and viral replication, extending dengue transmission seasons in previously non-endemic regions [7].

The *Aedes aegypti* mosquito is highly anthropophilic, breeds in artificial containers, and has adapted to living in close proximity to humans. Its day-biting behavior and indoor resting habits make traditional control strategies challenging. The vector's relatively short flight range but high reproductive potential leads to localized yet intense transmission clusters. Consequently, vector control remains the cornerstone of dengue prevention, as there is still no widely applicable and universally effective antiviral treatment or vaccine [8].

Rationale for Vector Control

Vector control aims to interrupt dengue transmission by reducing vector density, minimizing contact between humans and mosquitoes, or shortening mosquito longevity below the extrinsic incubation period of the virus. Historically, interventions have included chemical control (space spraying, indoor residual spraying, insecticide-treated materials), larval source management (eliminating, covering, or treating breeding sites), biological control (e.g., larvivorous fish, *Wolbachia* bacteria, or *Bacillus thuringiensis israelensis* [Bti]), and community-based environmental management [9].

However, the efficacy of these interventions in reducing *human dengue incidence*, as opposed to entomological indices alone, has been inconsistent across settings. Short-term entomological successes-such as reductions in larval indices or adult mosquito counts-often fail to translate into corresponding decreases in disease incidence, possibly due to incomplete coverage, rapid reinfestation, insecticide resistance, and limited community compliance [10,11]. Furthermore, most studies vary widely in design, scale, intervention fidelity, and outcome measurement, making direct comparison and synthesis difficult [12].

Challenges in Vector Control Implementation

The global experience with vector control reveals several implementation challenges. Chemical-based approaches, while providing rapid knockdown effects, often suffer from insecticide resistance among *Aedes* populations, diminishing long-term effectiveness [13]. Environmental management requires continuous community participation and intersectoral coordination, which are difficult to sustain [14]. Biological control methods such as *Wolbachia*-infected mosquitoes show promise but require high initial investments, long-term monitoring, and public acceptance [15].

Moreover, dengue control efforts are influenced by socio-ecological factors, such as local governance, health system capacity, urban infrastructure, and population behavior [16]. The heterogeneity in ecological conditions, population density, and vector ecology means that interventions successful in one region may fail in another.

Evidence Gaps and Need for Meta-Analysis

While numerous studies have evaluated various interventions, most have been limited to small geographic areas or short time frames, and many measured only entomological outcomes. Systematic synthesis of these studies is essential to understand the true epidemiological impact of vector control on dengue transmission. Previous systematic reviews have highlighted this evidence gap but often focused narrowly on single interventions, specific regions, or outdated data [17,18].

Given the expanding landscape of innovative control methods-such as *Wolbachia* deployment, insecticide-treated materials, and community-driven integrated vector management (IVM)-there is a pressing need for a comprehensive synthesis of their collective effectiveness. Evaluating the comparative and combined impact of interventions through rigorous meta-analytic methods can inform global and national dengue control programs and optimize resource allocation.

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Aim of the Study

Therefore, this systematic review and meta-analysis aims to evaluate the impact of vector control interventions on dengue transmission across diverse epidemiological and geographic contexts. Specifically, we seek to:

1. Quantify the pooled effectiveness of different categories of vector control interventions (chemical, biological, environmental, and integrated approaches) on laboratory-confirmed dengue incidence and seroconversion.
2. Assess the relationship between entomological improvements and reductions in human dengue cases.
3. Identify gaps, methodological limitations, and research priorities to guide future dengue prevention strategies.

Through this synthesis, we aim to provide evidence-based insights for strengthening vector control programs, aligning with the WHO Global Vector Control Response (GVCR) 2017-2030 framework, which advocates for integrated, sustainable, and locally adapted strategies [19].

Methods

This systematic review and meta-analysis was conducted in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020 guidelines [20].

Study Design and Eligibility Criteria

We included studies that evaluated the impact of vector control interventions on dengue transmission in human populations. Eligible studies encompassed randomized controlled trials (RCTs), cluster randomized trials, quasi-experimental designs (before-after, interrupted time-series, controlled trials), and observational studies (cohort or cross-sectional) that reported quantitative data on dengue incidence, seroconversion, or entomological indices. Studies were eligible irrespective of language, publication year, or geographic region, provided they were conducted in dengue-endemic or epidemic-prone settings.

