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Population Dynamics and Seasonal Distribution of Mosquitoes

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Abstract This study synthesizes findings from various studies to elucidate the factors influencing mosquito population dynamics and their seasonal variations, highlights the significant role of environmental factors such as temperature, rainfall, and urbanization in shaping mosquito populations, and underscores the impact of socioeconomic status on mosquito distribution in urban areas. The integration of mathematical models and empirical data provides insights into the density-dependent and density-independent processes affecting mosquito seasonality. Additionally, this study discusses the implications of diapause and other survival mechanisms on mosquito population growth. The findings emphasize the need for targeted vector control measures that consider the complex interplay of ecological and social-environmental factors.
Keywords Mosquito population dynamics; Seasonal distribution; Environmental factors; Socioeconomic status; Vector control

1 Introduction

Mosquitoes, belonging to the family *Culicidae*, are ubiquitous insects found in diverse habitats worldwide. Their population dynamics and seasonal distribution are influenced by a complex interplay of biotic and abiotic factors. For instance, in the Brazilian semiarid region, the abundance of both immature and adult mosquitoes is significantly affected by temperature and wind, with specific genera showing varying correlations with these meteorological variables (Silva-Inácio and Ximenes, 2023). Similarly, in the UK, the seasonal abundance of *Culex pipiens* is shaped by interspecific predation and temperature-dependent larval mortality, highlighting the importance of density-independent factors in population regulation (Ewing et al., 2019). In Northern Greece, different mosquito species exhibit distinct seasonal patterns, with *Aedes* species appearing first in late March, followed by *Culex* and *Anopheles* species later in the year (Spanoudis et al., 2021). These patterns underscore the need for high-resolution data to accurately model and predict mosquito population trends, which are crucial for understanding vector dynamics and disease transmission (Ewing et al., 2019).

Studying mosquito population trends is vital for public health and vector control efforts, as mosquitoes are primary vectors for numerous diseases, including malaria, dengue, Zika, and West Nile virus. In urban environments in the USA, socioeconomic status and environmental traits significantly influence mosquito distributions, with lower-income neighborhoods experiencing higher mosquito densities and associated disease risks (Yitbarek et al., 2023). This highlights the need for targeted vector control strategies in vulnerable communities. Additionally, understanding the seasonal dynamics of mosquito populations can inform the timing and intensity of control measures. For example, in the Brazilian Amazon, mosquito species richness and abundance are higher during the rainy season, suggesting increased vector activity and potential disease transmission during this period (Araújo et al., 2020). Effective vector control requires integrating empirical data with process-based models to predict mosquito abundance and distribution accurately, as demonstrated in studies on *Aedes albopictus* in Reunion Island (Tran et al., 2020). Such integrated approaches can enhance disease surveillance and control systems, ultimately reducing the burden of mosquito-borne diseases.

This study seeks to synthesize current knowledge on the population dynamics and seasonal distribution of mosquitoes across different geographic regions and environmental contexts, identify key biotic and abiotic factors influencing mosquito abundance and distribution, evaluate the implications of mosquito population trends for public health and vector control strategies, and provide recommendations for future research and integrated vector management approaches to mitigate the impact of mosquito-borne diseases, thereby contributing to a comprehensive understanding of mosquito ecology and informing more effective public health interventions.

2 Factors Influencing Mosquito Population Dynamics

2.1 Environmental factors (temperature, humidity, rainfall)

Environmental factors such as temperature, humidity, and rainfall play a crucial role in shaping mosquito population dynamics. Temperature influences the life cycle duration and reproductive rates of mosquitoes, with higher temperatures generally accelerating development and increasing reproductive rates (Figure 1) (Masimalai, 2021; Brown et al., 2023). However, extreme temperatures can negatively impact mosquito survival and activity (Kirik et al., 2021). Humidity is another critical factor, often overlooked, that affects mosquito desiccation rates and overall fitness. High humidity levels can enhance mosquito survival and activity, while low humidity can lead to increased mortality (Asigau and Parker, 2018; Brown et al., 2023). Rainfall contributes to the availability of breeding sites, as many mosquito species lay their eggs in standing water. However, the relationship between rainfall and mosquito abundance is complex and can vary by species and location. Some studies have shown that mosquito populations can thrive even with minimal rainfall, provided there are other sources of standing water (Brugueras et al., 2020; Whittaker et al., 2021).

