Journal of Scientific Research and Development (2025) Vol. 24 (1) 139-152

A bi-annual journal published by the Faculty of Science, University of Lagos, Nigeria
http://jsrd.unilag.edu.ng/index.php/jsrd

Influence of habitat characteristics and climate on *Anopheles coluzzii* breeding in urban Lagos Nigeria

Adedapo O. Adeogun[1,2]*, Ayodele S. Babalola[1], Olagundoye Olalekan[1], Oyeniyi Tolulope[1], Adekunle Olanrewaju[1], Adediran Adewale[1], Oyelude Funmilola Janet[3], Fawole Jumoke[4], Adesoye Oluwaseun Adegbola[5], Julius A. Bamidele[4], Abimbola Oshinowo[6]

[1]Department of Public Health and Epidemiology, Nigerian Institute of Medical Research, Yaba Lagos Nigeria.
[2]Department of Animal and Environmental Biology, Osun State University, P.M.B. 4494, Osogbo, Osun State, Nigeria
[3]Department of Biology Education, Lagos State University Distance Learning Centre, Abeokuta, Ogun State
[4]Department of Pure and Applied Zoology, Federal University of Agriculture, Abeokuta, Nigeria
[5]Department of Biological Sciences, University of Abuja, Abuja Nigeria
[6]Lagos State Malaria Elimination Program, Lagos State Ministry of Health, Lagos State
*Corresponding author: dapoadeogun@hotmail.com

(Received 31 July 2025/Revised 06 October 2025/Accepted 14 October 2025)

Abstract

Malaria remains a major public health concern in Nigeria, where *Anopheles* mosquitoes are the primary vectors. Identifying ecological and climatic drivers of larval habitats is crucial for developing targeted control strategies, particularly in rapidly urbanizing settings like Lagos State. Larval surveys were conducted across six Local Government Areas (Ikorodu, Badagry, Ojo, Amuwo-Odofin, Kosofe, and Lagos Mainland). *Anopheles coluzzii* larvae were collected using standard dippers and pipettes, morphologically identified, and confirmed to species level by PCR. Physicochemical parameters of breeding water (pH, conductivity, total dissolved solids, oxidation–reduction potential, and temperature) were measured in situ with a multimeter. Nineteen bioclimatic variables were obtained from the CHELSA database. Data analysis included chi-square and t-tests for associations between habitat features and larval presence, correlation analysis, and Principal Component Analysis (PCA). Of 18 breeding sites surveyed, 8 (44.4%) were positive for *Anopheles* larvae, all identified as *Anopheles coluzzii*. Lagos Mainland sites harbored exclusively *Anopheles coluzzii*, while other LGAs showed mixed breeding with culicines. Small, rainfall-fed puddles were the predominant positive habitats, though water appearance and physicochemical parameters were not significantly associated with larval presence ($p > 0.05$). Bioclimatic analysis revealed significant correlations between larval presence and 12 variables. The strongest predictors were Temperature Annual Range, Maximum Temperature of the Warmest Month, and Mean Diurnal Range ($r > 0.8$, positive), while Precipitation Seasonality and Minimum Temperature of the Coldest Month showed strong negative associations ($r > 0.75$). PCA identified two components explaining 90.2% of the variance, highlighting precipitation and temperature drivers. *An. coluzzii* dominates urban Lagos larval habitats, with climate factors rather than local physicochemical conditions shaping their distribution. These findings emphasize the need to integrate climate-informed surveillance with larval source management, including targeted larviciding and environmental modification, into malaria control strategies.

Keywords: *Anopheles coluzzii*, larval habitats, bioclimatic variables, malaria control, Lagos

---

Introduction

Malaria remains one of the most persistent public health problems globally, majorly affecting sub-Saharan Africa. In 2023, an estimated 249 million malaria cases and 608,000 deaths were reported globally, with Africa accounting for approximately 94% of the disease burden (WHO, 2023). Nigeria alone contributes nearly 27% of global malaria cases and deaths, making her the country with the highest malaria burden globally (WHO, 2023). Despite large-scale control interventions such as the distribution of long-lasting insecticidal nets (LLINs), indoor residual spraying (IRS), and improved case management, malaria transmission continues to pose threats in many parts of Nigeria, with urban centers like Lagos presenting unique ecological and epidemiological challenges with respect to malaria control (Doumbe-Belisse *et al.,* 2021; Adeogun *et al.,* 2023).

Malaria transmission is closely tied to the ecology of its vectors. Primarily mosquitoes belonging to the *Anopheles gambiae* complex, which includes *An. gambiae sensu stricto*, *An. arabiensis, An. melas* and *An. coluzzii* as well as the *An. funestus* group transmits most of the malaria parasites in Nigeria. These species are highly anthropophilic and efficient at transmitting *Plasmodium falciparum*, the deadliest malaria parasite in Africa (Coetzee *et al.,* 2013). Historically, *An. gambiae* was considered the dominant vector in Africa including Nigeria, but growing evidence suggests ongoing species shifts and ecological adaptations that favor *An. coluzzii*, particularly in urbanized environments with permanent or semi-permanent water bodies (Akogbéto *et al.,* 2018; Ebhodaghe *et al.,* 2024). Such ecological dynamics complicate malaria control efforts by altering the breeding habitats, biting behavior, and insecticide resistance profiles of vectors.

Therefore, understanding larval ecology is important for malaria control, especially given the renewed interest in larval source management (LSM) as a complementary intervention to LLINs and IRS. Larval habitats are determined by physicochemical characteristics such as pH, temperature, conductivity, and dissolved oxygen, as well as broader bioclimatic factors including rainfall, temperature variability, and seasonality (Mala *et al.,* 2011; Emidi *et al.,* 2017). These factors not only influence the suitability of breeding sites but also affect larval development rates, adult survival, and vectorial capacity (Adeogun *et al.,* 2023; 2025). For instance, higher water temperatures can accelerate larval development and shorten the gonotrophic cycle, thereby increasing mosquito densities and transmission potential (Sharma *et al.,* 2025; Shafagh *et al.,* 2025). Equally, fluctuations in precipitation and extreme seasonal variability can disrupt breeding and reduce mosquito population or even drive them to locations where they are non-natives (Carlson *et al.,* 2023).

