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Mosquito diversity across altitudinal and land-use gradients in tropical Indonesia

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Abstract. *Jasmi RA, Hidayat E, Kurnia MF. 2026. Mosquito diversity across altitudinal and land-use gradients in tropical Indonesia. Biodiversitas 27 (2): d270227. https://doi.org/10.13057/biodiv/d270227.* Altitudinal variation is an important environmental factor influencing the distribution and dynamics of vector insect communities in tropical regions. However, information on how elevational gradients affect mosquito distribution and diversity in Banten Province remains limited. This study aimed to examine the association between elevation and key environmental factors in shaping mosquito diversity. Sampling was conducted at 13 sites ($n = 13$) across an elevational range of 12-815 masl. Mosquitoes were collected between 18:00 and 06:00 WIB (UTC+07:00). Environmental parameters recorded included air temperature, relative humidity, land-use category, vegetation, and the availability of aquatic habitats. Relationships between elevation, temperature, and humidity with abundance were analyzed using Spearman correlation. Differences in diversity among elevational zones were tested using the Kruskal-Wallis test, followed by Dunn's post hoc test. A total of 3,528 mosquitoes representing nine species and five genera were collected. Total mosquito abundance declined sharply with increasing elevation and was strongly negatively correlated with elevation ($r = -0.93$, $p<0.001$) but positively correlated with air temperature ($r = 0.77$, $p = 0.02$). *Culex quinquefasciatus* (79.13%) and *Culex vishnui* (19.27%) dominated lowland areas, whereas *Armigeres subalbatus* showed increased abundance at higher elevations. Species richness remained relatively stable along the elevational gradient (2-4 species), indicating that elevation primarily influenced species dominance and abundance distribution rather than the number of species present. These findings suggest that elevation is strongly associated with mosquito diversity. Based on vector abundance and composition, potential transmission risk may be higher in lowland areas; however, pathogen prevalence was not assessed in this study. Because the study was observational, with possible collinearity between elevation and temperature and limited high-elevation replication, causal interpretations should be made cautiously.

Keywords: Banten, *Culex quinquefasciatus,* elevational gradient, microclimate, species distribution

INTRODUCTION

Mosquitoes are major vectors of infectious diseases that remain significant public health challenges in tropical and subtropical regions, including dengue, chikungunya, filariasis, and malaria (Abraham et al. 2024; Listiono et al. 2024; Minwuyelet et al. 2025; Visser et al. 2025). Understanding patterns of mosquito diversity and abundance in relation to environmental factors is therefore essential not only for epidemiology but also for ecology. Beyond their medical relevance, mosquitoes are integral components of freshwater and terrestrial food webs, serving as prey, occasional pollinators, and contributors to nutrient cycling. Shifts in mosquito diversity composition may thus signal broader habitat transformation, land-use change, and microclimatic variation. Viewing mosquitoes simultaneously as disease vectors and ecological indicators enables biodiversity-based insights to inform applied vector management.

Mosquito distribution and abundance are shaped by temperature, humidity, vegetation structure, larval habitat availability, and human activity (da Silva and Scalize 2023; Chaiphongpachara et al. 2024). Altitudinal gradients offer a natural framework to examine these drivers because elevation systematically influences temperature, moisture, and habitat configuration. Studying mosquito communities along elevational gradients, therefore, provides insight into how environmental heterogeneity and anthropogenic pressure interact to structure vector assemblages.

Banten Province, at the western tip of Java Island, encompasses diverse landscapes ranging from hot, humid coastal lowlands to cooler mountainous regions with denser vegetation. This environmental heterogeneity creates ecological gradients likely to influence mosquito diversity. The close juxtaposition of coastal settlements, agricultural areas, peri-urban zones, and montane habitats makes Banten a suitable natural system for examining spatial variation in mosquito assemblages. Elevation-related differences in microclimate and land use may shape species dominance patterns, particularly among medically important genera such as *Aedes*, *Culex*, and *Anopheles*.

Despite this suitability, studies of mosquito ecology along elevational gradients in Banten remain limited. Research in Indonesia has often been geographically restricted or focused on single taxa. For instance, Sayono et al. (2017) analyzed the relationship between elevation and *Aedes aegypti* larval density in Central Java, while Ndoen et al. (2010) examined anopheline distribution and diversity. Although informative, these studies did not assess mosquito diversity across multiple genera along elevational and land-use gradients. In contrast, the present study is operationally "comprehensive": it integrates multi-site sampling along a continuous elevational range, includes multiple mosquito genera, applies standardized nocturnal adult collections, and records microclimatic variables concurrently at each site. This design enables direct comparison of abundance, dominance, and diversity within a unified analytical framework.

Climate change and land-use conversion are expected to alter mosquito distributions and potentially modify disease transmission dynamics. Empirical data on mosquito diversity across elevational gradients are therefore critical for understanding ecological responses to environmental change and for supporting adaptive vector management.

This study analyzes the association between elevation and mosquito diversity in Banten Province, identifies environmental variables correlated with variation in abundance and composition, and describes dominance patterns across ecological zones from coastal lowlands to mountainous areas. We hypothesize that mosquito diversity varies systematically along the elevational gradient, with declining total abundance and shifts in species dominance at higher elevations. We further hypothesize that temperature is the primary environmental variable associated with changes in abundance and composition, whereas habitat characteristics—including the presence of aquatic breeding sites—were recorded observationally and interpreted qualitatively rather than quantitatively tested. Species richness is expected to remain relatively stable along the gradient.

Accordingly, this study addresses three questions: (i) how do mosquito abundance, diversity, and dominance differ among lowland, mid-elevation, and highland zones; (ii) how are these patterns associated with elevation-related microclimatic variables, particularly air temperature and humidity; and (iii) which species exhibit the strongest elevational responses across ecological zones in Banten Province? By integrating ecological and applied perspectives, this research advances understanding of how environmental gradients structure mosquito communities while remaining relevant for regional vector surveillance and ecosystem-based control planning.

