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Housing structure shapes dengue transmission dynamics in a rapidly urbanizing Malaysian district

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Dengue fever continues to pose a significant public health threat in Malaysia, particularly in peri-urban districts undergoing rapid residential expansion. However, the extent to which housing structures influence dengue transmission remains poorly quantified. This study investigated the temporal, proportional, and spatial dynamics of dengue across five housing categories; landed properties, high-rise residential units, traditional/rural houses, institutional quarters, and others in Kuala Selangor from 2020 to 2024. A total of 5,426 laboratory-confirmed dengue cases obtained from the national e-Notifikasi system were geocoded and classified by housing type. Temporal trends were examined using weekly epidemic curves, proportional contributions were calculated for each housing category, and spatial clustering was assessed using Kernel Density Estimation (KDE) in ArcGIS Pro. Landed properties were the dominant transmission environment, contributing 73.4% of all cases and consistently driving major seasonal peaks during epidemiological weeks 20–35, coinciding with the southwest monsoon. High-rise residential areas accounted for 16.1% of cases and exhibited persistent low-level transmission throughout the year, indicating a potential role as an endemic reservoir between epidemic cycles. Traditional/rural houses (5.5%), institutional quarters (3.4%), and other categories (1.6%) contributed only sporadically. KDE mapping revealed persistent hotspots in central and southern Kuala Selangor, primarily within peri-urban landed housing estates, with smaller recurrent clusters in high-rise complexes. These findings demonstrate that housing typology is a critical determinant of dengue transmission risk. Landed properties amplify monsoon-driven outbreaks through abundant outdoor breeding habitats, while high-rise buildings sustain inter-epidemic transmission via sheltered, indoor breeding sites. Integrating housing-specific intelligence into Malaysia's Integrated Vector Management (IVM) framework can enable more targeted, proactive, and spatially adaptive dengue prevention strategies.

Keywords Dengue transmission, Housing typology, Spatial epidemiology, Temporal analysis, Vector management

Dengue fever remains one of the most significant vector-borne diseases in Malaysia, posing a continuous public health challenge despite decades of nationwide control efforts[1]. Transmitted primarily by *Aedes aegypti* and *Aedes albopictus*, the disease thrives under tropical climatic conditions and rapidly adapts to human-modified environments[2,3]. Over the past decade, Malaysia has experienced cyclical dengue epidemics with expanding geographic coverage, driven by uncontrolled urbanization, inconsistent waste management, and changes in residential development patterns[4]. While national surveillance data provide insights into overall trends, there is limited understanding of how different housing structures contribute to dengue transmission dynamics, particularly in peri-urban settings where urban and rural features overlap[5,6].

Existing studies have highlighted the strong link between rainfall, temperature, and vector abundance, emphasizing the seasonal drivers of dengue outbreaks[7–9]. However, most analyses focus on climatic and

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demographic factors at broad spatial scales, often overlooking local environmental characteristics such as housing design, building density, and peridomestic water management[10,11]. These factors influence mosquito breeding potential and human–vector contact rates but remain underexplored in Malaysian dengue research[12]. Consequently, the absence of fine-scale housing-based assessments limits the ability of local authorities to prioritize high-risk areas and tailor vector control strategies effectively. In Selangor the state contributing the highest proportion of Malaysia's dengue cases peri-urban districts such as Kuala Selangor have undergone rapid transformation, with agricultural and forested areas converted into mixed housing developments[13]. The emergence of dense landed housing estates alongside high-rise apartments and traditional villages has created new ecological conditions that facilitate mosquito proliferation throughout the year[14]. Despite the availability of long-term dengue notification data, there remains a lack of spatially explicit analyses linking these housing typologies to temporal and seasonal patterns of disease. This gap hampers efforts to identify the structural and environmental factors sustaining dengue transmission in expanding peri-urban landscapes.

To address this, the present study aims to examine the temporal, proportional, and spatial dynamics of dengue transmission across major housing categories in Kuala Selangor from 2020 to 2024. By integrating surveillance data with geospatial analysis, the study seeks to: (i) Characterize seasonal and annual dengue trends across housing types; (ii) Quantify the relative contribution of each housing category to overall transmission; and (iii) Map spatial clusters of dengue cases to identify persistent hotspots within residential areas. Through this housing-centered approach, the study provides a new perspective on dengue risk assessment, offering evidence-based insights for more targeted and sustainable vector control. The findings aim to support Malaysia's Integrated Vector Management (IVM) framework by demonstrating how housing structure and urban form can be used as key indicators in predicting dengue transmission risk and guiding localized public health interventions.

Housing structure and dengue transmission

Previous studies have demonstrated that dengue transmission is strongly influenced by housing structure, urban form, and surrounding environmental conditions[15,16]. Landed residential properties, characterised by individual compounds, open yards, and peridomestic water-holding containers, have consistently been associated with higher Aedes breeding density and increased dengue risk, particularly during rainy seasons[17]. Studies from Malaysia and other dengue-endemic countries have shown that roof gutters, discarded containers, ornamental plants, and water storage practices in landed houses provide optimal breeding habitats for *Aedes* mosquitoes[18].

In contrast, high-rise residential environments present a different transmission ecology[19]. Although often perceived as lower risk due to reduced ground-level exposure, multiple studies have reported persistent dengue transmission in multi-storey buildings, driven by indoor and semi-indoor breeding sites such as rooftop water tanks, corridor drains, flowerpots, and shared facilities[20,21]. Vertical dispersal of *Aedes* mosquitoes within high-rise buildings has been documented, allowing sustained transmission even during drier periods and inter-epidemic intervals[22]. Beyond housing typology, peri-urban environments have been increasingly recognised as critical zones for dengue emergence and persistence[23]. These areas often combine high population mobility, heterogeneous land use, incomplete infrastructure, and rapid housing development, creating complex ecological conditions favourable to mosquito proliferation. Spatial epidemiological studies using GIS and kernel density estimation have further demonstrated that dengue hotspots tend to recur in specific residential zones rather than shifting randomly across landscapes[1,24]. Despite this growing body of evidence, few studies in Malaysia have systematically examined dengue transmission across multiple housing categories over extended time periods using integrated temporal and spatial analyses. Existing research has often focused on single housing types, short outbreak periods, or broad administrative scales, limiting operational applicability for local authorities. The present study addresses this gap by providing a housing-centered, multi-year spatial epidemiological assessment of dengue transmission in a rapidly urbanising peri-urban district.

