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Original Article

MOSQUITO POPULATION DYNAMICS IN GREATER HYDERABAD: SPATIAL VARIABILITY, SPECIES DIVERSITY, AND LINKS TO URBAN WATER AND HOUSING

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ABSTRACT

Background: Rapid urbanization in tropical megacities creates diverse microhabitats that sustain dense mosquito populations. Greater Hyderabad Municipal Corporation, with over 10 million residents, faces significant public health concerns regarding mosquito-borne diseases.

Methods: A systematic entomological survey was conducted (2016 and2018) across 18 sampling circles in five administrative zones. Mosquitoes were identified using CDC miniature light traps and outdoor resting collections. Spearman rank correlations assessed associations between abundance and urban ecological variables (water body density and informal housing).

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Results: A total of 9,021 mosquitoes representing 12 species were identified. Culex quinquefasciatus was dominant (64.27%). The North Zone recorded the highest abundance (31.78%) and richness (S=11), correlating with water body density (rs=0.700). High slum densities in South and Central zones were linked to elevated Cx. quinquefasciatus and Anopheles stephensi populations.

Conclusion: These findings establish a zone-stratified baseline for Greater Hyderabad Municipal Corporation, linking mosquito dynamics to urban landscape. The results underscore the urgent need for ecologically informed, zone-specific integrated vector management.

INTRODUCTION

Mosquitoes (Diptera: Culicidae) remain one of the deadliest foes of humans, responsible for an estimated over 700,000 deaths annually worldwide through their roles as biological vectors of malaria, dengue, chikungunya, filariasis, Japanese encephalitis, Zika, and West Nile fever (BOGOCH et al., 2016; WEI et al., 2026). According to WHO World Malaria Report 2022, malaria alone accounted for approximately 608,000 deaths in 2022, underscoring the disproportionate burden of mosquito-borne disease in tropical and subtropical regions. The global impact of these diseases is concentrated in rapidly urbanizing centers, where ecological conditions favor dense mosquito populations. (SINKA et al., 2010).

In this context, two features of contemporary urban environments in South Asia merit particular attention as drivers of mosquito population dynamics. First, water body configuration—the type, distribution, and condition of permanent and ephemeral aquatic habitats—determines the carrying capacity and species composition of larval mosquito communities (BHATT et al., 2013; KLINKENBERG et al., 2008). Polluted lakes and open drainage channels favor *Culex quinquefasciatus* and *Armigeres subalbatus*, while relatively clean water storage containers and cisterns support *Anopheles stephensi* (SHARMA, 1996). Second, housing type—particularly the presence of informal settlements (slums) characterized by overcrowding, inadequate sanitation, open drains, and minimal solid waste management—amplifies adult mosquito densities through the accumulation of organic matter, stagnant water, and reduced access to public health infrastructure (PATZ et al., 2004). Despite their relevance, neither water body proximity nor housing informality has been systematically quantified as a correlate of mosquito population dynamics in Hyderabad (Images 1 and 2).

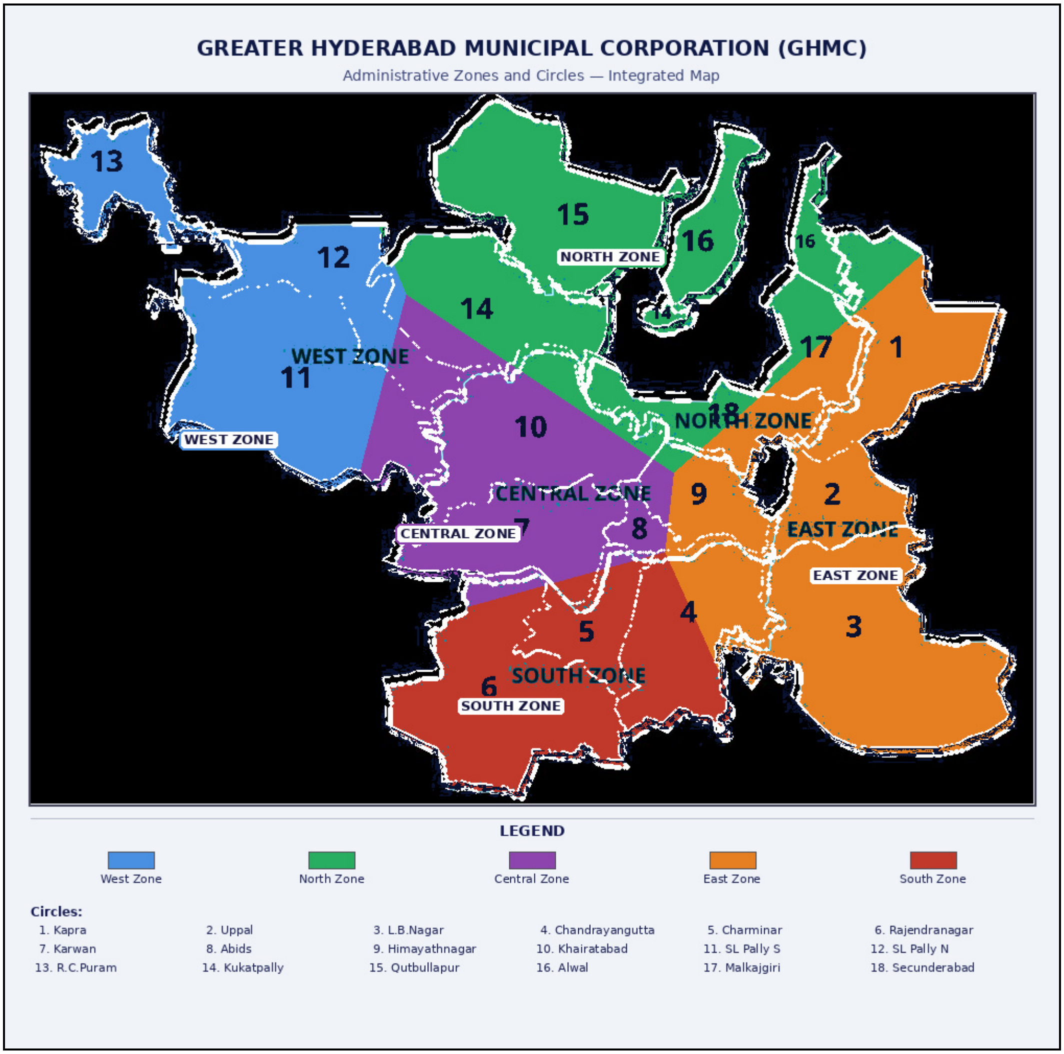

Image 1. Zone map of Greater Hyderabad Municipal Corporation (GHMC) showing the five administrative zones (East, West, North, South, and Central) and their spatial extent. (*Source*: GHMC 2016)

