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Seasonal Dynamics and Habitat Characteristics of Mosquito Populations in a Tropical Environment

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Abstract Mosquito populations in tropical environments exhibit marked seasonal dynamics shaped by climatic variability, habitat availability, and human disturbance. This paper examines how temperature, rainfall, humidity, and ecological conditions influence temporal changes in mosquito abundance and distribution, with particular attention to the relationship between seasonal patterns and habitat characteristics. Both natural habitats, such as wetlands, ponds, and vegetated areas, and artificial habitats, including urban containers, drainage systems, and domestic water storage sites, are considered in order to understand their roles in sustaining mosquito breeding and survival. The study also explores species-specific responses to environmental drivers, showing that different mosquito taxa vary in their seasonal peaks and habitat preferences. In addition, the paper reviews commonly used field sampling methods, statistical analyses, and spatial tools such as geographic information systems and remote sensing for monitoring mosquito populations and identifying high-risk habitats. The findings highlight that seasonal mosquito dynamics in tropical regions are closely linked to habitat heterogeneity and environmental change, which together affect the risk of vector-borne disease transmission. A better understanding of these interactions can support more targeted habitat management and seasonally optimized mosquito control strategies for improving public health outcomes in tropical settings.

Keywords Mosquito populations; Tropical environments; Seasonal dynamics; Habitat characteristics; Vector control

1 Introduction

Mosquitoes play a critical role in tropical regions as vectors of numerous infectious diseases that significantly impact public health worldwide. Tropical climates, characterized by warm temperatures and high humidity, provide ideal conditions for mosquito breeding and survival, facilitating the transmission of pathogens such as dengue, malaria, Zika, and chikungunya viruses. The burden of these vector-borne diseases is particularly severe in tropical areas due to the year-round presence of mosquitoes and the complex interactions between environmental factors and mosquito biology. Understanding mosquito population dynamics in these regions is essential for developing effective control strategies to reduce disease transmission and protect vulnerable populations (Blanco-Sierra et al., 2024; García-Súarez et al., 2024).

Research on mosquito ecology in tropical environments has advanced considerably, focusing on how seasonal changes and habitat characteristics influence mosquito abundance and species composition. Studies have demonstrated that climatic variables such as temperature, rainfall, and humidity are major drivers of mosquito life cycles, affecting their reproduction, development, and survival rates. Additionally, anthropogenic factors like urbanization alter habitat availability and quality, influencing mosquito community structure and vector potential. Recent modeling efforts have integrated environmental data with mosquito life history traits to predict spatiotemporal population dynamics across diverse tropical landscapes. These approaches highlight the importance of local-scale ecological studies to capture the variability in mosquito populations driven by both natural seasonality and human-induced habitat changes (García-Súarez et al., 2024; Rakotoarison et al., 2025).

This study aims to elucidate the seasonal dynamics and habitat characteristics of mosquito populations within a tropical environment to inform vector control efforts. By characterizing how environmental variables and habitat types affect mosquito abundance and diversity over time, this research seeks to identify key factors that govern vector population fluctuations. The findings will contribute to optimizing surveillance programs and tailoring control interventions according to seasonal patterns and habitat preferences of different mosquito species. Ultimately, understanding these ecological relationships is vital for mitigating the public health risks posed by mosquitoes in tropical regions under changing climatic conditions (Hinne et al., 2021; Blanco-Sierra et al., 2024).

2 Study Area and Ecological Background

2.1 Tropical climate characteristics and seasonal classification

Tropical regions are characterized by consistently high temperatures and significant humidity levels, creating an environment conducive to mosquito survival and reproduction. These climates typically exhibit distinct wet and dry seasons rather than the four-season pattern seen in temperate zones. The wet season, marked by heavy rainfall, increases the availability of aquatic habitats necessary for mosquito larval development, while the dry season often limits breeding sites but may still support mosquito populations in permanent water bodies or human-made containers. Temperature fluctuations within tropical climates also influence mosquito physiology and behavior, with warmer conditions generally accelerating development rates and increasing biting frequency (De Mello et al., 2022; Mazarire et al., 2024). Microclimatic variations caused by factors such as vegetation cover can further modulate local temperature and humidity, thereby affecting mosquito abundance and species distribution within tropical landscapes (Figure 1) (Abdullah et al., 2025).

Seasonal classification in tropical environments is often based on precipitation patterns, with the rainy season promoting peak mosquito activity due to increased habitat availability. However, temperature and humidity also play critical roles in shaping seasonal dynamics. For example, studies have shown that relative humidity above certain thresholds enhances adult mosquito survival, while temperature influences both larval development time and adult longevity. These climatic variables interact complexly to produce temporal fluctuations in mosquito populations that vary across different tropical ecosystems. Understanding these seasonal patterns is essential for predicting periods of heightened vector-borne disease risk and optimizing timing for control interventions (Chaiphongpachara et al., 2024; Arisanti et al., 2025).

