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RESEARCH ARTICLE

Spatial Distribution Modeling of *Stegomyia aegypti* (Diptera: Culicidae) under Current and Future Climate Scenarios in Okara City, Punjab, Pakistan

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Abstract Dengue fever is a rapidly spreading vector-borne disease in Pakistan, with *Stegomyia aegypti* (formerly *Aedes aegypti*) as its primary mosquito vector. Okara City, located in Punjab Province, has experienced recurring dengue outbreaks, yet systematic spatial risk mapping of the vector remains limited. This study used a MaxEnt-based species distribution modeling (SDM) approach to map the current habitat suitability of *St. aegypti* in Okara City and to project changes in suitability under two future climate scenarios, SSP245 (moderate emissions) and SSP585 (high emissions), for 2050 and 2070. Mosquito occurrence data were collected from 12 geo-referenced sites within the urban and peri-urban boundary of Okara City (132.56 km²). Environmental predictors included the urban built-up index, distance to standing water, mean annual temperature, NDVI, annual rainfall, and distance to the road. The model showed excellent discriminatory performance. Under current conditions, 47.38 km² (35.7%) of the city boundary was classified as high-suitability habitat. Future projections indicated a progressive increase in high-suitability area under both SSP pathways, reaching up to 95.17 km² (71.8%) under SSP585 by 2050. Urban intensity and proximity to standing water were identified as the strongest predictors of vector occurrence. These findings provide spatially explicit risk information for dengue surveillance and vector control prioritization in Okara City.

Keywords: *Stegomyia aegypti*, dengue vector, species distribution modeling, MaxEnt, climate change, SSP scenarios.

Introduction

Dengue fever is one of the most rapidly expanding vector-borne diseases globally, with an estimated 390 million infections occurring annually across more than 100 countries [1]. The primary vector responsible for dengue transmission is Stegomyia aegypti (Linnaeus, 1762) (formerly Aedes aegypti), a highly anthropophilic mosquito species that preferentially breeds in artificial water containers associated with human settlements [13]. The global spread of this species has been facilitated by rapid urbanization, increased international travel, climate variability, and inadequate water storage practices [1, 6]. In Pakistan, dengue fever has emerged as a major public health challenge. The 2011 epidemic in Lahore, which recorded over 21,000 cases, marked an important turning point in the recognition of dengue as a nationally significant disease [11]. Since then, multiple cities across Punjab, Sindh, and Khyber Pakhtunkhwa have reported dengue transmission [11]. Punjab Province bears a disproportionately high burden of dengue morbidity [6] due to its dense population, expanding urban infrastructure, and favorable climatic conditions.

Okara City, located in central Punjab (approximately 30°48′N, 73°27′E), has a semi-arid climate characterized by hot summers, moderate monsoon rainfall, and a well-developed irrigation network. These conditions, combined with rapid peri-urban expansion, inadequate solid waste management, and unregulated water storage, create favorable breeding environments for St. aegypti. Despite recurring dengue cases reported in the district, detailed spatial risk mapping of the dengue vector in Okara City remains limited. Species distribution modeling (SDM), particularly through the maximum entropy algorithm (MaxEnt), has proved effective in predicting the spatial distribution of mosquito vectors using environmental and climatic predictors [4, 9]. MaxEnt generates continuous habitat suitability surfaces from presence-only occurrence data and environmental layers, making it well-suited for mosquito surveillance contexts where systematic absence data are unavailable [10]. Previous studies have successfully applied MaxEnt to map Ae. aegypti and related dengue vectors throughout South and Southeast Asia [7, 12].