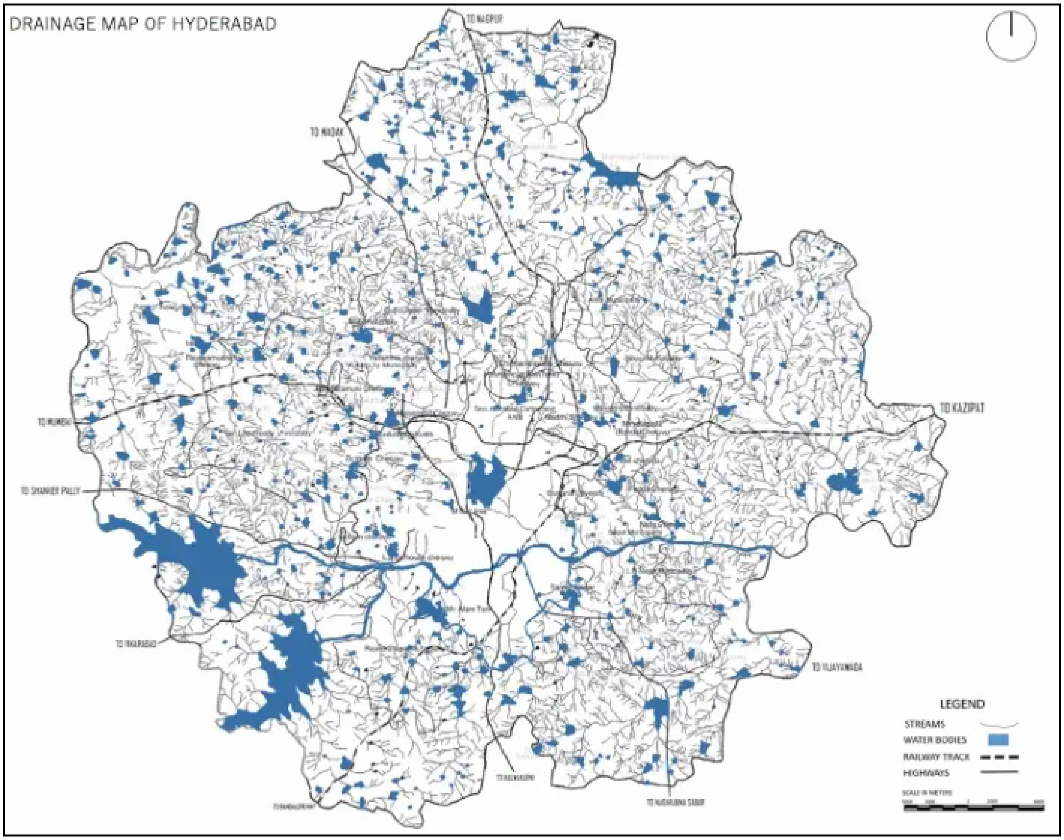

Image 2. Drainage map of Hyderabad Urban Development Authority (HUDA) area showing major water bodies, rivers (Musi), drains, and drainage networks relevant to mosquito breeding habitat distribution. (*Source*: HUDA)

Greater Hyderabad Municipal Corporation (GHMC), with a jurisdictional area of 650 km² and a population exceeding 10 million, is one of India's most rapidly urbanizing metropolises and a globally recognized technology and pharmaceutical hub. The city contains 1,476 identified slums housing approximately 1.95 million residents (CENSUS OF INDIA, 2011), and historically supported thousands of water bodies—of which fewer than 500 survive, most severely degraded by encroachment and organic pollution. The Musi River bisects the city from west to east, and its banks—particularly in the Central and South zones—are recognized hotspots of mosquito breeding. Despite its public health significance, comprehensive zone-stratified entomological surveys quantifying mosquito population dynamics and urban ecological correlates must be recorded on a periodic basis.

The present study reports: (1) mosquito species composition, and diversity across 18 sampling circles in five administrative zones of GHMC; (2) Population dynamics indicators including sex ration, blood-feeding, and swarm behavior; (3) Urban ecological associations between mosquito abundance and two key variables – proximity to water bodies and informal housing density – with implications for integrated vector management.

MATERIALS AND METHODS

***Study Area*:**

The study was conducted within the jurisdiction of GHMC, Telangana State, India (17°19'–17°33' N; 78°18'–78°38' E; elevation ~536 masl). GHMC covers approximately 650 km² and is administratively divided into five zones (East, West, North, South, and Central) comprising 150 wards and 18 circles.

The city experiences a semi-arid tropical climate with mean annual temperatures of 20–40°C, annual rainfall of approximately 812 mm concentrated in the southwest monsoon (June–September), and relative humidity of 40–90%. The Musi River traverses the city's Central and South zones. Key water bodies include Hussain Sagar (4.4 km², North Zone), Osman Sagar and Himayat Sagar reservoirs (West Zone periphery), Mir Alam Tank (South Zone), are among the major water bodies, while numerous degraded tanks and drains distributed across all zones. Informal settlement (slum) distribution is highly heterogeneous: the Central Zone contains the largest concentration (33 of 72 formally surveyed slums), followed by the West Zone (18), South (9), North (7), and East (5) zones These figures derive from contemporaneous GHMC surveys (2014-16), which align with the temporal frame of our entomological collections (2016 and 2018). See Image 1 (zone map) and Image 2 (drainage map) for spatial context.