Figure 1 Aerial view of non-dengue and dengue hotspots with GOS trap placement. The image presents an aerial view of the designated non-dengue hotspot (A) and dengue hotspot (B) within the study area. GOS (Gravid Oviposition Sticky) traps are strategically positioned across both sites to monitor Aedes mosquito populations. The spatial arrangement of traps provides comprehensive coverage, facilitating the study of mosquito activity and distribution patterns relative to environmental characteristics. This layout supports comparisons of Aedes species distribution and dengue virus prevalence between the two distinct ecological settings (Adopted from Abdullah et al., 2025)

2.2 Types of typical ecosystems

Tropical regions encompass a variety of ecosystems that provide diverse habitats for mosquitoes, including dense forests, wetlands, agricultural landscapes, and urban areas. Forested environments offer shaded breeding sites such as tree holes and leaf axils, supporting species adapted to sylvatic habitats. Wetlands and rice paddies create extensive aquatic habitats favorable for larval development of several vector species like Anopheles mosquitoes associated with malaria transmission. Urban environments introduce artificial containers and water storage systems that serve as prolific breeding grounds for *Aedes aegypti* and *Aedes albopictus*, vectors responsible for dengue and other arboviral diseases (García-Súarez et al., 2024; Nayak et al., 2025). The heterogeneity of these ecosystems influences mosquito community composition by providing niches suited to different species' ecological preferences.

Land use changes such as urbanization significantly alter habitat availability and microclimatic conditions within tropical landscapes. Urban areas often experience higher temperatures (urban heat island effect) and reduced vegetation cover compared to natural habitats, which can favor certain mosquito species over others. Fragmented urban landscapes with mixed residential and cropland areas have been identified as hotspots for Aedes breeding due to abundant artificial containers combined with suitable climatic conditions. Conversely, natural wetlands maintain stable populations of other vector species like Mansonia mosquitoes that rely on aquatic vegetation during their immature stages. Thus, ecosystem type strongly shapes the spatial distribution patterns of mosquitoes by influencing habitat suitability at local scales (Bennett et al., 2021; García-Súarez et al., 2024).

2.3 Major mosquito species and their distribution patterns

Several key mosquito species dominate tropical environments due to their adaptability to diverse habitats and climatic conditions. Among these are *Aedes aegypti* and *Aedes albopictus*, which are primary vectors of dengue virus; their distributions often overlap but show microhabitat preferences influenced by vegetation cover and urbanization gradients. For instance, *Ae. albopictus* tends to be more abundant in vegetated suburban or rural areas with higher humidity levels, whereas *Ae. aegypti* thrives in densely populated urban settings with warmer microclimates (Bennett et al., 2021; Abdullah et al., 2025). Both species exhibit seasonal fluctuations linked to rainfall patterns that create breeding sites in artificial containers.

Anopheline mosquitoes responsible for malaria transmission also display distinct spatial distributions shaped by ecological factors such as water quality parameters (pH, salinity), illumination levels in breeding sites, temperature ranges, and predator presence. Species like *Anopheles vagus* dominate rice-growing agroecosystems where flooded fields provide ideal larval habitats. Climatic variables including temperature peaks around 23°C~24°C combined with high relative humidity optimize biting rates for several Anopheles species (Arisanti et al., 2025). Additionally, Culex mosquitoes are widespread across various tropical habitats due to their tolerance of diverse environmental conditions but show abundance patterns influenced by diurnal temperature ranges (García-Súarez et al., 2024). Understanding these species-specific distribution patterns is crucial for targeted vector surveillance and control strategies tailored to local ecological contexts.

3 Seasonal Dynamics of Mosquito Populations

3.1 Variations in mosquito population density across seasons

Mosquito populations in tropical environments exhibit pronounced seasonal fluctuations, often characterized by peaks in abundance during or shortly after the rainy season when breeding habitats are most abundant. Studies monitoring mosquito activity have documented bimodal or unimodal seasonal patterns depending on local climatic conditions and species composition. For example, research conducted in Mediterranean botanical gardens showed that adult mosquito abundance followed a seasonal pattern influenced by temperature but with two distinct peaks linked to cumulative rainfall events, highlighting the complex interplay between climate and mosquito life cycles (Blanco-Sierra et al., 2024). Similarly, long-term surveillance across urbanization gradients in Yucatan, Mexico, revealed that mosquito densities varied significantly over the year, with higher captures during wetter months and lower numbers during dry periods, reflecting the dependence of larval habitats on precipitation (García-Súarez et al., 2024).

Seasonal variations are not uniform across all tropical regions or mosquito species; some areas experience extended periods of high mosquito abundance due to persistent favorable conditions. Modeling studies incorporating temperature and rainfall data from multiple African sites demonstrated that mosquito populations could peak once to multiple times annually depending on regional climate patterns. In locations with less pronounced dry seasons, such as parts of Ghana, mosquitoes maintain relatively high densities year-round, whereas other regions show prolonged low-abundance periods lasting several months (Baafi and Hurford, 2025). These findings emphasize the importance of local climatic context in shaping temporal population dynamics and suggest that vector control programs must be tailored to regional seasonal profiles for maximum effectiveness.