Material and methods

Study area

This study was conducted in Kuala Selangor District, located on the northwestern coast of Selangor, Malaysia (3.35°N, 101.25°E) (Fig. 1). The district covers approximately 1,194 km^2 and comprises a heterogeneous mix of urban, peri-urban, and rural landscapes. Residential development in Kuala Selangor is dominated by landed housing estates, including terrace, semi-detached, and detached houses, which account for the majority of occupied residential areas, particularly in rapidly expanding peri-urban zones such as Ijok, Bestari Jaya, Jeram, and Puncak Alam[25]. High-rise residential developments are comparatively fewer and are concentrated in specific localities, mainly within newer townships and institutional zones, while traditional and rural houses persist in villages and agricultural fringes. This housing composition reflects Kuala Selangor's transitional urban–rural character, where low- to medium-density landed properties remain the predominant built form.

Kuala Selangor experiences a tropical rainforest climate, characterized by uniformly high humidity and rainfall throughout the year. The average annual temperature ranges between 24 °C and 33 °C, with mean annual rainfall exceeding 2,200 mm[26]. Two distinct monsoon seasons influence local weather: the northeast monsoon (November–March) brings heavy rainfall and cooler winds, while the southwest monsoon (May–September) results in warmer, drier conditions with intermittent storms. These climatic conditions create favorable environments for *Aedes aegypti* and *Aedes albopictus* breeding, particularly in domestic and peri-domestic containers found within residential areas. The district was selected due to its rapid urban expansion, heterogeneous housing patterns, and recurrent dengue outbreaks recorded by the Ministry of Health (MOH) Malaysia. Kuala Selangor serves as a key peri-urban transition zone where urban development interfaces with rural and agricultural landscapes providing an ideal setting to examine how housing structure and environmental features influence dengue transmission risk.

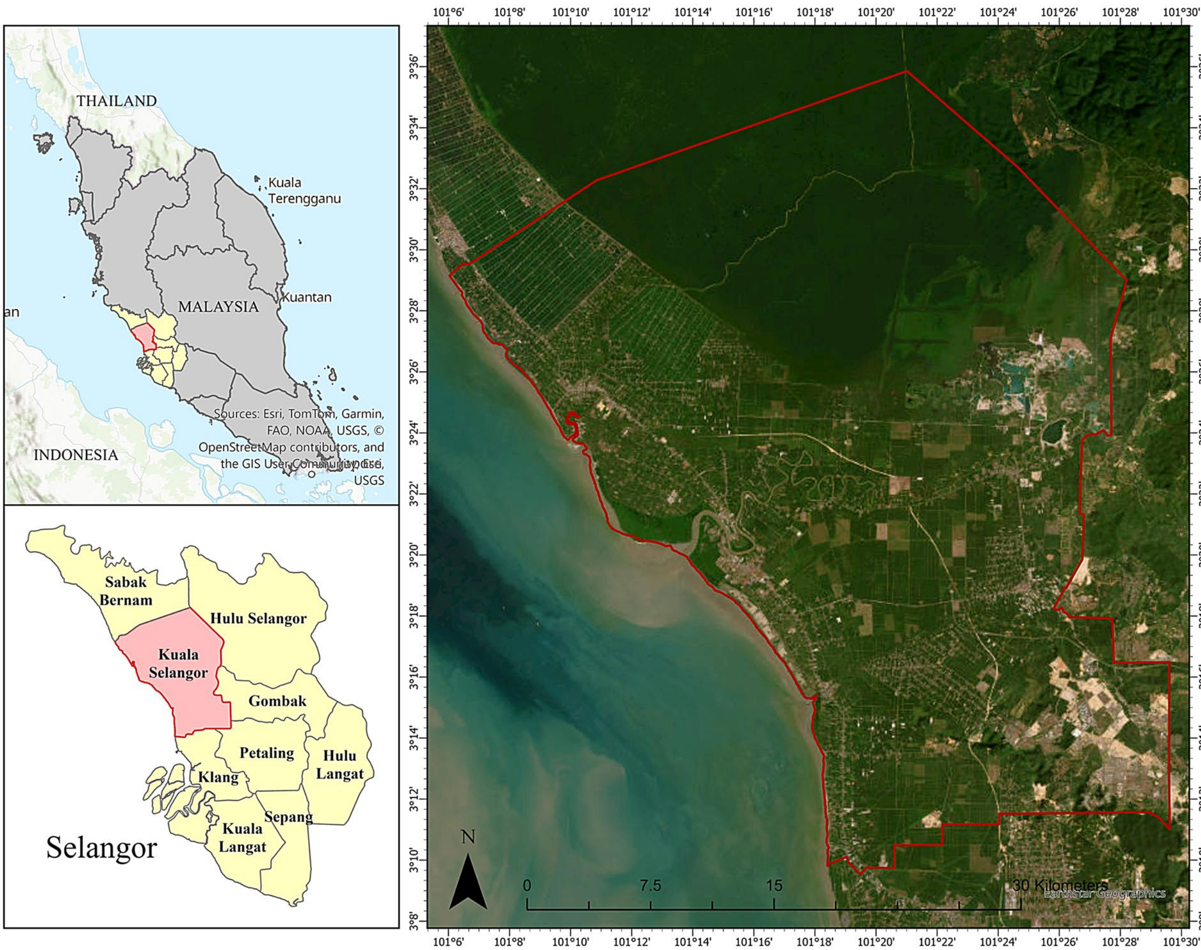

Fig. 1. Location of the study area. The maps show Kuala Selangor District, Selangor, Malaysia. (**A**) Location of Selangor within Peninsular Malaysia. (**B**) Administrative boundary of Kuala Selangor within Selangor State. (**C**) Satellite basemap of Kuala Selangor with the district boundary outlined in red. The map was created by the authors using ArcGIS Pro version 3.1 (Esri, Redlands, CA, USA; https://www.esri.com/arcgis-pro) under the WGS 1984 coordinate reference system. Basemap data were sourced from Esri, NOAA, USGS, FAO, and OpenStreetMap contributors.

