



BIOLOGICAL AND SUSTAINABLE CONTROL OF MOSQUITO VECTORS: A BIBLIOMETRIC ANALYSIS

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Abstract

Mosquito vectors transmit dengue, chikungunya, and Zika, posing a major global public health problem. In Mexico, mosquito control has primarily relied on insecticides such as temephos, malathion, cypermethrin, and deltamethrin. However, the rise of insecticide resistance in mosquito populations has reduced the effectiveness of these chemical treatments, highlighting the need for alternative, sustainable strategies. This study aimed to identify major scientific advances, key issues, emerging trends, and principal scientific collaboration groups in this field through bibliometric analysis. The Scopus and Web of Science databases were used, with search terms including "Aedes aegypti," "Aedes albopictus," or "Culex quinquefasciatus" combined with "biological control," "biocontrol," or "sustainable control." Results revealed promising strategies for sustainable mosquito vector control, such as the use of Wolbachia, *Bacillus thuringiensis* var. *israelensis*, *Lysinibacillus sphaericus*, entomopathogenic fungi, and nanoparticles. Additionally, five major scientific collaboration groups were identified, led by entomologists and parasitologists. However, compared with the USA, India, and Brazil, the participation of Mexico was limited. The findings underscore the need for Mexico to move beyond generalized strategies and invest in innovative, locally developed biological solutions for mosquito vector control. Strengthening national research efforts and promoting technologies tailored to the local context will be essential to ensure a sustainable, effective, and long-term impact on vector-borne diseases.

Keywords: Public health, microorganism, arbovirus, population regulation, biological strategies, sustainable management.

1. Introduction

As a consequence of their role as vectors of highly epidemiologically significant arboviruses, *Aedes aegypti* and *Aedes albopictus* represent a substantial threat to global public health, as they are responsible for the transmission of dengue virus (DENV), chikungunya virus (CHIKV), and Zika virus (ZIKV) [1]. Likewise, *Culex quinquefasciatus* is recognized as a vector of several medically important pathogens,



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including Zika virus [2]. In Mexico, these mosquito species are widely distributed [3]. According to recent data, Mexico reported 125,160 dengue cases and 30 Zika cases in 2024 [4].

The dengue virus is endemic to tropical regions; however, the global expansion of the disease has been driven by the adaptation of mosquito vectors to urban environments, increased human mobility, and changing climatic conditions [5]. Dengue is mainly transmitted by *Ae. aegypti* and *Ae. albopictus* [6]. According to the World Health Organization [7], about 390 million cases of dengue are recorded annually worldwide, and the disease mainly affects Africa, Southeast Asia, and Latin America. In Mexico, more than 250,000 cases of dengue have been recorded during the last six years (2018–2024), and the highest occurrence took place in Veracruz, Tamaulipas, and Chiapas [4].

The initial stages of DENV infection may be asymptomatic; however, the disease can result in fever, headache, skin rashes, generalized muscle and joint pain, nausea, and vomiting [8]. If the condition worsens, patients can suffer from coagulopathy, which increases the fragility and permeability of blood vessels. This condition is called dengue hemorrhagic fever (DHF) and, in severe cases, it can result in hypovolemic shock or dengue shock syndrome (DSS), both of which can be fatal [5].

The first outbreaks of CHIKV were limited to Africa and Asia; subsequently, it spread in 2005, affecting more than 300,000 people in the Indian Ocean islands [9]. From 2013 to 2023, a total of 1,207,475 suspected cases of chikungunya were reported in the Americas [10], CHIKV is transmitted to humans by *Ae. aegypti* and *Ae. albopictus* [11].

Up to 28% of CHIKV cases are asymptomatic. The symptoms of the disease include an acute, non-fatal, and self-limited fever, as well as muscle pain, joint inflammation, headache, nausea, skin rashes, and fatigue [12]. The symptoms appear between the first and the third week; however, a third of the patients experience rheumatic symptoms for months and, in some cases, even for years [13]. The virus infection affects not only the mobility of the patients but also their overall welfare, quality of life, and capacity to cope with everyday activities [12].

After its outbreak in several regions of Uganda, ZIKV was isolated for the first time in 1947 [14]. In 2015, global outbreaks were recorded in Africa, the Americas, Asia, and the Pacific region. On 1 February 2016, the World Health Organization declared ZIKV a public health emergency of international concern. Since 2015, 900,000 suspected cases of ZIKV have been recorded in 80 countries [15]. From 2015 to 2024, Mexico recorded 20,189 cases of ZIKV [16].

ZIKV is mainly transmitted by *Ae. aegypti* and other vector species such as *Ae. polynesiensis* (Marks, 1951) and *Ae. albopictus* [17]. ZIKV symptoms include high fever, rashes, joint pain, conjunctivitis, headache, and muscle pain. Complications may include Guillain-Barré syndrome, a serious condition that can endanger human life [18]. ZIKV also has serious consequences for the fetus during pregnancy, including microcephaly and neurological deterioration [17].

The reduction of vector populations still plays a major role in the prevention and reduction of the transmission of arboviral diseases [19]. The Mexican NOM-032-SSA2-2014 regulates epidemic surveillance and the promotion, prevention, and control of vector-transmitted diseases [20]. The Centro Nacional de Programas Preventivos y Control de Enfermedades (CENAPRECE: National Center for Preventive Programs and Disease Control) has developed strategies to control *Ae. aegypti* through entomological studies, entomo-virological surveillance (which includes the collection of adult mosquitoes to detect the virus), and insecticide applications [21].

The Methodological Guide for Larval Control Actions [22] recommends the use of specific insecticides and bioinsecticides during the larval stage, including: temephos, spinosad, *Bacillus thuringiensis var. israelensis* (Barjac, 1978), methoprene, novaluron, and pyriproxyfen. The Methodological Guide for Indoor Residual Spraying [23] and the Methodological Guide for Spatial Spraying [24] recommend the

use of bendiocarb, propoxur, chlorpyrifos-ethyl, pirimiphos-methyl, and malathion for the adult stage.

CENAPRECE promotes a variety of control products such as *Bacillus thuringiensis* var. israelensis (Bti), methoprene (S-Methoprene), spinosad (spinosyns A and D), and novaluron ((RS)-1-[3-chloride-4-(1,1,2-trifluoride-2-trifluoromethoxy) phenol]-3-(2,6-difluorobenzoyl) urea). However, Mexico still uses temephos (phosphorothioate of o, o, o, o'-tetramethyl-o, o'-Thio-di-p-phenylene) [25]. The following products are used to control adult vectors: pyrethroids (PYR) — such as cypermethrin, cyfluthrin, deltamethrin, and bifenthrin —; organophosphates (OP) — such as malathion and chlorpyrifos —; and carbamates (CARB) — such as bendiocarb [26,27].

