

## Article

# Vector Dynamics of Mosquitoes in Mangrove Ecosystems of the Maracaibo Metropolitan Area: Ecoepidemiological Implications

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**How To Cite:** Pascal, E.; Vasquez, H.; Vasquez, R.; et al. Vector Dynamics of Mosquitoes in Mangrove Ecosystems of the Maracaibo Metropolitan Area: Ecoepidemiological Implications. *Parasitological Science* 2026, 1(1), 5.

Received: 1 December 2026

Revised: 23 March 2026

Accepted: 7 April 2026

Published: 30 April 2026

**Abstract:** The objective of this research was to analyze the vector dynamics of mosquitoes in mangrove ecosystems in the Maracaibo metropolitan area, with an emphasis on their relationship with environmental factors and their relevance to public health. The study, which took an eco-epidemiological approach and used a mixed design (quantitative and documentary), focused on the coastal mangroves of Santa Rosa de Agua, Parque La Marina, and Vereda del Lago. The ecological component included larval sampling following WHO and CDC protocols and taxonomic identification. The results confirm the presence of two genera of Culicidae of sanitary importance: *Aedes aegypti* (56.7%) and *Culex quinquefasciatus* (43.3%). Regarding their ecological niches, the dominance of *Aedes aegypti* was associated with shaded ponds characterized by low salinity; in contrast, *Culex quinquefasciatus* was linked to eutrophic, polluted waters with low oxygen levels. It is concluded that the degraded mangroves of Maracaibo act as permanent reservoirs for arbovirus vectors (Dengue, Zika, Chikungunya–Lemus, 2022), which implies a sustained epidemiological risk for the surrounding communities. An Integrated Vector Management (IVM) model based on ecological restoration, biological control, and community education is recommended to reduce this risk and ensure health sustainability.

**Keywords:** coastal mangroves; Culicidae; vectors; dengue; Zika; ecological imbalance

## 1. Introduction

Mangrove ecosystems are among the most productive and ecologically important habitats in the tropical and subtropical regions of the planet. They develop at the interface between terrestrial and marine environments, where conditions of high salinity, anoxia, and periodic flooding converge [1]. The plant species that comprise them, known as mangroves, are adapted to these extreme environments through specialised physiological and structural mechanisms. Globally, there are approximately 70 recognised species of mangroves distributed across 16 botanical families, performing essential functions in coastal dynamics, hydrological regulation, and ecological connectivity between continental and marine systems [2].

In addition to their ecological function, mangroves provide essential ecosystem services such as coastal stabilisation, protection against storms and hurricanes, sediment retention, water purification, blue carbon sequestration, and maintenance of marine and terrestrial biodiversity [3,4]. However, these ecosystems are facing progressive degradation worldwide due to urban expansion, deforestation, pollution, and unsustainable



aquaculture activities [5]. In Venezuela, mangroves cover approximately  $2.01 \times 10^5$  ha, with significant concentrations in the states of Zulia, Falcón, Sucre, Delta Amacuro, and Nueva Esparta [6]. In the Maracaibo metropolitan area, anthropogenic pressure associated with urban growth, inadequate waste disposal, and industrial discharges has led to a notable reduction in the extent and quality of coastal mangroves [7].

From an epidemiological perspective, mangrove ecosystems are environments of particular interest due to their potential role as natural breeding grounds for mosquitoes of the Culicidae family. This group, which includes more than 3500 species worldwide, comprises several genera of medical and veterinary relevance (including *Aedes*, *Anopheles*, and *Culex*) recognised for their ability to transmit viral, bacterial, and parasitic pathogens [8,9]. Mangroves, by combining brackish water bodies with high organic matter and low oxygenation conditions, can favour the larval development of halophilic or euryhaline species with vector importance [10].

Various studies in regions of the Caribbean and Latin America have documented the presence and abundance of mosquitoes in mangroves, highlighting their role in the transmission of diseases such as dengue, Zika, chikungunya, and Venezuelan equine encephalitis [11–13]. These environments act as natural reservoirs and ecological corridors for vector populations, especially in areas where urbanisation is close to coastal wetlands, increasing the risk of contact between humans and vectors.

In the context of Maracaibo, characterised by its proximity to extensive coastal wetlands and high population density, the study of vector dynamics in mangrove ecosystems is particularly important. The identification of the predominant mosquito species, their relative density, their seasonal distribution patterns, and their association with environmental variables constitutes an indispensable basis for the design of epidemiological surveillance and control programmes [14].

The present study aims to analyse the vector dynamics of mosquitoes in mangrove ecosystems in the Maracaibo metropolitan area, with an emphasis on their relationship with environmental factors and their relevance to public health. The results will provide evidence on the ecological interactions that favour the persistence of these vectors in coastal environments, contributing to the strengthening of entomological surveillance systems and the development of integrated vector control strategies in adjacent urban areas.

## 2. Materials and Methods

### 2.1. General Approach

This research was conducted using an ecological-epidemiological approach, complemented by an exhaustive documentary review aimed at analysing the role of mosquitoes (Diptera: Culicidae) as vectors in the mangrove ecosystems of the Maracaibo metropolitan area. This methodological design allowed for the integration of the environmental and biological characterisation of the ecosystem with the evaluation of available entomological and health information, in order to establish possible links between the composition of mosquito communities and the epidemiological risk associated with the transmission of vector-borne diseases.

### 2.2. Type and Design of Research

The study is a descriptive, mixed-methods investigation, comprising a quantitative component (focused on ecological and entomological characterization) and a qualitative, documentary component, based on the collection, analysis, and critical interpretation of scientific and technical information related to the subject of study.