MATERIALS AND METHODS

Study area

The study was conducted from November 2021 to December 2022 in Banten Province, Indonesia (Figure 1). Mosquito sampling in the lowland areas of Serang City was conducted during November and December 2021, whereas sampling in the Mount Karang region (mid- and high-elevation zones) was carried out during November and December 2022. Mosquito sampling was performed at 13 observation sites representing an elevational range between 12 and 815 m above sea level (masl) (Table 1). The study locations were categorized into three main zones: lowland areas in Serang City (<350 masl), mid-elevation zones (350-700 masl), and high-elevation zones (>700 masl) in the Mount Karang region, Pandeglang Regency.

Table 1. Sampling locations in Banten Province, Indonesia

Sampling location	Elevation	Coordinate point
Serang City		
Point 1	12 m asl	-6.06535, 106.15483
Point 2	14 m asl	-6.07372, 106.15306
Point 3	24 m asl	-6.12192, 106.17863
Point 4	28 m asl	-6.12254, 106.17491
Point 5	39 m asl	-6.15768, 106.17167
Point 6	64 m asl	-6.17906, 106.16518
Mount Karang		
Point 7	389 m asl	-6.28947, 106.09991
Point 8	474 m asl	-6.28676, 106.09248
Point 9	555 m asl	-6.27868, 106.09150
Point 10	624 m asl	-6.26766, 106.08940
Point 11	673 m asl	-6.26342, 106.08264
Point 12	752 m asl	-6.26376, 106.07819
Point 13	815 m asl	-6.26431, 106.07484

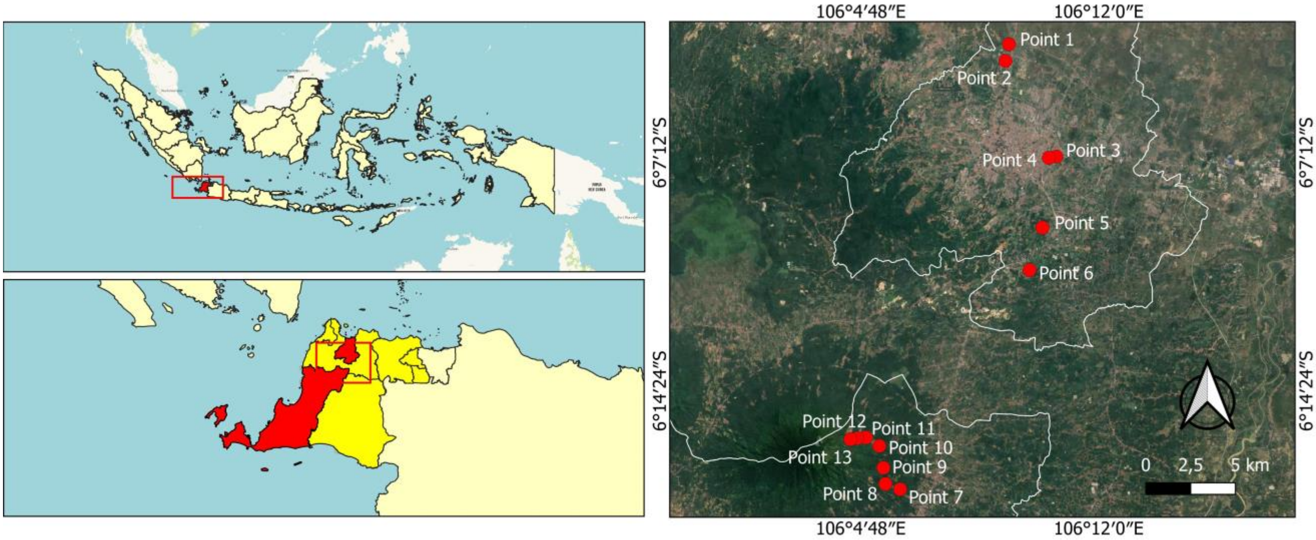

Figure 1. Map of 13 sampling locations in Serang City and Mount Karang, Pandeglang Regency, Banten Province, Indonesia

Procedures

Adult mosquitoes were collected at each sampling point for two sampling nights at each elevational site. Sampling was conducted under non-rainy weather conditions, both indoors and outdoors, with standardized sampling effort across all locations, including equal sampling duration (18:00-06:00 WIB; UTC+07:00). At each site, four trained collectors participated, with two assigned indoors and two outdoors. Collectors were rotated every two hours between indoor and outdoor positions to reduce collector-related bias and variation in sampling effort. Mosquitoes were captured using insect nets and aspirators. These active collection methods were selected to enable targeted sampling of host-seeking and resting mosquitoes in both indoor and outdoor environments under standardized human landing exposure conditions. We acknowledge that this approach is collector-dependent and may introduce detectability bias, potentially favoring easily accessible or resting individuals. Species more responsive to passive trapping methods (e.g., light traps) may therefore be underrepresented in the dataset, and this limitation is considered in the interpretation of results. Collected specimens were placed in labeled collection cups and transported to the laboratory for identification. All sampling activities were conducted with permission from local authorities and property owners. Collectors provided informed consent and used appropriate protective measures during sampling.

Morphological identification was performed under a stereo microscope at 20× and 40× magnification using standard identification keys to the species level, following the WHO Pictorial Identification Key of Important Disease Vectors in the WHO South-East Asia Region (WHO 2020) and the Illustrated Keys to the Mosquitoes of Thailand series (Rattanarithikul et al. 2005, 2006, 2010). Voucher specimens were preserved and deposited in the Biology Laboratory, Faculty of Science, UIN Sultan Maulana Hasanuddin Banten, as a reference collection for future verification.