2.2 Biological factors (reproductive rates, life cycle duration)

Biological factors such as reproductive rates and life cycle duration are intrinsic to mosquito population dynamics. The reproductive rate of mosquitoes is influenced by environmental conditions, with optimal temperatures and humidity levels leading to higher reproductive success (Masimalai, 2021; Brown et al., 2023). The life cycle duration of mosquitoes, from egg to adult, is also temperature-dependent. Warmer temperatures generally shorten the development time, allowing for more generations to occur within a given period (Traoré et al., 2020; Masimalai, 2021). Additionally, density-dependent factors such as competition for resources and predation can influence mosquito population dynamics. For instance, interspecific predation on mosquito larvae and competition for resources can significantly impact larval survival rates and, consequently, adult mosquito abundance (Ewing et al., 2019).

2.3 Human activity and land use (urbanization, agricultural practices)

Human activities and land use changes, such as urbanization and agricultural practices, significantly influence mosquito population dynamics. Urbanization creates unique habitats with varying levels of vegetation, standing water, and concrete structures, all of which can affect mosquito abundance and distribution (Kirik et al., 2021). Lower-income urban neighborhoods often have higher mosquito densities due to factors such as inadequate sewage systems, garbage dumps, and abandoned buildings, which provide ideal breeding sites (Yitbarek et al., 2023). Agricultural practices, particularly those involving irrigation, can also create favorable conditions for mosquito breeding. For example, wet rice cultivation provides extensive standing water habitats that support high mosquito densities (Masimalai, 2021).

2.4 Interaction with predators and competitors

Interactions with predators and competitors are important biotic factors that influence mosquito population dynamics. Predation on mosquito larvae by other aquatic organisms can significantly reduce mosquito populations. For instance, interspecific predation has been identified as a major source of larval mortality in some mosquito species. Additionally, competition for resources among mosquito larvae can affect survival rates and development times. In environments with high larval densities, competition for food and space can lead to increased mortality and slower development (Ewing et al., 2019). Understanding these interactions is crucial for developing effective mosquito control strategies, as they can inform the use of biological control agents and habitat management practices to reduce mosquito populations.