Recent studies have highlighted the increasing breeding and resilience of *Anopheles* species in polluted or anthropogenically modified environments, habitats previously dominated by *Culex* mosquitoes (Kudom *et al.,* 2015; Antonio-Nkondjio *et al.,* 2011). In rapidly urbanizing areas like Lagos, human activities such as poor drainage, improper waste disposal, and infrastructure expansion create new breeding sites that sustain year-round mosquito breeding (Afrane *et al.,* 2012).

Consequently, Lagos represents a high-risk zone where environmental and bioclimatic factors intersect with anthropogenic pressures to sustain malaria transmission. This underlines the urgent need for localized ecological studies that can inform targeted control strategies.

While national-level ecological niche modeling studies, such as those by Adeogun *et al.* (2023), have identified precipitation and temperature as key determinants of *Anopheles* distribution across Nigeria, there remains a paucity of more localized data on the physicochemical and climatic drivers of larval habitats in Lagos State. Most existing research has focused on adult mosquito bionomics and insecticide resistance, with little attention given to the ecological intricacies of larval breeding sites. Generating such evidence is importantl, as larval habitat characterization can support predictive risk mapping, enhance surveillance, and guide larviciding programs within integrated vector management frameworks (WHO, 2012).

Therefore, this study aimed to investigate the influence of physicochemical and bioclimatic factors on *Anopheles* larval presence across selected sites in Lagos State, Nigeria. This study assessed breeding site characteristics, measured key water quality parameters, and analyzed bioclimatic variables using multivariate techniques. We also conducted molecular identification to determine the specific *Anopheles* species present. By combining field-based data with ecological analyses, this study provides insight into the environmental drivers of *Anopheles* distribution in an urban malaria setting. The findings are expected to contribute to evidence-based malaria control, particularly through the design of locally adapted strategies such as targeted larviciding, environmental management, and improved vector surveillance systems.

Materials and Methods

Study Area

The study was conducted in Lagos State, Nigeria, one of the most densely populated states in sub-Saharan Africa and a region with perennial malaria transmission. Lagos lies within the humid tropical zone, characterized by two distinct rainy seasons (April–July and September–November) and a dry season (December–March). The state is highly urbanized, with rapid population growth and extensive human settlement patterns that create diverse mosquito breeding habitats. Six Local Government Areas (LGAs) were selected to represent different ecological and urbanization gradients: Ikorodu, Badagry, Ojo, Amuwo-Odofin, Kosofe, and Lagos Mainland (Figure 1). These LGAs encompass both coastal and inland environments, with varying degrees of anthropogenic influence such as industrial activity, urban drainage, and peri-urban agriculture, which are known to affect mosquito ecology.

Larval Collection and Identification

Larval sampling was carried out in the six LGAs between April to July 2023. Potential breeding habitats, including puddles, ditches, ponds, and other stagnant water bodies, were systematically surveyed. Standard dippers (350 mL) and pipettes were used to collect mosquito larvae from accessible sites. Collected larvae were transferred into labeled plastic containers filled with water from their breeding sites and transported to the laboratory for identification. Morphological identification was performed using standard taxonomic keys to distinguish Anopheles larvae from culicine species. A subset of Anopheles larvae was preserved in ethanol for molecular identification, which was carried out using PCR assays targeting species-specific markers to confirm members of the *Anopheles gambiae* complex.

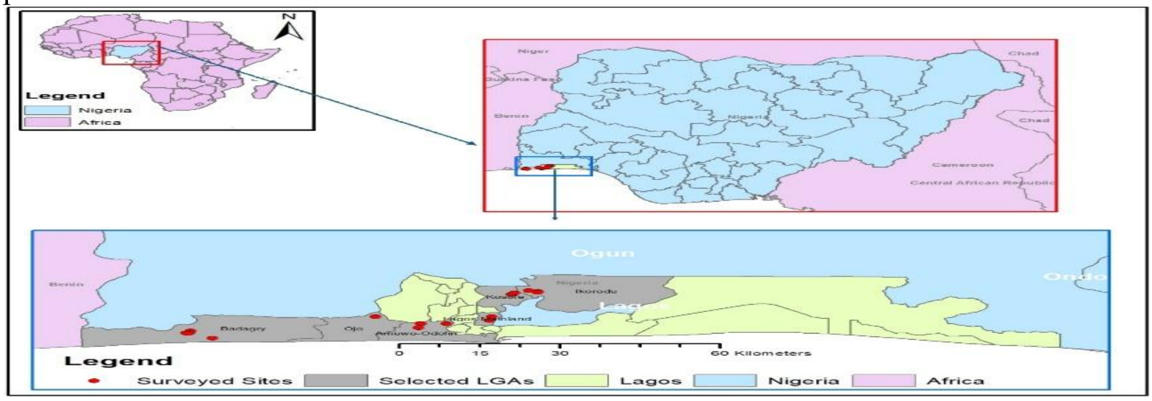


Figure 1: Study area showing Lagos State and location of breeding sites

Physicochemical Parameters of Breeding Water

At each positive and negative breeding site, physicochemical parameters of the water were measured in situ using a portable multiparameter water quality meter (model number: HQ2200 manufactured by Hach Company, China). The device was standardized following the manufacturer's instructions. Parameters recorded included pH, electrical conductivity (EC), total dissolved solids (TDS), oxidation–reduction potential (ORP), and water temperature. These measurements provided insights into the micro-ecological characteristics that may influence larval survival and breeding site suitability.