During each sampling night, air temperature and relative humidity were recorded hourly using a digital thermohygrometer (Extech 44570). The instrument was placed at a height of approximately 1.5 m above ground level, at least 1 m away from walls or other hard surfaces, and housed in a simple radiation shield consisting of a light-colored, ventilated plastic container to avoid direct exposure to sunlight or rain. The use of a radiation shield was intended to improve measurement consistency among sites. According to manufacturer specifications, the instrument has an accuracy of approximately ±1°C for temperature and ±4% for relative humidity, and these uncertainties were considered when interpreting microclimatic differences among sites. Prior to field deployment, the consistency of instrument readings was verified using a simple two-point reference approach to ensure measurement stability. Temperature and humidity measurements were intended to capture relative differences among locations rather than absolute microclimatic values. Hourly measurements were averaged to obtain nightly estimates of temperature and humidity, and data from two sampling nights were combined to generate mean values for each location. Other environmental variables—including land-use type, vegetation presence, water sources, and the presence of domestic animals—were systematically recorded using standardized observation sheets. Indoor and outdoor catches were pooled as total nightly catches and subsequently accumulated to obtain total catches per site.

Data analysis

The collected data were analyzed descriptively, and relative abundance, species richness, and biodiversity indices were calculated.

$$\text{Relative Abundance (\%)} = \left(\frac{n_i}{N}\right) \times 100$$

Where, n_i: the number of individuals of species *i* or at elevation *i*, and *N*: the total number of individuals of all species.

Species richness (S) was calculated as the total number of species recorded at each site, where higher S values indicate a greater number of species.

Data analysis also employed several biodiversity indices to assess the mosquito diversity at each location, namely Simpson's dominance index, Simpson's diversity index, Shannon's diversity index, and Pielou's evenness index (Magurran 2004). Values of each biodiversity index were interpreted comparatively among sampling locations to evaluate relative differences in diversity rather than assigning rigid categorical labels.

The level of dominance was calculated using Simpson's dominance index (D):

$$D = \sum \left(\frac{n_i}{N}\right)^2$$

Where, values approaching 1 indicate the presence of a highly dominant species, and values approaching 0 indicate a more even assemblage.

Diversity values were calculated using Simpson's diversity index (1-D):

$$1 - D = 1 - \sum \left(\frac{n_i}{N}\right)^2$$

Where, values approaching 1 indicate high diversity, and values approaching 0 indicate low diversity.

Shannon's diversity index (H'):

$$H' = -\sum \left(\frac{n_i}{N}\right) \ln \left(\frac{n_i}{N}\right)$$

Where, values approaching 0 indicate low diversity, and values approaching 4 indicate high diversity.

The Pielou's evenness index (J):

$$J = \frac{H'}{\ln(S)}$$

Where, J values approach 1, it indicates that all species have nearly equal numbers of individuals, whereas values approaching 0 indicate that one or a few species are highly dominant.

All statistical analyses employed non-parametric approaches because the sample size per location was relatively small (n = 13) and most variables did not meet the assumption of normality based on the Shapiro-Wilk test. Relationships between elevation, temperature, and relative humidity with both total mosquito abundance and species-specific abundance were examined using Spearman's rank correlation. Correlations involving total abundance and diversity-level indices were defined a priori as primary analyses, whereas species-level correlations were considered exploratory. In addition to adjusted p-values, results were interpreted conservatively by emphasizing effect size (correlation coefficient) and consistency of ecological patterns rather than statistical significance alone. Differences in abundance, biodiversity indices, and species richness among the three elevational zones were tested using the Kruskal-Wallis test. Pairwise differences among zones were subsequently assessed using Dunn's post hoc test (Dunn 1964) with Bonferroni correction. However, the high-elevation zone included only two sampling sites (n = 2), resulting in unbalanced group sizes and reduced stability of post hoc inference. Therefore, pairwise comparisons involving the high-elevation zone should be interpreted with caution. To complement significance testing, descriptive comparisons and effect size estimates were also examined, particularly for contrasts involving the high-elevation group. All statistical analyses were performed using SPSS v27.

Given the very strong correlation between elevation and temperature, collinearity was recognized as an important limitation in interpreting the results. The correlation between elevation and temperature was formally tested; however, because the study design was observational, the independent effects of these two variables could not be clearly disentangled. Consequently, simple regression or partial correlation analyses were treated as exploratory and were not intended for causal inference. In addition, due to the large number of statistical tests conducted across multiple species and diversity indices, p-values were interpreted conservatively to avoid overinterpretation.

RESULTS AND DISCUSSION

Environmental conditions and microclimatic parameters

The environmental conditions at each sampling point showed clear variation along the altitudinal gradient in Banten Province. The lowland areas in Serang City were dominated by urban to semi-urban zones, the mid-elevation zone of the Mount Karang area shifted to semi-urban to rural environments, and the highland zone was entirely rural with low anthropogenic activity (Table 2).

Mean air temperature declined with elevation, with a difference of 7.07°C outdoors and 6.53°C indoors between the lowland coast and the highest settlement on Mount Karang. Relative humidity showed more fluctuation among sites; however, it generally tended to be higher at higher elevations (Table 3). This pattern confirms that the elevational gradient in the study area generates distinct and consistent microclimatic conditions.