Chemicals, both as larvicides and adulticides, have been repeatedly used as a strategy within the programs aimed at controlling dengue vectors. Nevertheless, their long-term application has caused mosquitoes to develop resistance to these products [28]. In Mexico, *Ae. aegypti* has mainly developed resistance to pyrethroids (PYR 12–14) [26]. In certain regions of Mexico, mosquitoes have developed moderate resistance to organophosphates (OP), particularly temephos [25]. Likewise, *Ae. albopictus* has developed resistance to malathion, permethrin, deltamethrin, and chlorpyrifos [26].

Since the introduction of CHIKV (2014) and ZIKV (2015), the Mexican public health system has investigated integrated strategies to control vectors and tackle these diseases. The reduction of mosquito vector populations is still a key step in the programs aimed at controlling DENV, CHIKV, and ZIKV [19]. A major concern in Mexico is finding more sustainable and biological alternatives to address arboviral infections and mosquito vector resistance to insecticides [25].

In this context, the growing evidence of insecticide resistance highlights not only the limitations of control strategies based on chemical compounds, but also the urgent need to transition toward more sustainable and long-lasting approaches [27]. Integrated vector management (IVM) has evolved to incorporate environmentally responsible strategies that reduce selective pressure on mosquito populations while maintaining long-term effectiveness [29,30].

Within this framework, biological control has emerged as a sustainable and eco-friendly alternative for regulating mosquito populations through natural ecological interactions [31,32]. Biological control involves the use of living organisms, such as predators, pathogens, and other natural enemies, to suppress vector populations and reduce dependence on chemical insecticides [33]. This strategy has been widely integrated into vector management programs because it is target-specific, environmentally safer, potentially cost-effective, and capable of providing long-term control with lower ecological impact than insecticide-based approaches [32].

Sustainable vector control encompasses environmentally responsible strategies aimed at reducing adverse impacts on ecosystems and human health beyond the exclusive use of living organisms [34]. These approaches include plant-derived compounds, bioinsecticides, nanoemulsions, and eco-friendly nanomaterials designed to enhance efficacy while minimizing non-target toxicity [35,36]. Although both biological and sustainable control seek to reduce dependence on synthetic insecticides, biological control relies on direct interactions between natural enemies and vectors, whereas sustainable control represents a broader integrative framework that combines low-impact technologies within integrated vector management programs [31,37].

Considering innovative strategies to biologically control mosquito vectors is a key element in preventing outbreaks and mitigating mosquito resistance to traditional chemical products [38]. Given the large volume of research on these subjects, using methods based on meta-analysis of data (e.g., bibliometrics) is fundamental. This method applies statistical and visual techniques to identify patterns in scientific literature, facilitating a comprehensive analysis of the information [39,40].

Consequently, a bibliometric analysis was conducted using the Scopus and Web of Science databases.

The objective was to identify the major advances regarding biological and sustainable control strategies (used to regulate mosquito vector populations), the main research trends, and the most prominent international collaboration groups. In addition, the participation and contribution of Mexico was evaluated to promote domestic research and development of biological and sustainable strategies, particularly in regions with high incidence of mosquito-borne diseases.

2. Materials and Methods

The study was conducted through a comprehensive bibliometric search in two major bibliographic databases: Scopus and the Science Citation Index Expanded (SCI-Expanded) of Web of Science. The use of multiple databases is essential to ensure comprehensive coverage and reliability in bibliometric analyses [41].

The search was carried out on February 20 (Scopus) and February 21 (Web of Science), 2024. The search strategy combined the terms “*Aedes aegypti*” OR “*Aedes albopictus*” OR “*Culex quinquefasciatus*” with “biological control” OR “biocontrol” OR “sustainable control,” applied to the title, abstract, and keywords fields. No time restrictions were applied. The following document types were included: articles, conference papers, book chapters, letters, and notes.

In Scopus, a total of 1,398 records were retrieved. After applying filters to include only documents with complete bibliographic information and performing a manual screening to exclude unrelated studies, 897 documents were retained. These were distributed as follows: 873 (97.28%) articles, 12 (1.36%) conference papers, 9 (0.91%) book chapters, 2 (0.23%) letters, and 1 (0.11%) note.

In Web of Science, 1,458 records were initially identified. Following the same filtering and manual selection criteria, 921 documents were retained, including 893 (96.95%) articles, 15 (1.62%) conference papers, 10 (1.08%) book chapters, 2 (0.21%) letters, and 1 (0.10%) (Figure 1).

After merging the datasets from both databases, a total of 1,818 records were obtained prior to deduplication. Duplicate records ($n = 570$) were identified and removed through manual verification. The final dataset consisted of 1,248 unique documents, which were used for subsequent bibliometric analysis. These included 1,206 (96.63%) articles, 19 (1.52%) conference papers, 18 (1.44%) book chapters, 3 (0.24%) letters, and 2 (0.16%) notes (Figure 1).

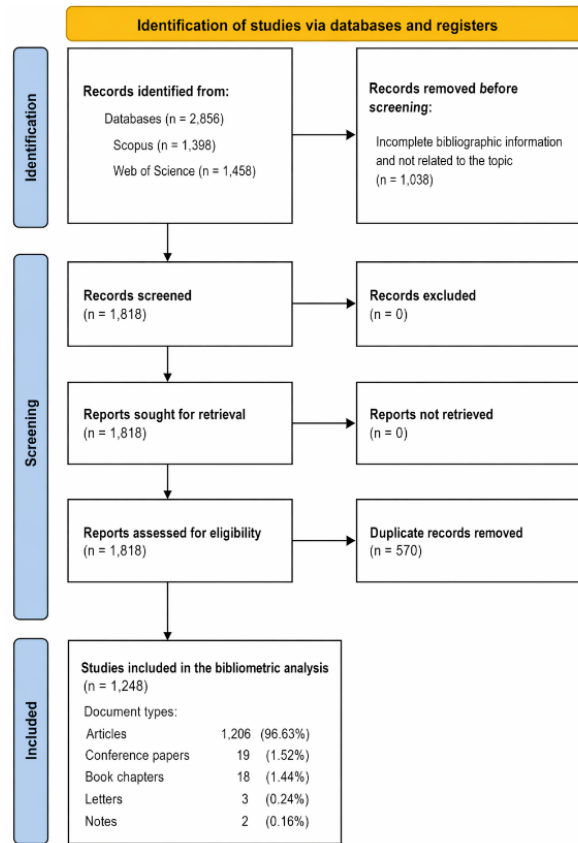


Figure 1: Flowchart of analyzed and excluded articles.

Bibliometric analysis was performed using VOSviewer software (version 1.6.20, 2023), developed by Van Eck and Waltman. This tool was used to construct and visualize bibliometric networks, including co-authorship, co-occurrence, and citation analysis. Its main advantage lies in its capacity to generate large-scale, high-quality visual maps that facilitate data interpretation [42,43].