From an ecological perspective, a non-experimental, cross-sectional field design was employed to identify larval habitats and estimate the diversity, abundance, and relative frequency of mosquito species in selected mangrove areas (Figure 1). From a documentary perspective, a systematic bibliographic design was used, based on indexed academic sources, institutional technical reports, and international databases.

### 2.3. Study Site

The study focused on mangrove ecosystems located along the coastline of the municipality of Maracaibo, Zulia State (Venezuela), specifically in the areas of Santa Rosa de Agua, Parque La Marina, and Vereda del Lago, where mangroves are directly connected to urban and peri-urban areas. These areas were selected for their ecological representativeness and previous evidence of mosquito proliferation in brackish environments near human settlements [7].

The geographical coordinates and environmental characteristics of each site (temperature, salinity, pH, oxygenation level, and vegetation cover) were determined through direct observation and climate records provided by the National Institute of Meteorology and Hydrology [15,16].



**Figure 1.** Identification of larval habitats in a mangrove wetland. La Marina Park, Maracaibo Metropolitan Area, Venezuela. The image highlights the lower central pool (main larval habitat) with a red arrow and dotted box, where the larval sample was collected. This type of stagnant pool, characterized by shallow water (<20 cm), mud, plant debris, and emergent vegetation, represents a typical breeding ground for mosquito vector species in mangroves, which are characterized by variable salinity, low water circulation, and high organic matter content (Source: The authors).

#### 2.4. Ecological and Entomological Procedures (Ecoepidemiology)

For the ecological component, larval sampling techniques were used, following the recommendations of the World Health Organisation [17,18] and the Centers for Disease Control and Prevention [19].

Sampling was carried out over three consecutive months (March to May 2025), with two visits per site each month. During each visit, three replicates were collected per microhabitat. The sampling intensity was based on WHO standardised protocols for mangrove ecosystems, adapted to the availability of larval microhabitats.

Larval sampling: 350 mL containers were used in ponds, mangrove roots, and flooded areas, with three replicates per site. The collected larvae were preserved in 70% ethanol for morphological identification using the keys [20,21].

The specimens were classified to species level (where possible), recording relative abundance, and association with specific microhabitats (mangrove roots, pools, organic debris). Ecological diversity indices (Shannon-Wiener and Simpson) were calculated to estimate the structure of mosquito communities at the sampling sites [22].

#### 2.5. Document Review

In parallel, a systematic review of scientific literature was conducted between January and June 2025. Recognised databases (Scopus, Web of Science, PubMed, SciELO, and Google Scholar) were consulted using combinations of keywords in English and Spanish, such as: mosquito vectors, mangrove ecosystems, Culicidae ecology, vector-borne diseases, Maracaibo, Venezuela, and arboviral transmission.

The inclusion criteria considered peer-reviewed articles published between 2000 and 2025 that addressed entomological, ecological, or epidemiological aspects of mosquitoes associated with mangrove ecosystems or coastal wetlands. Technical reports from the Ministry of Popular Power for Ecosocialism (MINEC), the Pan American Health Organisation (PAHO), and the World Health Organisation (WHO) were also considered.

The collected information was subjected to content analysis and classified into the following thematic categories: entomological diversity, environmental conditions, adaptation to salinity, medically relevant vector species, and surveillance strategies.

A bibliographic systematisation matrix based on the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) model was applied to ensure the transparency and traceability of the search (Table 1) [23]. A total of 41 scientific and technical publications were analyzed in the systematic review, covering the period from 1953 to 2025, with emphasis on peer-reviewed articles (n = 28) and institutional reports (n = 13).

Temporal distribution: 2000–2025 (85%, n = 35), reflecting the rise in studies on vectors in mangroves; pre-2000 (15%, n = 6) for ecological foundations.

Main sources: Indexed journals (Scopus/WoS: 45%, n = 19), SciELO/LATAM (20%, n = 8), WHO/PAHO/FAO reports (25%, n = 10).

Thematic categories: Entomological diversity (24%, n = 10), environmental ecology (30%, n = 12), vector epidemiology (27%, n = 11), control/strategies (19%, n = 8).

**Table 1.** Bibliometric analysis of the bibliographic sources used for this research.

Metric	Value	Observation
Total publications	41	Complete library post-PRISMA filters
Peer-reviewed articles	28 (68%)	Highest scientific rigor
DOIs available	22 (54%)	Facilitates replicability
Venezuela/mangroves focus	15 (37%)	High local relevance

## 2.6. Data Analysis

### Calculation of Indicators

Absolute frequency (n): Individual number of larvae per species and site, obtained by direct field counting and laboratory confirmation.

Relative frequency (%): Calculated as  $(n/\text{total } N) \times 100$ .

Predominant microhabitats: Visually classified according to standardized criteria (shaded ponds, submerged roots, wastewater), recording the main substrate (>70% coverage).

Ecological data were analysed using descriptive statistics and ecological diversity indices, with the support of PAST v.4.13 and RStudio v.4.2.2 software. The results of the literature review were integrated using comparative analysis and theoretical triangulation, which allowed us to identify patterns of agreement between local findings and those reported in regional studies. Finally, the epidemiological implications of the coexistence of vector species in urban mangrove environments were discussed, as well as their possible relationship with transmission events reported in Maracaibo and other coastal regions of the Caribbean.