Table 2. Land characteristics and area categories at different elevations

Main zone	Location elevation (masl)	Area category	Land characteristics	Natural aquatic habitats*	Artificial aquatic habitats**
Lowland	12	Urban	Flat, trees, rice fields and irrigation networks with turbid water	✓	✓
	14	Urban	Flat, dominated by drainage ditches and domestic water puddles	✓	✓
	24	Urban	Flat, limited natural vegetation (shrubs and grasses)	-	✓
	28	Urban	Flat, dense residential area with minimal natural vegetation	✓	✓
	39	Semi-urban	Flat, wetlands, rice field areas, and small river streams	✓	✓
	64	Semi-urban	Flat, relatively dense tree vegetation	✓	-
Mid-elevation	389	Semi-urban	Slope, dominated by trees, presence of domestic animals (chickens, ducks)	✓	✓
	474	Semi-urban	Slope, tree vegetation, domestic animals (chickens, ducks)	✓	✓
	555	Rural	Slope, agricultural area, trees, domestic animals (chickens, ducks, dogs)	-	✓
	624	Rural	Slope, agricultural area, trees, domestic animals (chickens, ducks, dogs)	✓	✓
	673	Rural	Slope, agricultural area, trees, domestic animals (chickens, ducks, geese, dogs)	✓	✓
Highland	752	Rural	Slope, agricultural area, trees, domestic animals (chickens, ducks, geese, dogs)	✓	✓
	815	Rural	Slope, agricultural area, trees, domestic animals (chickens, ducks, geese, dogs), many goat pens	✓	✓

Note: *Natural aquatic habitats include wetlands, rice fields, irrigation channels, rivers/streams, natural puddles, and phytotelmata (e.g., tree holes and leaf axils). Among these habitat types, phytotelmata were the most consistently observed and were recorded at the majority of sampling sites. **Artificial aquatic habitats include drainage ditches, domestic water containers, animal drinking containers, discarded containers such as used cans and plastic bottles, and other man-made water-holding structures. Among these habitat types, discarded containers (e.g., cans and bottles) were commonly encountered across sampling sites

Table 3. Mean air temperature and relative humidity at each sampling site along the elevational gradient

Microclimatic parameter	Location elevation (masl)												
	12	**14**	**24**	**28**	**39**	**64**	**389**	**474**	**555**	**624**	**673**	**752**	**815**
Mean outdoor Temperature (°C)	26.88	28.68	25.87	25.98	27.18	25.87	23.48	23.25	23.49	23.67	22.67	21.81	21.61
Mean indoor Temperature (°C)	28.41	29.17	27.12	26.77	28.6	26.87	24.94	24.45	23.87	24.4	23.26	23.06	22.64
Mean outdoor Humidity (%)	90.16	80.5	88.16	87.83	88.29	88.25	86.33	90.66	86.45	76.83	86.91	94.08	85.12
Mean indoor Humidity (%)	81.04	76.5	78.29	76.75	78.16	82.25	82.91	81.91	86.29	74	83.16	82.41	79.66

Mosquito abundance and elevational patterns

A total of 3,528 individual mosquitoes representing 9 species from 5 genera—*Culex, Armigeres, Aedes, Mansonia*, and *Anopheles*—were recorded. Abundance was highest in the warm lowland coastal areas and declined progressively with increasing elevation, reaching its lowest value at the highest settlement on Mount Karang. Spearman's correlation analysis revealed a strong negative association between elevation and mosquito abundance ($p < 0.001$; $r = -0.934$). The highest density was recorded at 12 masl (1,093 individuals), whereas the lowest occurred at 815 masl (14 individuals), confirming a sharp decline in abundance along the elevational gradient (Figure 2).

Distribution of mosquito genera and species along the elevational gradient

The genus *Culex* dominated the mosquito assemblage, particularly *Culex quinquefasciatus*, with a relative abundance of 79.13% (2,792 individuals) and *Culex vishnui* with a relative abundance of 19.27% (680 individuals). Both *Cx. quinquefasciatus* and *Cx. vishnui* were present at all sampling points, with the highest abundances recorded in the warm lowland sites along the coast, gradually declining toward the highland areas. At nearly all elevations, *Cx. quinquefasciatus* remained the dominant species, except at 815 m asl, where the abundances of *Cx. quinquefasciatus* and *Cx. vishnui* were nearly equal. Several species exhibited restricted elevational distributions. *Culex gelidus* (relative abundance 0.05%; 2 individuals) was recorded only at the highest elevation. *Anopheles subpictus* (0.02%; 1 individual) and *Mansonia annulifera* (0.02%; 1 individual) were found exclusively at 39 m asl, whereas *Mansonia annulata* (0.14%; 5 individuals) occurred only at 389 and 555 m asl. *Aedes albopictus* (0.28%; 10 individuals) appeared sporadically across low, mid, and high elevations, while *Aedes aegypti* (0.39%; 14 individuals) was consistently recorded in lowland sites but occurred only sporadically in mid- and high-elevation areas. *Armigeres subalbatus* was rarely found in lowland areas characterized by dense human settlements and limited natural vegetation, yet it was consistently present at elevations above 555 m asl, peaking at 624 m asl and declining again toward 815 masl (Table 4).

Spearman's correlation analysis revealed a strong negative relationship between elevation and the abundance of *Cx. quinquefasciatus* ($p<0.001$; $r = -0.940$) as well as *Cx. vishnui* ($p = 0.016$; $r = -0.649$), indicating a marked decline in the abundance of both species with increasing elevation. In contrast, *Ar. subalbatus* showed a strong positive correlation with elevation ($p = 0.017$; $r = 0.646$), suggesting that its abundance increased at higher altitudes. Because the assemblage was overwhelmingly dominated by *Cx. quinquefasciatus* (79.13%) and *Cx. vishnui* (19.27%), species-level correlation analyses were restricted to taxa with sufficient abundance to ensure statistical robustness. For rarer taxa with very low individual counts, correlation results were treated as descriptive only and were interpreted with caution due to potential instability arising from sparse data.