Data type	Variables / information	Source	Temporal coverage
Dengue surveillance data	Laboratory-confirmed dengue cases, date of symptom onset, residential address	e-Notifikasi system, Ministry of Health (MOH) Malaysia (via Kuala Selangor District Health Office)	January 2020 – December 2024
Housing structure data	Housing type, building form, residential classification	Kuala Selangor District Council administrative records	Static
Geospatial location data	Geographic coordinates of residential addresses	Google Earth Pro; ArcGIS Pro 3.1 (Esri)	2020–2024
Land-use and administrative boundaries	District boundary, residential land-use layers	Department of Survey and Mapping Malaysia (JUPEM); Selangor State Planning Unit (UPEN Selangor)	Latest available datasets
Drone-assisted aerial imagery	Housing layout, land-use context, building structure	UAV surveys conducted with institutional approval	Selected periods within study timeframe

Table 1. Summary of data sources used in this study. This table summarises all datasets and information sources used in the study. Dengue surveillance data constituted the primary analytical dataset for temporal, proportional, and spatial analyses. Climatic information was referenced only to provide seasonal context and was not included as analytical input data.

Data collection

Table 1 summarises all datasets used in this study and clarifies their respective roles. Laboratory-confirmed dengue cases from the national e-Notifikasi surveillance system formed the primary dataset for temporal, proportional, and spatial analyses. Housing structure data from the Kuala Selangor District Council were used to classify cases into five housing categories. Residential addresses were geocoded and validated using GIS platforms, while official land-use and administrative boundary layers provided spatial reference for mapping.

Drone-assisted aerial imagery was used as supplementary spatial validation to support housing classification and hotspot interpretation. Climatic information, including monsoon season definitions, was referenced only to contextualise seasonal patterns and was not included as analytical input data.

Confirmed dengue case data covering the period from January 2020 to December 2024 were obtained from the e-Notifikasi surveillance system, administered by the Kuala Selangor District Health Office, under the Ministry of Health (MOH) Malaysia. Each record contained essential epidemiological information including the date of symptom onset, case classification, and residential address. To ensure data reliability, only laboratory-confirmed dengue cases were included in this analysis, while suspected or unverified cases were excluded. All records were anonymized prior to processing to comply with ethical and confidentiality requirements. During the study period, a total of 5,873 dengue cases were reported in Kuala Selangor District through the e-Notifikasi system. Of these, 5,426 cases (92.4%) were laboratory-confirmed and met the inclusion criteria for this study. The remaining 447 cases (7.6%) were excluded due to incomplete residential address information, duplication, or classification as suspected cases without laboratory confirmation. Each included record contained essential epidemiological information, including date of symptom onset, case classification, and residential address. To ensure data reliability and consistency, only laboratory-confirmed dengue cases with complete spatial information were included in the analysis, while suspected or unverifiable cases were excluded. All records were anonymised prior to processing to comply with ethical and confidentiality requirements.

Residential addresses were geocoded using Google Earth Pro and subsequently validated in ArcGIS Pro 3.1 (Esri, Redlands, CA, USA) to generate accurate spatial coordinates for each case. To enhance spatial accuracy and contextual validation, drone-assisted aerial surveys were used to support high-resolution verification of residential layouts, housing boundaries, and surrounding land-use features, particularly in rapidly developing peri-urban areas where satellite imagery may be outdated or obscured. Unmanned aerial vehicle (UAV) imagery enabled clearer identification of housing typologies (e.g., landed versus high-rise structures), access roads, open yards, drainage networks, and construction-related water-holding features that are not consistently visible in conventional basemaps. This approach strengthened the reliability of housing classification and improved interpretation of spatial clustering patterns. The geocoded locations were then classified into five housing categories: landed properties, high-rise residential units, traditional and rural houses, special categories (institutional buildings and government quarters), and others (Table 2). The classification of housing types was guided by a structured, multi-criteria approach designed to reflect meaningful differences in building structure, residential layout, and potential Aedes breeding ecology. Housing categories were defined a priori based on (i) structural form (e.g., single-unit versus multi-storey buildings), (ii) land-use designation and planning records obtained from the Kuala Selangor District Council, and (iii) dominant residential function (private, institutional, or mixed-use).

Landed properties included terrace, semi-detached, and detached houses characterised by individual compounds, open yards, roof gutters, and outdoor water-holding features. High-rise residential units comprised flats, apartments, and condominiums with multiple storeys, shared facilities, and semi-indoor environments. Traditional and rural houses referred to kampung-style or wooden dwellings, often elevated and located within vegetated or agricultural settings. Special categories included government quarters, hostels, and institutional residences with managed infrastructure and centralized facilities, while the 'others' category captured mixed or unclassified housing types that did not fit consistently within the main groups. Validation of housing classification was conducted through cross-referencing multiple spatial data sources, including official land-use and residential shapefiles from the Department of Survey and Mapping Malaysia (JUPEM) and the Selangor State Planning Unit (UPEN Selangor). In addition, high-resolution satellite imagery and drone-assisted aerial surveys were used to visually verify building structure, height, and surrounding environmental features, particularly in rapidly developing peri-urban areas. Discrepancies were resolved through consensus review by the research team in consultation with local public health officers familiar with the study area. This classification framework ensured internal consistency across the dataset and allowed meaningful comparison of dengue transmission dynamics across housing types with distinct structural and ecological characteristics.

Temporal and seasonal analysis

Weekly dengue case data were analyzed to describe seasonal patterns and fluctuations in transmission intensity across the study period (2020–2024). Cases were organized according to epidemiological weeks (1–52) following

Housing Category	Description / Examples	Structural Characteristics	Epidemiological Significance
Landed properties	Terrace, semi-detached, and detached houses	Individual compounds, open yards, roof gutters, garden containers	Major breeding foci; high rainfall runoff and outdoor container habitats
High-rise residential	Flats, apartments, and condominiums	Multi-storey structures, shared facilities, rooftop tanks, corridor drains	Continuous low-level transmission due to indoor/sheltered breeding sites
Traditional & rural houses	Kampung-type and wooden houses	Elevated flooring, natural surroundings, proximity to vegetation	Sporadic outbreaks linked to peri-domestic and natural water-holding areas
Special categories	Government quarters, institutional buildings, hostels	Clustered, managed environments with centralized water systems	Localized clusters; potential institutional outbreak nodes
Others	Mixed or unclassified housing	Transitional or mixed-use developments	Minimal contribution; included for completeness

Table 2. Classification of housing categories and data processing framework used in this study. Housing categories were defined based on structural characteristics, land-use designation, and validated spatial interpretation to ensure epidemiological relevance and analytical consistency.

the national surveillance calendar. The time-series dataset was used to observe temporal trends and identify epidemic peaks, seasonal recurrence, and inter-epidemic intervals. To minimize short-term variability and highlight underlying seasonal trends, weekly case counts were smoothed using a moving average approach. This smoothing procedure was applied to reduce high-frequency noise commonly present in routine dengue surveillance data, including week-to-week stochastic fluctuations in case reporting, reporting delays associated with weekends and public holidays, variations in healthcare-seeking behaviour, and administrative batching of notifications. Such short-term variability can obscure broader epidemiological patterns when raw weekly counts are interpreted directly. The moving average did not remove true epidemic signals but served to dampen irregular, non-epidemiological variation, allowing clearer visualization of sustained transmission trends, seasonal peaks, and inter-epidemic periods. This approach is particularly useful for guiding interpretation of surveillance-based time-series data and is recommended for early-career researchers working with routine infectious disease notification systems. A temporal dataset was constructed for each housing category to compare fluctuations across different residential environments. The analysis focused on identifying the timing, duration, and intensity of transmission peaks for landed, high-rise, and traditional housing areas. All temporal analyses and visualizations were performed using R software (version 4.3.2).