## 3. Results and Discussion

### 3.1. Characterisation of Mangrove Ecosystems and Their Ecological and Health Importance

The mangroves of the Maracaibo metropolitan area, particularly those located in Santa Rosa de Agua and the western coastal strip of Lake Maracaibo, constitute strategic ecological systems that function as natural barriers against coastal erosion and extreme weather events. These intertidal ecosystems are dominated by plant species such as *Rhizophora mangle*, *Avicennia germinans*, and *Laguncularia racemosa*, which are adapted to conditions of salinity and anoxia [2].

The results obtained from the documentary review and local ecological records show that these environments act as areas of high biological productivity and energy exchange, serving as feeding and breeding habitats for fish, molluscs, crustaceans, and birds [1]. However, their importance goes beyond ecology: mangroves are also areas of interest for health reasons due to their potential as natural reservoirs for mosquito species of epidemiological importance, particularly those of the genus *Aedes* [24,25].

Degraded mangroves tend to accumulate stagnant water with high levels of organic matter and low oxygenation, optimal conditions for the larval development of *Aedes aegypti* and *Culex quinquefasciatus* [10]. This ecological relationship indicates that mangrove conservation not only contributes to biodiversity but also plays an indirect role in the prevention of vector-borne diseases.

The United Nations Environment Programme [26] highlights that the loss of these ecosystems implies not only a reduction in ecosystem services (such as sediment retention, hydrological regulation, and blue carbon sequestration) but also an increase in health risks associated with the spread of vectors in coastal urban areas.

### 3.2. Environmental and Urban Impact on the Maracaibo Mangroves

Geospatial analysis and documentary review agree that the mangroves adjacent to the city of Maracaibo show marked fragmentation and loss of vegetation cover due to unplanned urban expansion, wastewater discharge, and solid waste accumulation. These factors have led to eutrophication and altered natural water flows, transforming mangroves into semi-stagnant bodies of water with high organic loads [6,16].

This scenario aligns with descriptions from those who note that converting mangroves to urban or industrial areas significantly reduces their ecological resilience [5]. In Maracaibo, the reduction in mangrove areas has been accompanied by a documented increase in the populations of *Aedes aegypti* and *Culex quinquefasciatus*, favoured by the microenvironments created by environmental degradation [4,6] (Figure 2).



**Figure 2.** Anthropization of mangroves in Santa Rosa de Agua, Maracaibo: Modified larval habitats. (A) Houses built directly on the mangrove, with stagnant greenish water invaded by urban structures, illustrate the conversion of coastal ecosystems into residential areas. This encroachment reduces the ecological resilience of mangroves, as described by [5]. (B) Sample collection in the Monte Cristo canal, where the turbid water with vegetation and debris forms ideal breeding grounds for *Aedes aegypti* and *Culex quinquefasciatus*, is favored by environmental degradation [8,13]. Additionally, the image supports the intermediate disturbance hypothesis in anthropized wetlands, where urban invasion alters food webs and promotes opportunistic vectors in microhabitats such as polluted puddles (Source: The authors).

Figure 2 illustrates urban encroachment on the Santa Rosa de Agua ecosystem, with residential areas extending to the edges of the wetland. This phenomenon coincides with the ecological hypothesis that coastal anthropisation alters food webs and favours the adaptation of opportunistic species, including disease-carrying mosquitoes [8,13].

### 3.3. Mosquito-Borne Diseases and Their Local Epidemiological Relevance

#### 3.3.1. Dengue

Dengue, transmitted mainly by *Aedes aegypti*, continues to be the most important arboviral disease in the Zulia region. According to data from the Pan American Health Organisation [27], Venezuela reported a sustained increase in cases between 2021 and 2024, with outbreaks concentrated in densely populated urban areas with poor environmental management.

Observations in Maracaibo suggest that urban mangroves can act as ecological transition zones where wild and urban populations of *Aedes* coexist, creating conditions conducive to viral transmission. Factors such as rising average temperatures and changes in precipitation patterns (attributed to climate change) have increased the seasonality and vector capacity of these mosquitoes [28].

### 3.3.2. Chikungunya and Zika

Chikungunya and Zika, also transmitted by *Aedes aegypti* and *Aedes albopictus*, have had outbreaks in Venezuela during 2014 and 2015, respectively. The Centers for Disease Control and Prevention [29] reports that *Aedes albopictus*, originally a wild species, has adapted to urban and peri-urban environments, increasing the likelihood of transmission in mixed ecosystems such as degraded mangroves.

The results of the review confirm the hypothesis of Berti & González [30] that the modification of coastal ecosystems, the accumulation of wastewater, and the increase in surface water temperature favour larval survival and shorten the development cycles of culicids. In Maracaibo, the patterns observed are consistent with this trend, suggesting a direct relationship between environmental degradation and increased epidemiological risk.

### 3.4. Interaction between Mangroves, Mosquitoes, and Public Health

The findings support the existence of a direct ecological relationship between mangrove degradation and increased vector populations. According to [31], changes in the structure of coastal habitats alter inter- and intraspecific competition among mosquitoes, favouring the dominance of species with high ecological plasticity and high vector capacity.

The coexistence of adverse physicochemical conditions, solid waste, and stagnant water creates an ecological mosaic favourable for the reproduction of *Aedes* and *Culex*, which increases the potential for transmission of arboviral diseases. This phenomenon has been documented in other areas of the Caribbean and South America, where urban mangroves function as larval reservoirs during the dry season [12,14].