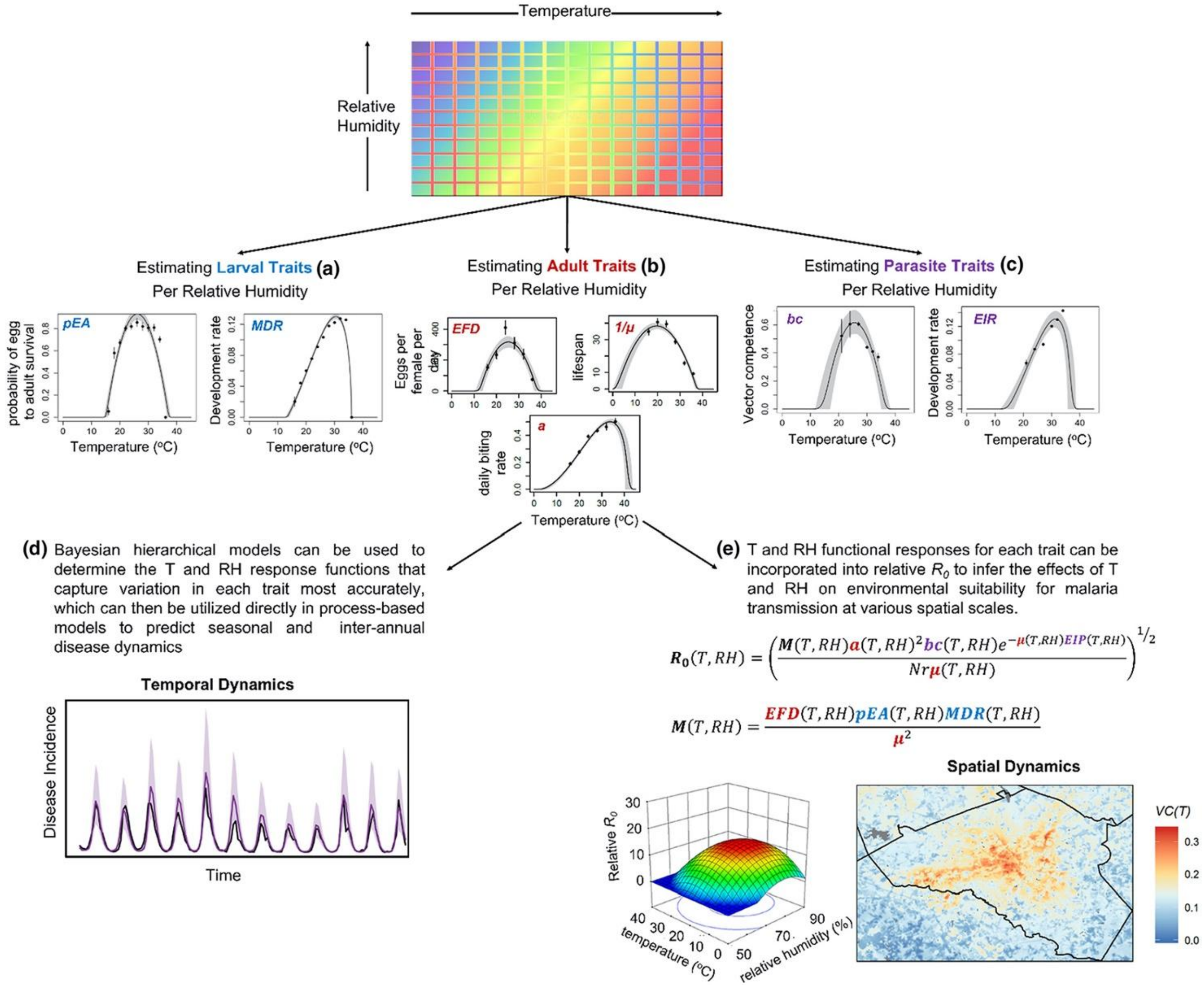

Figure 1 Laboratory work with field derived mosquitoes can be conducted to estimate the effect of multiple environmental variables on mosquito fitness, population dynamics and pathogen transmission (Adopted from Brown et al., 2023)

Image caption: For example, mosquitoes could be housed across a range of constant temperature (*T*) and relative humidity (*RH*) conditions that are reflective of monthly field conditions. From these experiments, one can estimate the effects of variation in these environmental variables on key *larval traits* (a: mosquito development rate (*MDR*) and the probability of egg to adult survival (*pEA*)), *adult traits* (b: per capita mortality rate (μ), per capita eggs laid per day (*EFD*) and per capita daily biting rate (*a*)) and *parasite / pathogen traits* (c: vector competence (*bc*) and the extrinsic incubation period (*EIP*)). (d) Bayesian hierarchical models can be used to develop *T* and *RH*response surfaces for each trait, which can either be incorporated in process-based modelling approaches to infer effects on seasonal and interannual variation in vector-borne pathogen transmission dynamics. (e) Bayesian models can also be used to generate a *T* and *RH* dependent, relative R_0 model that can be used to predict environmental suitability for pathogen transmission at various spatial scales. A crucial detail for modelling approaches, based on the evidence presented in Box 2, is that the effects of *T* and *RH* will be interactive, not additive (Adopted from Brown et al., 2023)