3.2 Effects of rainfall, temperature, and humidity on population fluctuations

Rainfall is a primary driver of mosquito population dynamics as it creates and replenishes aquatic habitats necessary for larval development. Accumulated precipitation in the weeks preceding sampling has been consistently identified as a significant predictor of adult mosquito abundance across diverse tropical settings. For instance, studies in Yucatan found that accumulated rainfall four weeks prior strongly correlated with increased captures of multiple species including *Culex quinquefasciatus* and *Aedes aegypti* (García-Súarez et al., 2024). However, excessive rainfall can sometimes flush out larvae or reduce habitat stability, indicating a nonlinear relationship between precipitation and mosquito populations.

Temperature influences multiple aspects of mosquito biology including development rate, survival, and biting frequency. Warmer temperatures generally accelerate larval maturation and increase adult activity but may also elevate mortality if exceeding optimal thresholds. Research from central Thailand coconut plantations showed that while meteorological variables did not always have statistically significant effects on Culex abundance individually, seasonal temperature variation was linked to changes in wing morphology indicative of phenotypic plasticity (Laojun et al., 2025). Relative humidity further modulates adult survival; higher humidity levels enhance longevity and feeding activity. Studies from temperate regions also highlight species-specific responses to weather variables such as diurnal temperature range affecting Culex species differently (Figure 2) (Baril et al., 2023). Together, these climatic factors interact dynamically to produce complex seasonal fluctuations in mosquito populations.

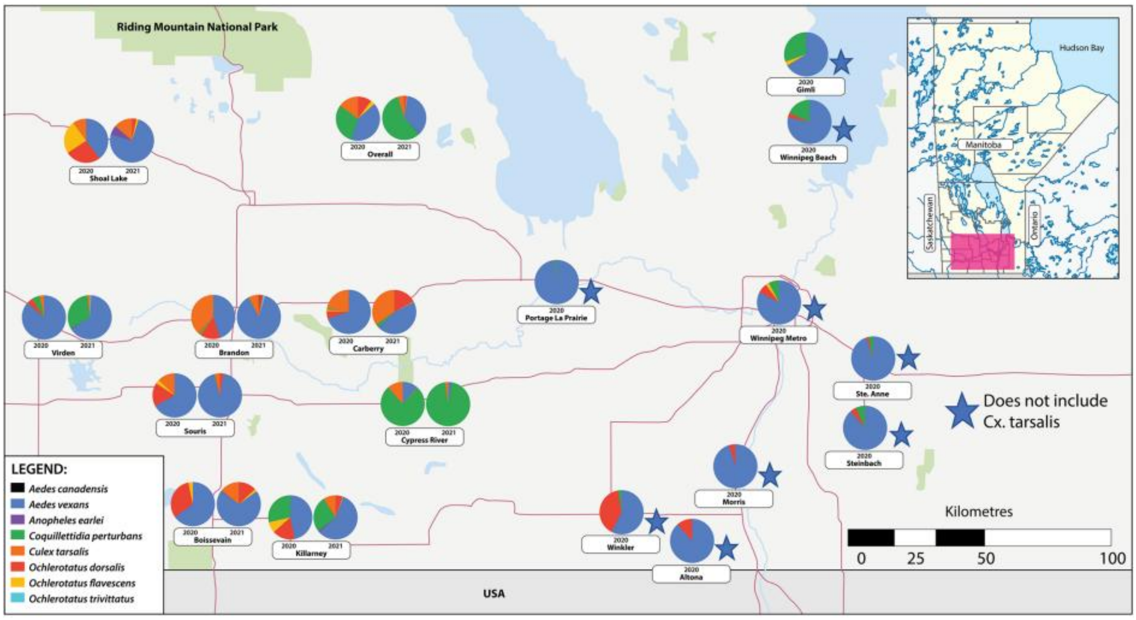

Figure 2 Relative trap counts for the eight most commonly found mosquito species in 2020 and 2021. Mosquitoes were captured on a weekly basis (May to September) from 17 sampling sites throughout Manitoba, Canada. *Culex tarsalis* counts are not included for all locations in the eastern part of the region (denoted with an asterisk*). *Ae. canadensis*, *An. earlei*, *Oc. trivittatus*, and *Oc. triseriatus* were not surveyed in 2020. We collected one *Oc. triseriatus* in 2021, which was not included on the figure (Adopted from Baril et al., 2023)

3.3 Seasonal differences among mosquito species

Different mosquito species exhibit distinct seasonal patterns driven by their ecological adaptations and habitat preferences. *Aedes aegypti* typically peaks during warm wet seasons when artificial containers fill with water in urban environments, whereas *Ae. albopictus* may show greater abundance in more vegetated suburban or rural areas with higher humidity (Blanco-Sierra et al., 2024; García-Súarez et al., 2024). Anopheline mosquitoes responsible for malaria transmission often display seasonality closely tied to agricultural practices and natural water availability; for example, *Anopheles vagus* thrives in flooded rice paddies during rainy seasons (Rakotoarison et al., 2025). Species like *Culex sitiens* and *Culex gelidus* show differing peak abundances within the same region one peaking early in the rainy season and another later reflecting niche partitioning (Laojun et al., 2025).