In this study, “biological control” primarily refers to the use of living organisms, such as predators, parasitoids, and pathogens, to regulate pest populations [31]. However, because this is a bibliometric analysis, “sustainable control” strategies were also considered to provide broader results, as they are commonly associated with environmentally friendly vector control approaches [34].

3. Results

3.1. Year of the Scientific Literature

A total of 1,248 documents obtained from both databases was evaluated to determine the evolution of the scientific literature (Figure 2). “The Bionomics of *Lankesteria culicis* and *Aedes aegypti*” (1970) was the first article about the biological control of mosquito vectors. That study evaluated the *Lankesteria culicis* protozoan as a potential biological agent for the control of *Ae. aegypti* larvae. Although the results did not show significant pathological effects on mosquitoes, a reduction in the life expectancy of infected females was observed. These results were fundamental for future research on the use of microorganisms to control vectors.

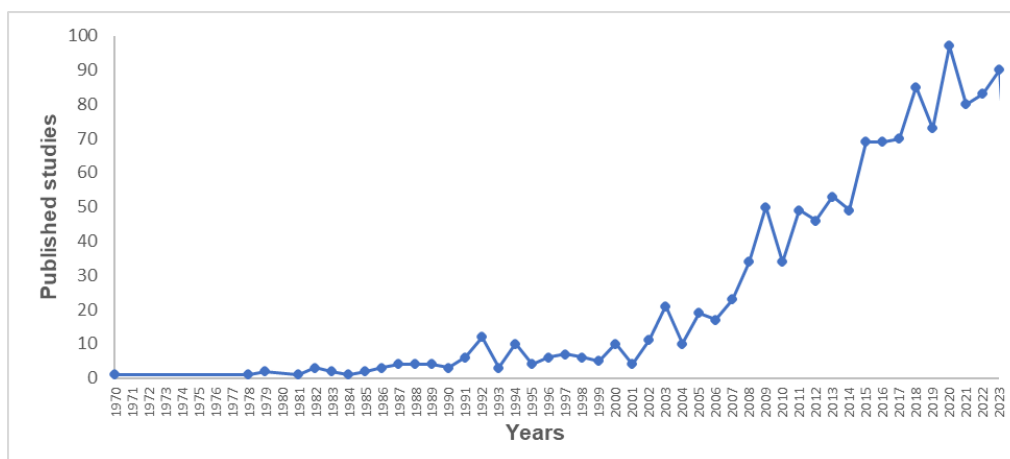


Figure 2: Annual distribution of all the articles about biological control of mosquito vectors found in the databases (1970–2023).

3.2. Top Ten Journals by Number of Articles

The highest number of articles were found in 10 journals. Their thematic categories were indexed according to the SCImago Journal Rank (SJR), an indicator that measures the quality of scientific journals (Table 1). These results showed that the five journals with the highest number of articles on the subject were: *Biological Control* (46 articles; 3.68%); *Parasites and Vectors* (44 articles; 3.46%); *Journal of Medical Entomology* (42 articles; 3.36%); *Parasitology Research* (40 articles; 3.20%); and *Journal of Invertebrate Pathology* (35 articles; 2.8%).

Table 1: Production analysis of the journals based on the number of articles and their SJR category.

Journal	No of Publications	Country	Category according to SJR
Biological Control	46	United States	Agricultural and Biological Sciences Agronomy and Crop Science Insect Science
Parasites and Vectors	44	United Kingdom	Immunology and Microbiology Parasitology Medicine Infectious Diseases
Journal of Medical Entomology	42	United States	Agricultural and Biological Sciences Insect Science Immunology and Microbiology Parasitology Medicine Infectious Diseases Veterinary Veterinary (miscellaneous)
Parasitology Research	40	Germany	Agricultural and Biological Sciences Insect Science

			Immunology and Microbiology Parasitology Medicine Infectious Diseases Medicine Veterinary
Journal of Invertebrate Pathology	35	United States	Agricultural and Biological Sciences Ecology, Evolution, Behavior and Systematics
Journal of the American Mosquito Control Association	34	United States	Agricultural and Biological Sciences Ecology, Evolution, Behavior and Systematics Insect Science Medicine Public Health, Environmental and Occupational Health
Medical and Veterinary Entomology	32	United Kingdom	Agricultural and Biological Sciences Ecology, Evolution, Behavior and Systematics Insect Science Immunology and Microbiology Parasitology Veterinary
Biocontrol Science and Technology	31	United Kingdom	Agricultural and Biological Sciences Agronomy and Crop Science Insect Science
Plos Neglected Tropical Diseases	30	United States	Medicine Infectious Diseases Public Health, Environmental and Occupational Health Pharmacology, Toxicology and Pharmaceutics Pharmacology, Toxicology and Pharmaceutics (miscellaneous)

3.3. Titles of the Most Cited Articles

The references cited in different studies were evaluated to determine which were most frequently used by researchers and which could offer new contributions to this field. Table 2 shows the ten most frequently cited articles. The article that was cited the most was "Successful Establishment of *Wolbachia* in *Aedes* Populations to Suppress Dengue Transmission." This article was likely selected as a result of the knowledge it provided about the use of *Wolbachia*. This bacterium has been the center of attention since its discovery, as a consequence of its capacity to suppress the replication of arboviruses transmitted by such vectors as dengue (DENV), yellow fever virus (YFV), and Zika (ZIKV) [32].

Table 2: Titles of the Most Frequently Cited Articles

Authors	Title	DOI	Source title	Cited by
(Hoffmann et al. 2011)	Successful establishment of <i>Wolbachia</i> in <i>Aedes</i> populations to suppress dengue transmission	10.1038/nature10356	Nature	1036
(Murugan et al. 2015)	Cymbopogon citratus-synthesized gold nanoparticles boost the predation efficiency of copepod <i>Mesocyclops aspericornis</i> against malaria and dengue mosquitoes	10.1016/j.exppara.2015.03.017	Experimental Parasitology	216
(Roni et al. 2015)	Characterization and biotoxicity of <i>Hypnea musciformis</i> synthesized silver nanoparticles as potential eco-friendly control tool	10.1016/j.ecoenv.2015.07.005	Ecotoxicology and Environmental Safety	180

	against <i>Aedes aegypti</i> and <i>Plutella xylostella</i>			
(Silva et al. 2008)	Effects of essential oils on <i>Aedes aegypti</i> larvae: Alternatives to environmentally safe insecticides	10.1016/j.biortech.2007.05.064	Bioresource Technology	178
(Kay y Nam 2005)	New strategy against <i>Aedes aegypti</i> in Vietnam	10.1016/S0140-6736(05)17913-6	Lancet	176
(Fillinger et al. 2003)	Efficacy and efficiency of new <i>Bacillus thuringiensis</i> var. <i>israelensis</i> and <i>Bacillus sphaericus</i> formulations against Afrotropical anophelines in Western Kenya	10.1046/j.1365-3156.2003.00979.x	Tropical Medicine & International Health	173
(Kamaraj et al. 2009)	Larvicidal potential of medicinal plant extracts against <i>Anopheles subpictus</i> Grassi and <i>Culex tritaeniorhynchus</i> Giles	10.1007/s00436-008-1306-8	Parasitology Research	159