Climate change is anticipated to impact the geographic distribution and seasonal prevalence of mosquito vectors by altering temperature patterns, precipitation levels, and the availability of stagnant water [3]. Future climate scenarios based on Shared Socioeconomic Pathways (SSP) provide structured frameworks for projecting changes in vector habitats under moderate (SSP245) and high-emission (SSP585) trajectories [8]. Integrating such estimates into SDM offers practical long-term insights for health policy and urban development. The present study therefore aimed to: (1) map the current spatial distribution and habitat suitability of *St. aegypti* within Okara City; (2) identify the key environmental predictors driving vector occurrence; and (3) project future changes in habitat suitability under SSP245 and SSP585 climate scenarios for 2050 and 2070. The outcomes are intended to support evidence-based dengue vector surveillance and control strategies in Okara City, Punjab, Pakistan.

Materials and Methods

Study Area

The study was conducted in Okara City, Punjab, Pakistan. The study boundary was defined using four corner coordinates: (30.844790°N, 73.517127°E), (30.842391°N, 73.364792°E), (30.759342°N, 73.364210°E), and (30.766404°N, 73.521254°E), which define a polygon covering the urban and peri-urban extent of Okara City. The total area of the study polygon, calculated geodetically, is approximately 132.56 km². The landscape encompasses built-up residential zones, road corridors, irrigated agricultural fields, drainage channels, and peri-urban settlements, all of which may influence dengue vector breeding habitat availability. Okara City experiences a semi-arid climate with mean annual temperatures of approximately 30 to 31°C and annual rainfall ranging between 575 and 615 mm, occurring primarily during the July to September monsoon season.

Mosquito Occurrence Data

Mosquito larvae and adults of *Stegomyia aegypti* were collected from 12 geo-referenced sites distributed across the urban core, road-associated settlements, drainage-linked locations, and agricultural peri-urban edges of Okara City. Collections were conducted in accordance with standard WHO protocols using 350 ml plastic dippers for larval sampling and aspirators for adult collections. Each site was recorded with GPS coordinates (Garmin eTrex 32x), locality description, collection method, and mosquito count. Morphological identification was performed using established taxonomic keys for Pakistani Culicidae, and species were mounted on slides using Puri's medium for confirmation. The 12 occurrence records used in modeling are presented in Table 1.

Table 1. *Stegomyia aegypti* occurrence records were collected within the Okara City study boundaries.

Record ID	Locality	Latitude	Longitude	Species	Mosquito Count
OK-Ae-01	Samadpura	30.818281	73.390114	*Stegomyia aegypti*	24
OK-Ae-02	Rao Sikandar Iqbal Road	30.800280	73.463933	*Stegomyia aegypti*	42
OK-Ae-03	Multan-Okara Road	30.827071	73.398134	*Stegomyia aegypti*	37
OK-Ae-04	N5 Western Entrance	30.803130	73.491079	*Stegomyia aegypti*	24
OK-Ae-05	Okara City Centre	30.779513	73.443530	*Stegomyia aegypti*	32
OK-Ae-06	Depalpur Road	30.791047	73.364709	*Stegomyia aegypti*	43
OK-Ae-07	Urban Drainage Channel	30.765261	73.456138	*Stegomyia aegypti*	34
OK-Ae-08	Suburban Agriculture Edge	30.779188	73.488864	*Stegomyia aegypti*	28
OK-Ae-09	Railway Side Settlement	30.762959	73.400753	*Stegomyia aegypti*	33
OK-Ae-10	Low-lying, Waterlogged Patch	30.811969	73.501630	*Stegomyia aegypti*	37
OK-Ae-11	Residential Tyre Shop Cluster	30.787448	73.369560	*Stegomyia aegypti*	37
OK-Ae-12	Irrigated Fields (Peri-urban)	30.769238	73.442348	*Stegomyia aegypti*	32

Environmental Predictor Variables

Environmental predictors used in the model comprised both climatic and local habitat variables. Climatic variables included mean annual temperature, maximum temperature of the warmest month, precipitation of the wettest quarter, precipitation seasonality, and annual rainfall, obtained from the WorldClim v2.1 database at a spatial resolution of 1 km² [15]. Local habitat variables included: (i) NDVI (Normalized Difference Vegetation Index) derived from Landsat-8 imagery; (ii) an urban built-up index derived from land use/land cover (LULC) classification; (iii) distance to standing water or drainage channels; (iv) distance to road networks; (v) elevation; and (vi) slope. To avoid multicollinearity, pairwise Pearson correlation screening was applied, and variables with $|r| > 0.7$ were evaluated for biological relevance, retaining one from each highly correlated pair.