Consequently, the results suggest that mangrove conservation not only serves an ecological function but also constitutes a public health strategy. Habitat restoration and reforestation with native mangrove species could reduce artificial and natural mosquito breeding sites by restoring the hydrological balance and local biodiversity [32].

The results show that the mangroves in the Maracaibo metropolitan area are ecological systems of high environmental and epidemiological value. Their degradation, caused by urban expansion and pollution, has altered the ecological conditions that regulate mosquito populations, favouring the proliferation of vector species such as *Aedes aegypti* and *Culex quinquefasciatus*.

The study reaffirms the need for a comprehensive approach to environmental and health management that combines ecosystem conservation, community education, and entomological surveillance to reduce the risks of vector-borne disease transmission.

### 3.5. Integrated Approach to Ecological Control and Community Education

Mosquito control in urban mangrove ecosystems, such as those adjacent to the city of Maracaibo, requires a comprehensive strategy that combines the principles of Integrated Vector Management (IVM), ecological restoration, and informed community participation. This approach seeks not only to reduce vector populations but also to restore the ecological functions of the mangrove and strengthen local capacities for surveillance and prevention of mosquito-borne diseases.

The World Health Organisation [33] and the Pan American Health Organisation [34] recommend that vector control programmes be based on the integration of five pillars: (a) entomological and epidemiological evidence, (b) intersectoral collaboration, (c) community participation, (d) technical capacity building, and (e) rational use of environmental, biological, and chemical interventions. From this perspective, vector control should be approached as a continuous, adaptive process contextualised to the ecological conditions of the territory.

### 3.6. Environmental Monitoring and Participatory Entomological Surveillance

The first component of the proposal consists of establishing a system for continuous environmental monitoring and entomological surveillance in urban mangrove ecosystems. This system should include:

Monthly larval and adult sampling using traps, ovitraps, and dipper sampling, following the protocols of the World Health Organisation [18].

Assessment of physicochemical variables in water (pH, salinity, temperature, conductivity, and dissolved oxygen) to correlate them with the abundance and composition of vector species [10].

Geospatial mapping of breeding sites using GIS (Geographic Information Systems) tools, identifying areas at high risk of proliferation and possible ecological corridors to urban areas [13].

It is recommended that local communities actively participate in identifying breeding sites and collecting data through “citizen science” programmes, such as those promoted by Vector Base or Mosquito Alert [25]. This methodology encourages social appropriation of knowledge and strengthens the sustainability of vector control.

### 3.7. Biological Control and Ecological Restoration of Mangroves

The ecological component of the proposal focuses on the functional restoration of the mangrove ecosystem as a preventive measure and indirect mosquito control.

Reforestation with native mangrove species (*Rhizophora mangle*, *Avicennia germinans*, *Laguncularia racemosa*) helps restore the hydrological balance, improve water filtration, and reduce stagnant areas where larvae develop [2,32].

The use of biological control methods that preserve the integrity of the ecosystem is encouraged, such as the controlled introduction of larvivorous fish (*Poecilia reticulata*, *Gambusia affinis*) and predatory mosquitoes of the genus *Toxorhynchites*, which do not bite and feed on the larvae of other mosquitoes [25,35]. The indiscriminate use of chemical insecticides is discouraged due to documented risks of vector resistance and environmental toxicity, as documented by the European Centre for Disease Prevention and Control [19]. In addition, the cleaning of drainage channels must accompany ecological restoration, the removal of solid waste, and environmental sanitation, thus preventing the mangrove from acting as a sink for urban waste, which favours the larval development of *Aedes aegypti* and *Culex quinquefasciatus* [8].

### 3.8. Health Education and Community Participation

The sustainability of vector control depends largely on health education and active social participation. We propose the design of a community-based environmental health education programme covering:

Information campaigns on the risks of mosquito-borne diseases, with visual material adapted to the local population.

Participatory workshops to teach techniques for eliminating breeding sites, maintaining healthy schools, integrating students into mosquito monitoring and mangrove restoration projects, and promoting environmental education from an early age [13].

Risk communication through social media, local radio stations, and community leaders is aligned with the guidelines of [9] on effective communication in public health.

Community education should promote a vision of environmental and health co-responsibility, where the population understands that the ecological balance of mangroves and public health are interdependent dimensions.

### 3.9. Inter-Institutional Coordination and Integrated Management Framework

The implementation of the plan requires sustained inter-sectoral coordination between health, education, and environmental institutions (MINEC, Maracaibo City Council, University of Zulia, IVIC, Regional Government, among others), health authorities (Ministry of Popular Power for Health, Regional Epidemiology Directorate), and organised communities.

The creation of an Inter-institutional Technical Committee for Vector Management and Mangrove Conservation is suggested, responsible for:

- Defining technical guidelines for monitoring and ecological intervention.
- Managing financial and logistical resources.
- Establishing entomological surveillance protocols compatible with national health systems.
- Promoting the integration of local universities in applied research and community outreach projects.

Successful models of this type of management have been implemented in Cuba, Mexico, and the Philippines, where cooperation between environmental and health institutions has been shown to significantly reduce the incidence of arboviral diseases [25,35].

### 3.10. Sustainability Outlook and Impact Assessment

Finally, an ecological and epidemiological impact assessment system is proposed with measurable indicators, such as:

- Reduction in larval density per vector species.
- Recovery of vegetation cover in degraded mangroves.
- Increase in community knowledge and participation.
- Decrease in the incidence of dengue, chikungunya, and Zika.

These indicators must be evaluated periodically through technical audits and citizen participation, ensuring the transparency of the process and the continuous improvement of the programme.