Seasonal timing also affects life stage distributions within species populations. Stage-structured models reveal that eggs, larvae, pupae, and adults respond differently to environmental cues such as temperature and rainfall throughout the year. This results in shifts not only in total abundance but also in population age structure which can influence disease transmission potential (Baafi and Hurford, 2025). Moreover, urbanization gradients modify these seasonal dynamics by altering habitat availability and microclimate conditions favoring some species over others (García-Súarez et al., 2024; Whittaker et al., 2022). Understanding these interspecific differences is critical for designing targeted vector control strategies that consider both temporal windows of peak risk and species-specific ecology.

4 Types and Characteristics of Mosquito Habitats

4.1 Natural habitats

Natural mosquito habitats in tropical environments primarily include standing water bodies such as ponds, swamps, slow-moving streams, and phytotelmata water-holding structures in plants like bromeliads and bamboo internodes. These habitats provide essential aquatic environments for mosquito larvae development. For example, *Anopheles funestus*, a major malaria vector in southeastern Tanzania, predominantly breeds in small spring-fed pools, natural ponds that retain water most of the year, and slow-moving river tributaries with clear water and emergent vegetation (Nambunga et al., 2020). Similarly, phytotelmata in tropical forests support diverse mosquito communities; bamboo internodes have been shown to harbor high species richness and abundance due to favorable microhabitat conditions such as temperature and pH (De Almeida et al., 2025). Vegetated areas adjacent to water bodies often offer shaded breeding sites that protect larvae from predators and extreme environmental fluctuations.

The physicochemical characteristics of these natural habitats influence mosquito species composition and larval productivity. Studies in Iran found significant differences among mosquito species in their preferences for chloride content and water temperature but not for pH or turbidity (Amini et al., 2020). In addition, dissolved oxygen levels, alkalinity, and emergent plant coverage have been linked to larval abundance for various species including *Anopheles vagus* and *Culex quinquefasciatus* (Bashar et al., 2016). The permanence of water bodies also plays a role; permanent or semi-permanent habitats tend to support stable populations of certain vectors by providing consistent breeding sites throughout the year (Dida et al., 2018; Nambunga et al., 2020). Understanding these natural habitat features is critical for identifying key breeding sites for vector control efforts.

4.2 Artificial habitats

Urbanization creates numerous artificial aquatic habitats that serve as prolific breeding grounds for mosquitoes, especially container-breeding species like *Aedes aegypti*. Common urban habitats include buckets, flower pots, ornamental bromeliads, discarded tires, drainage systems, and water storage containers. Research conducted in Miami-Dade County demonstrated that *Ae. aegypti* was highly concentrated in specific neighborhoods where such artificial containers were abundant (Wilke et al., 2019). These man-made habitats often lack natural predators and provide stable microclimates favorable for larval development. The spatial clustering of these breeding sites within urban landscapes highlights the importance of targeted source reduction strategies.

Artificial habitats vary widely in their physical characteristics but generally share features such as small volume, intermittent water availability, and proximity to human dwellings. Studies from semi-urban Dhaka revealed that chemical oxygen demand and dissolved oxygen levels influenced the abundance of Culex larvae in drainage ditches and other urban water bodies (Bashar et al., 2016). Additionally, urban microclimates characterized by higher temperatures (urban heat islands) can accelerate mosquito development rates compared to rural settings (Wilke et al., 2019). The diversity of artificial habitats supports multiple mosquito species simultaneously; however, *Ae. aegypti* tends to dominate container habitats while Culex species are more common in larger drainage systems or polluted waters (Wilke et al., 2019; Bashar et al., 2016). Effective control requires understanding the heterogeneity of these anthropogenic environments.

4.3 Physicochemical properties of habitats

The physicochemical environment within mosquito larval habitats significantly affects species presence, abundance, and developmental success. Key parameters include water temperature, pH, electrical conductivity (EC), total dissolved solids (TDS), turbidity, dissolved oxygen (DO), alkalinity, chloride content, and light exposure. For instance, studies from West Azerbaijan Province in Iran reported significant interspecific differences in chloride content and temperature preferences among mosquito larvae but no significant variation regarding pH or turbidity (Amini et al., 2020). Similarly, research along the Mara River basin found strong correlations between larval abundance and DO levels as well as temperature and turbidity (Dida et al., 2018).

Light exposure influences habitat suitability by affecting algal growth and predator presence; shaded or partially shaded sites often harbor different mosquito assemblages than open sunlit pools. Water temperature typically ranges between 25°C to 29°C in productive tropical habitats such as those used by *Anopheles funestus* (Nambunga et al., 2020), with warmer temperatures generally accelerating larval development but potentially increasing mortality if too high. Electrical conductivity and TDS reflect mineral content which can affect larval survival differently across species; some Culex mosquitoes tolerate higher salinity levels while others prefer fresher waters (Wang et al., 2020; Martínez-Barciela et al., 2025). Overall, the complex interplay of these physicochemical factors shapes habitat quality and determines which mosquito species can successfully exploit particular aquatic environments (Figure 3).