Proportional contribution analysis

The proportional contribution of each housing category to the total dengue burden was calculated to determine the relative influence of different residential environments on transmission. Housing type was treated as a contextual exposure variable representing shared structural design, surrounding environmental features, and routine water-holding practices that collectively shape Aedes breeding potential and human–vector contact. Weekly dengue case counts for each housing type were expressed as a percentage of the total number of cases reported during the same epidemiological week. The calculation followed the formula:

$$P_i = \frac{C_i}{\sum_{i=1}^{n} C_i} \times 100$$

where C_i represents the weekly number of dengue cases for housing category *i*, and $\sum C_i$ is the total number of cases across all housing categories for that week. The proportional contribution of each housing category to the total dengue burden was calculated to determine the relative influence of different residential environments on transmission. Weekly dengue case counts for each housing type were expressed as a percentage of the total number of cases reported during the same epidemiological week. This approach allows both cumulative (total case burden) and temporal (weekly fluctuations) relationships between dengue transmission and housing patterns to be examined. Total case counts reflect the long-term contribution of specific housing environments to dengue persistence, whereas weekly case patterns capture short-term transmission dynamics driven by seasonal conditions operating within those housing contexts.

Spatial analysis and hotspot mapping

Spatial analysis was performed in ArcGIS Pro 3.1 using Kernel Density Estimation (KDE) to detect spatial clustering of dengue cases across Kuala Selangor between 2020 and 2024. The KDE bandwidth was optimized based on Silverman's rule of thumb, ensuring a balanced representation of case density and spatial precision. The resulting heatmaps illustrated persistent and emerging dengue hotspots, highlighting high-risk zones by housing type. Base maps and shapefiles for residential and land-use boundaries were obtained from the Department of Survey and Mapping Malaysia (JUPEM) and the Selangor State Planning Unit (UPEN Selangor). All spatial data were projected using the WGS 1984 coordinate system for standardization and comparability.

Ethical considerations

This study utilized secondary surveillance data obtained with formal approval from the Medical Research and Ethics Committee (MREC), Ministry of Health Malaysia (NMRR ID: 25–02,921-CR1). Ethical clearance was granted on 1 October 2025, with approval valid until 1 October 2026. The study was conducted in accordance with national data protection regulations and institutional ethical standards. No human subjects were directly involved, and all data were anonymized prior to analysis. All information was treated with strict confidentiality and used solely for the purpose of this research.

Results

Temporal patterns of dengue transmission by housing category

Between 2020 and 2024, dengue transmission in study area displayed remarkable temporal and spatial heterogeneity across housing typologies, revealing a finely structured pattern of epidemic recurrence and persistence (Fig. 2). Landed properties emerged as the principal foci of dengue activity, accounting for the overwhelming majority of reported cases throughout the six-year observation period. Epidemic peaks were not only recurrent but also seasonally synchronized, predominantly occurring between epidemiological weeks 20 and 35 coinciding with Malaysia's southwest monsoon period. This temporal alignment highlights the climatic coupling between rainfall accumulation, increased surface water retention, and subsequent proliferation of *Aedes* breeding habitats. The cyclical surge in cases within landed areas thus represents a strong signature of rainfall-driven vector amplification and human exposure dynamics.

The temporal trajectory of high-rise residential areas contrasted sharply with that of landed properties. Although the total number of cases in high-rise zones was considerably lower, their contribution to the epidemic

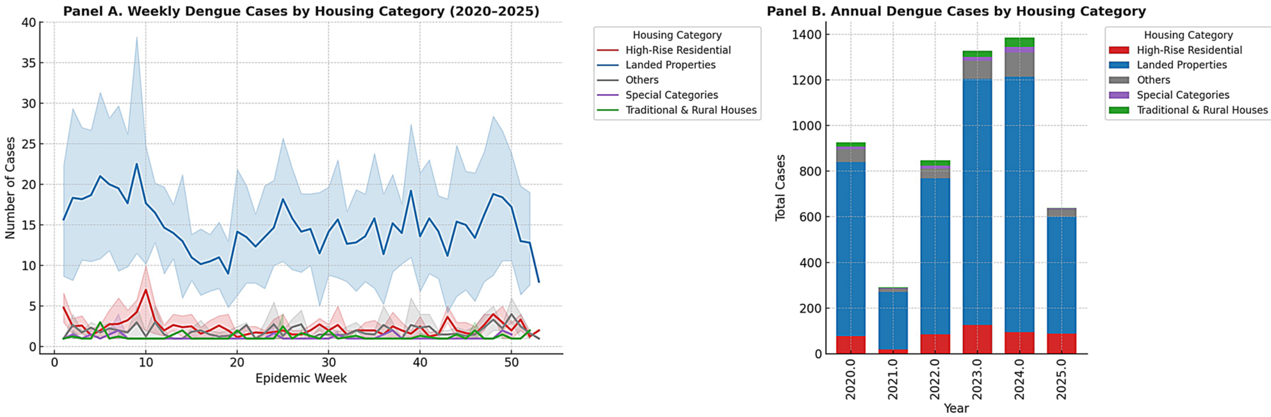

Fig. 2. Seasonal and annual distribution of dengue cases in Puncak Alam, 2020–2024, stratified by housing category. (**Panel A**) shows weekly epidemic trends by housing category, highlighting the strong seasonal dominance of *landed properties* with recurrent mid-year peaks, while *high-rise residential* areas exhibit smaller but consistent contributions. *Traditional and rural houses*, *special categories*, and *others* remain minor contributors throughout the study period. (**Panel B**) presents the annual total case counts by housing category, demonstrating that *landed properties* consistently accounted for the majority of dengue cases across all years, followed by *high-rise residential* units, whereas the other categories contributed only marginally.

curve was persistent and distributed across nearly all weeks of the year. These smaller but recurrent infection waves suggest an endemic maintenance cycle potentially influenced by continuous vector survival within shaded, semi-indoor environments, water storage containers, or rooftop drainage systems. The presence of consistent baseline transmission in high-rise units implies that vertical urban housing may sustain low-intensity dengue circulation even during inter-epidemic intervals, effectively bridging transmission between major seasonal outbreaks. Traditional and rural houses, as well as the special-category dwellings (e.g., government quarters and institutional facilities), exhibited distinct temporal isolation, contributing only sporadic or short-lived spikes in case numbers. These minor surges often corresponded with localized outbreaks, possibly linked to transient human mobility, targeted introduction of infected vectors, or lapses in environmental management. The "other" housing category comprising mixed or non-classified units showed negligible epidemic signals, reinforcing the dominance of landed and high-rise environments in shaping the district's overall transmission profile.