Bioclimatic Variables

Bioclimatic variables were sourced from the CHELSA (Climatologies at High Resolution for the Earth's Land Surface Areas) database (version 2.1), which provides high-resolution (30 arc-second, ~1 km) global climate data (Karger *et al.,* 2017). A total of 19 standard bioclimatic variables representing long-term annual trends, seasonality, and extreme environmental conditions (temperature and precipitation) were extracted for the study area. These variables are widely used in species distribution modeling and ecological studies because of their relevance to biological processes. For this study, the bioclimatic variables were clipped to Lagos State boundaries and linked with larval occurrence data to assess ecological associations.

Data Analysis

Data were analyzed using R statistical software (version 4.4.0). Descriptive statistics were used to summarize the distribution of larval habitats and site positivity. A chi-square test was employed to examine the association between categorical breeding site characteristics (e.g., water appearance, vegetation presence) and the presence of *Anopheles* larvae. Independent samples t-tests were conducted to compare mean values of physicochemical parameters between positive and negative breeding sites.

To evaluate the influence of climatic factors, correlation analysis was applied to test associations between larval presence and bioclimatic variables. Principal Component Analysis (PCA) was further used to reduce dimensionality, identify the most influential variables, and address multicollinearity inherent in environmental datasets. Statistical significance was determined at $p < 0.05$.

Results

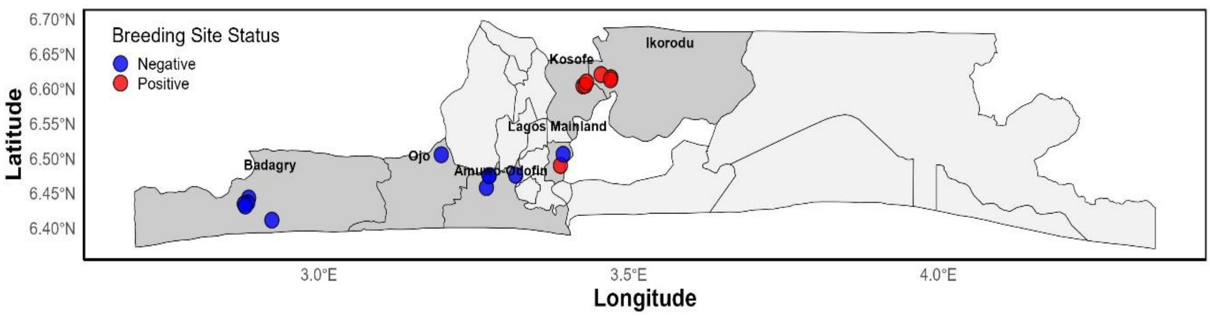
Description of larval habitat and site positivity

In all breeding site types, only small puddles were found to be positive for *Anopheles* mosquitoes. The major source of water was rainfall, with the water ranging from clear to turbid, dark, or occasionally oily. All the breeding sites were sunlit, with some surrounded by vegetation. Figure 2 shows the status of the breeding sites visited and the mosquito species identified across the six LGAs. The results revealed that 8 out of the 18 breeding sites, spanning three LGAs (Ikorodu, Kosofe, and Lagos Mainland), were positive for *Anopheles* mosquitoes (Figure 2a). Among these three LGAs, only the sites visited in Lagos Mainland had exclusively *Anopheles* mosquitoes, while the rest showed mixed breeding of Anophelines and Culicines (Figure 2b).

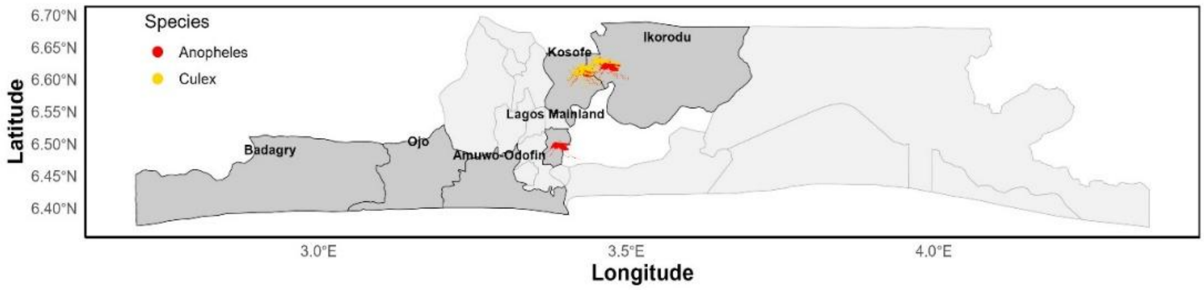
Association between breeding site characteristics, physicochemical parameters, and larval presence

Figure 3 presents the results of the association between water appearance, vegetation presence, and larval presence across the study sites. The results showed that a higher proportion of positive sites were found in dark, polluted, and oily water compared with clear water, although the differences observed were not statistically significant ($p > 0.05$). Similarly, the presence of vegetation did not appear to significantly affect mosquito presence in the study areas, as a slightly higher proportion of positive breeding sites ($p > 0.05$) lacked vegetation (Figure 3).

Figure 4 presents the results of the association between physicochemical parameters and larval presence across the study sites. The results showed that the mean water oxidation-reduction potential (ORP), pH, and temperature were slightly higher in positive breeding sites compared with negative sites, whereas mean electrical conductivity and total dissolved solids (TDS) were slightly lower in positive breeding sites. However, the differences observed were not statistically significant ($p > 0.05$).