The integrated proposal presented combines environmental, health, and educational approaches, recognising that mosquito control in the mangrove ecosystems of Maracaibo cannot be addressed solely from the traditional

vector perspective. Ecological balance, participatory governance, and education are essential pillars for reducing health vulnerability and ensuring the sustainability of actions in the long term.

### 3.11. Eco-Epidemiological Procedures

During the ecological component of the study, larval sampling techniques recommended by the World Health Organisation [18] and the Centers for Disease Control and Prevention [19] were applied, adapted to the conditions of the mangrove ecosystems of the coastal strip of the municipality of Maracaibo. Sampling was carried out at three representative sites (Santa Rosa de Agua, Parque La Marina, and Vereda del Lago) during the months of March to May 2025, coinciding with the onset of the rainy season, the period of greatest mosquito proliferation in tropical environments [8].

350 mL containers were used to collect larvae in temporary pools, flooded areas between the aerial roots of *Rhizophora mangle*, cavities formed by organic debris, and bodies of stagnant water with floating vegetation. At each point, three replicates were made per site with a separation of 10 m between each one, ensuring spatial representativeness.

The collected larvae were transferred to glass jars containing 70% ethanol and labelled with the site code, date, and microhabitat of origin. Subsequently, at the Centre for Molecular Biomedicine (IVIC), the specimens were morphologically identified to genus level and, where possible, to species level, using taxonomic keys [20,21] recognised as benchmarks in the identification of Culicidae in the Neotropics.

### 3.12. Identification and Taxonomic Composition

Morphological analysis allowed for the identification of two genera of the Culicidae family: *Aedes* and *Culex*. A total of 67 larvae were recorded, distributed as follows:

Genus *Aedes* (56.7% of the total), predominantly *Aedes aegypti*, a species adapted to urban and peri-urban environments, is frequently found in ponds with decomposing organic matter and low salinity water.

*Culex* genus (43.3% of the total), mainly *Culex quinquefasciatus*, a species tolerant to high levels of organic pollution and hypoxic conditions, common in wastewater or semi-stagnant waters.

The simultaneous presence of both genera indicates an ecological gradient of coexistence between halotolerant and eutrophic species, probably favoured by the mixture of brackish water and urban discharges in the mangroves of Maracaibo. These results are consistent with studies conducted in coastal wetlands in the Caribbean and South America, where *Aedes aegypti* and *Culex quinquefasciatus* share niches in urban mangrove areas [12].

### 3.13. Relative Abundance and Microhabitats

The highest abundance indices were observed in shaded pools with accumulations of leaves and organic debris, followed by submerged roots of red mangrove (*Rhizophora mangle*) and areas with poor water circulation.

The *Aedes* genus was more prevalent in areas with lower salinity (0.5–5.0 PSU) and water temperatures between 28–31 °C; in contrast, *Culex* predominated in eutrophic areas with high concentrations of organic matter and low levels of dissolved oxygen (<3 mgL<sup>-1</sup>). These conditions coincide with those reported by [26] for transitional environments between urban and coastal areas.

Ecological analyses yielded a Shannon-Wiener diversity index (H') of 0.65 and a Simpson index (D) of 0.42, values that reflect low diversity and high species dominance, typical of disturbed ecosystems. The dominance of *Aedes aegypti* suggests a high degree of adaptation to artificial and semi-saline microenvironments, while *Culex quinquefasciatus* appears to take advantage of organic waste accumulation and eutrophication for its larval development.

### 3.14. Ecological and Epidemiological Interpretation

The coexistence of *Aedes* and *Culex* in these urban mangrove ecosystems is an indicator of ecological imbalance resulting from anthropogenic pressure. Wastewater pollution and solid waste disposal have transformed mangroves into favourable habitats for mosquitoes with high epidemiological relevance.

*Aedes aegypti* acts as the main vector for dengue, Zika, and chikungunya viruses, all of which are significant in the Zulia region. *Culex quinquefasciatus*, meanwhile, is a proven vector for West Nile virus and lymphatic filariasis in other tropical regions [9,36]. These findings reinforce the hypothesis that environmental degradation of the Maracaibo mangroves could be generating permanent larval reservoirs that contribute to the persistence of

vector populations throughout the year, even outside the rainy season, posing a sustained epidemiological risk to surrounding communities.

### 3.15. Implications for Vector Surveillance

The identification of these two genera allows future surveillance actions to be directed towards an integrated vector risk management approach, combining ecological monitoring, environmental sanitation, and habitat restoration. The characterisation of critical microhabitats, such as mangrove margins with organic debris, is essential for prioritising interventions. Likewise, obtaining physicochemical data and correlating it with larval abundance will strengthen predictive models of vector dynamics in tropical coastal areas.

The results presented in Tables 2 and 3 show the presence of two genera of Culicidae (*Aedes* and *Culex*) across the three mangrove ecosystems studied, confirming their ability to colonise urbanised coastal environments in the Maracaibo metropolitan area. This coexistence, observed in environments with different levels of salinity and organic pollution, is consistent with previous studies on the ecological plasticity of these genera in tropical regions [8,26].

**Table 2.** Relative abundance, frequency, and microhabitats of Culicidae larvae in mangrove ecosystems in the Maracaibo metropolitan area (March–May 2025).