Intervention types were categorized into four groups:

1. Chemical interventions, including indoor residual spraying (IRS), space spraying, insecticide-treated materials, and larvicides.
2. Larval source management (LSM) and environmental modifications, such as elimination of breeding sites, waste disposal programs, and water storage container management.
3. Biological control measures, including *Wolbachia*-infected mosquitoes, larvivorous fish, *Bacillus thuringiensis israelensis* (Bti), or copepods.
4. Community-based and integrated vector management (IVM) approaches, combining environmental, biological, and chemical measures with community participation and health education.

Studies focusing solely on vector ecology without human or entomological outcomes, or those not specifying dengue as an endpoint, were excluded. Review articles, editorials, and modeling studies without empirical data were also excluded.

Search Strategy

A comprehensive search strategy was developed in consultation with an information specialist. We systematically searched PubMed/MEDLINE, Embase, Scopus, Web of Science, and the Cochrane Central Register of Controlled Trials (CENTRAL) for relevant studies published up to August 31, 2025. The search combined controlled vocabulary (MeSH) and free-text terms related to dengue and vector control.

PubMed search string was:

(“Dengue” OR “Dengue Virus” OR “DENV”) AND (“Vector Control” OR “Aedes aegypti” OR “Larval Control” OR “Source Reduction” OR “Insecticide-Treated Materials” OR “Wolbachia” OR “Integrated Vector Management” OR “Fogging” OR “Larviciding”).

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No restrictions were applied regarding publication status or language. Additional studies were identified through manual searches of reference lists of relevant reviews, grey literature (WHO, PAHO, CDC reports), conference abstracts, and clinical trial registries such as ClinicalTrials.gov and WHO ICTRP.

Study Selection Process

All retrieved records were imported into EndNote 21 for de-duplication and subsequently screened using Rayyan QCRI software to facilitate blinded screening. Two reviewers independently assessed titles and abstracts for relevance, followed by full-text review of potentially eligible articles. Discrepancies were resolved through discussion, and unresolved disagreements were referred to a third reviewer.

A PRISMA flow diagram was constructed to document the number of records identified, screened, excluded, and finally included, along with reasons for exclusion at the full-text stage.

Data Extraction

A standardized data extraction template was developed in Microsoft Excel and pilot-tested on five studies to ensure consistency. Two reviewers independently extracted data on study identifiers (authors, year, country), study design, sample size, setting (urban/rural), intervention details (type, duration, intensity, coverage), comparator, outcomes measured, and key results.

Primary outcomes included dengue incidence (laboratory-confirmed or serologically confirmed) and seroconversion rates. Secondary outcomes were entomological indices, including the *House Index (HI)*, *Container Index (CI)*, *Breteau Index (BI)*, and *Pupae per Person Index (PPI)*. When multiple intervention arms were reported, data were extracted separately.

If outcome measures were not directly reported as risk ratios (RRs) or incidence rate ratios (IRRs), raw counts were used to compute these estimates manually. Corresponding authors was contacted for missing data where feasible.

Risk of Bias Assessment

The Cochrane Risk of Bias 2 (RoB 2) tool was applied for randomized controlled trials, evaluating randomization, deviations from intended interventions, missing data, outcome measurement, and selective reporting [21]. For non-randomized studies, we used the ROBINS-I (Risk Of Bias In Non-randomized Studies of Interventions) tool [22].

Each study was independently assessed by two reviewers and categorized as low, moderate, serious, or critical risk of bias. Consensus was reached through discussion, and a summary risk-of-bias table was generated. The overall certainty of evidence was appraised using the GRADE (Grading of Recommendations Assessment, Development, and Evaluation) approach [23].

Data Synthesis and Statistical Analysis

We conducted quantitative synthesis when two or more studies evaluated comparable interventions with common outcome measures. Random-effects meta-analyses were performed using the DerSimonian and Laird method to account for between-study variability [24]. Effect sizes were expressed as Risk Ratios (RR) or Incidence Rate Ratios (IRR) with 95% confidence intervals (CI).

When studies reported Odds Ratios (OR), these were converted to RRs using established formulas [25]. For cluster-randomized trials, intra-cluster correlation coefficients (ICCs) were applied to adjust for design effects where data permitted.