(a)



(b)

Figure 2: Status of breeding sites (a) and mosquito species found (b) across the 6 LGAs of Lagos State

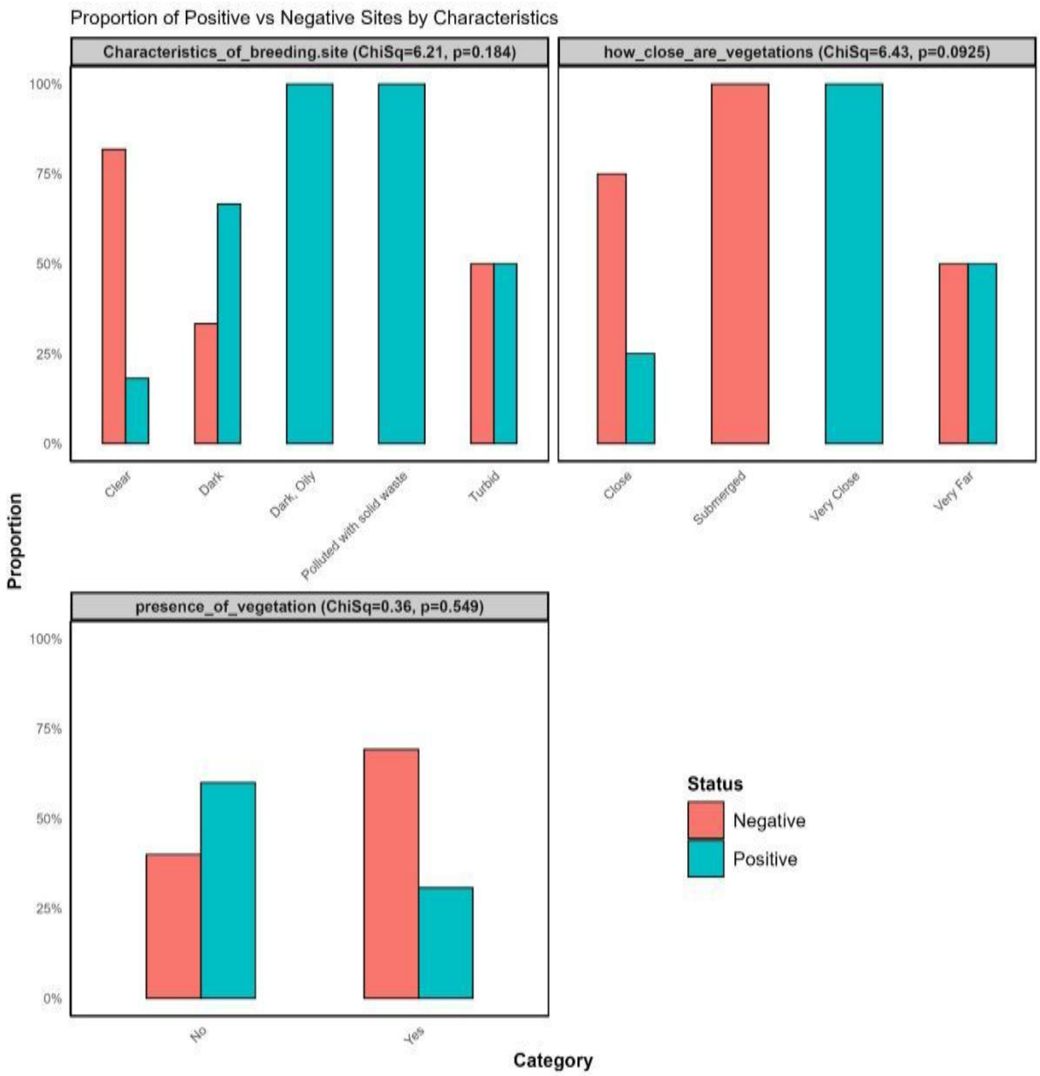


Figure 3: Association between water appearance, vegetation presence and larval presence

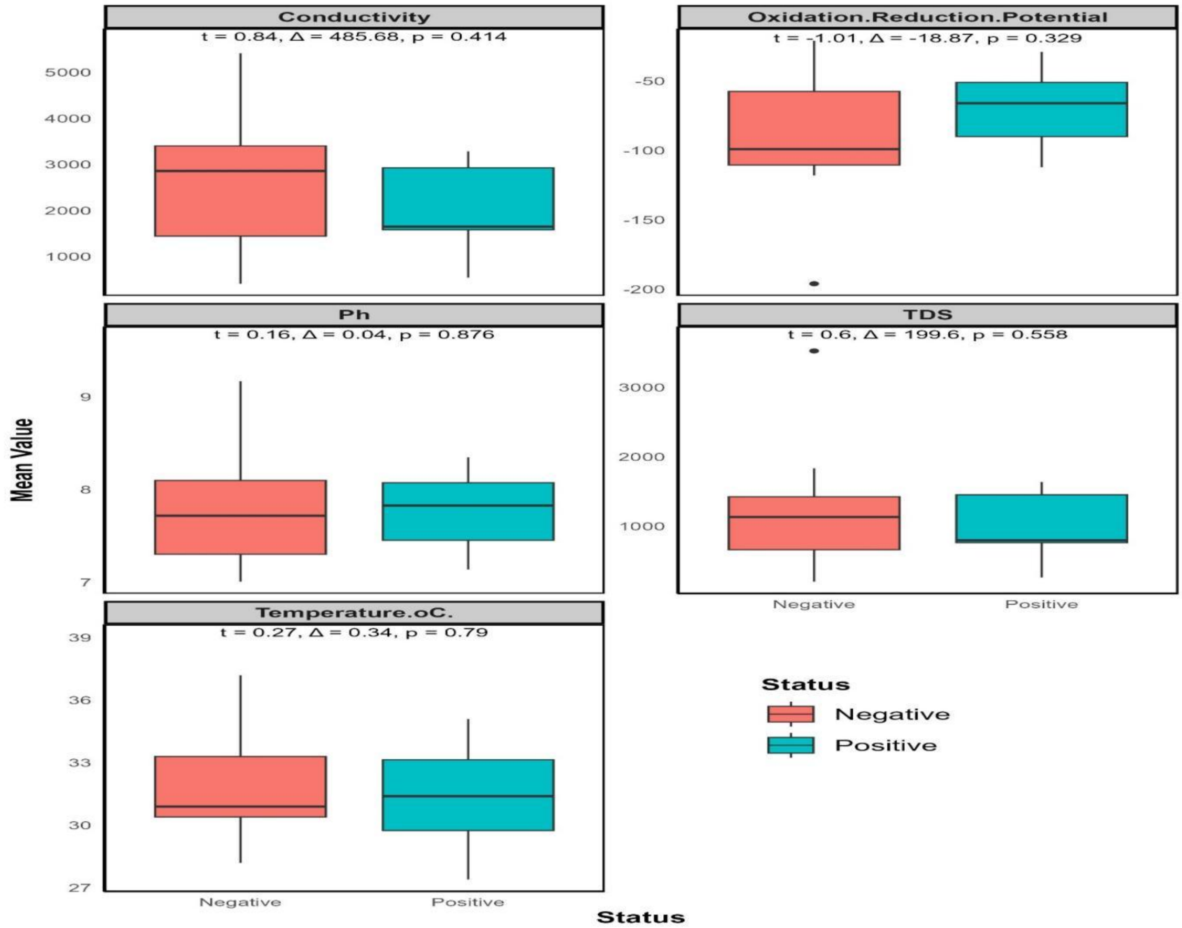


Figure 4: Association between physicochemical parameters and larval presence across the study sites