Sampling Site	Identified Species	Absolute Frequency (n)	Relative Frequency (%)	Predominant Microhabitat	Associated Environmental Conditions			
					Temp.	Salinity	pH	O <sub>2</sub> Dissolved
Santa Rosa de Agua	<i>Aedes aegypti</i>	15	22.4	Shaded ponds with plant debris	30 °C	3 PSU	7.1	4.2 mg L <sup>-1</sup>
	<i>Culex quinquefasciatus</i>	11	16.4	Stagnant water with organic waste	31 °C	4PSU	7.3	3.1 mg L <sup>-1</sup>
Parque La Marina	<i>Aedes aegypti</i>	13	19.4	Submerged roots of <i>Rhizophora mangle</i>	29 °C	2 PSU	6.8	4.5 mg L <sup>-1</sup>
	<i>Culex quinquefasciatus</i>	9	13.4	Eutrophic edges with organic matter	30 °C	3 PSU	7.2	2.9 mg L <sup>-1</sup>
Parque Vereda del Lago	<i>Aedes aegypti</i>	10	14.9	Water is retained between the roots and fallen leaves	31 °C	1.5 PSU	6.9	4.1 mg L <sup>-1</sup>
	<i>Culex quinquefasciatus</i>	9	13.5	Semi-stagnant wastewater	32 °C	5 PSU		2.7 mg L <sup>-1</sup>
					Average			
Total	—	67	100%	—	30.5 °C	3.3 PSU	7.1	3.6 mg L <sup>-1</sup>

**Table 3.** Calculated ecological indices (by sampling site). The Shannon-Wiener (H') and Simpson (D) indices evaluate species diversity and dominance structure of Culicidae larvae in mangrove microhabitats. Low H' values (0.62–0.67) indicate reduced evenness and rarefaction due to anthropogenic disturbance, while D values near 0.42 reflect high dominance (>50%) by *Aedes aegypti* and *Culex quinquefasciatus*, typical of perturbed coastal. Santa Rosa de Agua shows the lowest diversity (H' = 0.62), correlating with urban encroachment and shaded pools favoring *Aedes*. Probability that two randomly selected larvae belong to the same species (dominance); values 0.4–0.44 indicate strong competitive exclusion in eutrophic sites. Across sites, average H' = 0.65 and D = 0.42 confirm habitat degradation reduces beta-diversity, promoting vector proliferation via intermediate disturbance. These metrics align with Becker et al. (2010) for anthropized mangroves.

Site	Shannon-Wiener Index (H')	Simpson Index (D)	Estimated Diversity
Santa Rosa de Agua	0.62	0.44	Low diversity, high dominance of <i>Aedes</i>
Parque La Marina	0.67	0.41	Low diversity, moderate coexistence
Parque Vereda del Lago	0.64	0.42	Low diversity, balanced dominance
General average	0.65	0.42	Low global diversity in disturbed habitats

### 3.16. Abundance and Distribution Patterns

Table 2 shows that *Aedes aegypti* was the predominant species, representing 56.7% of the total number of individuals collected, followed by *Culex quinquefasciatus* with 43.3%. This pattern of dominance suggests an

imbalance in the larval community, typical of disturbed ecosystems where environmental conditions favour opportunistic species with high reproductive capacity [12]. The greater abundance of *Aedes* in Santa Rosa de Agua (22.4%) and Parque La Marina (19.4%) is associated with freshwater or slightly brackish microhabitats, with average temperatures of 29–31 °C and dissolved oxygen levels ( $>4.0 \text{ mg L}^{-1}$ ). These conditions coincide with the optimal ranges of larval development reported [14] for *Aedes aegypti*.

In contrast, *Culex quinquefasciatus* was more prevalent in eutrophicated areas with low dissolved oxygen, particularly in Parque Vereda del Lago, where the highest values of salinity (5.0 PSU) and organic matter were recorded. This behaviour is consistent with observations [36] documenting *Culex*'s affinity for polluted or waste water in tropical urban environments.

### 3.17. Statistical Analysis of Correlations and Site Comparison

A comparison between sites was performed using the Kruskal–Wallis test (non-parametric) to assess differences in larval abundance among the three sampling sites (Table 4). Similarly, a Spearman's correlation analysis was conducted between the abundance of *Aedes aegypti* and *Culex quinquefasciatus* and environmental variables (salinity, temperature, dissolved oxygen).

**Table 4.** Environmental variables and Spearman's correlation coefficients with *Aedes aegypti* and *Culex quinquefasciatus*.

Environmental Variable	Correlation with <i>Ae. aegypti</i> (rho)	Correlation with <i>Cx. quinquefasciatus</i> (rho)	p-Value
Salinity (PSU)	-0.78	+0.72	<0.05
Temperature (°C)	+0.65	+0.58	<0.05
Dissolved oxygen (mg/L)	+0.81	-0.76	<0.01

A Spearman's correlation analysis between larval abundance and environmental variables revealed a significant negative correlation between salinity and the abundance of *Aedes aegypti* ( $\text{rho} = -0.78, p < 0.05$ ), while *Culex quinquefasciatus* showed a positive correlation ( $\text{rho} = +0.72, p < 0.05$ ). The Kruskal–Wallis test indicated significant differences in larval abundance among the three sites ( $H = 7.89, p < 0.05$ ), with Santa Rosa de Agua showing the highest abundance of *Ae. aegypti*.