Collectively, these patterns reveal a dual transmission architecture: a seasonally amplified, rainfall-sensitive epidemic core centered in landed properties, and a persistent, low-grade transmission background sustained by high-rise residential environments. The interplay between these two systems likely facilitates year-round viral circulation, enabling dengue to persist across climatic transitions and re-emerge with enhanced intensity during favorable environmental windows. Such housing-specific temporal dynamics underscore the necessity of spatially differentiated vector-control strategies, targeting both the expansive outdoor breeding habitats characteristic of landed areas and the concealed, artificial water-holding niches prevalent in multi-storey dwellings.

Seasonal intensity and heatmap correlations

The heatmap in seasonal patterns of dengue activity across different housing categories in Puncak Alam. Landed properties recorded the highest and most consistent number of cases, especially during weeks 20–35 of each year. This period corresponds to Malaysia's southwest monsoon, when heavy rainfall and higher humidity provide ideal conditions for *Aedes* mosquito breeding. The repeated appearance of these mid-year peaks shows that dengue outbreaks in landed areas follow a predictable seasonal pattern driven by climate. High-rise residential areas showed smaller but continuous increases in cases that often overlapped with the peaks in landed properties. This overlap suggests that transmission in high-rise areas is connected to outbreaks in nearby landed neighborhoods. The steady presence of cases throughout the year also suggests that mosquitoes may survive in indoor or sheltered places such as rooftop drains, flower pots, or water tanks even when outdoor breeding decreases. These environments allow dengue transmission to continue during drier months. Traditional and rural houses, as well as special categories such as government quarters and institutions, showed only a few short-term spikes in dengue cases. These were likely caused by small, local outbreaks rather than sustained transmission. The "other" category contributed very few cases overall. In summary, the heatmap highlights two key patterns: landed properties drive the main seasonal outbreaks, while high-rise buildings maintain a low but steady level of dengue transmission throughout the year. Together, these housing types create a continuous transmission cycle that allows the virus to persist in the community. Identifying these seasonal and structural differences is important for planning targeted control activities especially before and during the mid-year peak season when dengue risk is highest (Fig. 3).

Proportional contribution and epidemic dynamics

As illustrated in Fig. 4, dengue transmission in Puncak Alam was strongly influenced by housing type, with a clear and consistent pattern across the six-year period. Landed properties consistently accounted for the majority

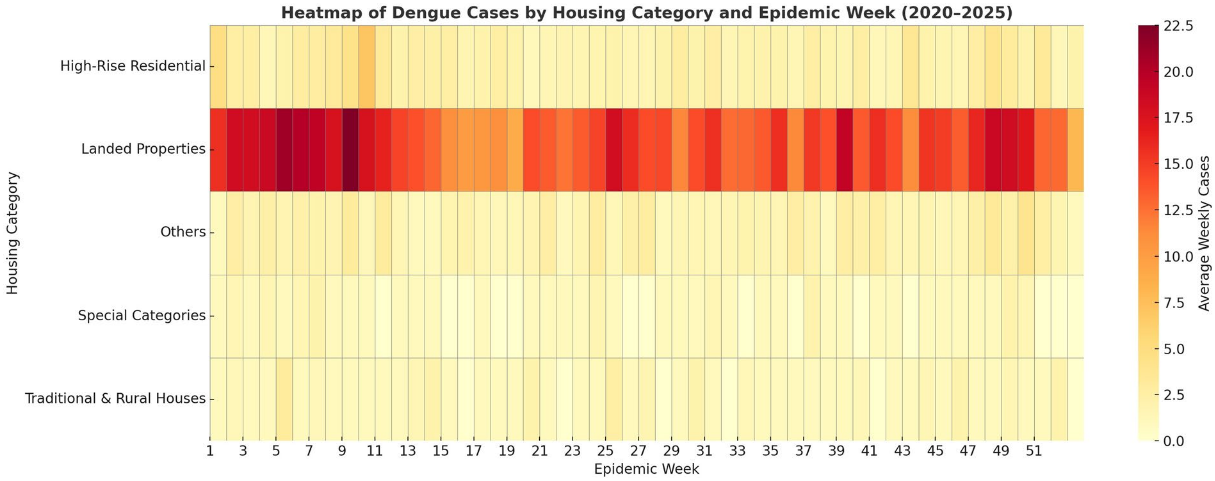

Fig. 3. Heatmap of dengue cases in Puncak Alam by housing category and epidemic week, 2020–2024. The x-axis represents epidemic weeks (1–52), while the y-axis represents housing categories. Color intensity reflects the average number of weekly cases. Dengue incidence is consistently highest in landed properties, with pronounced peaks during weeks 20–35, indicating strong seasonal dynamics. High-rise residential areas contribute smaller but noticeable surges overlapping the landed property peaks, while traditional & rural houses, special categories, and others contribute minimally with occasional localized peaks. This visualization highlights both the seasonality of transmission and the dominant role of landed properties in sustaining dengue outbreaks.

of dengue cases across the study period, contributing approximately 70–80% of weekly reported infections. This sustained dominance across both cumulative and weekly analyses indicates that landed housing environments provide persistent ecological conditions favourable for dengue transmission, rather than representing isolated outbreak events. The regular rise and fall of cases in landed areas closely followed the seasonal rainfall pattern, making them the primary driver of local epidemics.