Relationship between bioclimatic variables and larval breeding sites positivity

Of all the bioclimatic variables used in this study, only three (Annual Mean Temperature, Precipitation of the Wettest Month, and Temperature Seasonality) were not significantly correlated with mosquito presence (Table 1). Of the twelve variables that showed a significant relationship, the five strongest, in descending order, were: Temperature Annual Range, Maximum Temperature of the Warmest Month, and Mean Diurnal Range (positively correlated, with correlation coefficients > 0.8), followed by Precipitation Seasonality and Minimum Temperature of the Coldest Month (negatively correlated, with correlation coefficients > 0.75) (Table 1).

The results of the principal component analysis (PCA) are presented in Figure 5 (A–C) and Table 2. The analysis identified two major principal components (PCs) accounting for 90.2% of the variation observed with respect to Anopheles larval presence. PC1 alone accounted for 67.1% of the variation (Figure 5C), indicating that variables with higher loadings on this component are more influential than others. The top three most important variables on PC1 were Precipitation of the Driest Quarter (bio17), Annual Precipitation (bio12), and Maximum Temperature of the Warmest

Month (bio5) (Figure 4a and b), while the top three on PC2 were Temperature Seasonality (bio4), Precipitation Seasonality (bio15), and Minimum Temperature of the Coldest Month (bio6). The PCA loadings for the top variables on PC1 were all at least 0.94, while those for PC2 were all at least 0.64 (Table 2).

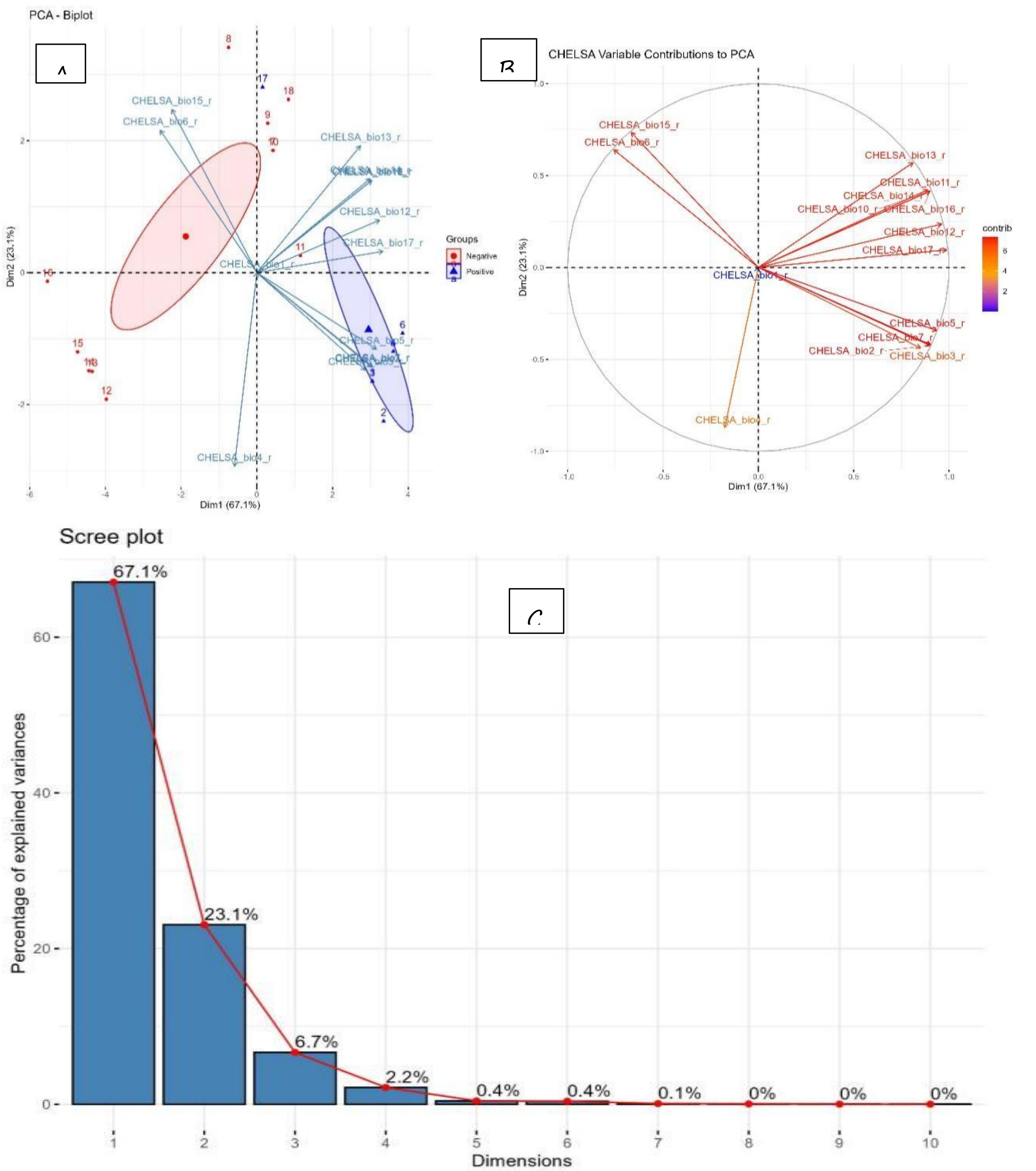


Figure 5: Principal component analysis (a) biplot, (b) variables contributions to PCA (c) Scree plot showing percentage of explained variance for each principal component