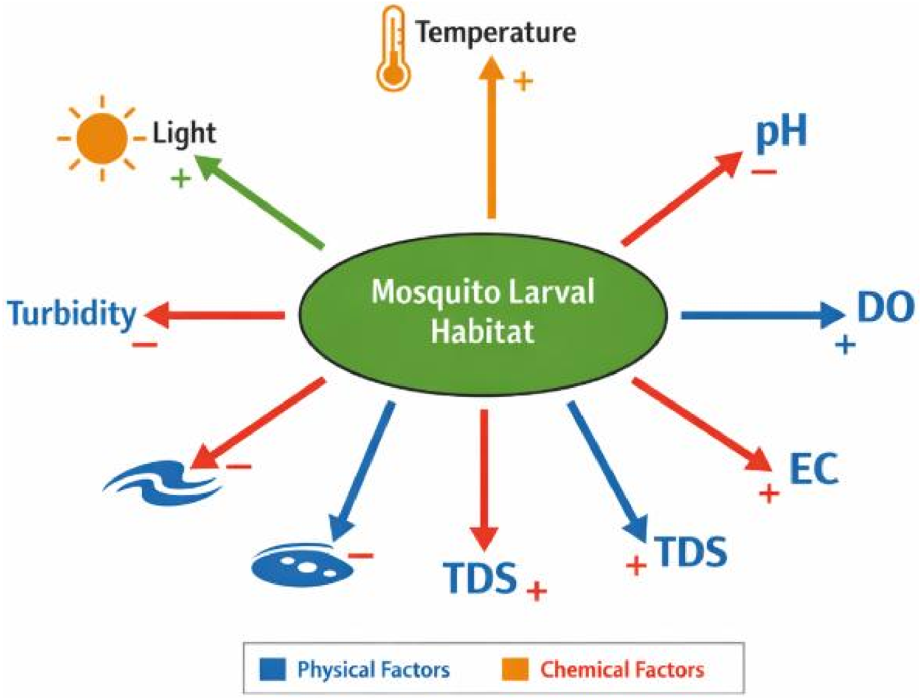

Figure 3 Conceptual diagram illustrating the influence of physicochemical parameters on mosquito larval habitat suitability and species distribution. Arrows indicate the direction and relative strength of influence of each environmental factor

5 Driving Mechanisms of Environmental Factors on Populations and Habitats

5.1 Relationships between climatic factors and mosquito life cycles

Climatic factors such as temperature, rainfall, humidity, and photoperiod play critical roles in regulating mosquito life cycles by influencing development rates, survival, reproduction, and behavior. Temperature affects the speed of larval development and adult activity; warmer conditions generally accelerate growth but can increase mortality if exceeding species-specific thresholds. For example, accumulated rainfall in the weeks preceding sampling strongly correlates with increased mosquito abundance by creating suitable aquatic habitats for larvae, while diurnal temperature range influences species like *Culex quinquefasciatus* and *Aedes aegypti* differently (García-Súarez et al., 2024). Additionally, humidity modulates host-seeking and oviposition behaviors, with higher humidity enhancing adult survival and feeding activity (Meuti, 2025). Photoperiod cues induce diapause or arrested development in temperate mosquitoes to survive unfavorable seasons, though tropical species may respond differently due to less pronounced seasonal changes (Meuti, 2025).

Interactions among these climatic variables create complex temporal patterns in mosquito populations. Nonlinear relationships have been observed where extremely high temperatures reduce abundance despite otherwise favorable conditions (Ferraguti et al., 2024). Rainfall not only provides breeding sites but also interacts with urban environmental factors to influence local mosquito distributions (Wouters et al., 2024). Seasonal peaks in mosquito populations often coincide with periods of optimal temperature and sufficient precipitation, but these patterns vary by species and location. Understanding these multifactorial climatic influences is essential for predicting population dynamics under changing climate scenarios and for timing vector control interventions effectively (Blanco-Sierra et al., 2024; García-Súarez et al., 2024).

5.2 Impacts of human activities on habitat formation

Human activities profoundly shape mosquito habitats by altering land use, water management, and urban infrastructure. Urbanization creates artificial breeding sites such as water containers, drainage systems, and abandoned infrastructure that support container-breeding species like *Aedes aegypti* and *Aedes albopictus* (Little et al., 2017; Wouters et al., 2024). Studies show that infrastructural decay combined with vegetation presence increases mosquito abundance in urban neighborhoods; abandoned blocks with more vegetation harbor larger populations due to increased habitat availability (Little et al., 2017). Moreover, impervious surfaces associated with urbanization influence microclimates by increasing temperatures (urban heat islands) which can accelerate mosquito development rates (García-Súarez et al., 2024; Vandergiessen et al., 2025).