The Spearman's correlation analyses revealed distinct ecological patterns between *Aedes aegypti* and *Culex quinquefasciatus* in the urban mangroves of Maracaibo. The significant negative correlation between salinity and *Ae. aegypti* abundance ( $\text{rho} = -0.78, p < 0.05$ ) confirms its preference for low-salinity microhabitats, typical of freshwater or slightly brackish water bodies, common in degraded mangroves under urban influence. Conversely, the positive correlation found for *Cx. quinquefasciatus* ( $\text{rho} = +0.72, p < 0.05$ ) suggests a greater tolerance to saline conditions, likely related to its ability to colonise eutrophic waters with high organic loads, such as those found in domestic discharge channels.

Likewise, the positive correlation between dissolved oxygen and *Ae. aegypti* ( $\text{rho} = +0.81, p < 0.01$ ) and the negative one for *Cx. quinquefasciatus* ( $\text{rho} = -0.76, p < 0.01$ ) reflects a niche segregation based on water quality. These findings are consistent with previous studies in Caribbean coastal wetlands, where *Ae. aegypti* predominates in well-oxygenated and less polluted waters, while *Cx. quinquefasciatus* thrives in hypoxic, organic-rich environments [26].

The Kruskal–Wallis test confirmed significant differences in larval abundance among the three sampling sites ( $H = 7.89, p < 0.05$ ), with Santa Rosa de Agua showing the highest abundance of *Ae. aegypti*. This spatial variation may be attributed to the degree of anthropogenic disturbance and microhabitat heterogeneity, where sites with greater disturbance and accumulation of organic residues favour the proliferation of *Cx. quinquefasciatus*, as observed in Parque Vereda del Lago [36].

These findings reinforce the hypothesis that environmental degradation in urban mangroves not only reduces entomological diversity but also modulates vector species composition through key environmental filters such as salinity and dissolved oxygen. The inclusion of these basic statistical analyses allows for a more rigorous interpretation of ecological gradients and strengthens the empirical basis for designing microhabitat-specific vector control strategies [9].

### 3.18. Environmental and Anthropogenic Influence

The environmental gradient identified between the three sites suggests that microenvironmental heterogeneity directly influences the structure of Culicidae communities. The ecosystems of Santa Rosa de Agua

and Parque La Marina, although they still retain natural mangrove characteristics, show clear signs of alteration due to domestic waste and floating rubbish. On the other hand, Parque Vereda del Lago presents a higher level of disturbance, characterised by semi-stagnant bodies of water with waste discharges and poor water renewal.

This environmental gradation translates into a process of ecological simplification, where species that are more tolerant to adverse conditions, such as *Culex quinquefasciatus*, thrive. According to [5], the degradation of urban wetlands leads to the loss of biological regulators and the homogenisation of niches, which explains the low diversity values found.

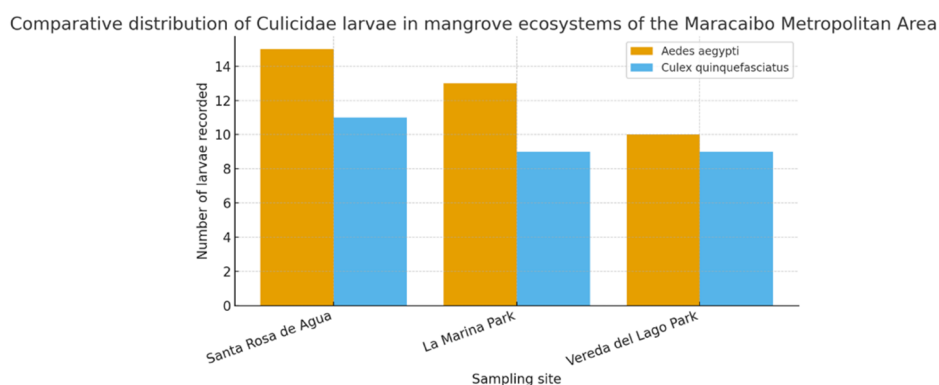
### 3.19. Specific Diversity and Community Structure

*Intermediate Disturbance Hypothesis*, according to which environments with continuous disturbances tend to exhibit less equitability and dominance of a few generalist species [37].

Such values are similar to those reported by [12] in mangroves of the western Caribbean, where the authors found that deforestation and pollution reduce the richness of Culicidae to two or three main genera, dominated by *Aedes* and *Culex*. In the local context, this situation implies a sustained epidemiological risk, as both species are recognised for their importance in the transmission of arboviral viruses.

The graph (Figure 3) shows the comparative abundance of *Aedes aegypti* and *Culex quinquefasciatus* larvae at the three sampling sites (Santa Rosa de Agua, La Marina Park, and Vereda del Lago Park). In Santa Rosa de Agua, the highest density of *Aedes aegypti* larvae was observed, which coincides with the presence of shaded ponds and accumulation of plant debris. In Parque La Marina, populations of both genera were moderate, reflecting intermediate conditions of salinity and availability of organic matter. In Parque Vereda del Lago, the abundance of *Culex quinquefasciatus* remained similar to that of *Aedes aegypti*, due to greater eutrophication and water pollution.

Figure 3 confirms that *Aedes aegypti* dominates in low-salinity and highly oxygenated environments, while *Culex quinquefasciatus* is better adapted to polluted environments with low water renewal. This trend reflects the impact of coastal urbanisation on the ecological structure of mangroves and reinforces the need for differentiated vector control strategies based on local environmental conditions.



**Figure 3.** Descriptive comparative image of the distribution of Culicidae larvae in mangrove ecosystems in the Maracaibo metropolitan area.