Table 1: Correlation coefficients between bioclimatic variables and presence of *Anopheles* mosquitoes

Variable	Code	Correlation	p-value
Annual Mean Temperature	CHELSA_bio1_r	0.001	0.981
Mean Temperature of Warmest Quarter	CHELSA_bio10_r	0.495	0.037*
Mean Temperature of Coldest Quarter	CHELSA_bio11_r	0.495	0.037*
Annual Precipitation	CHELSA_bio12_r	0.681	0.002**
Precipitation of wettest month	CHELSA_bio13_r	0.430	0.075
Precipitation of driest month	CHELSA_bio14_r	0.518	0.028*
Precipitation Seasonality	CHELSA_bio15_r	**-0.790**	0.000***
Precipitation of Wettest Quarter	CHELSA_bio16_r	0.563	0.015*
Precipitation of Driest Quarter	CHELSA_bio17_r	0.713	0.001**
Mean Diurnal Range	CHELSA_bio2_r	**0.806**	0.000***
Isothermality	CHELSA_bio3_r	0.702	0.001**
Temperature Seasonality	CHELSA_bio4_r	0.299	0.229
Maximum Temperature of Warmest Month	CHELSA_bio5_r	**0.822**	0.000***
Minimum Temperature of Coldest Month	CHELSA_bio6_r	**-0.779**	0.000***
Temperature Annual Range	CHELSA_bio7_r	**0.822**	0.000***

Note: p-values with asterisks * connotes significant differences * 0.05, **0.01 *** <0.0001

Table 2: Variable loading on principal components

Variable	Code	PC1	PC2
Annual Mean Temperature	CHELSA_bio1_r	0.000	0.000
Mean Temperature of Warmest Quarter	CHELSA_bio10_r	*0.901*	0.416
Mean Temperature of Coldest Quarter	CHELSA_bio11_r	*0.901*	0.416
Annual Precipitation	CHELSA_bio12_r	**0.962**	0.236
Precipitation of wettest month	CHELSA_bio13_r	*0.811*	0.570
Precipitation of driest month	CHELSA_bio14_r	*0.888*	0.422
Precipitation Seasonality	CHELSA_bio15_r	-0.666	**0.734**
Precipitation of Wettest Quarter	CHELSA_bio16_r	*0.900*	0.415
Precipitation of Driest Quarter	CHELSA_bio17_r	**0.988**	0.096
Mean Diurnal Range	CHELSA_bio2_r	*0.902*	-0.425
Isothermality	CHELSA_bio3_r	*0.850*	-0.438
Temperature Seasonality	CHELSA_bio4_r	-0.175	**-0.870**
Maximum Temperature of Warmest Month	CHELSA_bio5_r	**0.937**	-0.344
Minimum Temperature of Coldest Month	CHELSA_bio6_r	*-0.757*	**0.641**
Temperature Annual Range	CHELSA_bio7_r	*0.905*	-0.421

Discussion

Malaria remains a persistent disease affecting the majority of people in sub-Saharan Africa, including Nigeria, for over a century. Understanding *Anopheles* larval habitat characteristics is essential for vector control and, by extension, malaria prevention. This study explored how physicochemical and bioclimatic factors influence the distribution of *Anopheles* mosquitoes in Lagos State, Nigeria.

Our findings highlight small puddles as the primary breeding sites for *Anopheles* mosquitoes in the study areas, with rainfall as the main water source and water conditions ranging from clear to turbid, dark, or occasionally oily. All breeding sites were sunlit, with some surrounded by vegetation. Previous studies have reported that mosquito breeding habitats in urban areas are strongly influenced by anthropogenic pressures, including organic and nutrient pollution (Wen *et al.,* 2017; Wang *et al.,* 2020; Schrama *et al.,* 2020).

Notably, Lagos Mainland sites harbored exclusively *Anopheles* mosquitoes, whereas other LGAs exhibited mixed breeding with *Culex* species. This is not surprising, as several studies have documented the adaptation of *An. gambiae* s.l. to nutrient-rich and polluted habitats, which were previously dominated by *Culex* mosquitoes (Kudom *et al.,* 2015; Kabula *et al.,* 2011; Emidi *et al.,* 2017; Antonio-Nkondjio *et al.,* 2011; Huzortey *et al.,* 2022). Such adaptation could undermine vector control strategies, as habitats that previously targeted only *Culex* are now shared with malaria vectors. The presence of mixed breeding in other LGAs underscores the need for integrated vector management strategies to address multiple mosquito species simultaneously (Afrane *et al.,* 2012).

Molecular identification confirmed all *Anopheles* larvae as *An. coluzzii*, a species known to be highly anthropophilic and an efficient malaria vector (Ebhodaghe *et al.,* 2024). Adeogun et al. (2023) suggested a possible ongoing species replacement from *An. gambiae* to *An. coluzzii* in Nigeria, potentially linked to expanded LLIN coverage and use, as well as changing climatic conditions. This highlights the necessity of continuous vector surveillance to provide timely, evidence-based insights for control programs and policymakers. Control strategies may need to be reoriented to target *An. coluzzii*, which has been reported as an important vector of *Plasmodium malariae*. Both *An. coluzzii* and *An. gambiae* efficiently transmit *P. falciparum* and *P. ovale*, but studies in Benin have suggested that *An. coluzzii* may play a more prominent role in malaria transmission than *An. gambiae* (Zoh *et al.,* 2020; Akogbéto *et al.,* 2018). The exclusive detection of *An. coluzzii* in Lagos Mainland therefore has important implications, as interventions in such urban environments should prioritize larval source management, environmental modification, and targeted larviciding.