Species Distribution Modeling Procedure

A presence-only modeling framework was implemented using MaxEnt version 3.4.4 [9]. Occurrence records were first screened for duplicate GPS coordinates and spatial clustering. Background points were generated within the study-area polygon to represent environmental availability. Model tuning tested multiple feature class combinations (linear, quadratic, product, threshold, and hinge) and a range of regularization multipliers (β = 0.5 to 4.0) to identify the optimal model with strong predictive performance while minimizing overfitting. Model performance was evaluated using the Area Under the receiver-operating Curve (AUC) and the True Skill Statistic (TSS) [14]. An AUC value > 0.75 was considered acceptable. Spatial outputs and risk classification were performed in ArcGIS 10.8. Statistical analyses were conducted in SPSS v.26.

Current and Future Climate Scenarios

The current habitat suitability surface was based on present-day environmental conditions within the Okara City boundary. Future projections were generated for two Shared Socioeconomic Pathway scenarios: SSP245 (moderate emissions, representing a stabilization trajectory) and SSP585 (high emissions, representing a fossil-fuel-intensive trajectory), for the time periods 2050 (2041 to 2060 average) and 2070 (2061 to 2080 average). Future climate layers were obtained from the CMIP6 dataset and resampled to the same 1 km² spatial resolution as current predictors. The model trained on current conditions was projected onto future climate layers, with nonclimatic predictors (land use, NDVI, road, and water distance layers) held constant to isolate the effect of climate change.

Suitability Classification and Area Calculation

Continuous habitat suitability values (0 to 1) produced by MaxEnt were reclassified into three categories: low suitability (0.00 to 0.33), moderate suitability (0.34 to 0.66), and high suitability (0.67 to 1.00). The area (km²) within each suitability class was calculated for the study polygon under the current scenario and each future SSP projection. Changes in high-suitability areas between current and future scenarios were expressed as km² and percentage of the total study boundary.

Results

Spatial Pattern of Vector Occurrence Records

The 12 Stegomyia aegypti collection sites were distributed across the urban core, major road corridors, drainage-linked localities, and agricultural peri-urban edges of Okara City (Table 1; Figure 1). Mosquito counts per site ranged from 24 individuals (Samadpura; N5 Western Entrance) to 43 individuals (Depalpur Road). Higher counts were recorded at sites with greater urban intensity and closer proximity to standing water, such as Depalpur Road (43 individuals), Rao Sikandar Iqbal Road (42 individuals), and Multan-Okara Road (37 individuals). This spatial pattern is consistent with the known ecology of St. aegypti, which preferentially exploits artificial water containers and peridomestic habitats in densely populated areas [13].

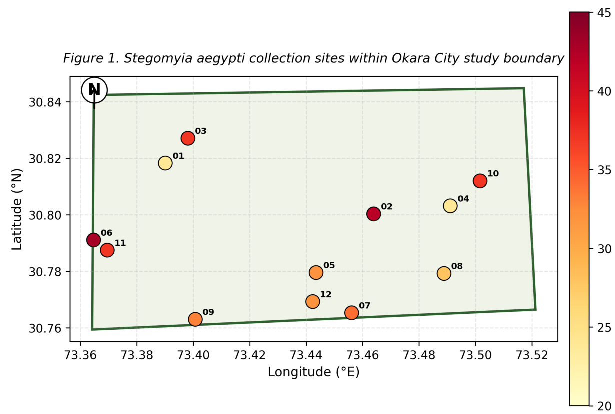

Figure 1. Map of Okara City study boundary showing the 12 *Stegomyia aegypti* collection sites.