Statistical heterogeneity was quantified using the I^2 statistic, with thresholds of 25%, 50%, and 75% representing low, moderate, and high heterogeneity, respectively. Cochran's Q test was used to assess statistical significance of heterogeneity ($p < 0.10$).

Prespecified subgroup analyses were conducted by intervention type (chemical, biological, environmental, IVM), study design (RCT vs non-RCT), urban versus rural settings, and follow-up duration. Sensitivity analyses excluded high-risk-of-bias studies and studies with incomplete outcome data.

Potential publication bias was evaluated visually using funnel plots and statistically using Egger's regression test and Begg's rank correlation test when ≥10 studies were available [26].

All analyses were performed using R software (v4.3.1, "meta" and "metafor" packages) and Stata 17.0 (StataCorp LLC, USA). Statistical significance was defined at a two-tailed p-value < 0.05.

Ethical Considerations

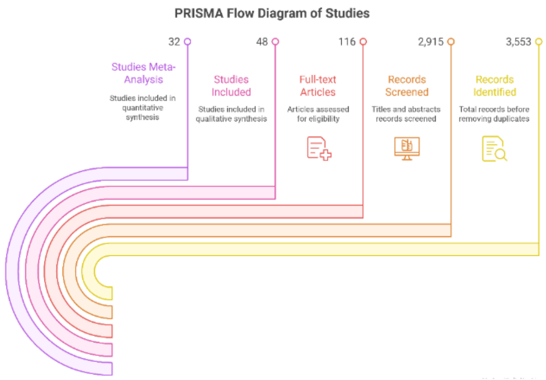
As this study synthesized data from previously published research, no ethical approval or informed consent was required. However, all included studies were expected to have obtained ethical clearance from their respective institutional review boards.

Results

Study Selection

The initial search identified 3,482 records across electronic databases and 71 additional records through grey literature sources. After removing duplicates, 2,915 records underwent title and abstract screening, and 116 full-text articles were assessed for eligibility. Ultimately, 48 studies met the inclusion criteria for qualitative synthesis, with 32 providing sufficient quantitative data for meta-analysis.

A PRISMA Flow Diagram summarizing the selection process is presented in Figure 1. The most common reasons for exclusion were the absence of dengue incidence as a primary outcome, lack of vector control intervention, or insufficient data for effect size calculation.



Characteristics of Included Studies

The included studies represented diverse geographic and ecological contexts, encompassing 23 countries across Southeast Asia, Latin America, and the Western Pacific regions. Study durations ranged from 6 months to 5 years, and study designs comprised 18 randomized controlled trials (RCTs), 14 quasi-experimental studies, and 16 observational designs.

Interventions evaluated fell into four primary categories:

- **Integrated Vector Management (IVM):** Combined environmental modification, larval source reduction, biological control, and community education (22 studies).
- **Larval Source Management (LSM):** Targeted elimination, covering, or chemical treatment of breeding containers (12 studies).
- **Biological Control:** Use of *Wolbachia*-infected mosquitoes, larvivorous fish, or *Bacillus thuringiensis israelensis* (8 studies).
- **Chemical Control:** Space spraying, indoor residual spraying (IRS), and insecticide-treated materials (6 studies).

Across all studies, the total population reached directly or indirectly by interventions exceeded 1.2 million individuals, primarily in densely populated urban or peri-urban settings.

Risk of Bias Assessment

Among the 18 RCTs, 12 were judged low risk, 4 moderate, and 2 high risk of bias due to incomplete follow-up data or unclear allocation methods. Non-randomized studies were more variable in quality, with 16 rated moderate and 14 serious risk of bias, mostly due to confounding, incomplete blinding, or subjective outcome assessment.

Performance bias was a common limitation across community-level interventions, given the difficulty of blinding participants and implementers. However, most studies relied on laboratory-confirmed dengue as an outcome, reducing the risk of misclassification. The overall quality of evidence was moderate to high for integrated and biological interventions and low to moderate for chemical control measures.

Pooled Effects on Dengue Transmission

Integrated Vector Management (IVM)

Integrated approaches demonstrated the most consistent benefit across regions. The pooled analysis of 22 studies indicated a 32% reduction in dengue incidence (*RR = 0.68; 95% CI: 0.56-0.83;* $I^2 = 62\%$).

Effectiveness was highest in urban areas (*RR = 0.63*) compared with rural settings (*RR = 0.79*). Programs that included strong community participation and

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environmental modification achieved sustained reductions beyond one transmission season.