High-rise residential areas contributed a smaller but stable proportion of weekly cases throughout the year. The persistence of weekly cases within high-rise settings, despite lower total case numbers, suggests continuous low-level transmission linked to shared indoor and semi-indoor breeding environments, reinforcing the relevance of housing structure in shaping both total burden and temporal dynamics. The remaining housing types including traditional and rural houses, government quarters, institutions, and others together contributed less than 10% of total cases. Their impact on overall dengue transmission was therefore limited and likely linked to short-term, localized outbreaks rather than sustained epidemics.

Overall, these findings reveal a stable hierarchy of dengue transmission risk across housing types, with landed properties as the dominant source, high-rise buildings as a secondary but steady contributor, and other housing types playing only minor roles. This consistent pattern across years suggests that dengue risk in Puncak Alam is strongly shaped by housing design and surrounding environmental features. The results highlight the need for targeted vector control strategies focusing on outdoor habitats in landed zones and indoor water containers in high-rise residences to effectively reduce the overall transmission cycle.

Spatial distribution of case clusters

Spatial analysis using kernel density estimation (Fig. 5) revealed clear patterns in the distribution of dengue cases across Puncak Alam from 2020 to 2024. The results showed that persistent and intense dengue hotspots were concentrated in landed residential areas, particularly in the central and southern parts of the study area. These locations were characterized by moderate housing density, high vegetation cover, and extensive outdoor spaces conditions that favour mosquito breeding and human–vector contact. The abundance of shaded areas, ornamental plants, and uncovered water containers around these houses likely created microhabitats that allowed *Aedes* mosquitoes to survive and reproduce efficiently, sustaining continuous transmission during peak seasons.

The spatial clustering pattern also reflects the peri-urban nature of Puncak Alam, where rapid development and mixed land use have created environments that combine both urban and rural characteristics. Such transitional zones often lack consistent waste management and drainage systems, leading to water stagnation in construction sites, roadside drains, and household areas. These factors enhance the risk of *Aedes* proliferation, making peri-urban landed areas key drivers of dengue persistence in the district. In contrast, high-rise residential clusters were more localized but recurrent. These hotspots were often confined to specific building complexes, suggesting that transmission may be influenced by vertical movement of mosquitoes within floors or by shared water storage systems, such as rooftop tanks, corridors, or common waste areas. The repetition of clusters in the same high-rise zones across multiple years indicates that once dengue is introduced, it can circulate within these buildings for prolonged periods, supported by the presence of both human hosts and sheltered breeding sites.

Meanwhile, traditional and rural settlements, as well as special-category housing (e.g., government quarters and institutional compounds), showed only scattered and isolated case points. These areas did not exhibit

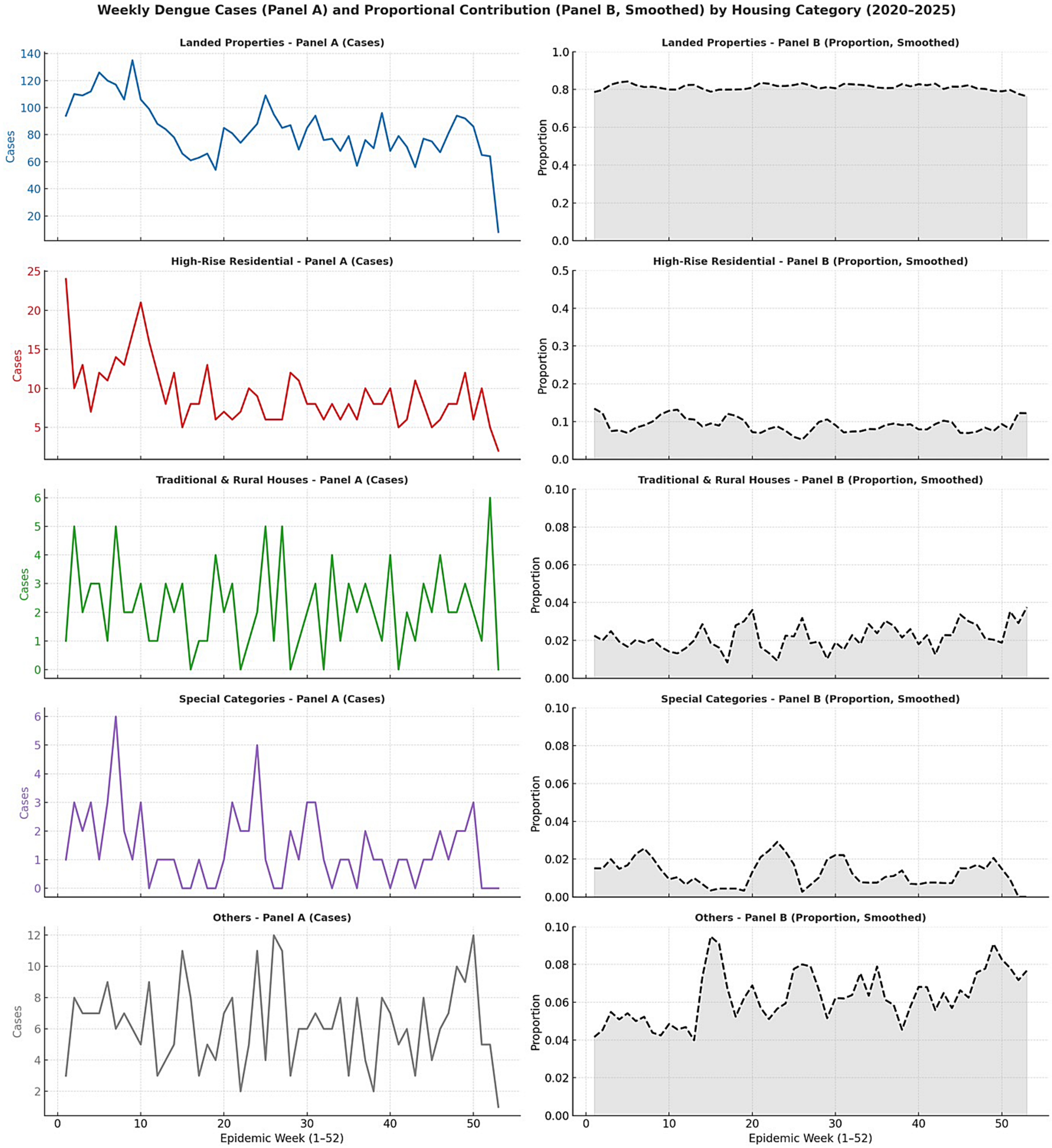

Fig. 4. Weekly dengue cases (Panel A) and proportional contribution (Panel B) by housing category in Puncak Alam, 2020–2024. (**Panel A**) displays the temporal dynamics of absolute weekly dengue cases across five housing categories, highlighting the dominance of landed properties, which exhibit recurrent mid-year epidemic peaks. High-rise residential units contribute smaller but consistent waves, while traditional & rural houses, special categories, and others show sporadic and localized case counts. (**Panel B**) presents the smoothed proportional contribution of each housing type relative to the total weekly burden, with customized y-axis scaling to enhance clarity (landed = 0–1, high-rise = 0–0.5, others = 0–0.1). Landed properties consistently account for the majority of weekly cases (~ 70–80%), high-rise residences contribute ~ 10–20% with occasional seasonal rises, and the remaining categories rarely exceed 10% of the total burden.