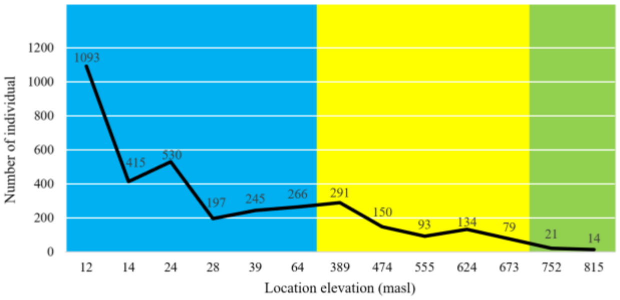

Figure 2. Total number (abundance) of mosquitoes recorded at each elevation point. Blue indicates the low-elevation zone, yellow the mid-elevation zone, and green the high-elevation zone

Table 4. Relative abundance and number of each nocturnal mosquito species recorded at each elevation point

Species	Location elevation (masl)													Total	Relative abundance
	12	14	24	28	39	64	389	474	555	624	673	752	815		
Cx. quinquefasciatus	696	367	406	179	241	195	261	148	89	126	67	12	5	2,792	79.13%
Cx. vishnui	394	46	122	14	1	69	18	2	1	1	1	5	6	680	19.27%
Cx. gelidus	-	-	-	-	-	-	-	-	-	-	-	-	2	2	0.05%
Ar. subalbatus	-	-	1	-	-	1	5	-	1	7	5	2	1	23	0.65%
Ae. aegypti	1	1	1	4	1	-	2	-	1	-	2	1	-	14	0.39%
Ae. albopictus	2	1	-	-	-	1	1	-	-	-	4	1	-	10	0.28%
Ma. annulata	-	-	-	-	-	-	4	-	1	-	-	-	-	5	0.14%
Ma. annulifera	-	-	-	-	1	-	-	-	-	-	-	-	-	1	0.02%
An. subpictus	-	-	-	-	1	-	-	-	-	-	-	-	-	1	0.02%
Total	1,093	415	530	197	245	266	291	150	93	134	79	21	14	3,528	

Relationship between microclimatic parameters and mosquito abundance

The elevational gradient showed a strong and significant negative relationship with outdoor and indoor air temperature, reflecting a decrease in temperature with increasing elevation. In contrast, elevation did not exhibit a significant relationship with outdoor and indoor relative humidity (Table 5). Outdoor temperature was significantly and positively associated with total mosquito abundance (p = 0.02; r = 0.773), indicating that warmer microclimatic conditions were linked to higher abundance. Similarly, indoor air temperature was strongly and positively correlated with total mosquito abundance ($p<0.001$; $r = 0.896$), whereas indoor relative humidity showed no significant association ($p = 0.334$). In contrast, outdoor relative humidity showed no significant relationship ($p = 0.748$). At the species level, outdoor temperature was significantly and positively correlated with the abundance of *Cx. quinquefasciatus* ($p = 0.001$; $r = 0.792$), and this relationship was even stronger for indoor temperature ($p = 0.001$; $r = 0.912$). In contras *Ar. subalbatus* exhibited a significant negative correlation with outdoor temperature ($p = 0.031$; $r = -0.598$), and a similarly significant negative correlation with indoor temperature ($p = 0.025$; $r = -0.615$). Other species demonstrated no meaningful associations with either temperature or humidity. Several taxa were represented by very low numbers of individuals ($n = 1$-5) and were recorded at only a single site (e.g., *Anopheles subpictus* and *Mansonia annulifera*). Therefore, no strong ecological inferences regarding elevational limitation or microclimatic preferences were made for these rare taxa. Their occurrence is treated as preliminary detection records that require confirmation through additional sampling. Taken together, and primarily driven by patterns observed in the dominant and sufficiently abundant taxa, these findings indicate that temperature is the most influential microclimatic factor determining both species-specific and total abundance patterns, particularly along the elevational gradient where temperature decreases markedly.

Diversity, dominance, and inter-species distribution of individuals

The diversity indices showed consistent patterns along the elevational gradient. In the low to mid-elevation areas (12-673 m asl), mosquito communities were dominated by one or two species, with relatively high Simpson's dominance index values (0.53-0.97). This was accompanied by low diversity, reflected in Simpson's diversity index values ranging from 0.03 to 0.46 and Shannon's diversity index values from 0.10 to 0.67. Low Pielou's evenness index values (0.06-0.48) indicated uneven distribution of individuals among species in these elevation zones. In contrast, mosquito communities at high elevations (752-815 m asl) exhibited a distinct structure. Dominance values were lower (0.33-0.39), while diversity levels were higher, as indicated by increased Simpson's diversity index (0.60-0.66) and Shannon's diversity index (1.17-1.19). Species evenness was also greater at these elevations, with Pielou's evenness index ranging from 0.73 to 0.86. Species richness was relatively uniform along the altitudinal gradient, with the number of species ranging from two to six per site (Table 6). Consistent with Table 7, species richness did not differ significantly among elevational zones. However, differences in detectability across land-use types and sampling methods—particularly for diurnal or crepuscular *Aedes* species—may have influenced richness estimates and should be considered when interpreting these patterns.

The Shapiro-Wilk test confirmed that all mosquito diversity variables—total abundance, Simpson's dominance index, Simpson's diversity index, Shannon's diversity index, Pielou's evenness index, and species richness—did not meet the assumption of normality ($p < 0.05$). Therefore, non-parametric analyses were applied. Sample sizes for each elevational zone and the complete Kruskal-Wallis test statistics for each variable are presented in Table 7. The results indicated significant differences among elevational zones for several mosquito diversity attributes, including total abundance, dominance, dominance-based diversity, and species evenness. In contrast, Shannon's diversity index and species richness did not differ significantly among elevational zones. Although Shannon's diversity index showed a tendency toward marginal significance, this pattern was treated as statistically non-significant and cautiously interpreted as weak variation along the elevational gradient.