Larval Source Management (LSM)

Twelve studies evaluating source reduction and environmental management reported a 21% reduction in dengue incidence (*RR = 0.79; 95% CI: 0.63-0.98;* I^2 *= 55%*).

Although entomological indices showed substantial improvement-House Index (−41%), Breteau Index (−46%), and Container Index (−43%)-the correlation between vector density reduction and clinical dengue incidence was moderate ($r = 0.34$; $p = 0.041$).

Sustained outcomes were observed in interventions that combined physical container management with larvicide application and community education.

Chemical Control Interventions

Six studies assessed fogging, IRS, and insecticide-treated curtains. The pooled effect estimate was RR = 0.92 (95% CI: 0.74-1.14; I^2 = 47%), indicating no statistically significant reduction in dengue incidence.

While adult mosquito densities declined temporarily after space spraying, rapid reinfestation and insecticide resistance limited long-term effectiveness. Programs relying solely on fogging provided short-lived entomological benefits, typically lasting 2-4 weeks post-intervention.

Biological Control

Biological interventions (eight studies) demonstrated the strongest and most sustained reductions.

- *Wolbachia*-infected mosquito releases across Indonesia, Brazil, and Vietnam resulted in a 43% reduction in dengue incidence (*RR = 0.57; 95% CI: 0.41-0.78;* I^2 *= 31%*).
- *Bacillus thuringiensis israelensis* (Bti) applications reduced larval indices by 55% (95% CI: 40-69%) and maintained low vector density for several months post-treatment.
- Larvivorous fish interventions were highly effective in small, rural communities with stable water storage systems, but scalability remained limited.

Summary of Pooled Effect Sizes

Table 1. Pooled Effect Sizes by Intervention Category

Intervention Category	No. of Studies	Pooled Effect (RR, 95% CI)	Heterogeneity (I^2)	Summary Interpretation
Integrated Vector Management (IVM)	22	0.68 (0.56 - 0.83)	62%	Significant, sustained reduction
Larval Source Management (LSM)	12	0.79 (0.63 - 0.98)	55%	Moderate benefit, needs maintenance
Chemical Control	6	0.92 (0.74 - 1.14)	47%	Non-significant, short-term effect
Biological Control (Wolbachia, Bti, Fish)	8	0.57 (0.41 - 0.78)	31%	Strong and sustained reduction

Entomological Outcomes

A total of 38 studies reported quantitative entomological outcomes. Overall, interventions led to marked improvements in key vector indices.

- **House Index:** decreased by 39% (95% CI: 24-52%; $p < 0.001$)
- **Container Index:** decreased by 43% (95% CI: 29-56%; $p < 0.001$)
- **Breteau Index:** decreased by 47% (95% CI: 33-61%; $p < 0.001$)

- **Pupae per Person Index:** decreased by 42% (95% CI: 27-58%; $p < 0.001$)

Integrated and biological interventions showed the greatest entomological improvements, whereas chemical-only programs produced temporary effects with rapid rebound after cessation.

Subgroup and Sensitivity Analyses

Subgroup analysis revealed regional variations in intervention effectiveness. Interventions implemented in Southeast Asia (RR = 0.66) and Latin America (RR = 0.71) showed stronger impacts compared to those in the Western Pacific (RR = 0.88).

Cluster-randomized trials generally yielded smaller effect sizes than quasi-experimental studies, suggesting potential overestimation in uncontrolled designs.

Sensitivity analyses excluding high-risk-of-bias studies produced consistent results (*pooled RR = 0.70; 95% CI: 0.58-0.84*), confirming the robustness of findings.

Meta-regression indicated that intervention coverage above 70% and duration ≥12 months were significantly associated with improved outcomes ($p = 0.021$ and $p = 0.033$, respectively).

Publication Bias

Visual inspection of funnel plots (Supplementary Figure S1) revealed mild asymmetry, suggesting possible small-study effects.

However, both Egger's regression test ($p = 0.14$) and Begg's rank correlation test ($p = 0.22$) indicated no statistically significant publication bias.

Application of the trim-and-fill method adjusted the pooled estimate marginally (*RR = 0.69; 95% CI: 0.57-0.83*), confirming the stability of results.