***Mosquito Collection*:**

Indoor mosquito collections were conducted using Centre for Disease Control (CDC) miniature light traps baited with CO_2 positioned approximately 1.5 m above floor level inside residential premises across each of the 18 circles. Traps were operated from dusk to dawn (18:00–06:00 h). Outdoor collections employed sweep netting and direct sampling of resting mosquitoes in peridomestic sites. In Kapra Circle (East Zone), outdoor swarming aggregations were sampled using sweep nets during evening crepuscular hours. Collections were conducted between 2016 and 2018 at multiple points across the year to coincide with principal mosquito activity periods. . All specimens were transported to the laboratory in ice-packed containers. Swarm sampling was conducted opportunistically when aggregations were encountered, and is reported here as supplementary ecological data rather than as a standardized component of the survey.

***Specimen Identification and Data Recording*:**

All mosquitoes were identified to species under a stereomicroscope using the keys of (BARRAUD, 1934; CHRISTOPHERS, 1933; REINERT, 1975; NAGPAL & SHARMA, 1995; TYAGI et al., 2016). Sex was determined by antenna morphology. The abdominal condition of indoor females was classified as blood-fed (fully or partially engorged) or unfed. Counts were tabulated by species, circle, zone, collection method, sex, and abdominal condition.

***Urban Ecological Variables*:**

Two urban ecological variables were assessed at the zone level as potential predictors of mosquito population dynamics. (1) **Water body density:** The estimated number of proximate water bodies per zone (lakes, tanks, and major drains within or immediately adjacent to zone boundaries) was derived from Hyderabad Municipal Development Authority (HMDA) and GHMC drainage mapping. (2) **Informal housing (slum) density:** Zone-wise slum count was derived from the GHMC Slum Free City survey GHMC (2014). These variables were used to assess Spearman rank correlations with zone-level total mosquito abundance.

***Statistical Analysis*:**

All statistical analyses were performed using RS studio (R CORE TEAM, 2023) version 4.3.1. Species diversity was quantified using species richness (S), the Shannon-Wiener diversity index (H), Simpson's diversity index (D), and Pielou's evenness (J) (OKSANEN et al., 2022). A chi-square goodness-of-fit test assessed deviation from uniform species distribution. A chi-square test evaluated zone-wise heterogeneity in total abundance. The Shapiro-Wilk test confirmed violation of normality in circle-level counts; accordingly, the Kruskal-Wallis non-parametric test was applied to compare abundance across zones. Spearman rank correlation (r_s) examined relationships between: (a) total circle abundance and *Cx. quinquefasciatus* proportional dominance; (b) zone-level mosquito abundance and water body count; and (c) zone-level abundance and slum density. A chi-square test compared blood-fed to unfed female frequencies. Statistical significance was defined as $p < 0.05$. Figures were created using the R programming language.

RESULTS

Overall Mosquito Abundance and Collection:

A total of 9,021 mosquitoes representing 12 species across five genera were collected from GHMC (Table 1; Figure 1). Indoor (CDC light trap) collections yielded 5,025 specimens (55.70%) and outdoor methods accounted for 3,996 specimens (44.30%). The indoor collection comprised 4,054 females (80.67%) and 971 males (19.33%), yielding a female:male ratio of 4.18:1 (Figure 6A).

Table 1. Zone-wise indoor and outdoor mosquito abundance in Greater Hyderabad Municipal Corporation (GHMC).

Zone	Indoor (N)	(%)	Outdoor (N)	(%)	Total	% of GHMC
East	778	51.69	727	48.31	1,505	16.68
West	770	59.51	524	40.49	1,294	14.34
North	1,590	55.46	1,277	44.54	2,867	31.78
South	442	69.72	192	30.28	634	7.03
Central	1,445	53.11	1,276	46.89	2,721	30.16
GHMC Total	**5,025**	**55.70**	**3,996**	**44.30**	**9,021**	**100.00**

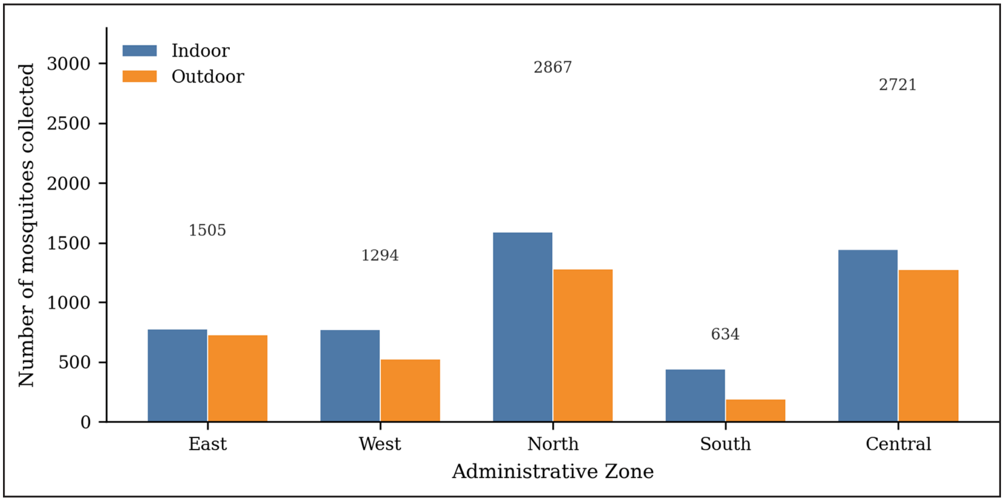

Fig. 1. Zone-wise indoor and outdoor mosquito abundance in GHMC (Total N = 9021 specimens)