Post hoc analysis using Dunn's test with Bonferroni correction showed that significant differences in mosquito abundance occurred primarily between the low- and high-elevation zones (adjusted *p* = 0.023), whereas comparisons between the high-middle (adjusted *p* = 0.625) and middle-low zones (adjusted *p* = 0.186) were not statistically significant. For Simpson's dominance index, a significant difference was detected between the high- and middle-elevation zones (adjusted *p* = 0.039), while the high-low (adjusted *p* = 0.313) and low-middle zone pairs (adjusted *p* = 0.641) did not differ significantly. A similar pattern was observed for Simpson's diversity index, with a significant difference between the high- and middle-elevation zones (adjusted *p* = 0.039), whereas the other zone pairs did not show statistically meaningful differences (high-low: adjusted *p* = 0.313; low-middle: adjusted *p* = 0.641). For Pielou's evenness index, a significant difference was again identified between the middle- and high-elevation zones (adjusted *p* = 0.038), while comparisons between the high-low (adjusted *p* = 0.311) and low-middle zones (adjusted *p* = 0.639) were not significant.

Given that the high-elevation zone was represented by only two sites (752-815 m asl), post hoc results should be interpreted cautiously, as values may disproportionately influence comparisons from a single location. To complement p-values, median and interquartile range (IQR) values are reported for each elevational zone. For total abundance, medians (IQR) were 340.5 (250.3-501.3) in the low zone, 134 (93-150) in the middle zone, and 17.5 (14-21) in the high zone, with a median difference of 323 between the low and high zones. For Simpson’s dominance index, medians (IQR) were 0.72 (0.61-0.82) in the low zone, 0.88 (0.80-0.91) in the middle zone, and 0.36 (0.33-0.39) in the high zone, with a median difference of 0.52 between the middle and high zones. For Simpson’s diversity index, medians (IQR) were 0.28 (0.17-0.38), 0.11 (0.08-0.19), and 0.63 (0.60-0.66) for the low, middle, and high zones, respectively, corresponding to a median difference of 0.52 between the middle and high zones. Similarly, Pielou’s evenness index showed medians (IQR) of 0.36 (0.28-0.43) in the low zone, 0.25 (0.22-0.25) in the middle zone, and 0.80 (0.73-0.86) in the high zone, yielding a median difference of 0.55 between the middle and high zones. Reporting these effect sizes reduces overreliance on statistical significance and highlights the magnitude and direction of differences among elevational zones.

Table 5. Correlation between elevation and indoor-outdoor temperature and relative humidity

Variable pair	Spearman’s r	p-value	Interpretation
Elevation - Mean outdoor temperature	-0.894	< 0.001	Significant negative correlation
Elevation - Mean indoor temperature	-0.940	< 0.001	Significant negative correlation
Elevation - Mean outdoor humidity	-0.143	0.642	Not significant
Elevation - Mean indoor humidity	0.174	0.401	Not significant

Table 6. Values of Simpson's Dominance Index, Simpson's Diversity Index, Shannon's Diversity Index, Pielou's Evenness Index, and Species richness at each sampling site

Biodiversity indices	Location elevation (m asl)												
	12	14	24	28	39	64	389	474	555	624	673	752	815
Simpson's dominance index	0.53	0.79	0.64	0.83	0.96	0.60	0.80	0.97	0.91	0.88	0.72	0.39	0.33
Simpson's diversity Index	0.46	0.20	0.36	0.16	0.03	0.39	0.19	0.03	0.08	0.11	0.27	0.60	0.66
Shannon's diversity index	0.67	0.38	0.56	0.35	0.10	0.62	0.45	0.10	0.23	0.24	0.61	1.17	1.19
Pielou's evenness index	0.48	0.27	0.40	0.32	0.06	0.44	0.25	0.25	0.14	0.22	0.38	0.73	0.86
Species richness (species)	4	4	4	3	5	4	6	2	5	3	5	5	4

Table 7. Results of the Kruskal-Wallis test for mosquito diversity attributes among elevational zones

Biodiversity indices	Low (n = 6)	Mid (n = 5)	High (n = 2)	H	df	*p*
Total abundance	6	5	2	8.196	2	0.017
Simpson's dominance index	6	5	2	6.262	2	0.044
Simpson's diversity Index	6	5	2	6.262	2	0.044
Shannon's diversity index	6	5	2	5.585	2	0.061
Pielou's evenness index	6	5	2	6.279	2	0.043
Species richness (species)	6	5	2	0.616	2	0.735

Discussion

The elevational gradient in this study functions as a proxy representing changes in environmental conditions—particularly temperature, land use, and the availability of aquatic habitats—which together are associated with variation in mosquito diversity in Banten Province. The decline in abundance observed at higher elevations reflects a combination of these factors rather than a single effect or a direct causal relationship. Because the study design is correlational, the findings indicate strong associations rather than independent causal effects of each variable. Areas at higher elevations generally have lower temperatures, lower settlement intensity, and fewer drainage channels, artificial containers, or domestic waste that can serve as larval habitats. Although drainage density, container availability, and habitat persistence were not quantitatively measured in this study, these factors are proposed as ecological mechanisms consistent with field observations and established literature. In addition, hydrological characteristics—such as rapid runoff and a lack of water-retaining depressions—cause aquatic habitats to persist for shorter periods, limiting their suitability for larval development. These habitat-related interpretations should therefore be considered hypothesis-driven explanations rather than directly tested variables. Collectively, these changes are consistent with the observed decrease in mosquito abundance along the elevational gradient.

In contrast, the lowland coastal areas of Serang provide a set of conditions that favor high mosquito abundance: warmer temperatures, a greater availability of permanent and semi-permanent aquatic habitats, and more intense human activity, which increases opportunities for blood meals and oviposition sites. The more stable microhabitat conditions in the lowlands are reflected in much higher mosquito abundance compared with the 815 m asl site, which recorded only 14 individuals.