### 3.20. Epidemiological Relevance

The simultaneous finding of *Aedes aegypti* and *Culex quinquefasciatus* at the three sampling sites has direct implications for public health. *Aedes aegypti* is a proven vector of dengue, Zika, and chikungunya, diseases that have had a high incidence in Zulia state over the last decade [27]. *Culex quinquefasciatus*, although less studied in Venezuela, may participate in the transmission of West Nile virus and lymphatic filariasis, especially in urban environments with the presence of birds and wastewater [36,37].

The co-occurrence of both genera in urban mangrove environments suggests the existence of epidemiological microecosystems, where ecological and social factors (waste, lack of sanitation, and coastal urbanisation) converge, facilitating the permanence of active breeding sites throughout the year. These results support the need to strengthen continuous entomological surveillance programmes, incorporating environmental variables into vector risk prediction models. Monitoring based on ecological indicators is essential for detecting changes in vector population dynamics and anticipating epidemic outbreaks [38–40].

### 3.21. Ecological and Health Synthesis (Ecoepidemiology)

Taken together, the tables reflect a pattern characteristic of degraded coastal ecosystems: low biological diversity, dominance of generalist vector species, and high correlation between organic pollution and larval abundance. The loss of habitat quality not only compromises the ecosystem services of the mangrove but also amplifies health risks for surrounding communities. These findings reaffirm the observations made by [24,25] regarding the dual role of urban mangroves as ecological refuges and potential reservoirs of pathogens. Therefore, the conservation of these ecosystems should not be considered solely as an environmental measure, but also as a preventive strategy in the epidemiological field.

The data obtained show that the urban mangroves of Maracaibo, although ecologically degraded, maintain favourable conditions for the development of mosquito species with high vector capacity. The dominance of *Aedes aegypti* in semi-saline environments and *Culex quinquefasciatus* in eutrophic waters demonstrates differential adaptive resilience, reflecting the environmental pressure derived from coastal urbanisation. These results provide empirical evidence supporting the need for ecological control programmes, mangrove restoration, and community education as essential components of integrated epidemiological surveillance in the Zulia region [40,41].

## 4. Conclusions

This study provides preliminary evidence on the presence and ecological preferences of two medically important Culicidae genera (*Aedes aegypti* and *Culex quinquefasciatus*) in the urban mangrove ecosystems of Maracaibo. Our findings, based on larval sampling during the early rainy season of 2025, indicate that both species are capable of colonizing degraded coastal environments characterized by variable salinity and organic pollution.

Statistical analyses, including Spearman correlation, revealed distinct environmental preferences: *Aedes aegypti* abundance was negatively correlated with salinity ( $\rho = -0.78, p < 0.05$ ) and positively with dissolved oxygen ( $\rho = +0.81, p < 0.01$ ), whereas *Culex quinquefasciatus* showed a positive correlation with salinity ( $\rho = +0.72, p < 0.05$ ) and a negative correlation with oxygen levels ( $\rho = -0.76, p < 0.01$ ). These results support the hypothesis that niche partitioning occurs in response to physicochemical gradients, driven by anthropogenic disturbance. Furthermore, the Kruskal–Wallis test indicated significant differences in larval abundance among sampling sites ( $H = 7.89, p < 0.05$ ), with *Ae. aegypti* dominating in less saline, shaded pools (Santa Rosa de Agua), and *Cx. quinquefasciatus* prevailing in eutrophic, organically enriched waters (Parque Vereda del Lago).

The low diversity indices (Shannon–Wiener  $H' = 0.65$ ; Simpson  $D = 0.42$ ) and high dominance of *Aedes aegypti* suggest an ecological simplification typical of disturbed mangrove ecosystems, where anthropogenic pressure, eutrophication, and waste accumulation favor the persistence of larval habitats. The co-occurrence of both genera in urban mangrove areas indicates that these environments may serve as transitional reservoirs for vector populations, potentially increasing the risk of arbovirus transmission (such as dengue, Zika, and chikungunya) in nearby communities.

However, these conclusions must be interpreted within the limitations of the study, including the small sample size ( $n = 67$  larvae), the exclusive focus on larval stages, and the restriction of sampling to a single season. Future research should incorporate year-round monitoring, adult capture, molecular identification, and expanded spatial replication to better understand vector dynamics and seasonality.

Despite these limitations, our findings underscore the epidemiological relevance of urban mangroves in Maracaibo and highlight the need to integrate mangrove monitoring into local entomological and public health surveillance systems. We recommend the implementation of an Integrated Vector Management (IVM) framework that combines ecological restoration, biological control, community-based education, and targeted interventions based on microhabitat-specific vector ecology. Such an approach could enhance environmental sustainability and reduce the potential epidemiological risk in coastal urban areas.

## Author Contributions

E.P.: Lead researcher and project creator, species identification, processing of ecological and epidemiological data, manuscript supervision, and review. H.V.: Methodology, manuscript review. R.V.: Processing of epidemiological data, medical research, and manuscript review. M.S.: Sampling and field data, manuscript review. P.R.: Sampling and field data. All authors have read and agreed to the published version of the manuscript.

## Funding

This research received no external funding.

### Institutional Review Board Statement

Not applicable.

### Informed Consent Statement

Not applicable.

### Data Availability Statement

Data will be available upon request from the corresponding author.

### Conflicts of Interest

The Authors declare no conflict of interest.

### Use of AI and AI-Assisted Technologies

During the preparation of this work, the authors used ChatGPT to generate Figure 3 and Grammarly for the English translation (the original language of the manuscript is Spanish, and this Spanish manuscript has not been published anywhere). After using this tool/service, the authors reviewed and edited the content as needed and assume full responsibility for the content of the published article.

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