	(Diptera: Culicidae)			
(Murugan et al. 2015)	Toxicity of seaweed-synthesized silver nanoparticles against the filariasis vector <i>Culex quinquefasciatus</i> and its impact on predation efficiency of the cyclopoid crustacean <i>Mesocyclops longisetus</i>	10.1007/s00436-015-4417-z	Parasitology Research	138
(Scholte et al. 2007)	Infection of adult <i>Aedes aegypti</i> and <i>Ae. albopictus</i> mosquitoes with the entomopathogenic fungus <i>Metarhizium anisopliae</i>	10.1016/j.actatropica.2007.04.011	Acta Tropica	130
(Autran et al. 2009)	Chemical composition, oviposition deterrent and larvicidal activities against <i>Aedes aegypti</i> of essential oils from <i>Piper marginatum</i> Jacq. (Piperaceae)	10.1016/j.biortech.2008.10.055	Bioresource Technology	127

3.4. Co-authorship Analysis

A total of 5,076 authors were identified. Authors with a minimum production of five articles were selected (Figure 3), yielding a total of 89 prominent and important authors. These authors are linked through a co-authorship network. They actively collaborate in research and publish joint articles within these networks, showing clear scientific interaction and cooperation patterns.

The resulting co-authorship network illustrates collaborative relationships among these authors, revealing clear patterns of scientific interaction and cooperation. It is important to note that, although all authors were considered in the initial dataset, only those meeting the defined threshold were included in the visual network.

The most prominent authors in this scientific field were: Giovanni Benelli, Kadarkarai Murugan, and C. Luz. Benelli has published 42 articles and has been cited 2,147 times. He also stood out as a principal collaborator in research on the biological management of mosquito vectors. Meanwhile, Murugan has published 26 articles and has been cited 1,400 times. Finally, C. Luz has published 24 articles and has been cited 401 times. All the authors are specialists in alternative biological control research.

In Mexico, the author with the greatest number of collaborations (6) was the entomologist Mario Rodríguez-Pérez.

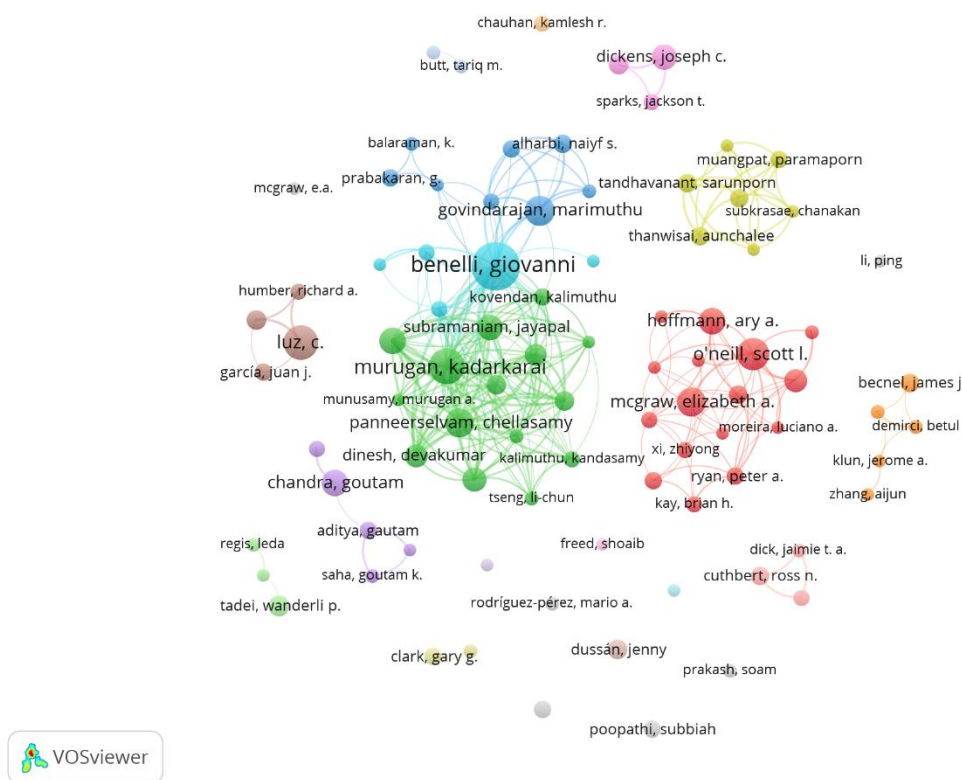


Figure 3: Visualization (VOSviewer software) of the most representative authors within the network (minimum of 5 published articles).

3.5. Analysis of the Most Cited Countries

Table 3 presents the top ten countries with the highest number of citations and scientific production. The United States ranks first (9,568 citations), followed by India (5,769), Australia (5,584), Brazil (3,784), and Italy (2,550). These data indicate that the United States is not only the leading producer of scientific output but also the most cited by the scientific community, reflecting its strong research infrastructure and technological development in the field of biological control.

Although Mexico did not rank among the top ten countries in terms of scientific production or citations, a total of 49 publications with Mexican institutional affiliation were identified, representing approximately 3.9% of the analyzed dataset. This corresponds to a moderate contribution to the international scientific literature within the scope of this study.

Table 3: Analysis of countries with the most citations and documents worldwide.

Country	No of citations	No of papers
USA	9568	305
India	5769	235
Australia	5584	114
Brazil	3784	196
Italy	2455	60
China	1902	103
United Kingdom	1759	69
France	1200	51
Saudi Arabia	1183	47

3.6. Analysis of the Countries with the Highest Scientific Production

The countries with the highest scientific production (Figure 4) are shown from darkest to lightest colors, indicating the proximity of publication dates of the identified articles. The countries with the most recent articles include Saudi Arabia, Pakistan, and Chile. Meanwhile, Mexico was neither prominent nor current in its articles.

The five countries that stood out for their scientific literature in this field were the USA, India, Australia, and China. Meanwhile, only 49 articles were found from Mexico; this number was lower than that of the leading country (305 articles).