Anthropogenic stressors such as eutrophication and salinization of water bodies also affect mosquito population parameters by modifying survival rates, development times, and reproductive behaviors. Experiments demonstrate that increased nutrient pollution enhances larval survival and egg-laying behavior while salinity negatively impacts survival at higher temperatures (Boerlijst et al., 2022). These human-induced environmental changes often interact synergistically with climatic factors to promote mosquito proliferation. Consequently, human-driven habitat modifications are key drivers of spatial heterogeneity in mosquito populations and must be integrated into vector control strategies to address disease risks effectively (Little et al., 2017; Boerlijst et al., 2022).

5.3 Biological factors

Biological interactions including predation and interspecific competition significantly influence mosquito population dynamics within their habitats. Predators such as fish, aquatic insects, and other invertebrates regulate larval densities by consuming immature stages, thereby affecting overall population size and species composition. The presence or absence of natural predators varies across habitat types; artificial containers often lack predators compared to natural water bodies, allowing some species like *Aedes aegypti* to thrive in urban environments (Wouters et al., 2024). Interspecific competition among co-occurring mosquito species can lead to niche partitioning or competitive exclusion depending on resource availability and environmental conditions.

These biological factors interact with environmental variables to shape community structure; for instance, habitat heterogeneity created by human activities may alter predator-prey dynamics or competitive relationships among mosquitoes (Vandergiessen et al., 2025). Sugar feeding behavior influenced by vegetation availability also affects adult fitness and population persistence across landscapes differing in ecological complexity (Vandergiessen et al., 2025). Understanding these biotic mechanisms alongside abiotic drivers is crucial for developing comprehensive models of mosquito ecology that inform targeted control measures addressing both environmental management and biological regulation.

6 Research Methods and Data Analysis Techniques

6.1 Mosquito sampling and monitoring methods

Mosquito sampling methods vary widely depending on the target life stage and species behavior, with adult trapping and larval surveys being the most common approaches. Adult mosquito collection often employs traps such as BG-Sentinel II (BGS), BG Gravid Traps (GAT), and sweep netting, each with distinct advantages. A multi-country study in Pacific Island nations found BGS traps to be the most effective in capturing a higher number of mosquitoes without significant species bias, making them suitable for routine surveillance in diverse tropical settings (Craig et al., 2025). Larval surveys complement adult trapping by identifying breeding sites through dipping or direct collection from aquatic habitats, providing critical data on immature stages that inform control strategies (Becker et al., 2010). Combining multiple sampling methods targeting different mosquito behaviors enhances surveillance comprehensiveness and reduces bias inherent in single-method approaches (Van De Straat et al., 2021).

Operational feasibility is a key consideration in selecting sampling techniques, especially in resource-limited or remote tropical environments. Simpler, durable tools that require minimal maintenance are preferred for sustained monitoring programs (Craig et al., 2025). Passive surveillance methods, including community-based reporting and citizen science initiatives, have gained traction as cost-effective supplements to active trapping by expanding spatial coverage and enabling early detection of invasive species (Kampen et al., 2015). Additionally, behavioral monitoring technologies such as high-resolution video tracking and AI-driven analysis offer promising avenues for detailed studies of mosquito activity patterns but remain underutilized in field surveillance (Javed et al., 2024). Overall, integrating diverse sampling tools tailored to local ecological contexts improves data quality for vector management.

6.2 Statistical and modeling approaches for data analysis

Analyzing mosquito population data requires robust statistical and modeling techniques to accurately estimate abundance, species composition, and temporal trends while managing large sample sizes efficiently. Subsampling methods have been developed to reduce labor-intensive processing of large mosquito collections without compromising accuracy. For instance, area-based subsampling of 20% of specimens provides reliable estimates of total numbers and dominant species proportions with acceptable error margins (~12% for specimen counts) (Jaworski et al., 2019). Image processing software like ImageJ has also demonstrated resilience and precision in digitized optical counting across varying sample conditions, offering an efficient alternative to manual enumeration (Faraji et al., 2025). These approaches enable timely decision-making critical for vector control interventions.

Modeling frameworks often incorporate generalized linear mixed models (GLMMs) to account for spatial-temporal variability and hierarchical data structures inherent in mosquito surveillance datasets (Craig et al., 2025). Multimethod sampling designs facilitate more comprehensive models by capturing diverse vector behaviors influencing disease transmission risk (Van De Straat et al., 2021). Advanced statistical analyses also support molecular xenomonitoring efforts by evaluating how different collection strategies affect parasite detection rates within mosquito populations (Reimer and Pryce, 2023). Integrating these quantitative tools with ecological knowledge enhances predictive capacity regarding population dynamics under changing environmental conditions. Thus, combining subsampling efficiency with sophisticated modeling strengthens entomological research outcomes.

6.3 Applications of remote sensing and GIS in habitat analysis

Remote sensing (RS) and geographic information systems (GIS) have revolutionized habitat analysis by enabling large-scale mapping and monitoring of environmental variables relevant to mosquito ecology. High-resolution satellite imagery facilitates identification of potential breeding sites such as water bodies, vegetation cover, and urban infrastructure features that influence habitat suitability (Javed et al., 2024). GIS platforms integrate spatial data layers including climate variables, land use patterns, and vector occurrence records to model habitat distribution and predict hotspots for targeted interventions. These technologies enhance understanding of landscape-level drivers shaping mosquito populations beyond localized field surveys.