Although darker, polluted, or oily waters were associated with slightly higher larval presence, these differences were not statistically significant. Vegetation presence also did not significantly affect mosquito occurrence, suggesting that other ecological or environmental factors may play stronger roles in determining breeding site suitability (Emidi *et al.,* 2017; Adeogun *et al.,* 2023). Monitoring physicochemical parameters nonetheless remains valuable for predicting high-risk areas and optimizing interventions.

Analysis of bioclimatic variables revealed that most factors were significantly correlated with larval presence, except for Annual Mean Temperature, Precipitation of the Wettest Month, and Temperature Seasonality. Of the twelve variables showing significant associations, the five strongest were: Temperature Annual Range, Maximum Temperature of the Warmest Month, and Mean Diurnal Range (all positive), and Precipitation Seasonality and Minimum Temperature of the Coldest Month (both negative). The strong positive correlation with temperature-related variables demonstrates the adaptability of *An. coluzzii* to environments with wide temperature fluctuations and high thermal maxima. This supports previous findings that *Anopheles* mosquitoes thrive under warmer conditions that accelerate larval development and shorten the gonotrophic cycle, thereby enhancing transmission potential (Sharma *et al.,* 2025; Shafagh *et al.,* 2025). The importance of Mean Diurnal Range suggests that daily temperature variations may create microclimates favorable to larval survival, even when average temperatures alone may seem less suitable.

Conversely, the negative association with Precipitation Seasonality and Minimum Temperature of the Coldest Month indicates that highly seasonal rainfall and cooler minima are less favorable for *Anopheles* breeding. These findings align with ecological niche studies showing reduced mosquito survival in areas with prolonged dry seasons or low minimum temperatures, which can interrupt breeding cycles and reduce vector persistence (Mala *et al.,* 2011; Adeogun *et al.,* 2023). From a policy perspective, this suggests that areas with extreme rainfall variability may experience episodic transmission, requiring flexible and seasonal interventions, such as targeted larviciding during peak rainfall periods and surveillance in transitional seasons.

Principal Component Analysis (PCA) identified two major components explaining 90.2% of the variation, with PC1 accounting for 67.1%. Key drivers included Precipitation of the Driest Quarter, Annual Precipitation, and Maximum Temperature of the Warmest Month, while PC2 was driven by Temperature Seasonality, Precipitation Seasonality, and Minimum Temperature of the Coldest Month. PCA proved advantageous over ordinary correlation analysis by reducing dimensionality and highlighting the most influential factors among interdependent variables (Carlson *et al.,* 2023). Our findings are consistent with Adeogun et al. (2023), who used ecological niche modeling to predict the distribution of the *An. gambiae* complex in Nigeria. Their study identified precipitation-related variables, with some temperature-related influences, as key determinants of distribution—closely aligning with the important variables identified in our PCA. The convergence between localized field data and nationwide ecological modeling reinforces the conclusion that temperature and precipitation dynamics are reliable predictors of mosquito breeding sites, perhaps more so than site-level physicochemical parameters alone.

From a public health perspective, these findings highlight the importance of integrating ecological and climate-informed strategies into malaria control. In urban areas dominated by *An. coluzzii*, intensive larval source management and habitat modification should be prioritized. In contrast, rural and peri-urban areas with mixed species composition will require integrated approaches addressing multiple vectors. Furthermore, understanding the role of key climatic variables can enhance predictive risk mapping and improve the timing and targeting of interventions such as larviciding, drainage, and environmental sanitation (Shafagh *et al.,* 2025).

This study has some limitations. The cross-sectional design provides only a snapshot in time and may not capture seasonal variations in mosquito breeding. Additionally, by focusing mainly on physicochemical and bioclimatic variables, other ecological determinants such as microbial interactions, predator-prey dynamics, and human-driven environmental modifications may have been overlooked. Future longitudinal studies incorporating these broader determinants will be important for refining understanding of mosquito ecology and strengthening evidence-based malaria control strategies.

Conclusion

This study characterized *Anopheles* larval habitats across six LGAs in Lagos State and found that *Anopheles coluzzii* dominates urban breeding sites. Climatic factors, rather than local physicochemical conditions, appear to be the primary drivers of larval distribution. These findings underscore the importance of integrating climate-informed surveillance with larval source management, including targeted larviciding and environmental modification, into malaria control strategies. Looking forward, incorporating ecological and climatic insights into vector control programmes could enhance the effectiveness of interventions and support Nigeria's broader malaria elimination efforts.

References

Adeogun, A. O., Babalola, A. S., Oyale, O. O., Oyeniyi, T., Omotayo, A., Izekor, R.T., et al. (2025) Spatial distribution and geospatial modeling of potential spread of secondary malaria vectors species in Nigeria using recently collected empirical data. *PLoS ONE* 20(4): e0320531. https://doi.org/10.1371/journal.pone.0320531

Adeogun, A., Babalola, A. S., Okoko, O. O., Oyeniyi, T., Omotayo, A., Izekor, R. T. et al. (2023) Spatial distribution and ecological niche modeling of geographical spread of *Anopheles gambiae* complex in Nigeria using real time data. *Sci Rep* 13: 13679. https://doi.org/10.1038/s41598-023-40929-5

Afrane, Y. A., Lawson, B. W., Brenya, R. Kruppa, T. and Yan, G. (2012) The ecology of mosquitoes in an irrigated vegetable farm in Kumasi, Ghana: abundance, productivity and survivorship. *Parasites Vectors* 5: 233. https://doi.org/10.1186/1756-3305-5-233

Akogbéto, M. C., Salako, A. S., Dagnon, F., Aïkpon, R., Kouletio, M., Sovi, A. et al. (2018) Blood feeding behaviour comparison and contribution of *An. coluzzii* and *An. gambiae*, two sibling species living in sympatry, to malaria transmission in Alibori and Donga region, northern Benin, West Africa. Malar. J. 17: 307. https://doi.org/10.1186/s12936-018-2452-9