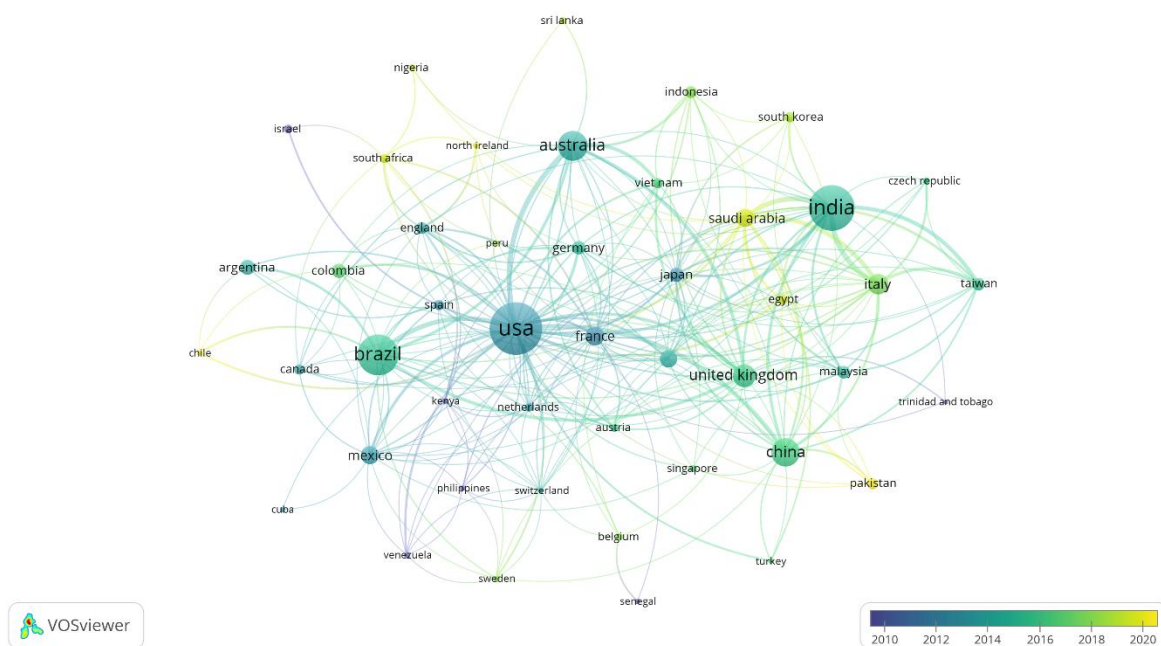


Figure 4: Visualization (VOSviewer software) of the citation network of countries with a minimum of 5 articles.

3.7. Co-occurrence Analysis

The co-occurrence analysis of keywords in the articles provided an overall view of the main research topics. A total of 7,850 words were identified in the articles and were further limited to those words that appeared at least 10 times. A visualization map of the network was developed using all the terms. The following terms were excluded because they were common or irrelevant for the map: article, methodology, multivariate analysis, study, principal component analysis, priority journal, questionnaire, questionnaire survey, regression analysis, research, research methods, biological, and biocontrol.

The co-occurrence analysis identified 297 terms and 6 clusters (Figure 5). The most frequent terms were marked with larger circles, while their proximity indicated their degree of association. The identified clusters showed core topics with various approaches and methodologies for the management of mosquito vectors, providing a clear view of the main research trends regarding the biological control of these insects.

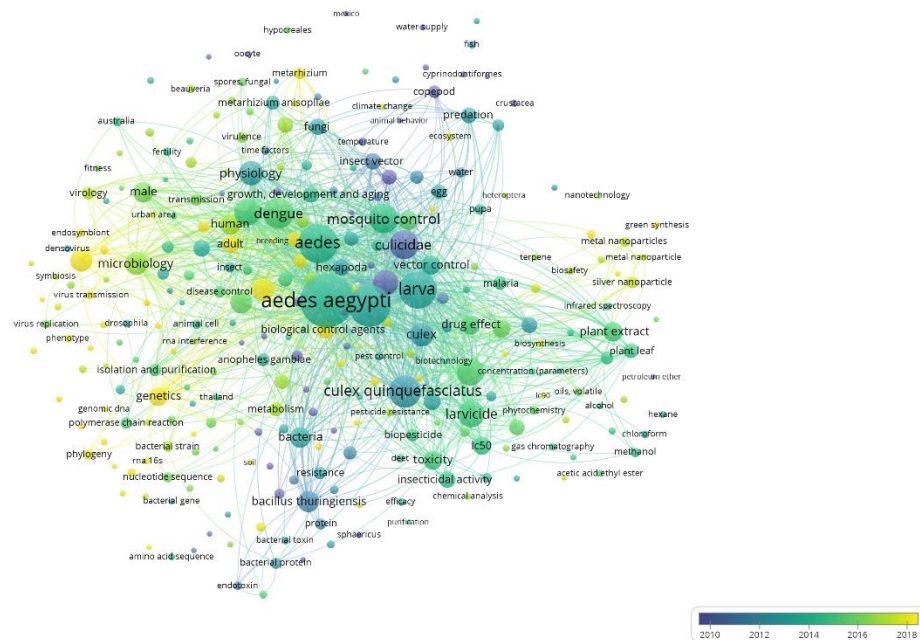


Figure 5: Visualization of the co-occurrence word network developed with the VOSviewer software (minimum selection: 10 occurrences for word).

3.7.1. Cluster 1:

Efficacy and efficiency of new *Bacillus thuringiensis* var. israelensis and *Bacillus sphaericus* formulations against Afrotropical anophelines in Western Kenya.

The link between terms such as "plant extract," "nanotechnology," "metal nanoparticle," and "green synthesis" suggested a growing trend toward the use of sustainable technologies and natural extracts. In addition, the association of "chemistry" with "infrared spectroscopy" and "biosynthesis," as well as the connection with "essential oil," "volatile oils," and "terpene," highlighted the efforts to develop larvicides and repellents based on active compounds from plants. In this context, nanotechnology is a promising tool in the innovation of sustainable solutions for vector control.

3.7.2. Cluster 2:

This group featured recurring "microbiology" and "biotechnology" themes, linked with the following topics: "*Bacillus thuringiensis* (Berliner, 1911)," "*Bacillus sphaericus* (Spitz, 1902)," "bacterial toxin,"

and "nematode." These topics are characteristic of alternative biological control of mosquito vectors. In addition, the co-occurrence of terms such as "DNA sequence," "phylogeny," and "nucleotide sequence" indicated that studies have been aimed at the genetic characterization of microorganisms. Meanwhile, concepts such as "RNA interference," "biosynthesis," and "enzyme activity" suggested the use of advanced molecular technologies to study and modify interactions between vectors and biological agents.