Emerging applications combine RS/GIS with behavioral monitoring tools to provide dynamic assessments of vector activity patterns over time (Javed et al., 2024). This integration supports adaptive management by allowing real-time evaluation of control measures' effectiveness across heterogeneous environments. Moreover, spatial analyses assist in stratifying risk areas based on environmental correlates derived from remotely sensed data, improving resource allocation efficiency (Kampen et al., 2015). Despite their potential, challenges remain regarding data resolution limitations and the need for ground-truthing to validate remote observations. Nonetheless, RS and GIS represent indispensable components of modern entomological research frameworks aimed at controlling mosquito-borne diseases effectively.

7 Results and Discussion

7.1 Correlation analysis between seasonal dynamics and environmental variables

Seasonal dynamics of mosquito populations show strong correlations with environmental variables such as temperature, precipitation, and habitat type, which collectively influence population fluctuations over time. Studies on other taxa in aquatic and terrestrial ecosystems reveal that population densities often peak during seasons with optimal climatic conditions; for example, bird populations increased by 65% in spring compared to fall, linked to habitat composition and seasonal factors (Azizoğlu et al., 2023). Similarly, scorpion foraging activity and microhabitat colonization vary seasonally, reflecting climatic impacts on population dynamics through resource availability and refuge use (Lira et al., 2018). These patterns suggest that mosquito populations likely respond similarly to seasonal environmental changes, with temperature and rainfall driving breeding site availability and survival rates (Figure 4).

Temporal variation in habitat quality also shapes species distribution and abundance by altering resource availability across seasons. Research on waterbirds demonstrated that seasonal deterioration of habitat quality leads to weakened distribution-abundance relationships later in the summer due to habitat homogenization (Charalambous et al., 2024). Migratory species exhibit seasonal shifts in habitat selection aligned with life-history stages, indicating that spatial distribution is dynamic and influenced by both local and landscape-scale environmental heterogeneity (Stanley et al., 2021). These findings underscore the importance of incorporating multiple environmental variables and temporal scales when analyzing mosquito seasonal dynamics to capture complex ecological responses accurately.

7.2 Relationships between habitat characteristics and population distribution

Habitat characteristics such as vegetation structure, water availability, and human disturbance strongly influence mosquito population distribution by affecting breeding site suitability and resource access. Studies on diverse taxa highlight that species richness and functional diversity differ between wet and dry habitats due to microhabitat preferences; for instance, scorpions showed higher functional richness in wet forests compared to semiarid areas, reflecting habitat-driven spatial segregation (Lira et al., 2018). Similarly, waterfowl populations varied significantly among habitats like open water surfaces versus reed beds, indicating that specific habitat types support different population densities (Azizoğlu et al., 2023). These patterns imply that mosquito species distributions are closely tied to fine-scale habitat features that determine larval development success and adult survival.

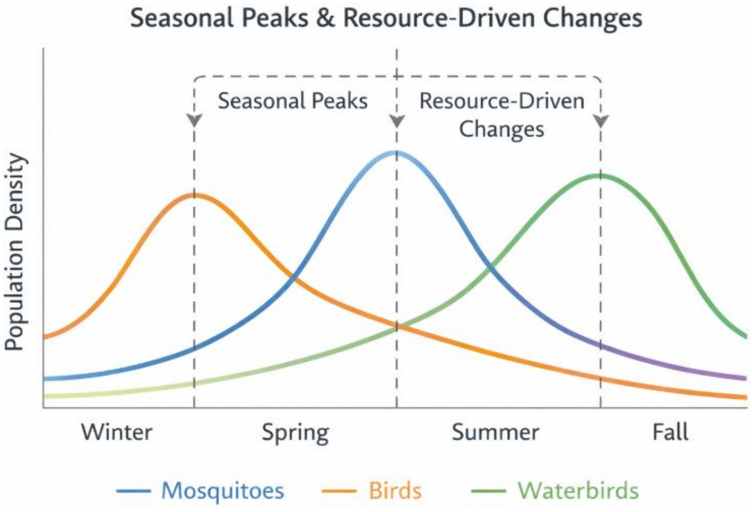

Figure 4 Comparative illustration of seasonal population dynamics across taxa, highlighting shared responses to environmental variability and resource availability

Human-modified landscapes further complicate these relationships by creating novel or altered habitats that can either promote or restrict mosquito proliferation. For example, urbanization often increases container habitats favorable for Aedes mosquitoes but may reduce natural breeding sites preferred by other species (Xu et al., 2024). Habitat fragmentation influences migratory bird distributions seasonally by modifying landscape composition, which may analogously affect mosquito dispersal and local abundance (Stanley et al., 2021). Understanding how natural habitat heterogeneity interacts with anthropogenic changes is essential for predicting spatial patterns of mosquito populations across tropical environments.