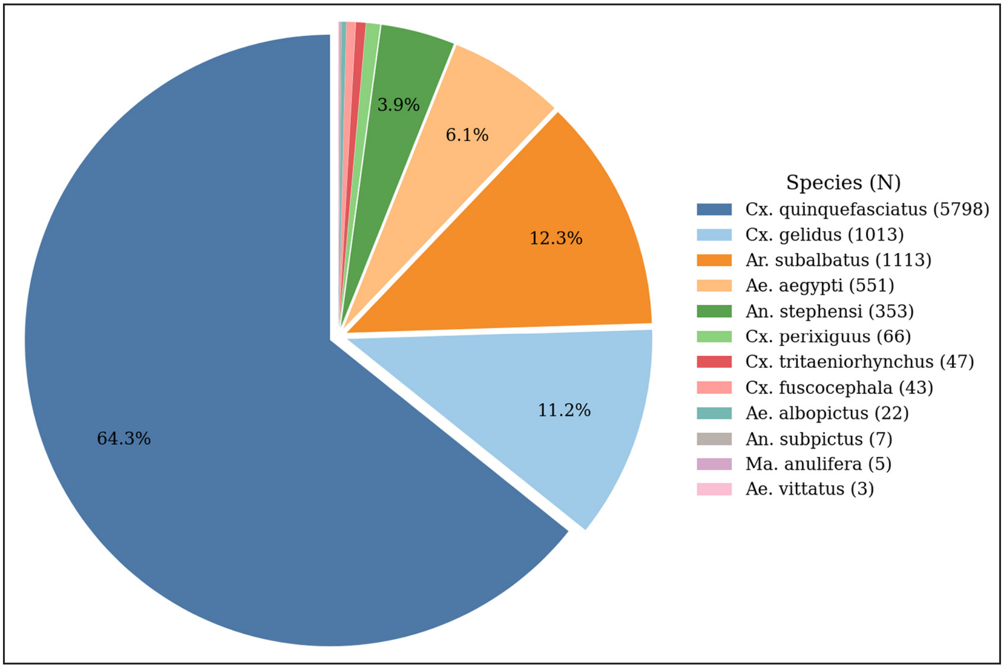

Fig. 2. Species composition of mosquitoes collected in GHMC (N = 9021 all collection methods combined)

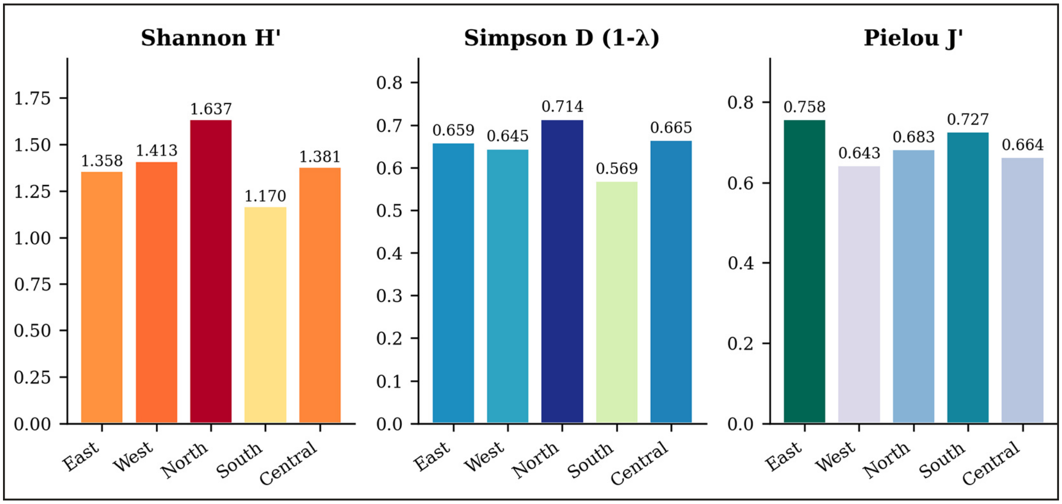

Fig. 3. Mosquito diversity indices by administrative zone (indoor collections)

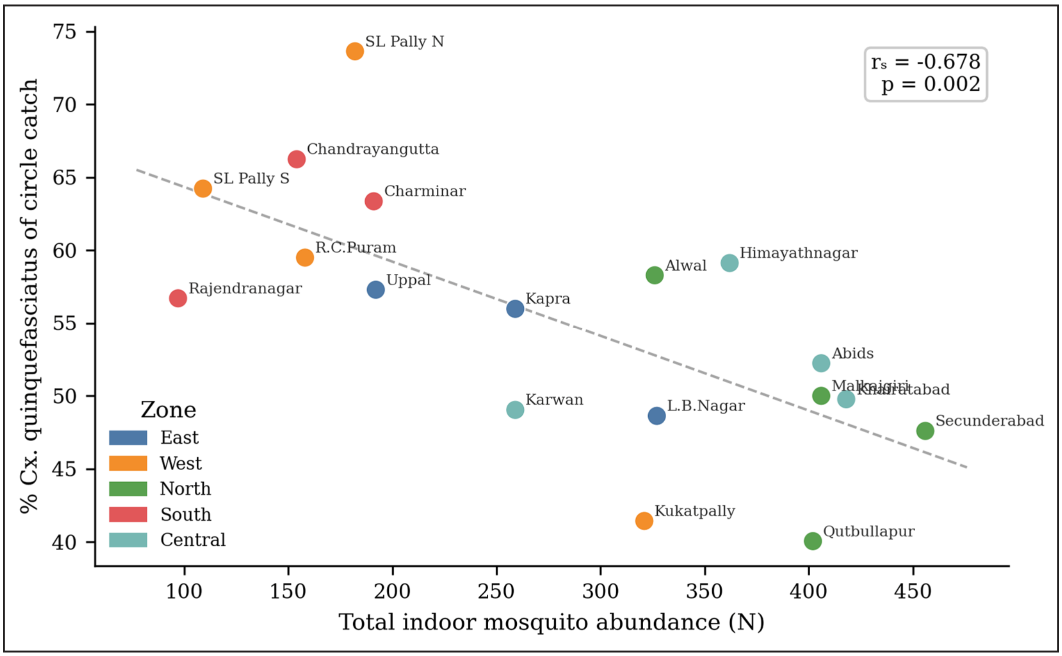

Fig. 4. Spearman correlation between circle abundance and *Cx. quinquefasciatus* dominance (r_{s} = - 0.678 p = 0.002 N = 18 circles)