3.7.3. Cluster 3:

In this group, "*Aedes aegypti*" was identified as a prominent node in the co-occurrence map, indicating its importance as a key topic within the analyzed articles. This term is closely related to other terms such as "*Aedes albopictus*," "dengue," "larvae," and "vector," suggesting that studies have been primarily focused on vector control and mosquito-borne diseases. This group included studies aimed at managing *Aedes aegypti* and its associated diseases, particularly emphasizing the understanding and control of biological cycles and intervention strategies. In addition, the most prominent term in the map was "Wolbachia." This term highlighted the interest in this bacterium as a biological control agent for mosquitoes and reflected the ongoing shift toward innovative methods, such as genetic manipulation and the release of Wolbachia-infected mosquitoes.

3.7.4. Cluster 4:

This group comprised ecological and environmental subjects and used terms such as "temperature," "ecosystem," and "climate change." These topics were focused on the environmental factors that influence the vector population dynamics and the diseases they transmit. Their link with terms such as "water" and "water supply" suggested an increasing interest in the interaction between environmental conditions and control strategies, including those based on intervention strategies in urban environments.

3.7.5. Cluster 5:

In this group, key topics related to "fungi," "fungus isolation," "fungus spore," "entomopathogenic fungi," and "fungal virulence" stood out. These terms were closely related to "*Beauveria bassiana*" (Balsamo-Crivelli, 1912) and "*Metarhizium anisopliae*" (Metschnikoff, 1879), two fungi used for the biological control of insects. These organisms have demonstrated high potential as biological agents in the management of several pests, including those that act as disease vectors (*Aedes aegypti*).

Effects of essential oils on *Aedes aegypti* larvae: Alternatives to environmentally safe insecticides

3.7.6. Cluster 6:

This group showed the most recent topics on the map: "biological control agents," "insecticide resistance," "pesticide resistance," "pyrethroid," and "mosquito vector." These terms encompass the current challenges faced by vector management strategies. The increasing resistance of mosquitoes to insecticides, particularly pyrethroids, poses a critical problem, limiting control efforts. This situation emphasizes the urgent need to develop new strategies and products that overcome mosquito resistance to insecticides. In addition, alternative control methods should be developed. In this context, the study of mosquito resistance to pesticides is not only fundamental to understanding the evolution of vectors but also to guiding future researchers toward more efficient and sustainable solutions.

3.7.7. *Relationship Between the Clusters*

The "*Aedes aegypti*" node was a central axis within the thematic network, connecting and linking different approaches related to vector management. Its relevance demonstrated the importance of this species as the main vector of DENV, ZIKV, and CHIKV. The interaction among "public health," "biological," "chemical," "ecological," and "technological" themes showed the multidisciplinary approach that characterizes current research on this subject. These interconnections emphasized the need to achieve vector control from integrated perspectives, through the combination of innovative and sustainable strategies that seek not only to eliminate mosquitoes but also to mitigate environmental impacts, develop emerging technologies, and protect public health.

4. Discussion

This study analyzed research trends regarding the biological and sustainable management of mosquito vectors. This subject has not been thoroughly studied in scientific literature to date. Significant findings are the consequence of innovative approaches: this study includes a comprehensive review of the literature and an analysis of related studies.

4.1. *Increase of Scientific Contributions*

The analysis of the scientific literature on the biological and/or sustainable management of mosquito vectors (Figure 2) revealed a clear temporal trend. The first scientific article on this topic was published in 1970, followed by a prolonged period of low scientific output for more than three decades. Starting in 2008, a sustained increase in the number of publications is observed, with notable growth that reached its peak around 2020, with approximately 100 documents published.

This growth reflects a shift in global research priorities and can be attributed to multiple converging factors. First, the increasing incidence and geographic expansion of arboviral diseases such as dengue, chikungunya, and Zika have intensified the demand for effective vector control strategies [7]; second, international initiatives led by organizations such as the World Health Organization have played a fundamental role, particularly through the Global Vector Control Response 2017–2030, which promotes integrated and sustainable approaches to vector management [30]; third, the widespread emergence of insecticide resistance has significantly reduced the effectiveness of conventional chemical control methods. Resistance to pyrethroids (e.g., permethrin, lambda-cyhalothrin, and alpha-cypermethrin) [28] and to organophosphates such as temephos has recently been documented (22), underscoring the urgent need to develop effective and sustainable mosquito management strategies [38].

Beyond these factors, the disciplinary distribution of publications provides additional insight into research trends (Table 1). The predominance of parasitology and ecology reflects a growing recognition of the need to understand vector–pathogen interactions and ecosystem dynamics in order to design effective and sustainable interventions. Parasitology studies provide crucial insights into vector–pathogen dynamics, while ecology analyzes the effects of control strategies on ecosystems and their long-term sustainability [44]. In this context, these categories promote the development of innovative and ecologically responsible tools for mosquito vector management.

The high production of documents with *Wolbachia*-based approaches among the most cited studies highlights a significant paradigm shift in mosquito control. The use of this endosymbiotic bacterium to reduce vector competence has gained global attention, particularly through large-scale implementation programs supported by the World Mosquito Program. Evidence suggests that the release of *Wolbachia*-infected mosquitoes can significantly reduce the transmission of arboviruses such as dengue, Zika, and chikungunya [45]. This strategy aligns with the recommendations of the World Health Organization,

which emphasize the integration of biological control methods into long-term vector management programs, rather than short-term interventions [30].

In parallel, the growing number of studies on nanoparticle-based mosquito control reflects their potential as effective and environmentally friendly alternatives to conventional insecticides. Metal nanoparticles, in particular, have demonstrated high efficacy against mosquito larvae and other insect pests. Recent evidence indicates that green-synthesized nanoparticles represent promising, more sustainable alternatives, with reduced toxicity profiles compared to conventional chemical insecticides [31,46]. However, despite their promising potential, further research is needed to evaluate their long-term ecological impacts and their scalability under field conditions[47].

It is important to note that, while these groups provide valuable insight into current research lines, they also reveal significant gaps. The concentration of studies on a limited number of biological agents and technologies suggests that other potentially effective strategies remain underexplored, which may limit the diversity and resilience of vector control programs, particularly in regions with a high disease burden but limited research capacity [48–50]

These findings have direct implications for public health. The uneven distribution of research efforts may delay the adoption of effective and locally adapted control strategies, thereby perpetuating the transmission of mosquito-borne diseases in vulnerable regions [50]. Furthermore, the continued reliance on a limited set of tools may increase the risk of resistance development, reducing the long-term effectiveness of vector control interventions [51].

From a policy perspective, the results highlight the need to strengthen international collaboration, increase investment in research on sustainable vector control, and promote the integration of biological and environmentally friendly approaches into national health programs. Institutions such as the World Health Organization advocate for Integrated Vector Management (IVM), which combines biological, environmental, and chemical strategies in a coordinated manner [49,50]. Future research should prioritize interdisciplinary approaches, field validation of emerging technologies[35,48].