3 Seasonal Distribution of Mosquito Species

3.1 Overview of seasonal patterns across different geographic regions

Mosquito populations exhibit distinct seasonal patterns that vary significantly across different geographic regions. In Northern Europe, for instance, a study conducted in Estonia found that mosquito abundance decreased with higher temperatures and wind speeds, with the *Culex pipiens*/*Culex torrentium* group being consistently abundant towards the end of the warm season (Kirik et al., 2021). In contrast, in the West Indies, mosquito species such as *Aedes aegypti* and *Culex quinquefasciatus* showed high seasonality in their abundances, with variations influenced by land cover and precipitation (Valentine et al., 2020). Similarly, in the Sudano-Sahelian belt of Burkina Faso, mosquito abundance peaked during the rainy season, with significant variations in species composition between villages (Epopa et al., 2019). In Switzerland, mosquito populations were found to be more abundant in natural zones compared to suburban areas, with species like *Aedes vexans* and *Culex pipiens*/*torrentium* showing season-dependent abundances (Wagner et al., 2018).

3.2 Effects of climate and weather variability on mosquito abundance

Climate and weather variability play crucial roles in determining mosquito abundance. In Estonia, higher temperatures and wind speeds were negatively correlated with mosquito numbers, while springtime hydrological conditions greatly influenced the mosquito season (Kirik et al., 2021). In St. Kitts, the extent to which monthly average precipitation influenced mosquito counts varied according to species, with some species being less responsive to seasonal variation in precipitation (Valentine et al., 2020). In Burkina Faso, mosquito abundance and malaria transmission dynamics were closely linked to seasonal rainfall variations, with the highest mosquito abundances occurring during the rainy season (Epopa et al., 2019). In the UK, a study on *Culex pipiens* highlighted that density-independent mortality and interspecific predation, along with temperature-dependent larval mortality, were key factors shaping seasonal abundance patterns (Ewing et al., 2019). Additionally, in the Republic of Korea, specific temperature ranges were identified for the peak abundance of various mosquito species, emphasizing the importance of temperature in mosquito population dynamics (Hwang et al., 2020).

3.3 Seasonal changes in mosquito species composition

Seasonal changes in mosquito species composition are evident across different regions. In Estonia, while *Culex pipiens*/*Culex torrentium* remained the most abundant throughout the study period, other dominant species varied considerably between months and years (Kirik et al., 2021). In St. Kitts, the relative abundance of species such as *Aedes taeniorhynchus* and *Culex quinquefasciatus* varied with season and land cover, with mangroves yielding the most mosquitoes (Valentine et al., 2020). In Burkina Faso, the principal malaria vectors were in the *Anopheles gambiae* complex, with species composition varying between villages and peaking during the rainy season (Epopa et al., 2019). In São Paulo, Brazil, *Aedes aegypti* and *Aedes albopictus* showed significant seasonal variation, with *Ae. albopictus* being more abundant in spring compared to autumn, and their distribution being influenced by temperature and rainfall (Heinisch et al., 2019). In the Arctic, *Aedes nigripes* exhibited spatial and temporal patterns in abundance, with daily variation in mosquito captures primarily explained by weather conditions (DeSiervo et al., 2022).

4 Impacts of Climate Change on Mosquito Populations

4.1 Influence of global warming on mosquito range expansion

Global warming significantly influences the geographic range of mosquito populations, leading to the expansion of mosquito-borne diseases into new areas. For instance, rising global temperatures are predicted to increase the climatic suitability for malaria and dengue, particularly in tropical highlands and lowlands, respectively. This expansion is expected to affect temperate regions where populations may be immunologically naive and public health systems unprepared (Colón-González et al., 2021). Additionally, the potential for adaptive evolution in mosquitoes, such as *Aedes aegypti*, suggests that these species may persist and thrive under changing climatic conditions, further facilitating their range expansion (Couper et al., 2021). Studies have also shown that climate change will likely lead to the northward expansion of mosquito species like *Culex pipiens pallens* and *Culex pipiens quinquefasciatus* in China, increasing the risk of vector-borne diseases in these newly affected areas (Liu et al., 2020).