Antonio-Nkondjio, C., Fossog, B. T., Ndo, C., Djantio, B. M., Togouet, S. Z., Awono-Ambene, P. et al. (2011) *Anopheles gambiae* distribution and insecticide resistance in the cities of Douala and Yaounde´ (Cameroon): influence of urban agriculture and pollution. *Malar J.* 10: 154. https://doi.org/10.1186/1475-2875-10-154 PMID: 21651761

Carlson, C. J., Bannon, E., Mendenhall, E., Newfield, T., Bansal, S. (2023) Rapid range shifts in African *Anopheles* mosquitoes over the last century. *Biol. Lett.* 19: 20220365 http://doi.org/10.1098/rsbl.2022.0365

Coetzee, M., Hunt, R. H., Wilkerson, R., Torre, A. D., Coulibaly, M. B., Besansky, N. J. (2013) *Anopheles coluzzii* and *Anopheles amharicus*, new members of the *Anopheles gambiae* complex. *Zootaxa* 3619 (3): 246–274. https://doi.org/10.11646/zootaxa.3619.3.2

Doumbe-Belisse, P., Kopya, E., Ngadjeu, C. S., Sonhafouo-Chiana, N., Talipouo, A., Djamouko-Djonkam, L. et al. (2021) Urban malaria in sub-Saharan Africa: dynamic of the vectorial system and the entomological inoculation rate. *Malar J* 20: 364. https://doi.org/10.1186/s12936-021-03891-z

Ebhodaghe, F.I., Sanchez-Vargas, I., Isaac, C., Foy, B. D., Hemming-Schroeder, E. (2024) Sibling species of the major malaria vector *Anopheles gambiae* display divergent preferences for aquatic breeding sites in southern Nigeria. *Malar J.* 23: 60. https://doi.org/10.1186/s12936-024-04871-9

Emidi, B., Kisinza, W. N., Mmbando, B. P., Malima, R. and Mosha, F. W. (2017) Effect of physicochemical parameters on *Anopheles* and *Culex* mosquito larvae abundance in different breeding sites in a rural setting of Muheza, Tanzania. *Parasites and Vectors* 10: 304. https://doi.org/10.1186/s13071-017-2238-x

Huzortey, A. A., Kudom, A. A., Mensah, B. A., Sefa-Ntiri, B., Anderson, B., Akyea, A. (2022) Water quality assessment in mosquito breeding habitats based on dissolved organic matter and chlorophyll measurements by laser-induced fluorescence spectroscopy. *PLoS ONE* 17(7): e025228.https://doi.org/10.1371/journal.pone.0252248

Kabula, B. I., Attah, P. K., Wilson, M. D., Boakye, D. A. (2011) Characterization of *Anopheles gambiae* s.l. and insecticide resistance profile relative to physicochemical properties of breeding habitats within Accra Metropolis, Ghana. *Tanzan J Health Res.* 2011: 13. https://doi.org/10.4314/thrb.v13i3.66915

Karger, D., Conrad, O., Böhner, J., Kawohl, T., Kreft, H., Soria-Auza, R. W. et al. (2017) Climatologies at high resolution for the earth's land surface areas. *Sci Data* 4: 170122 https://doi.org/10.1038/sdata.2017.122

Kudom, A. A. (2015) Larval ecology of *Anopheles coluzzii* in Cape Coast, Ghana: Water quality, nature of habitat and implication for larval control. *Malar J.* 14: 1–13. https://doi.org/10.1186/s12936-015-0989-4

Mala, A. O., Irungu, L. W., Shililu, J. I., Muturi, E. J., Mbogo, C. C., Njagi, J. K. et al. (2011) Dry season ecology of *Anopheles gambiae* complex mosquitoes at larval habitats in two traditionally semi-arid villages in Baringo, Kenya. *Parasites Vectors* 4: 25. https://doi.org/10.1186/1756-3305-4-25

Schrama, M., Hunting, E. R., Beechler, B. R., Guarido, M. M., Govender, D., Nijland, W. et al. (2020) Human practices promote presence and abundance of disease-transmitting mosquito species. *Scientific Reports*. 10: 13543. https://doi.org/10.1038/s41598-020-69858-3 PMID: 32782318

Shafagh, S. G., Moradi-Asl, E., Mirzagholipour, M., Sahlabadi, A. S., Esmaeili, S. V., Karami, C. (2025). Impact of Global Climate-Change on Ecology of *Anopheles* Mosquitoes: A Systematic Review. *Iranian journal of public health* 54(3): 542–553. https://doi.org/10.18502/ijph.v54i3.18247

Sharma, G., Khan, Z., Das, D., Singh, S., Singh, S., Kumar, M. et al. (2020) Thermal influence on development and morphological traits of Aedes aegypti in central India and its relevance to climate change. *Parasites Vectors* 18: 279 (2025). https://doi.org/10.1186/s13071-025-06924-7

Wang, Y., Yim, S. H. L., Yang, Y., Morin, C. W. (2020) The effect of urbanization and climate change on the mosquito population in the Pearl River Delta region of China. *Int J Biometeorol*. 64. https://doi.org/10.1007/s00484-019-01837-4 PMID: 31811391

Wen, Y., Schoups, G., Van De Giesen, N. (2017) Organic pollution of rivers: Combined threats of urbanization, livestock farming and global climate change. *Sci Rep*. 7: 7. https://doi.org/10.1038/srep43289 PMID: 28230079

World Health Organization (WHO). (2012). Larval source management: A supplementary measure for malaria vector control. An operational manual. WHO Press. https://apps.who.int/iris/handle/10665/85379

World Health Organization (WHO). (2023). World malaria report 2023. Geneva: WHO Press. https://www.who.int/publications/i/item/9789240086534

Zoh, D. D., Yapi, A., Adja, M. A., Guindo-Coulibaly, N., Kpan, D. M. S., Sagna, A. B. et al. (2020) Role of *An. gambiae* s.s. and *An. coluzzii* (Diptera: Culicidae) in human malaria transmission in rural areas of Bouaké, in Côte d'Ivoire. *J. Med. Entomol.* 57(4): 1254–1261