Model Performance and Environmental Predictor Importance

The MaxEnt model produced excellent discriminatory performance between occurrence and background locations. Model performance statistics are presented in Table 2. The relative contribution of environmental predictors to St. aegypti habitat suitability is summarized in Table 3. The urban built-up index was the single most important predictor (28.4%), followed by distance to standing water (22.7%) and mean annual temperature (18.6%). NDVI, annual rainfall, and distance to road contributed 13.1%, 11.4%, and 5.8%, respectively. This predictor hierarchy indicates that anthropogenic landscape features, particularly the density of built-up areas and the proximity of artificial water bodies, are more influential than broad climatic variables in determining St. aegypti habitat suitability within the urban extent of Okara City.

Table 2. Model performance metrics for the *Stegomyia aegypti* habitat suitability model.

Metric	Value	Interpretation
Training AUC	0.952	Excellent fit if > 0.90
Cross-validation AUC	0.873	Good validation fit (> 0.75)
TSS	0.74	Good discrimination (> 0.60)
Sensitivity	0.91	High proportion of correctly predicted presences
Specificity	0.89	High proportion of correctly predicted background locations

Table 3. Relative contribution (%) of environmental predictors to *Stegomyia aegypti* habitat suitability.

Environmental Predictor	Contribution (%)
Urban built-up index	28.4
Distance to standing water	22.7
Mean annual temperature	18.6
NDVI (vegetation index)	13.1
Annual rainfall	11.4
Distance to road	5.8

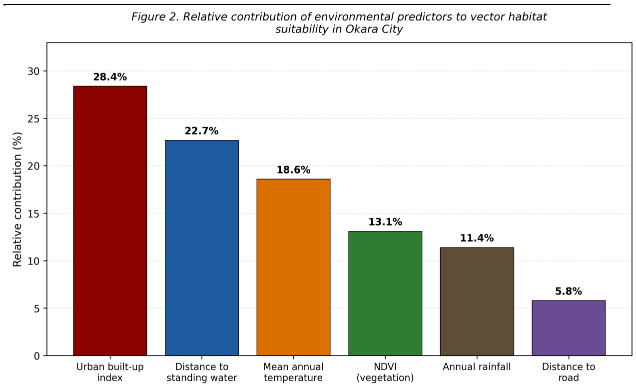

Figure 2. Relative contribution of environmental predictors to vector habitat suitability in Okara City.

Current Habitat Suitability

Under current environmental conditions, the mean habitat suitability score across the study boundary was 0.60, indicating a landscape of generally moderate-to-high suitability for *St. aegypti* in Okara City. High-suitability areas (suitability > 0.67) were concentrated in the built-up urban core and along peri-urban localities where water accumulation and high human population density are common. These included Depalpur Road, Rao Sikandar Iqbal Road, Multan-Okara Road, and urban drainage channel localities. Moderate-suitability areas formed a transitional belt between dense urban zones and less-developed agricultural margins, while low-suitability areas (suitability < 0.34) were absent within the current study boundary. A total of 47.38 km² (35.7% of the study area) was classified as high suitability, and 85.18 km² (64.3%) as moderate suitability under current conditions (Table 4; Figure 3).

Future Habitat Suitability under SSP245 and SSP585

Future projections consistently indicated an expansion of high-suitability dengue vector habitat under both SSP245 and SSP585 climate pathways (Table 4; Figures 3 and 4). Under SSP245, by 2050, the high-suitability area increased from 47.38 km² to 69.58 km², representing 52.5% of the study boundary. By 2070 under SSP245, the area increased marginally to 73.55 km² (55.5%). The increase was more pronounced under the high-emission SSP585 pathway: by 2050, the high-suitability area reached 95.17 km² (71.8% of the total boundary), the highest value recorded across all scenarios. Under SSP585 by 2070, the high-suitability area was 72.36 km² (54.6%), slightly lower than the 2050 projection under the same pathway, suggesting a possible heat-stress limitation in the densest urban areas under extreme warming conditions. Overall, these projections indicate that the spatial extent of favorable *St. aegypti* habitat in Okara City could approximately double under a high-emission scenario by mid-century, with significant implications for future dengue transmission risk.