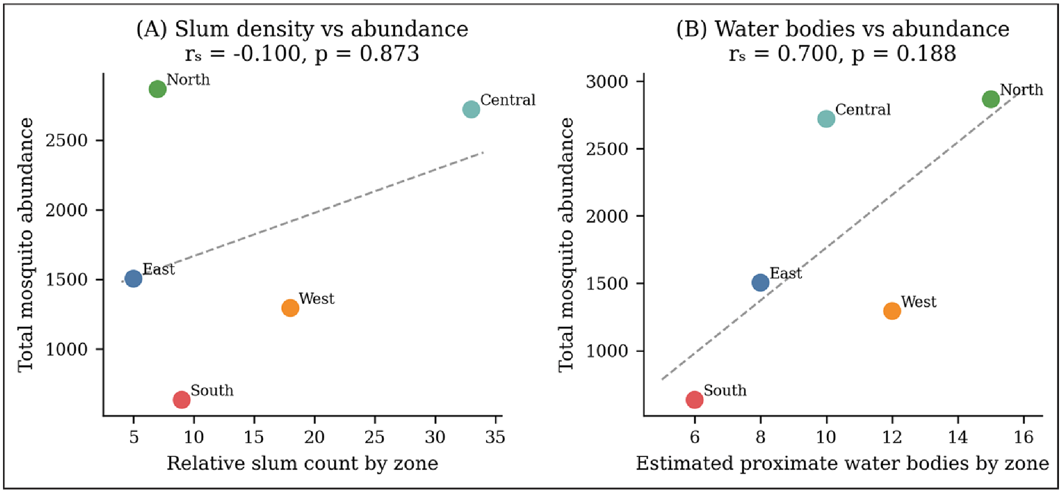

Figure 5. Association of housing type and water body proximity with mosquito population dynamics

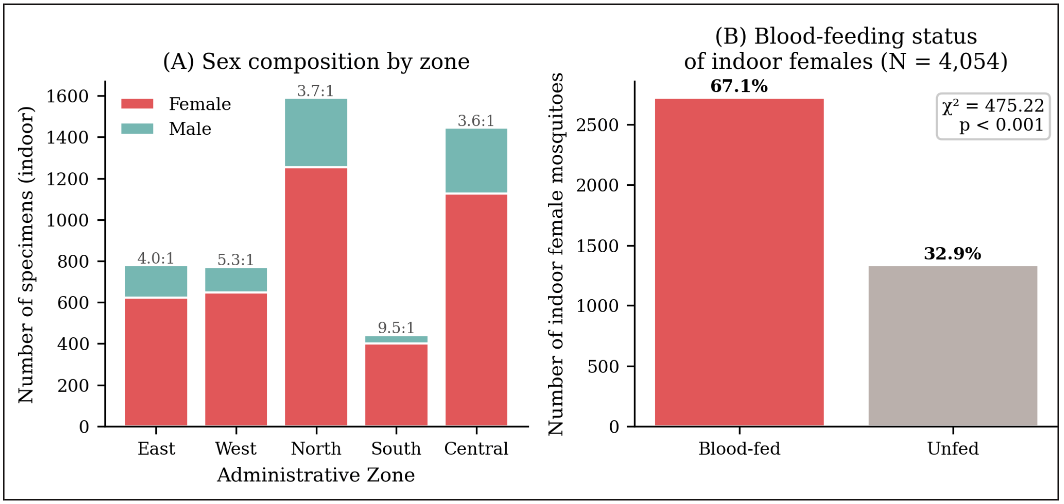

Figure 6. Sex ratios by zone and blood-feeding status of indoor female mosquitoes

***Species Composition and Population Structure*:**

Culex quinquefasciatus was overwhelmingly dominant, comprising 64.27% of all collected mosquitoes (52.84% of indoor catch; 78.65% of outdoor catch) (Table 2; Figure 2). *Armigeres subalbatus* ranked second overall (12.34%), followed by

Culex gelidus (11.23%), *Aedes aegypti* (6.11%), and *Anopheles stephensi* (3.91%). The remaining seven species—*Cx. perixiguus*, *Cx. tritaeniorhynchus*, *Cx. fuscocephala*, *Ae. albopictus*, *Ae. vittatus*, *An. subpictus*, and *Mansonia annulifera*—collectively contributed <2.15% of the total catch. Chi-square goodness-of-fit testing against a uniform distribution yielded $\chi^2 = 14{,}806.15$ (df = 11; $p < 2.2 \times 10^{-16}$), confirming an extremely non-uniform species distribution.

Table 2. Species-wise indoor and outdoor mosquito abundance in GHMC (total N = 9,021).