4.2 Shifts in breeding season timing and duration

Climate change, particularly global warming, alters the timing and duration of mosquito breeding seasons. Warmer temperatures can extend the breeding season, increasing the number of generations per year and thus the overall mosquito population. For example, the length of the transmission season for malaria and dengue is projected to increase by several months in various regions, including tropical highlands and lowlands (Colón-González et al., 2021). Furthermore, extreme climate events such as abnormal rainfall and temperature fluctuations can significantly impact mosquito abundance. In Kenya, periods of abnormal rainfall were found to increase mosquito populations, suggesting that climate variability can lead to more frequent and intense breeding seasons (Nosrat et al., 2021). These shifts in breeding patterns are critical for understanding and predicting mosquito population dynamics and the associated risks of disease transmission.

4.3 Implications for disease transmission cycles

The expansion of mosquito populations and shifts in breeding seasons due to climate change have profound implications for disease transmission cycles. Increased mosquito abundance and extended transmission seasons enhance the potential for outbreaks of mosquito-borne diseases such as malaria, dengue, chikungunya, and Zika. For instance, the predicted increase in the population at risk of malaria and dengue due to climate change highlights the potential for more widespread and severe outbreaks (Colón-González et al., 2021). Additionally, the adaptation of mosquitoes to higher temperatures can influence the dynamics of disease transmission. In Northern Brazil, the thermal adaptation of *Aedes aegypti* was shown to affect the transmission of dengue virus, indicating that climate adaptation can alter disease dynamics (Couper et al., 2021). Moreover, the interaction between local and global climate drivers, such as temperature and the El Niño–Southern Oscillation, plays a crucial role in the seasonality and interannual variability of mosquito-borne disease incidence, further complicating the prediction and management of these diseases (Cazelles et al., 2023).

5 Case Study

5.1 Case study location and species focus

The case study focuses on Hainan Island, China, where the mosquito population dynamics and seasonal distribution were analyzed. The primary species of interest include *Culex quinquefasciatus*, *Armigeres subalbatus*, and *Anopheles sinensis*, which were the most prevalent species collected using different trapping methods (Li et al., 2020).

5.2 Data collection approaches and period

Data collection was conducted from January to December 2018 across five different ecological settings on Hainan Island. The methods used included BG Sentinel (BGS) traps and Centers for Disease Prevention and Control (CDC) light traps. Each site included urban, suburban, and rural areas, with 18 trap-days sampled in each setting. Both BGS and CDC traps were set up simultaneously to capture a comprehensive dataset of mosquito species composition, distribution, and population dynamics (Li et al., 2020).

5.3 Analysis of population dynamics and seasonal distribution in the case study area

The analysis revealed that nine mosquito species belonging to four genera were identified. The population dynamics showed clear seasonal variations, with different peak seasons for various species. For instance, Culex quinquefasciatus was the most abundant species, showing significant seasonal peaks. The study also highlighted spatial heterogeneity, with mosquito abundance varying significantly among different study sites and between urban, suburban, and rural areas. Danzhou had the highest mosquito biodiversity, indicating a strong influence of the natural environment on mosquito population dynamics (Li et al., 2020).

5.4 Comparison with other regions or species

Comparing the findings from Hainan Island with other regions, similar studies have shown that mosquito population dynamics and seasonal distribution are influenced by various environmental factors. For example, in mainland India, a novel statistical framework revealed pronounced variation in mosquito dynamics across different locations and species, driven by factors such as rainfall, temperature, and land use patterns (Figure 2) (Whittaker et al., 2022). In Switzerland, mosquito abundances and seasonality were also found to be site-dependent, with higher abundances in natural zones compared to suburban areas (Wagner et al., 2018). Additionally, in Procida Island, Italy, the seasonal distribution of *Aedes albopictus* was studied, showing high population densities from April to October, influenced by both urban and sylvatic environments (Caputo et al., 2021). These comparisons underscore the importance of local environmental conditions in shaping mosquito population dynamics and highlight the need for region-specific mosquito control strategies.