Among the measured microclimatic variables, temperature was the factor most strongly associated with variation in both species-specific and total mosquito abundance, particularly along the elevational gradient that produced a clear decline in temperature. Warmer temperatures are known to accelerate larval development and shorten the gonotrophic interval, thereby increasing population growth potential (Shapiro et al. 2017; Asgarian et al. 2021). However, given the strong collinearity between temperature and elevation, this analysis cannot clearly disentangle the independent contributions of temperature and elevation. Separating these effects would require a broader study design or experimental measurements. In addition, although insects can stabilize body temperature through microhabitat selection (Dillon et al. 2006), the reduced abundance at lower-temperature sites suggests that species occurring at higher elevations may require more specialized physiological adaptations.

In contrast to temperature, relative humidity did not show a clear pattern along the elevational gradient. The absence of a significant relationship in this study is consistent with the findings of Wood et al. (2019) and Fernandez-Duque et al. (2023), but should be interpreted in light of field microclimatic conditions. Measurements were conducted primarily at night and within a relatively narrow humidity range typical of tropical environments, which may not have been sufficient to detect a measurable effect on abundance. Thus, while humidity can be an important factor in studies spanning broader climatic gradients, it does not appear to be a primary driver in the context of this study.

Culex quinquefasciatus and *Cx. vishnui* demonstrated broad ecological tolerance. The abundances of these two species were very high in lowland areas, particularly in densely populated settlements that provide numerous water collections with high organic content—habitats highly suitable for *Culex* larval development. In addition, lowland temperatures fall within the optimal range for the development of this genus, 25-30°C (Su et al. 2024), which enhances larval growth rates, reproduction, and survival. The dominance of *Culex* in urban ecosystems is not a local phenomenon; similar patterns have been reported across tropical regions in urban and semi-urban environments (Lapang et al. 2019; Izquierdo-Suzán et al. 2024; Krambrich et al. 2024). Therefore, the high prevalence of *Culex* in the lowlands of Banten reflects the combined influence of anthropogenic pressures, polluted microhabitats, and favorable thermal conditions. This finding is further supported by the strong Spearman correlation, indicating that *Cx. quinquefasciatus* may serve as an indicator of urbanization intensity and poor sanitation.

Culex gelidus was recorded only at the highest elevation sites, although this species is generally associated with aquatic vegetated habitats and rice fields (Ohba et al. 2015). The presence of livestock may influence this restricted distribution pattern. Field observations showed that the area had many goat pens, which created water pools rich in organic matter due to accumulated feces, urine, and feed runoff. The preference of *Cx. gelidus* for livestock blood and its tolerance for aquatic habitats with high organic content (Gould et al. 1962; Hasegawa et al. 2008) provide an ecological explanation for its limited yet specific occurrence. In addition, high rainfall in the upper elevation zone allows the formation of puddles on grassy soil, which have also been reported as potential larval habitats by Ramesh et al. (2015) and Balasubramanian et al. (2021).

The abundance of *Ar. subalbatus* showed a tendency to increase at higher elevations, where this species was recorded only at sites dominated by natural microhabitats such as leaf axils, shaded small ditches, and litter-filled puddles (Ikhsan et al. 2020; Kermelita et al. 2024). Our field observations indicated that this species persisted at lower temperatures in high-elevation zones, while it was not detected at sites with mean nocturnal temperatures above 26°C. This pattern is consistent with previous reports suggesting that the population dynamics of *Ar. subalbatus* are more strongly associated with rainfall and vegetation structure than with thermal constraints (Chaves et al. 2015).

The detection of *Ae. aegypti* and *Ae. albopictus* during nighttime collections indicates the presence of both species during that period. However, because sampling was conducted at night, the captured individuals may have included both resting and actively host-seeking mosquitoes;

therefore, these findings do not directly demonstrate nocturnal biting activity but rather reflect the local diversity. Spatially, *Ae. aegypti* predominated in lowland urban areas, likely associated with artificial habitats and high human host density, whereas *Ae. albopictus* was more sporadic and exhibited ecological flexibility. At higher elevations, their relative abundances were more balanced, suggesting ecological niche partitioning that facilitates coexistence. *An. subpictus* was recorded in very limited numbers and only at sites with rice fields and clear flowing water. This aligns with the ecological requirements of its larvae for water bodies with specific vegetation structures (Amini et al. 2020; Seal and Chatterjee 2023; Dalilah et al. 2024). This restricted distribution pattern indicates that anthropogenic pressures in urban lowlands have eliminated most Anopheles larval habitats, limiting the presence of *An. subpictus* to areas where water physicochemical conditions remain stable. Geographic variation reported by Ndoen et al. (2010) also shows that local environmental characteristics strongly influence this species' habitat preference.

Mansonia annulifera and *Ma. annulata* showed restricted distributions and low abundances in this survey, a pattern consistent with previous reports from Bogor and Bengkulu (Kermelita et al. 2024; Nirwan et al. 2024). *Mansonia* larvae are known to utilize the roots or stems of aquatic plants to obtain oxygen (Gass et al. 1983; Pimnon et al. 2024), and their presence is therefore often associated with aquatic habitats dominated by emergent or submerged vegetation. Our finding of low abundance is consistent with the observations of Abdulloh et al. (2024), who reported that *Mansonia* species tend not to occur abundantly in habitats subject to anthropogenic disturbance.

Species diversity and community shifts

Changes in mosquito diversity along the elevational gradient indicate that elevation serves as a primary driver of community dynamics. The high abundance and species dominance observed in low to mid-elevation areas result from warmer temperatures, the homogeneity of artificial habitats, and strong anthropogenic pressure. These conditions create uneven interspecific competition, ultimately favoring taxa that can adapt to these ecological niches, such as *Cx. quinquefasciatus* and *Cx. vishnui*. In contrast, highland areas exhibited higher diversity and a more even community composition. The decrease in dominance and the increase in evenness at high elevations suggest that cooler, more stable microclimatic conditions with minimal anthropogenic disturbance allow greater coexistence among multiple species. Environments with higher habitat heterogeneity reduce the competitive advantage of dominant lowland species, resulting in more balanced communities despite relatively lower total abundance. These findings align with community ecology theory, which posits that landscapes with low anthropogenic pressure and complex habitat structures support niche differentiation and coexistence (Afrane et al. 2012; Loaiza et al. 2017).