Species	Indoor ♀	Indoor ♂	Total Indoor	% Indoor	Outdoor	Grand Total	% GHMC
Cx. quinquefasciatus	2,103	552	2,655	52.84	3,143	5,798	64.27
Cx. gelidus	462	112	574	11.42	439	1,013	11.23
Ar. subalbatus	578	121	699	13.91	414	1,113	12.34
Ae. aegypti	471	80	551	10.97	0	551	6.11
An. stephensi	289	64	353	7.02	0	353	3.91
Cx. perixiguus	53	13	66	1.31	0	66	0.73
Cx. tritaeniorhynchus	36	11	47	0.94	0	47	0.52
Cx. fuscocephala	32	11	43	0.86	0	43	0.48
Ae. albopictus	17	5	22	0.44	0	22	0.24
An. subpictus	5	2	7	0.14	0	7	0.08
Ma. annulifera	5	0	5	0.10	0	5	0.06
Ae. vittatus	3	0	3	0.06	0	3	0.03
Total	**4,054**	**971**	**5,025**	**100.00**	**3,996**	**9,021**	**100.00**

Zone-wise Spatial Heterogeneity and Diversity:

The North Zone recorded the highest total mosquito abundance (2,867; 31.78% of GHMC total), followed by Central (2,721; 30.16%), East (1,505; 16.68%), West (1,294; 14.34%), and South (634; 7.03%) (Figure 1). Chi-square analysis confirmed highly significant spatial heterogeneity in indoor abundance across zones (χ^2 = 954.77; df = 4; $p < 0.001$).

Shannon diversity (H') for indoor collections ranged from 1.170 (South Zone) to 1.637 (North Zone). Species richness was greatest in the North (S = 11) and lowest in the South (S = 5). Pielou's evenness (J') was highest in the East Zone (J' = 0.758), indicating equitable species representation despite lower overall richness. Simpson's diversity (D) paralleled Shannon trends (Table 3; Figure 3).

Table 3. Mosquito species diversity indices by zone, GHMC (indoor collections).

Zone	N	S	H' (Shannon)	D (Simpson)	J' (Evenness)	F:M Ratio	Dominant Sp.
East	778	6	1.358	0.659	0.758	4.76:1	*Cx. quinquefasciatus*
West	770	9	1.413	0.645	0.643	4.20:1	*Cx. quinquefasciatus*
North	1,590	11	1.637	0.714	0.683	3.95:1	*Cx. quinquefasciatus*
South	442	5	1.170	0.569	0.727	4.53:1	*Cx. quinquefasciatus*
Central	1,445	8	1.381	0.665	0.664	4.03:1	*Cx. quinquefasciatus*
GHMC	**5,025**	**12**	**1.474**	**0.671**	**0.593**	**4.18:1**	***Cx. quinquefasciatus***

N = total individuals; S = species richness; H' = Shannon-Wiener index; D = Simpson's diversity (1-λ); J' = Pielou's evenness; F:M = female:male ratio.

Circle-wise Indoor Mosquito Abundance:

Circle-wise indoor catches ranged from 97 (Rajendranagar, South Zone) to 456 (Secunderabad, North Zone) (Table 4). The highest indoor abundances were in the North and Central zones, consistent with their greater water body proximity and urban habitat heterogeneity. Kruskal-Wallis analysis confirmed statistically significant inter-zone differences in circle-level abundance ($H = 12.51$; $df = 4$; $p = 0.014$; Figure 8). Spearman rank correlation between total circle abundance and the proportional contribution of *Cx. quinquefasciatus* was significantly negative ($r_s = -0.678$; $p = 0.002$; Figure 4), indicating that in circles with greater total mosquito abundance, other species contribute proportionally more—a pattern consistent with community diversification in ecologically heterogeneous habitats.

Table 4. Circle-wise indoor mosquito abundance and key species counts in GHMC.

Circle	**Zone**	**Total Indoor**	***Cx. quinquefasciatus* (N)**	***Cx. quinquefasciatus* (%)**	***An. stephensi* (N)**	***Ae. aegypti* (N)**	***Ar. subalbatus* (N)**
Kapra (1)	East	259	145	55.98	19	16	34
Uppal (2)	East	192	110	57.29	11	17	22
L.B.Nagar (3)	East	327	159	48.62	17	39	51
Chandrayangutta (4)	South	154	102	66.23	11	16	17
Charminar (5)	South	191	121	63.35	19	23	12
Rajendranagar (6)	South	97	55	56.70	6	12	8
Karwan (7)	Central	259	127	49.03	45	29	40
Abids (8)	Central	406	212	52.22	27	80	57
Himayathnagar (9)	Central	362	214	59.12	11	51	25
Khairatabad (10)	Central	418	208	49.76	9	31	97
SL Pally S (11)	West	109	70	64.22	5	15	13
SL Pally N (12)	West	182	134	73.63	2	13	8
R.C.Puram (13)	West	158	94	59.49	19	16	17
Kukatpally (14)	West	321	133	41.43	41	37	55
Qutbullapur (15)	North	402	161	40.05	34	45	52
Alwal (16)	North	326	190	58.28	21	29	71
Malkajgiri (17)	North	406	203	49.99	26	38	60
Secunderabad (18)	North	456	217	47.59	30	44	60

***Associations with Water Bodies and Informal Housing*:**

At the zone level, water body density showed a positive but statistically non-significant trend with total mosquito abundance ($r_s = 0.700$; $p = 0.188$), limited by the small sample of five zones. Qualitatively, the North Zone—with the greatest proximity to major water bodies including Hussain Sagar, Alwal Lake, Safilguda Lake, and the extensive drainage network of Malkajgiri and Secunderabad circles—recorded the highest mosquito abundance and diversity. Residential colonies established around Alwal Lake, Kapra, and Safilguda are recognized GHMC hotspots for mosquito activity. Slum density showed a negative trend ($r_s = -0.100$; $p = 0.873$) with total abundance when assessed at the zone level, reflecting the confounding of high Central Zone slum counts with that zone's lower-than-North mosquito abundance (Figure 5). However, at the circle level, circles with established informal settlements—Khairatabad, Karwan, L.B.Nagar, and Kukatpally—consistently recorded higher densities of *An. stephensi* and *Ae. aegypti* relative to lower-density circles, consistent with the known association between open water storage, inadequate drainage, and these species' breeding biology PATZ et al. (2004).