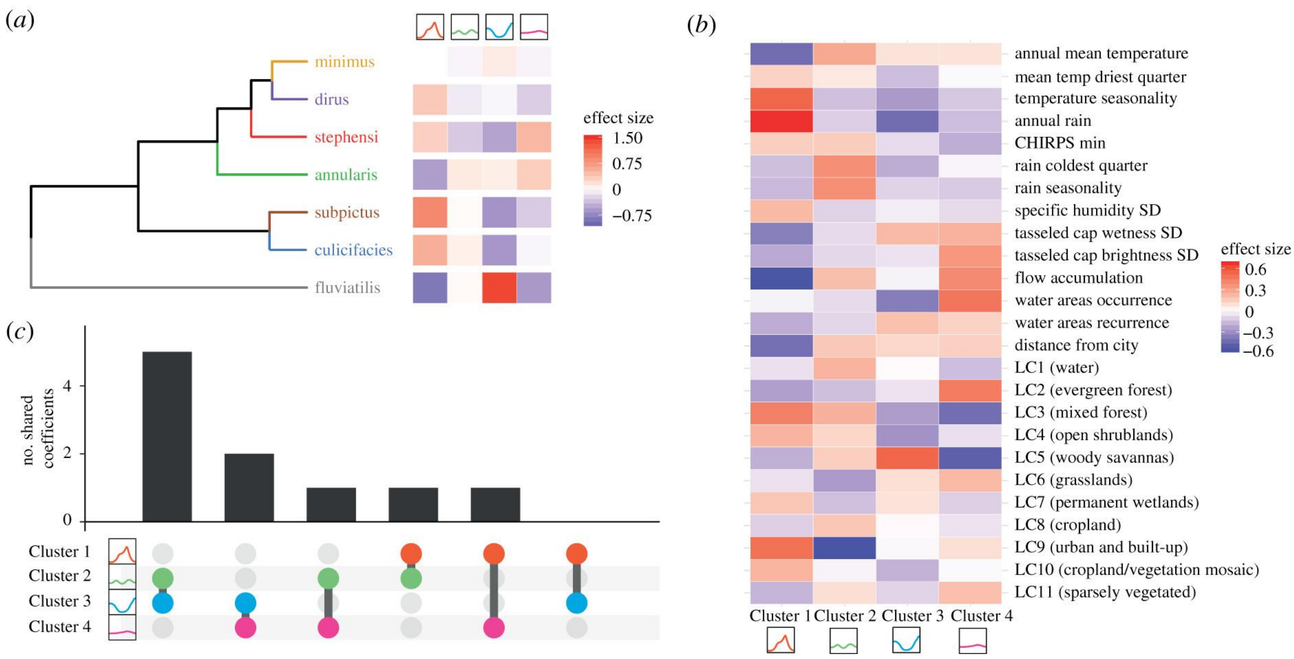

Figure 2 Exploring drivers of mosquito population dynamics using multinomial logistic regression (Adopted from Whittaker et al., 2022)

Image caption: (*a*) Hierarchical clustering of the regression results for each species complex, as defined by the set of coefficient values describing the strength of the association between that species complex and the particular cluster. (*b*) The strength of the association between each of the 25 environmental covariates used and the relevant temporal cluster. (*c*) Upset plot summarizing the top 15 environmental variable coefficients associated with each cluster. The *x*-axis indicates the specific pairwise cluster comparison, *y*-axis the number of shared top 15 covariates between the two clusters (Adopted from Whittaker et al., 2022)

Whittaker et al. (2022) explores mosquito population dynamics by modeling the associations between species complexes and environmental factors using multinomial logistic regression. It highlights distinct temporal patterns among mosquito species, with some species aligning more with seasonal peaks (e.g., monsoon-driven dynamics) while others exhibit perennial trends. Environmental variables, such as temperature, rainfall, and land cover, significantly influence these temporal clusters, suggesting that mosquito population trends are shaped by a combination of abiotic and biotic factors. The study's findings underscore the variability in mosquito species' responses to ecological conditions, emphasizing the importance of incorporating diverse environmental drivers into vector control strategies to effectively address the complex nature of mosquito ecology and mitigate the spread of mosquito-borne diseases.