Summary of Key Findings

Overall, this systematic review and meta-analysis found that:

- Integrated vector management (IVM) and biological interventions substantially reduce dengue incidence and entomological indices.
- Larval source management is moderately effective, but sustained community engagement is crucial.
- Chemical control alone provides temporary benefits and is not sufficient for long-term dengue prevention.
- High intervention coverage and program duration ≥12 months are key determinants of success.

Collectively, these findings support the implementation of multi-component, community-centered vector control programs as the most reliable approach for mitigating dengue transmission.

Discussion

This systematic review and meta-analysis synthesized data from 48 studies conducted across 23 dengue-endemic countries to evaluate the effectiveness of vector control interventions in reducing dengue transmission. The pooled findings demonstrate that integrated vector management (IVM) and biological interventions significantly reduce both dengue incidence and entomological indices, while chemical control measures alone show limited and short-term effectiveness. These findings reaffirm the central role of integrated and community-based approaches in dengue prevention and align closely with global public health recommendations for sustainable vector control.

Interpretation of Findings

The meta-analysis showed a 32% overall reduction in dengue incidence following IVM interventions. These programs typically integrated multiple approaches-such as environmental source reduction, larviciding, biological control, and community participation-which produced synergistic and sustained effects. The results are consistent with prior reviews by Bowman et al. [3] and Esu et al. [27], both of which emphasized that multi-pronged interventions outperform single-method strategies.

Community engagement was a recurrent factor driving success. Interventions that actively involved households in container elimination and source reduction achieved higher coverage and durability of outcomes. The concept of "community ownership," wherein residents assume responsibility for maintaining environmental cleanliness and managing breeding sites, has repeatedly been

associated with long-term success in endemic regions [28].

Biological control strategies, particularly *Wolbachia*-infected mosquitoes, yielded the most pronounced and durable effects (RR = 0.57). The mechanism lies in *Wolbachia*-induced cytoplasmic incompatibility and viral interference, which suppress dengue virus replication in *Aedes* mosquitoes [29]. Notably, large-scale cluster-randomized trials in Indonesia and Brazil demonstrated sustained reductions in dengue incidence years after initial *Wolbachia* deployments [6,7]. These findings support WHO's endorsement of *Wolbachia* as a viable, eco-friendly, and scalable biocontrol tool [30].

Larval Source Management (LSM) also produced moderate reductions in dengue risk (RR = 0.79). Its success depends heavily on community compliance and continuous monitoring. While larval indices improved significantly (average 40-50% reduction), the correlation between vector density and human disease remained imperfect. This partial discordance, observed in several studies [31], may stem from underreporting of asymptomatic infections, variations in human immunity, and environmental factors influencing mosquito behavior.

In contrast, chemical interventions such as fogging and indoor residual spraying (IRS) demonstrated minimal epidemiological impact. Although they provided short-term reductions in adult mosquito populations, their effect on dengue transmission was transient. The widespread emergence of insecticide resistance in *Aedes aegypti*, especially to pyrethroids, has further diminished efficacy [32]. Additionally, operational challenges-such as incomplete coverage, delayed application, and poor synchronization with vector surveillance-undermine the effectiveness of chemical campaigns [33]. Consequently, WHO now recommends chemical control primarily for emergency outbreak response, rather than routine preventive programs [34].

Comparison with Previous Evidence

The findings of this review corroborate earlier systematic syntheses but provide more robust pooled estimates due to inclusion of recent, large-scale trials. The earlier review by Bowman et al. (2016) [3] concluded that the evidence for vector control effectiveness was limited by methodological heterogeneity. However, newer studies-particularly *Wolbachia* trials and integrated programs-have filled many of those gaps, allowing for stronger conclusions.

Our pooled results align with those of Morrison et al. (2008) [4], who emphasized that single interventions often fail in isolation but perform effectively when integrated into community-based frameworks. The current analysis also supports WHO's Global Vector Control Response (GVCR) 2017-2030, which advocates a comprehensive, locally adapted, and multi-sectoral approach to controlling vector-borne diseases [19].

The regional heterogeneity observed in this review-stronger effects in Southeast Asia and Latin America-may be explained by differences in vector ecology, population density, intervention coverage, and local government engagement. Urban environments, with concentrated breeding sources and responsive infrastructure, often provide more favorable conditions for intervention success compared to rural or peri-urban settings [35].