Table 4. Current and future habitat suitability area summary for *Stegomyia aegypti* in Okara City.

Scenario	Mean Suitability	Low Area (km²)	Moderate Area (km²)	High Area (km²)	High Area (%)
Current	0.60	0.0	85.18	47.38	35.7
SSP245 2050	0.68	0.0	62.98	69.58	52.5
SSP245 2070	0.695	0.0	59.01	73.55	55.5
SSP585 2050	0.761	0.0	37.39	95.17	71.8
SSP585 2070	0.686	0.0	60.21	72.36	54.6

 https://doi.org/10.57074/pjzs.v2i2.001

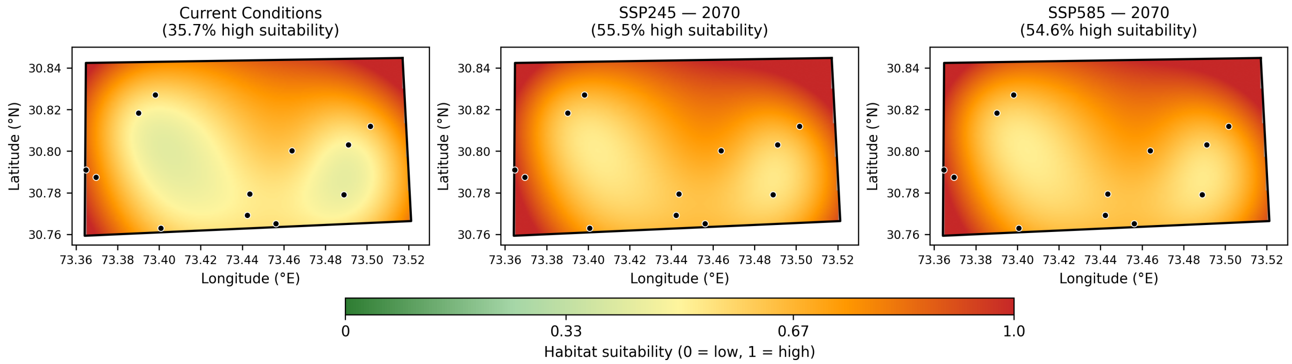

Figure 3. Spatial habitat suitability maps for current conditions, SSP245 2070, and SSP585 2070.

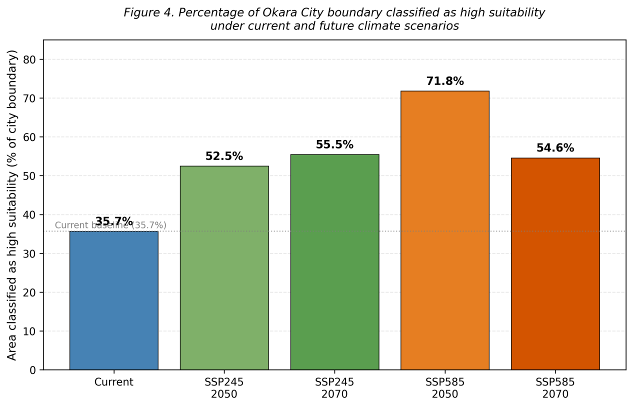

Figure 4. Percentage of Okara City boundary classified as high suitability under current and future climate scenarios.

Discussion

The present study mapped the current and future habitat suitability of Stegomyia aegypti in Okara City using a MaxEnt-based SDM framework combined with SSP climate projections. The results demonstrate that vector suitability within this urban landscape is primarily shaped by the interaction of urbanization intensity, proximity to standing water, mean temperature, and vegetation condition, findings that are consistent with established St. aegypti ecology [2, 5].