Blood-feeding Status of Indoor Females:

Among 4,054 indoor female mosquitoes, 67.12% (n ≈ 2,721) were blood-fed and 32.88% (n ≈ 1,333) were unfed. The predominance of blood-fed females was highly significant ($\chi^2 = 475.22$; df = 1; $p < 0.001$; Figure 6B), indicating intense and successful host-seeking activity within GHMC households and high vector-host contact rates.

Outdoor Swarming Behavior:

Five outdoor swarms were collected in Kapra Circle (East Zone), yielding 21,524 specimens with an extreme male bias: 21,425 males (99.54%) and 99 females (0.46%) (Table 5). *Culex quinquefasciatus* dominated swarms (94.81%; n = 20,407), followed by *Cx. gelidus* (3.40%), *Cx. fuscocephala* (1.46%), and *Ar. subalbatus* (0.33%).

Table 5. Composition and sex ratio of outdoor mosquito swarms in Kapra Circle, East Zone, GHMC.

Swarm	Species	Total (N)	Males	Females	% Male	% Female	Location
1–5 (pooled)	*Cx. quinquefasciatus*	20,407	20,347	60	99.71	0.29	Kapra Circle, East Zone
	Cx. gelidus	731	729	2	99.73	0.27	
	Cx. fuscocephala	314	313	1	99.68	0.32	
	Ar. subalbatus	72	36	36	50.00	50.00	
	Total	**21,524**	**21,425**	**99**	**99.54**	**0.46**	

DISCUSSION

Population Dynamics and Dominance of **Culex quinquefasciatus:**

The overwhelming dominance of *Cx. quinquefasciatus* (64.27% of total) at GHMC reflects its status as the quintessential synanthropic mosquito of tropical cities. This species thrives in organically enriched aquatic habitats—stagnant drains, septic overflow, sewage-contaminated water bodies—that are abundant throughout GHMC's peri-urban zones (SARKAR et al., 2013; WHO, 2004). Our finding that its proportional dominance declines significantly in circles with higher total abundance ($r_s = -0.678$; $p = 0.002$) suggests an ecological dynamic consistent with metacommunity theory (LEIBOLD et al., 2004), In biologically rich, heterogeneous habitats such as North Zone circles proximate to Hussain Sagar and Alwal Lake -secondary species coexist more equitably with *Cx. quinquefasciatus*, elevating community diversity.

***Water Bodies as Drivers of Mosquito Population Dynamics*:**

The positive association between water body density and total mosquito abundance in GHMC ($r_s = 0.700$, $p = 0.188$) was non-significant and is therefore presented as aqualitative trend rather than a statistical conclusion. Hussain Sagar and its Musi River drainage network sustain large *Cx. quinquefasciatus* and *Cx. gelidus* populations; peri-urban lakes (Alwal Lake, Safilguda, Kapra) in the North Zone support *Ar. subalbatus.* These observations highlight ecological plausibility but are not advanced as casual evidence.

***Informal Housing (Slums) and Mosquito Ecology*:**

Hyderabad's 1,476 slums represent concentrated nodes of elevated mosquito breeding risk. These conditions are precisely the ecological attributes exploited by *Cx. quinquefasciatus*, *Ae. aegypti*, and *An. stephensi*. The Central Zone, with the densest slum concentration, recorded the second-highest total mosquito abundance (2,721) and the highest absolute count of *Ae. aegypti* (191 indoor specimens). The non-significant correlation between slum density and mosquito abundance ($r_s = -0.100$; $p = 0.873$) is acknowledged as a limitation, likely reflecting confounding by intensive GHMC control operations. We therefore interpret these results cautiously and recommend future studies with finer-scale GIS buffers and control effort indices.

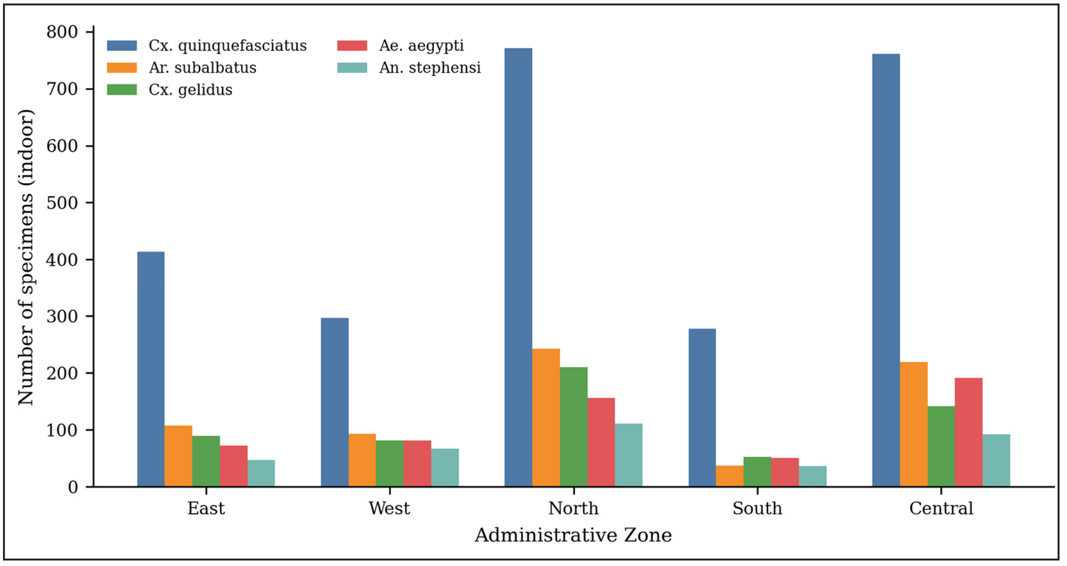

Fig. 7. Distribution of medically important mosquito species across GHMC zones (indoor collections; N = 5025)