Interestingly, species richness showed relatively small variation along the elevational gradient and did not exhibit a clear pattern with increasing altitude. This indicates that changes in diversity are primarily driven by the redistribution of abundance among species rather than by gains or losses in the number of species. Therefore, dominance-based diversity indices such as Simpson's proved more sensitive in detecting the effects of elevation compared to indices that emphasize species richness, such as Shannon's. This difference likely reflects the mathematical properties of Simpson’s index, which gives greater weight to dominant taxa and is therefore more responsive to shifts in species dominance, whereas Shannon’s index distributes weight more evenly across species. Consequently, assessing mosquito communities along altitudinal gradients should prioritize metrics responsive to changes in abundance distribution, as richness-based metrics alone are insufficient to capture the ecological dynamics occurring.

Differences in mosquito abundance and species composition along the elevational gradient have important implications for potential public health risks. In lowland areas, the dominance of *Cx. quinquefasciatus*, *Cx. vishnui*, and *Ae. aegypti* indicates that these regions may face a higher potential risk of arbovirus and filariasis transmission, given the well-established epidemiological roles of these species. Warm microclimatic conditions—which generally enhance gonotrophic cycle rates, blood-feeding frequency, and pathogen replication within vectors—combined with high human population density and the presence of stable larval habitats, may further increase transmission opportunities (Shapiro et al. 2017). However, this inference is based solely on vector abundance and composition, not on pathogen detection or confirmed human case data, and therefore should be interpreted as potential rather than realized transmission risk. Additionally, mosquito collections were conducted between 18:00 and 06:00 using nets and aspirators, which may preferentially capture resting or host-seeking individuals depending on local conditions. This sampling window could underrepresent strictly diurnal species or bias relative abundance estimates, and thus epidemiological interpretations should be made cautiously. In contrast, highland areas exhibit a more heterogeneous and seasonally variable risk profile. The presence of *Ar. subalbatus*, *Ae. albopictus*, *Mansonia* spp., and *Cx. gelidus* indicates that transmission risk does not disappear at higher elevations, but may instead shift in mechanism and source as vector species composition changes. Moreover, the presence of livestock may contribute to zoonotic transmission potential for more zoophilic species, such as *Cx. gelidus* and *Mansonia.*

These ecological implications demand context-specific vector control strategies. In urban lowland areas, priority interventions include reducing anthropogenic habitats through improved waste and drainage management, community education on water container maintenance, and sustained implementation of source reduction programs. Settlement-based entomological surveillance is also crucial for monitoring vector population changes that are strongly influenced by domestic practices and social dynamics.

In high-elevation rural areas, control approaches must be adapted to the local ecological characteristics. Interventions should consider the conservation of semi-natural habitats that serve as niches for various non-urban species. Managing seasonal water pools, improving rural sanitation, and implementing control measures in areas with high livestock density are essential steps to prevent vector proliferation without disrupting ecosystem functions. Seasonal monitoring—particularly at the onset and peak of the rainy season—is necessary because populations of dominant species at higher elevations are highly responsive to changes in microhabitat conditions.

These findings should be interpreted with caution due to several limitations. The study was based on observational data from 13 sites, limiting causal inference, and strong collinearity between elevation and temperature constrained the separation of their independent effects. Sampling focused on nocturnal adult mosquitoes and did not directly assess larval habitats or pathogen prevalence, which may influence epidemiological interpretation. Future studies should incorporate long-term and seasonal sampling, expand coverage of larval habitat characteristics, and integrate pathogen detection to better link mosquito diversity patterns with disease risk. The use of multivariate or experimental approaches to disentangle elevation, temperature, and land-use effects would further strengthen inference. Overall, this study provides robust ecological evidence that elevation-mediated environmental variation is a key determinant of mosquito diversity and offers a valuable basis for designing context-specific vector surveillance and control strategies across heterogeneous tropical landscapes.

Nevertheless, the principal limitations include the observational design with confounded elevation and land-use variation, strong collinearity between elevation and temperature, the small sample size in the high-elevation zone (n = 2), and potential bias associated with nocturnal adult sampling. Future research should incorporate quantitatively measured larval habitat variables, repeated multi-season sampling, and experimental or multivariate approaches capable of disentangling elevation, temperature, and land-use effects to strengthen causal inference.

In conclusion, this study demonstrates that elevation is a primary determinant shaping mosquito diversity, primarily through its influence on temperature and habitat transformation along the elevational gradient. Total abundance is affected by the interaction between elevation, temperature, and human population density, whereas local microhabitat conditions more strongly drive distribution patterns and diversity levels. The combined effects of these environmental factors can consistently explain the observed variation in species composition. These results underscore the need for long-term monitoring along elevational gradients to predict potential shifts in vector distribution driven by climate change, urbanization, and land-use conversion. Across 13 sites spanning 12-815 masl, a total of 3,528 mosquitoes representing nine species and five genera were recorded. Total mosquito abundance declined sharply with increasing elevation, showing a strong negative correlation with elevation ($r = -0.93$, $p<0.001$) and a significant positive association with air temperature ($r = 0.77$, $p = 0.02$). Lowland areas were strongly dominated by *Cx. quinquefasciatus* (79.13%) and *Cx. vishnui* (19.27%), whereas *Ar. subalbatus* increased in relative abundance at higher elevations. Diversity analyses revealed high dominance and low evenness at low to mid elevations, while highland sites (752-815 m asl) exhibited lower dominance and greater evenness, despite relatively stable species richness along the elevational gradient. This study not only elucidates the influence of elevation on mosquito distribution, abundance, and diversity but also provides a scientific basis for developing vector control strategies that align with the ecological characteristics of each elevational zone.

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