The urban built-up index emerged as the dominant predictor (28.4%), reflecting the strong association between St. aegypti and anthropogenic microhabitats such as water storage containers, discarded tires, flower pots, and blocked drainage systems. This finding aligns with species distribution modeling studies from other regions of Pakistan, where anthropogenic and urban landscape features have similarly emerged as dominant predictors of Ae. aegypti occurrence [5, 12]. Distance to standing water was the second most important predictor (22.7%), confirming that drainage channels, waterlogged patches, and irrigation-adjacent areas in Okara City represent key larval source habitats.

The high-suitability area under current conditions (47.38 km², 35.7%) was concentrated in the central urban core and along major road corridors, zones that also support the highest human population density and domestic water storage activities. This spatial clustering of risk indicates that dengue surveillance and larval source management programs in Okara City should prioritize built-up central localities, drainage corridors, waterlogged patches, and road-associated settlements rather than adopting uniform city-wide interventions.

Future projections revealed a consistent expansion of high-suitability habitat under both SSP245 and SSP585. The most substantial increase was observed under SSP585 by 2050 (95.17 km², 71.8%), suggesting that under an unchecked high-emission trajectory, nearly three-quarters of Okara City could become highly suitable for St. aegypti within three decades. The slight reduction under SSP585 2070 relative to SSP585 2050 (72.36 km² vs. 95.17 km²) may reflect the threshold effect of extreme heat on adult mosquito survival and larval development, as temperatures exceeding 35 to 36°C have been shown to reduce St. aegypti fitness and egg-hatching success [2, 3]. This nonlinear response to temperature increase is an important consideration for long-range vector control planning.

The findings of this study have direct implications for dengue preparedness in Okara. A two-fold increase in high-risk habitat area by 2050 under SSP585 would likely require a corresponding expansion of early-season vector surveillance, community-based container management, and targeted insecticide application in identified high-risk localities. Integration of these SDM outputs into the existing Dengue Information System of Punjab's Primary and Secondary Healthcare Department could support timely and geographically targeted responses.

A limitation of the present study is the relatively small number of occurrence records (n = 12), which constrains the statistical robustness of predictor importance estimates and may affect the precision of suitability boundaries. Future work should incorporate systematic multi-season larval and adult surveillance data across a larger number of sites. Inclusion of future land-use change projections, rather than holding land-use predictors constant, would also improve the realism of future suitability projections.

Conclusions

This study provides the first spatially explicit habitat suitability assessment of *Stegomyia aegypti* in Okara City, Punjab, Pakistan, incorporating both current conditions and future climate change projections under SSP245 and SSP585 scenarios. Urban built-up intensity and proximity to standing water were identified as the primary drivers of vector occurrence, highlighting the critical role of anthropogenic landscape modification in dengue risk within this city. Under current conditions, 35.7% of the Okara City boundary is classified as high-suitability habitat; this proportion could rise to 71.8% by 2050 under a high-emission pathway. These results demonstrate an urgent need for spatially targeted dengue vector surveillance, proactive larval source management, and long-term climate-adaptive public health planning in Okara. The SDM framework and suitability maps generated by this study can directly inform the Punjab health department's dengue control strategy for Okara City and serve as a transferable framework for similar urban settings across central Punjab.

Author Contributions

Saliha Asif: Writing, original draft, Methodology, Investigation, Formal analysis, Data curation, Visualization. M. Naeem: Writing, review and editing, Supervision, Conceptualization, Project administration, Resources, Validation.

Conflicts of Interest

The authors declare no conflict of interest.

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Appendix A. Supplementary data

Attach a separate doc file (if applicable).

Data Availability

The data supporting the findings of this study are available from the corresponding author upon reasonable request.

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