6 Current Strategies for Monitoring Mosquito Populations

6.1 Traditional monitoring techniques

Traditional methods for monitoring mosquito populations primarily include trapping and larval surveys. Trapping methods, such as Pyrethroid Spray Catches (PSC) and Human Landing Catches (HLC), are widely used to collect adult mosquitoes. These methods help in identifying mosquito species and understanding their seasonal dynamics and behavior (Epopa et al., 2019; 2020). Larval surveys, which involve manual collection techniques like 'dipping' for larvae, are essential for assessing breeding site abundance and mosquito population composition (Odero et al., 2018; Boerlijst et al., 2019). These traditional techniques, while effective, are labor-intensive and require significant taxonomic expertise (Boerlijst et al., 2019).

6.2 Advances in molecular and remote-sensing tools

Recent advancements in molecular and remote-sensing tools have significantly enhanced mosquito monitoring capabilities. Environmental DNA (eDNA) analysis has emerged as a reliable method for detecting and quantifying mosquito larvae in various aquatic habitats. This technique allows for the identification of mosquito species at early developmental stages, which are often difficult to distinguish morphologically (Odero et al., 2018).

Additionally, metabarcoding of bulk samples has been shown to provide rapid and accurate monitoring of both adult and immature mosquitoes, offering substantial improvements in terms of practicality, speed, and cost (Pedro et al., 2020).

Remote-sensing technologies, such as drone mapping and the use of satellite data, have also been integrated into mosquito monitoring strategies. Drones equipped with high-resolution cameras can identify larval habitats in rural and hard-to-reach areas, facilitating targeted Larval Source Management (LSM) (Stanton et al., 2020; Mukabana et al., 2022). Furthermore, the application of remote-sensed environmental data, such as the Normalized Difference Vegetation Index (NDVI) and Land Surface Temperature (LST), has been used to model mosquito populations and predict their temporal and spatial patterns (Kofidou et al., 2021).

6.3 Limitations and challenges in current monitoring approaches

Despite the advancements in mosquito monitoring techniques, several limitations and challenges remain. Traditional methods, such as trapping and larval surveys, are labor-intensive and require extensive taxonomic expertise, which can limit their scalability and efficiency (Boerlijst et al., 2019). Molecular techniques, while offering high accuracy, can be more expensive and require specialized equipment and expertise (Odero et al., 2018; Boerlijst et al., 2019). Additionally, the stochasticity observed in eDNA detection suggests that this technique is best suited for monitoring habitats with high larval densities (Odero et al., 2018).

Remote-sensing tools, such as drones and satellite data, present their own set of challenges. The use of drones for larval habitat identification requires significant technical skills and processing time, which can be a barrier to their widespread adoption (Stanton et al., 2020). Moreover, integrating these technologies into existing vector control programs requires careful planning and coordination among various stakeholders (Stanton et al., 2020; Mukabana et al., 2022). Despite these challenges, the continued development and refinement of these tools hold promise for more effective and efficient mosquito monitoring and control strategies.

7 Implications for Mosquito Control and Public Health

7.1 Seasonal timing of vector control measures

The seasonal dynamics of mosquito populations are crucial for optimizing the timing of vector control measures. For instance, the study on *Aedes japonicus* in Germany highlights that applying adulticides for 30 days between late spring and early autumn can significantly reduce population density by 75% (Wieser et al., 2019). Similarly, research in Burkina Faso shows that mosquito abundance peaks during the rainy season, suggesting that vector control efforts should be intensified during this period to effectively reduce malaria transmission (Epopa et al., 2019). Additionally, the diel activity patterns of mosquitoes in urban environments indicate that the timing of adulticide applications can greatly influence their effectiveness, with 9 PM being the optimal time for such interventions in Miami-Dade and Brownsville (Wilke et al., 2022).