4.2. *Principal Authors of the Research*

Figure 3 highlights the main authors contributing to research development in this field, organized into collaborative clusters. Five groups showed particularly strong interconnections. The first group is led by Scott L. O'Neill, with 22 publications and collaborations with 11 co-authors. His research has been closely associated with the implementation of *Wolbachia*-based strategies to reduce the transmission of dengue and other arboviral diseases, representing a key advancement in environmentally friendly vector control approaches [45].

The second group is led by Kadarkarai Murugan, who contributed 26 documents in collaboration with 20 authors. His work focuses on the development of nanopesticides and plant-based products, including neem, Aloe vera, and Moringa oleifera, as alternative tools for mosquito control. These approaches highlight the integration of nanotechnology and botanical resources in sustainable pest management [46].

The third group is led by Giovanni Benelli, with 42 publications and 25 collaborations. His research addresses insect behavior and the development of biological control strategies targeting both agricultural pests and disease vectors, contributing significantly to the advancement of eco-friendly control methods[31].

The fourth group is led by Paramaporn Muangpat, who has published 9 documents in collaboration with 6 authors. Her research primarily focuses on entomopathogenic nematodes (*Steinernema* and

Heterorhabditis) and their symbiotic bacteria (*Photorhabdus* and *Xenorhabdus*) as biological control agents against *Aedes* mosquitoes, highlighting their potential for sustainable vector control.[52,53].

Finally, Wolf Christian Luz leads another relevant research group associated with 24 publications. His research focuses on the use of entomopathogenic fungi, as environmentally friendly alternatives for the ovicidal control of *Aedes aegypti*. [54,55].

In Mexico, Mario Rodríguez-Pérez stands out with 6 publications. His work has focused on vector-borne diseases such as Zika, dengue, and chikungunya, contributing to the understanding of their epidemiology and control [56].

Although Mexico does not yet exhibit a highly consolidated collaboration network in this field, it shows strong potential for growth. Increasing concerns regarding mosquito resistance to chemical insecticides have created opportunities to expand research on sustainable and biological control strategies, positioning the country as a potential leader in this area.

4.3. Countries by Research Participation

According to the analysis of scientific production by country (Table 3), the United States maintains a clear leadership position, primarily supported by its strong research infrastructure and sustained investment in research and development (R&D) [57]. According to the World Bank, the country allocates a substantial proportion of its GDP to scientific activities, thereby promoting the generation of high-impact knowledge [58]. In addition, strong interdisciplinary collaboration and access to advanced technological resources have further consolidated its influence within the international scientific community [59].

In contrast, Mexico is not among the top ten countries in scientific production within the scope of this study, which is consistent with the regional inequalities observed across Latin American countries [58,59]. Nevertheless, the country has institutions such as the National Center for Preventive Programs and Disease Control (CENAPRECE), which implement large-scale vector control strategies, although many of these efforts are not necessarily reflected in indexed scientific publications.

Scientific production is closely associated with structural factors such as national investment in R&D, research system capacity, and the level of international collaboration, all of which vary considerably among countries [58–60].

In this context, the results highlight the need to strengthen the international visibility of research conducted in Mexico and other countries with similar contexts, as well as to promote the publication of locally generated knowledge [58,60]. Strengthening collaboration networks, increasing investment in research, and integrating operational and academic efforts could contribute to a more robust and impactful scientific production [58,59].

Countries with the highest scientific production in mosquito vector control generally combine sustained investment in science and technology with strong national and international collaboration networks [61]. This is reflected not only in the volume of publications but also in the capacity to develop innovative and sustainable vector control strategies [62].

Overall, these findings underscore the importance of strengthening scientific investment and international cooperation to address the challenges associated with mosquito-borne diseases [62]. Although the experience of countries such as the United States may serve as a useful reference, strategies should be adapted to the specific socioeconomic and epidemiological conditions of each national context [58,59].

4.4. Most Representative Research Topics

The results highlight the complexity and multidisciplinary nature of vector control research, particularly regarding *Aedes aegypti* and *Culex quinquefasciatus*. The analysis identified not only traditional approaches but also emerging trends that may transform future vector control strategies (Figure 5). The core cluster was dominated by terms associated with *Aedes aegypti*, emphasizing the central role of this vector in current scientific research.

The analysis highlights the connection between "biotechnology" and "microbiology." The latter plays a key role in the identification and study of microorganisms that can be used as biological agents to control pests and diseases. Microorganisms (bacteria, fungi, and viruses) can be used as control agents, providing environmental benefits as they reduce dependence on chemical methods and encourage more sustainable practices. This demonstrates the crucial role that microorganisms currently play in the biological strategies used to manage vectors; these strategies are implemented as part of biological control programs aimed at reducing mosquito populations [63].

The most prominent topics included "*Wolbachia*," presumably due to the extensive body of research on this endosymbiotic bacterium: a mosquito symbiont that can have a pathogenic effect on its host. Infecting *Aedes* with *Wolbachia* has become increasingly popular as an alternative strategy for the control of the spread of vector-borne diseases [64,65]. *Wolbachia* affects mosquito populations through two main mechanisms. First, it induces cytoplasmic incompatibility (CI), reducing the reproductive success of uninfected females mating with infected males. Second, it alters vector competence, thereby reducing arbovirus transmission [66].

The most recurrent topics were "*Bacillus thuringiensis*" (Bt) and "*Bacillus sphaericus*" (now "*Lysinibacillus sphaericus*"). These bacteria have attracted considerable attention because of their high larvicidal specificity and reduced environmental impact. Some *Bacillus* (e.g., *B. thuringiensis*) and *Lysinibacillus* (e.g., *L. sphaericus*) species can generate toxic crystals that specifically harm *Aedes aegypti* mosquitoes [67–69]. Bt is a good alternative to the indiscriminate use of chemical insecticides to control pest insects and is therefore the most commercialized bacterium in the world [70]. Bt produces three types of larvicidal proteins: Cry, which acts through crystal toxins; Cyt, a cytolysin that acts in parasporal crystals; and Vip, a protein produced during the vegetative stage that is toxic to many insects and nematodes [67–69].

Nematodes were another recurrent topic. Although numerous nematode families parasitize insects, relatively few studies have evaluated their potential for the control of *Ae. aegypti*. Research has mainly focused on the biological efficacy of *Heterorhabditis bacteriophora* (Poinar, 1975) against *Ae. aegypti* larvae, with reported mortality rates of up to 84%. Along the same line, a study conducted in Mexico using *Heterorhabditis bacteriophora* and *Steinernema carpocapsae* (Weiser, 1955) demonstrated the pathogenicity of infective juveniles (IJs) against third- and fourth-instar larvae of *Ae. aegypti*. [71].