7.3 Comparison with existing studies and interpretation of differences

Comparisons with existing ecological studies reveal both consistencies and divergences in how seasonal dynamics relate to environmental drivers across taxa. While many species exhibit clear seasonal peaks linked to climatic variables such as temperature and precipitation (Azizoğlu et al., 2023; Lira et al., 2018), the magnitude and timing of these peaks vary depending on life-history traits and regional conditions. For instance, migratory birds show complex habitat selection patterns influenced by breeding stage and landscape fragmentation not always paralleled in resident insect populations (Stanley et al., 2021). Differences may also arise from methodological approaches; some studies emphasize classical regression models while others advocate for more descriptive or predictive analytical methods to capture nonlinear or interactive effects better (Azizoğlu et al., 2023).

Discrepancies in observed patterns can result from varying spatial scales, taxonomic focus, or environmental contexts. For example, waterbird assemblages demonstrated a weakening of distribution-abundance relationships due to seasonal habitat degradation not universally reported in other groups (Charalambous et al., 2024). Additionally, climate change projections indicate potential shifts in species distributions over time that may alter established seasonal dynamics (Xu et al., 2024). These nuances highlight the need for integrative frameworks combining field data with advanced modeling techniques to interpret complex ecological processes governing mosquito populations effectively.

8 Control Strategies and Public Health Implications

Optimizing the timing of mosquito control interventions by aligning them with seasonal population dynamics can significantly enhance their effectiveness. Seasonal fluctuations in vector abundance, driven by environmental factors such as temperature and rainfall, influence disease transmission risk and thus the optimal periods for intervention. For example, modeling studies on vector-borne diseases demonstrate that applying control measures during peak vector growth phases or just before population surges can reduce disease burden more effectively than untimed efforts. However, reliance solely on rainfall as a predictor for timing may be insufficient, as some vectors show peak activity patterns poorly correlated with precipitation but more closely linked to temperature and land use. Therefore, integrating local entomological surveillance data with environmental monitoring is critical to identify precise windows for intervention. Mathematical models incorporating seasonality and time-dependent control parameters have been used to determine optimal strategies combining insecticide spraying and environmental decontamination. These studies reveal that while insecticide application alone may not fully eliminate vector populations, combining it with habitat management yields significantly better outcomes. Similarly, pest management research highlights that targeting specific life stages or age groups during vulnerable seasonal periods maximizes population suppression. Early-season interventions often reduce reproductive potential and seedbank densities in invasive species control, suggesting analogous benefits in mosquito management by preempting population buildup. Overall, adaptive timing of control efforts informed by seasonal dynamics enhances resource efficiency and public health impact.

Habitat management through environmental modification plays a crucial role in reducing mosquito breeding sites and interrupting transmission cycles. Environmental interventions such as removal of standing water, vegetation management, and sanitation reduce larval habitats and adult resting sites, thereby lowering vector densities. Studies emphasize that environmental decontamination can be more effective than insecticide spraying alone when integrated into control programs. Additionally, managing invasive plant species or modifying landscape features influences habitat suitability for mosquitoes by altering microclimatic conditions and resource availability. Such habitat-focused strategies complement chemical controls by addressing underlying ecological drivers of mosquito proliferation. The success of habitat management depends on understanding spatial heterogeneity and temporal changes in breeding site distribution. Remote sensing and GIS tools facilitate identification of high-risk habitats for targeted interventions, while community engagement enhances sustainability of environmental measures. Moreover, combining biological controls such as natural predators or parasitoids with habitat modification offers promising integrated pest management approaches that reduce reliance on chemicals. However, challenges remain in balancing effective habitat alteration with conservation goals and minimizing impacts on non-target species. Thus, environmentally based interventions require careful planning tailored to local ecological contexts to optimize public health benefits.

Effective mosquito control informed by seasonal dynamics and habitat characteristics has direct implications for reducing the burden of mosquito-borne diseases in tropical regions where transmission is often intense year-round but fluctuates seasonally. Timing interventions to coincide with periods preceding population peaks can lower infection rates more efficiently than random or calendar-based schedules (Huang et al., 2020; Morreale et al., 2024). This approach is particularly important in urbanizing tropical areas where land use changes alter vector ecology unpredictably. Integrating entomological surveillance data into disease models improves prediction accuracy for outbreak risk and guides resource allocation. Furthermore, combining chemical controls with environmental management addresses both adult vectors and immature stages, enhancing overall program efficacy while mitigating insecticide resistance development. Public health strategies must also consider socio-economic factors influencing community participation in habitat reduction efforts to ensure sustained impact. Advances in modeling optimal control strategies incorporating human behavior and vector ecology provide frameworks for designing cost-effective interventions adapted to local conditions. Ultimately, leveraging knowledge of seasonal mosquito dynamics alongside habitat management strengthens integrated vector management programs critical for controlling tropical diseases such as malaria, dengue, chikungunya, and Zika.

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Conflict of Interest Disclosure

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