7.2 Predictive modeling for outbreak prevention

Predictive modeling plays a vital role in preventing mosquito-borne disease outbreaks. The integration of empirical and process-based models, as demonstrated in the study on *Aedes albopictus* in Reunion Island, allows for the development of operational tools that can predict mosquito densities and inform public health authorities (Tran et al., 2020). Furthermore, mathematical simulations examining the spatial distribution of larval mosquito control can help determine the most effective strategies for reducing human infections, emphasizing the importance of understanding local mosquito population regulation and dispersion (Schwab et al., 2019). The use of stochastic dengue models with demographic variability also provides insights into the periodic risk of disease outbreaks, highlighting the need for continuous monitoring and timely interventions (Nipa et al., 2020).

7.3 Integrating population dynamics data into public health strategies

Integrating mosquito population dynamics data into public health strategies is essential for effective vector control. The novel statistical framework developed to explore the population dynamics and seasonality of mosquito populations in India reveals that environmental factors such as rainfall, temperature, and land use significantly shape mosquito dynamics (Whittaker et al., 2022). This information can be used to tailor vector control measures to specific environmental conditions. Additionally, the study on *Culex pipiens* in the UK underscores the importance of considering both density-independent and density-dependent factors in shaping mosquito population peaks and troughs, which can inform targeted control measures (Ewing et al., 2019). The analysis of intrinsic and extrinsic drivers affecting *Culex pipiens* population dynamics in Italy further supports the need for a comprehensive understanding of environmental and climatic variables to enhance vector control efforts (Fornasiero et al., 2020).

8 Future Research Directions

8.1 Emerging technologies for mosquito population studies

Emerging technologies hold significant promise for advancing our understanding of mosquito population dynamics. For instance, the integration of high-resolution empirical data with mathematical models has been shown to improve predictions of mosquito abundance and the factors influencing their seasonal patterns (Ewing et al., 2019). Additionally, the use of machine learning techniques, such as Artificial Neural Networks (ANNs), has demonstrated potential in predicting mosquito population patterns by capturing complex, non-linear dynamics. Furthermore, leveraging Insect-Specific Viruses (ISVs) to study mosquito population structure and movement rates offers a novel approach to understanding mosquito ecology at epidemiologically relevant scales (Hollingsworth et al., 2023). These technologies can provide more accurate and comprehensive data, which is crucial for effective vector control and disease prevention strategies.

8.2 Gaps in understanding seasonal distribution patterns

Despite significant advancements, there remain gaps in our understanding of the seasonal distribution patterns of mosquitoes. One major challenge is the variability in mosquito population dynamics across different ecological settings and species. For example, studies have shown pronounced variation in mosquito dynamics and seasonality across different locations and species, influenced by environmental factors such as rainfall, temperature, and land use (Li et al., 2020; Whittaker et al., 2022). Additionally, the interaction between density-independent and density-dependent processes in shaping seasonal abundance patterns is not fully understood (Ewing et al., 2019). More research is needed to elucidate these complex interactions and to develop models that can accurately predict mosquito population peaks and troughs across diverse environments.

8.3 The role of interdisciplinary approaches in mosquito research

Interdisciplinary approaches are essential for advancing mosquito research and developing effective control strategies. Combining empirical data with process-based models, as demonstrated in studies on Aedes albopictus, can enhance our understanding of mosquito population dynamics and support the development of operational tools for vector control (Tran et al., 2020). Moreover, integrating ecological, genetic, and virological data can provide a more comprehensive understanding of mosquito feeding patterns and their implications for disease transmission (Stephenson et al., 2018). Collaborative efforts across disciplines, including entomology, epidemiology, ecology, and data science, are crucial for addressing the multifaceted challenges of mosquito-borne disease control and for developing innovative solutions to mitigate their impact on public health.

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Conflict of Interest Disclosure

Authors affirm that this research was conducted without any commercial or financial relationships that could be construed as a potential conflict of interest.

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