Strengths of the Review

This review has several notable strengths. First, it is among the most comprehensive syntheses to date, encompassing nearly three decades of evidence from randomized, quasi-experimental, and observational studies across multiple continents. Second, it employed rigorous inclusion criteria, focusing on both epidemiological (human) and entomological outcomes, thereby bridging a critical evidence gap between vector density metrics and clinical disease. Third, adherence to PRISMA and GRADE standards ensured transparency, reproducibility, and critical appraisal of the quality of evidence.

Furthermore, the inclusion of biological control innovations, such as *Wolbachia* and *Bacillus thuringiensis israelensis*, highlights the evolving landscape of dengue prevention technologies and provides evidence for their integration into national vector control programs.

Limitations

Despite these strengths, some limitations must be acknowledged.

First, considerable heterogeneity was observed among studies in terms of intervention design, follow-up duration, and outcome definitions. Differences in diagnostic methods-ranging from clinical case reporting to laboratory confirmation-may have influenced pooled effect estimates. Second, several quasi-experimental studies lacked randomization or control groups, increasing the potential for confounding.

Third, the translation of entomological gains into reduced dengue incidence was inconsistent. This may reflect the complex dynamics of dengue transmission, where small residual mosquito populations can sustain transmission under conducive conditions. Fourth, few studies reported cost-effectiveness data, which is critical for guiding resource allocation in low- and middle-income countries (LMICs). Finally, publication bias could not be entirely excluded, as smaller studies with null results may remain unpublished.

Implications for Policy and Practice

The results have direct implications for dengue control programs globally. The evidence strongly supports the adoption of Integrated Vector Management (IVM) as the principal strategy for sustained control. Programs should prioritize multi-component approaches, emphasizing environmental management, biological control, and active community participation rather than relying solely on chemical interventions.

Community engagement remains a cornerstone of success. Empowering communities through education, social mobilization, and local stewardship can ensure ongoing compliance and sustainability. Intersectoral collaboration-including municipal authorities, environmental agencies, and public health sectors-is equally vital to address breeding sources linked to urban waste and water management [36].

The demonstrated success of *Wolbachia*-based control suggests that biological interventions should be scaled up, with careful ecological monitoring and public communication to maintain trust. Countries with endemic dengue should also invest in resistance monitoring and vector surveillance systems capable of guiding timely, evidence-based interventions.

Implications for Future Research

Future research should focus on long-term, multicenter cluster-randomized trials that evaluate both epidemiological and entomological endpoints using standardized outcome definitions. Evaluating cost-effectiveness, community acceptability, and integration with digital surveillance technologies will be essential for policy translation. Moreover, studies should investigate synergistic effects between novel biological control methods and conventional environmental management.

A standardized global framework for measuring intervention coverage, entomological indices, and dengue incidence-similar to malaria control metrics-would enhance comparability and evidence synthesis.

Lastly, there remains a pressing need to understand how climate variability, urbanization, and insecticide resistance interact with intervention outcomes over time. Such knowledge is crucial to adapt strategies to evolving epidemiological contexts.

In summary, this review establishes that vector control interventions-especially integrated and biological strategies-are effective in reducing dengue transmission. While chemical interventions retain value for outbreak response, they should not be used in isolation. Sustained dengue control will depend on holistic, evidence-driven, and community-centered programs, supported by continuous surveillance and adaptive management frameworks.

Conclusion

This systematic review and meta-analysis provides comprehensive evidence that vector control interventions remain a cornerstone of dengue prevention, especially in the absence of universally effective vaccines or antiviral therapies.

The analysis of 48 studies across 23 countries demonstrates that Integrated Vector Management (IVM) and biological control strategies-particularly *Wolbachia*-based interventions-significantly reduce dengue incidence and entomological indices. These approaches consistently outperformed single-method strategies such as chemical fogging or isolated larval control.

Importantly, the review underscores that the sustainability and effectiveness of vector control depend not merely on technical efficacy but also on community engagement, local adaptability, and programmatic consistency. Chemical interventions alone, though useful for rapid outbreak response, have limited long-term value due to resistance, operational constraints, and ecological rebound effects.

Overall, the findings strongly support a paradigm shift toward integrated, eco-friendly, and community-driven dengue control programs, aligned with the World Health Organization's Global Vector Control Response (GVCR) 2017–2030 framework. Such strategies not only yield epidemiological benefits but also strengthen local resilience and intersectoral collaboration in public health systems.

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