sustained or overlapping clusters across years, implying that transmission there was more sporadic and likely due to imported cases or temporary local outbreaks rather than ongoing endemic activity. Overall, the spatial distribution patterns confirm that landed residential zones act as the dominant epicenters of dengue transmission, while high-rise environments serve as secondary but persistent reservoirs. These findings emphasize the need for

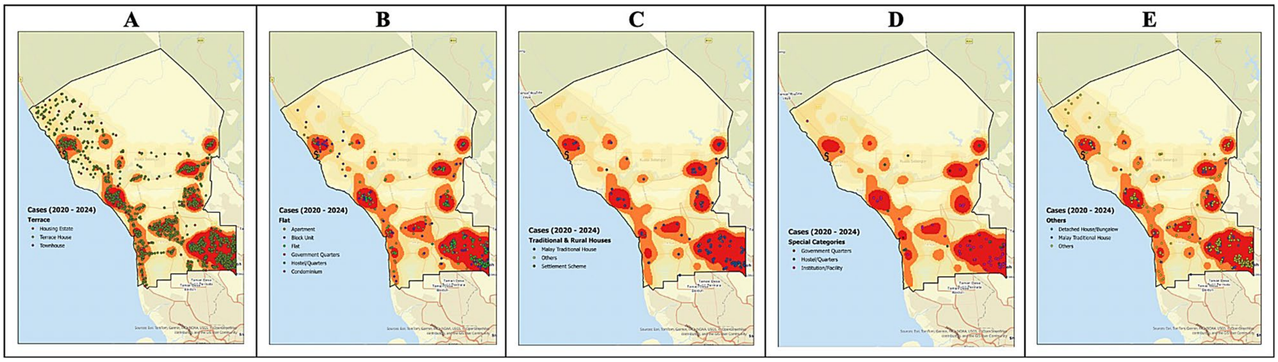

Fig. 5. Spatial distribution of dengue cases (2020–2024) across different housing types in the study area. Panel A presents cases in landed properties, Panel B in high-rise residential areas, Panel C in traditional and rural houses, Panel D in special categories such as government quarters and institutions, and Panel E in other housing types. The red gradient indicates areas with higher dengue case density based on kernel density estimation.

geographically tailored dengue control strategies focusing intensive source reduction and larval surveillance in high-density landed housing zones, while maintaining regular inspection and community engagement in high-rise residential blocks. Understanding how dengue clusters form and persist across different housing structures can help authorities prioritize high-risk areas for early intervention, ultimately reducing transmission at both community and district levels.

Discussion

This study provides one of the most detailed analyses to date on how dengue transmission patterns differ across housing types within a rapidly developing peri-urban setting in Malaysia. By combining temporal, proportional, and spatial analyses, the findings reveal a clear housing–epidemic relationship that drives both the persistence and resurgence of dengue in Kuala Selangor, Selangor. The results highlight that landed properties are the dominant epicenters of transmission, while high-rise residential areas maintain a secondary but continuous role in sustaining viral circulation during inter-epidemic periods. Together, these housing environments create a complementary transmission cycle that ensures dengue remains endemic throughout the year.

The predominance of dengue in landed properties demonstrates how environmental design strongly influences vector ecology. Open compounds, roof gutters, and ornamental plants around landed houses provide abundant breeding niches for *Aedes aegypti* and *Aedes albopictus*[27]. The synchronization of case peaks with the southwest monsoon further confirms the climate-sensitive nature of dengue transmission, where rainfall and humidity amplify breeding potential. These findings align with national dengue surveillance trends showing that suburban and landed zones repeatedly serve as outbreak nuclei during rainy seasons[28]. Importantly, the strong and predictable seasonal peaks observed here highlight a key opportunity for timed preventive interventions, such as larviciding and community cleanup campaigns before week 20 each year. Although the overall burden from high-rise residential areas was smaller, the continuous detection of cases across almost all weeks of the year indicates sustained low-level transmission within these environments. High-rise complexes often provide sheltered and semi-indoor breeding sites such as rooftop water tanks, corridor drains, and flowerpots that remain active even during dry periods. These settings can act as urban refuges for mosquito populations, supporting viral persistence when outdoor breeding declines[29,30]. The proportional increase in cases from high-rise areas during inter-peak periods suggests that they may serve as a bridging reservoir, allowing dengue to persist through seasonal troughs and facilitating reintroduction into landed neighborhoods once climatic conditions become favorable again. This interplay indicate the need for continuous surveillance and targeted inspection of multi-storey housing environments that may otherwise appear low-risk. Spatial mapping revealed that dengue hotspots were most persistent in the central and southern sectors of Kuala Selangor, coinciding with peri-urban zones experiencing active housing development. Such areas typically combine urban density with incomplete infrastructure poor drainage, unmanaged construction waste, and intermittent water supply all of which enhance *Aedes* breeding. These findings support the growing recognition that peri-urban transition zones are critical drivers of dengue in Malaysia, acting as ecological interfaces where human expansion intersects with vector habitats[31]. Meanwhile, the recurring but confined clusters in high-rise zones suggest that once dengue is introduced into a building complex, vertical transmission within floors or units may sustain localized outbreaks over multiple years[15,22,32]. These patterns call for micro-level vector management tailored to housing typologies integrating environmental design, sanitation, and resident behavior into control strategies.

The identification of housing-specific transmission patterns offers actionable insights for urban health policy. Traditional dengue control strategies in Malaysia often rely on broad community campaigns; however, the present findings demonstrate the value of differentiated interventions based on housing structure[33,34]. For landed properties, interventions should focus on outdoor source reduction, yard inspections, and community-led clean-up efforts prior to the monsoon. In contrast, high-rise programs must emphasize routine maintenance of rooftop drainage systems, inspection of common areas, and resident awareness on indoor breeding control.