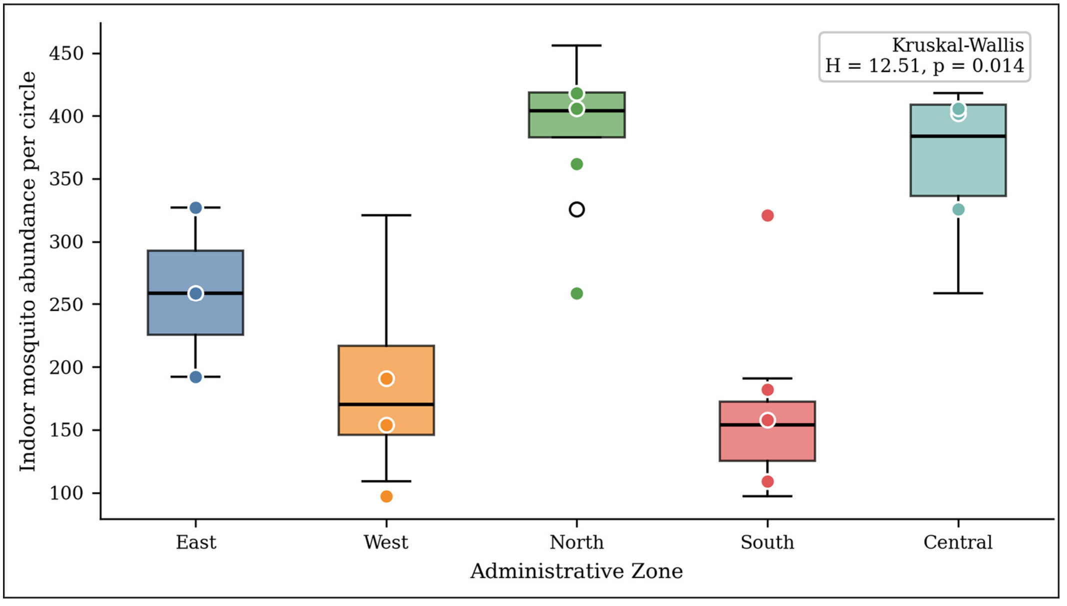

Fig. 8. Kruskal-Wallis test: circle-level mosquito abundance by zone p = 0.014) (H = 12.51 df = 4

Anopheles stephensi: ***An Urban Malaria Vector of Escalating Concern:***

Anopheles stephensi was recovered from all five zones (353 specimens; 3.91%), including circles with high slum densities. It is established across GHMC, coupled with high blood-feeding rates, implies malaria transmission potential. This species breeds in overhead tanks, cisterns, construction site water accumulations, and ornamental containers—habitats distributed across all socio-economic strata of Hyderabad (SHARMA, 1996). This is particularly concerning given *An. stephensi's* recent invasion of East African cities (SEYFARTH et al., 2019), which has been linked to its behavioral plasticity in urban environments strikingly similar to Hyderabad's.

Aedes aegypti, ***Arboviral Risk, and Hyderabad's Cosmopolitan Status:***

Aedes aegypti (551 specimens; 6.11%) was present in all zones, while the detection of *Ae. albopictus* provides a secondary arboviral vector pathway. Hyderabad's international airport underscores the city's global connectivity; however, this study does not present direct entomological data linking air travel to arboviral introductions. This contextual note is retained to highlight background risk, not as a data-driven conclusion. Given the city's high passenger traffic and international linkages, Hyderabad remains among India's potential gateways for imported dengue and Zika strains, with local amplification risk supported by the presence of competent vector species (BOGOCH et al., 2016; DHAR-CHOWDHURY et al., 2017; NAIK et al., 2023).

Swarming Behavior and Its Implications for Population Dynamics:

The five outdoor swarms in Kapra Circle (21,524 specimens; 99.54% male) represent some of the largest documented urban mosquito swarms in India. The extreme male predominance (M:F = 216:1) is diagnostic of mating aggregations (CHARLWOOD & JONES 1979; REISEN et al., 1986). These observations are integrated into the discussion as supplementary reproductive ecology data rather than standard outcome. Targeted adulticide application at known swarming sites during peak mating periods could reduce subsequent egg-laying and represent a resource-efficient supplementary control strategy (KARPATI et al., 2005).

Implications for Integrated Vector Management:

The zone-stratified data support evidence-based resource prioritization in GHMC. Limitations include reliance on zone-level ecological variables, absence of GIS buffer quantification, and non-significant correlations that restrict casual inference. These are acknowledged as baseline constraints, with future work recommended to incorporate multivariate models and spatially explicit predictors.

CONCLUSION

This study provides a zone-stratified characterization of mosquito population dynamics in Greater Hyderabad Municipal Corporation. Twelve species were documented across 18 sampling circles and five zones (total N = 9,021), with *Cx. quinquefasciatus* accounting for 64.27% of specimens. Significant non-uniform species distribution ($\chi^2 = 14{,}806.15$; $p < 0.001$) and inter-zone spatial heterogeneity ($\chi^2 = 954.77$; $p < 0.001$; Kruskal-Wallis $H = 12.51$; $p = 0.014$) were established. The North Zone recorded the highest species richness (S = 11) and diversity (H' = 1.637), consistent with its concentration of surviving water bodies. The Central Zone's highest slum density corresponded with elevated *Ae. aegypti* abundance, highlighting the link between informal housing and dengue risk. A negative correlation ($r_s = -0.678$; $p = 0.002$) between circle abundance and *Cx. quinquefasciatus* dominance suggests community diversification in ecologically complex habitats. The high blood-feeding rate (67.12%; $\chi^2 = 475.22$; $p < 0.001$) and widespread *An. stephensi* distribution indicate urban malaria transmission potential. Observations of large multi-species swarms (>21,000 individuals) contribute novel reproductive ecology data for urban India. These findings underscore the need for zone-specific, ecologically informed vector management in GHMC. Recommended priorities include water body restoration, improved sanitation in informal settlements, and strengthened surveillance for arboviral vectors. Policy implications are framed as evidence-informed suggestions rather than prescriptive directions, acknowledging that further GIS-based multivariate analyses are required to fully support operational planning.

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