"*Beauveria bassiana*," "*Metarhizium anisopliae*," and "fungi" were prominent topics (Figure 5). Dahmana and Mediannikov [38] simultaneously evaluated *B. bassiana* and *M. anisopliae* against *Ae. albopictus* and *Cx. quinquefasciatus* larvae; meanwhile, *B. bassiana* was tested against *Culex pipiens* (Linnaeus, 1758) adult mosquitoes. Entomopathogenic fungi have potential as suppressors of mosquito vectors. Although these fungi do not induce immediate death, they have sublethal and lethal effects during certain stages of the life cycle of mosquitoes. Given their capacity to overcome the resistance that mosquitoes have developed to immediate-action chemical insecticides currently in use, fungi can potentially serve as biological control agents. Given their effect on mosquitoes, the genera *Beauveria*, *Pythium*, *Metarhizium*, *Leptolegnia*, *Coelomomyces*, *Lagenidium*, and *Conidiobolus* have been evaluated [72].

Recent studies have highlighted the properties of *Beauveria bassiana* and *Metarhizium anisopliae* as specific pathogens against insects: they selectively attack their hosts without affecting non-target organisms (e.g., humans), making them a promising option for integrated pest management (IPM) programs [73]. Additionally, the development of new formulations and application methods for these entomopathogenic fungi — including advances in biotechnology and nanotechnology — has enhanced their effectiveness and increased their use in agricultural and urban environments. The most recent research topics have included these microorganisms, suggesting a trend toward the exploration of innovative biological solutions for the control of vectors and pests, in alignment with the growing concern about the environmental impact of traditional insecticides and the resulting resistance [74].

The "copepod" is another major theme, perhaps because copepods were among the first organisms studied as predators of mosquito larvae and pupae in aquatic environments, and they are considered useful for the reduction of Culicidae populations [75]. Most experiments have focused on *Mesocyclops*, and the following species have been tested as biological control agents against the larvae of several mosquito species, achieving various levels of success: *Mesocyclops longisetus* (Kiefer, 1929), *M. aspericornis* (Kiefer, 1936), *M. venezolanus* (López, 1937), *M. ruttneri* (López, 1937), *M. edax* (Kiefer, 1936), and *Macrocyclus albidus* (Jurine, 1820). Given their aggressiveness, all those species are considered predators of first-instar mosquito larvae and have successfully controlled mosquito vectors [76,77].

The most recent topics included "genetics," "DNA," and "RNA interference," suggesting a growing interest in understanding the genetic mechanisms of vectors and their pathogens. Likewise, their link with the "sterile insect technique" (SIT) methodology could help to eradicate medically relevant mosquito vectors in regions where arboviruses pose a serious threat to public health [78]. SIT is an eco-friendly approach used to control specific insect populations through massive breeding, radiation sterilization, and the release of large numbers of sterile male insects in each area [79].

The use of silver nanoparticles (AgNPs) and nanocomposites (NCs) has gained increasing attention in recent years due to their enhanced functional properties compared with individual nanoparticles [65]. Silver NCs, synthesized using materials such as polymers, silica, clays, or biopolymers, have shown potential for developing eco-friendly larvicidal and antimicrobial applications [80]. Furthermore, biosynthetic approaches employing low-cost biological residues and green synthesis methods have promoted the development of more sustainable and efficient vector control tools [53].

The analysis showed a trend toward transdisciplinarity, with a growing focus on innovative methods such as "nanotechnology" and "plant extracts," along with traditional strategies such as "entomopathogenic fungi," "bacteria," and "nematode." These research topics confirm the importance of ongoing research and development of sustainable methods to control mosquito populations and to prevent the spread of insect-borne diseases [81].

Likewise, the inclusion of recent concepts such as "resistance" and "climate change" reflects the response of the scientific community to global challenges, such as climate change and insecticide resistance, which hinder traditional vector control strategies.

Multidisciplinary studies are essential to address emerging problems associated with mosquito-borne diseases, and they represent sustainable and effective alternatives to combat vector-borne diseases. Meanwhile, their replication could have a significant impact on public health and improve the quality of life in areas where these diseases are endemic [38].

Several emerging approaches for the technological development of biological control alternatives are still in the early research and application stages, including: the sterile insect technique (SIT), the use of silver nanoparticles, and RNA interference (RNAi)-based bioinsecticides. These innovative approaches

have been considered among the most promising technologies [81]. Likewise, *Bacillus thuringiensis* var. *israelensis*, *Beauveria bassiana*, *Metarhizium anisopliae*, and other microorganisms mentioned throughout this study represent promising alternatives capable of complementing or potentially replacing conventional vector control strategies in the control of mosquito vectors.

5. Conclusion

Mosquito vector control continues to represent one of the major challenges for global public health, aggravated by the increasing resistance to chemical insecticides and their environmental impacts. Since the first use of a microorganism for mosquito vector control in 1970, interest in biological and sustainable alternatives has steadily increased, resulting in a total of 1,248 scientific publications that reflect the expansion and maturation of this research field.

The results reveal a transition from the classical concept of biological control toward more integrated, sustainable, and environmentally friendly approaches for mosquito vector management. Wolbachia-based strategies stand out among the most highly cited studies due to their effectiveness in reducing the transmission of dengue, Zika, and chikungunya. In addition, the growing interest in green-synthesized nanoparticles, entomopathogenic fungi, and nematodes demonstrates the diversification of innovative tools with the potential to strengthen more efficient and sustainable vector control programs.

The analysis also confirmed the relevance of scientific collaboration networks, identifying 89 key authors in the development of this research area. Giovanni Benelli stands out as one of the most influential international references in biological vector control, while in Mexico, Mario Rodríguez-Pérez represents one of the most important scientific collaboration networks in this field.

Overall, the findings highlight that strengthening research and international scientific cooperation is fundamental for the development of sustainable strategies adapted to current epidemiological contexts. This is particularly relevant for countries such as Mexico and other nations with similar conditions, where scientific production remains limited compared with leading countries. In this context, in addition to promoting greater investment in research, it is essential to strengthen international collaboration networks and increase the visibility of locally generated knowledge. Furthermore, future research should prioritize interdisciplinary approaches and the field validation of emerging technologies, thereby promoting the development, evaluation, and adoption of innovative and sustainable tools to address the current challenges of mosquito vector control at a global level.

Author Contribution

Conceptualization: MARS and FHR; Formal analysis: MARS and FHR; Investigation: MARS and FHR; Methodology: MARS and FHR; Software: MARS and FHR; Supervision: FHR, JAHC, and RAMMT; Validation: FHR, JAHC, and RAMMT; Visualization: FHR, JAHC, and RAMMT; Writing – original draft: MARS and FHR; Writing – review & editing: FHR, JAHC, and RAMMT.

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