Integration of these housing-based strategies into the national *Integrated Vector Management (IVM)* framework could significantly enhance outbreak preparedness in rapidly urbanizing districts. These results reflect broader dengue trends across Malaysia's expanding urban corridors, where diverse housing morphologies coexist within limited geographic spaces. The dual dynamic of seasonal amplification in landed areas and year-round persistence in high-rise settings may explain why dengue continues to rise despite ongoing control efforts. Recognizing these spatial–structural determinants is essential for designing predictive risk models and for guiding the allocation of surveillance resources. As climate variability intensifies and urbanization accelerates, adapting dengue control to specific housing environments will be key to achieving sustained reductions in disease burden.

The spatial patterns identified in this study provide important operational insights for dengue control at the district level. Persistent dengue hotspots were concentrated in the central and southern sectors of Kuala Selangor, primarily within peri-urban landed housing estates, while secondary but recurrent clusters were observed in selected high-rise residential complexes. These spatially stable patterns indicate that dengue transmission is not uniformly distributed across the district but is structured by both geography and housing morphology. Building on these findings, dividing the study area into operational control zones based on spatial clustering patterns and dominant housing typologies could substantially enhance the practical utility of dengue surveillance for local authorities. Zonal stratification would allow health officers to systematically identify areas with increasing transmission trends, characterise the prevailing housing environments within each zone, and implement interventions that are tailored to the specific ecological and structural conditions present. Such an approach facilitates more efficient allocation of resources and improves the timeliness of preventive actions. For instance, zones dominated by landed properties and characterised by recurrent mid-year epidemic peaks could be prioritised for pre-monsoon source reduction activities, including outdoor larval habitat management, roof-gutter maintenance, and community-based clean-up campaigns. In contrast, zones characterised by high-rise residential developments exhibiting persistent low-level transmission would benefit from continuous surveillance and inspection of indoor and semi-indoor breeding sites, such as rooftop water tanks, corridor drains, flowerpots, and shared facilities, which are less influenced by seasonal rainfall patterns. Although formal zoning was not implemented within the analytical framework of this study, the spatial outputs generated particularly the kernel density hotspot maps provide a robust empirical foundation for defining such zones in collaboration with district health offices and municipal councils. Importantly, this zonal, housing-informed approach aligns closely with Malaysia's Integrated Vector Management (IVM) framework and supports a strategic shift from reactive, blanket control measures towards proactive, spatially targeted dengue prevention strategies that are better suited to rapidly urbanising peri-urban districts.

The use of both total dengue case counts and weekly case distributions is epidemiologically justified when examining housing-related transmission patterns. Total case burden reflects the cumulative impact of housing environments that consistently support Aedes breeding and human exposure over time, thereby identifying dominant structural contributors to dengue persistence. In contrast, weekly case patterns provide insight into how transmission intensity fluctuates within these housing environments in response to seasonal drivers such as rainfall, humidity, and temperature. By integrating cumulative and weekly analyses, this study demonstrates that housing typology influences dengue transmission at multiple temporal scales: long-term structural risk is captured through total case contributions, while short-term epidemic dynamics are reflected in weekly trends. This dual-scale interpretation strengthens causal plausibility and supports the use of housing patterns as a meaningful unit of analysis for dengue surveillance and control planning.

Despite the strengths of this housing-based spatiotemporal analysis, several limitations should be acknowledged. First, the analysis focused on housing structure and residential typology as proxy indicators of shared environmental and behavioural conditions influencing dengue transmission. Environmental indices such as proximity to surface water, household-level water-holding features, and surrounding vegetation cover, which are known to influence mosquito breeding, were not explicitly quantified in this study. This decision was made due to the lack of consistent, high-resolution environmental data available across all residential areas and throughout the full study period. Including partial or unevenly measured environmental variables could introduce bias and reduce comparability across housing categories. The absence of housing-specific population denominators may influence direct comparisons of transmission intensity between housing types, particularly in areas with high residential density such as high-rise developments. Future studies integrating census-based micro-population data or building-level occupancy estimates would enable incidence-based risk assessment and strengthen causal inference. Additionally, this study relied on routine surveillance data, which may be subject to under-reporting or delays in notification. However, consistent reporting procedures across the study period and housing categories support the internal validity of the observed temporal and spatial patterns.

In summary, the study demonstrates that housing structure is not merely a background factor but a central determinant of dengue transmission dynamics. Landed properties fuel major seasonal outbreaks, while high-rise buildings sustain endemic transmission between peaks. Together, they create a resilient transmission system capable of maintaining dengue circulation year-round. These findings emphasize the importance of spatially adaptive, housing-focused control strategies that align with Malaysia's evolving urban landscape. Incorporating such evidence-based targeting into local and national health planning could transform dengue prevention from reactive response to proactive resilience.

Conclusion

This study demonstrates that housing structure plays a decisive role in shaping dengue transmission dynamics within Kuala Selangor's peri-urban landscape. Landed properties, with their abundant outdoor breeding habitats and vegetation–shade synergy, act as the primary epidemic core driving seasonal outbreaks, while high-rise residential areas sustain low-level year-round transmission that bridges inter-epidemic periods. These complementary dynamics create a continuous transmission cycle, enabling dengue persistence across climatic transitions. By quantifying temporal, proportional, and spatial patterns across distinct housing categories, this research provides actionable insights for housing-based vector control strategies under Malaysia's Integrated Vector Management (IVM) framework. The findings advocate for pre-monsoon outdoor source reduction in landed areas and routine indoor surveillance in multi-storey dwellings. Integrating such housing-specific intelligence into surveillance and urban planning systems can help local authorities transition from reactive fogging operations to proactive, data-driven vector control. This approach advances the practical implementation of precision public health, bridging environmental design with sustainable dengue prevention.

Data availability

The datasets generated and/or analyzed during the current study are available from the corresponding author on reasonable request. Spatial data layers (e.g., housing classification shapefiles, Kernel Density Estimation outputs) are archived at the Centre of Environmental Health & Safety, Universiti Teknologi MARA (UiTM). All spatial and statistical analyses were conducted using licensed software (ArcGIS Pro 3.1 and R 4.3.2) under institutional agreements, and data sharing follows UiTM and Ministry of Health Malaysia data governance policies.

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References

1. Hadi, Z. A. et al. Geospatial dynamics of dengue fever density In Kuantan, Malaysia: GIS-based approach. *Geography, Environ. Sustain.* **18**(1), 54–64 (2025).
2. Mantilla-Granados, J. S. et al. Environmental and anthropic factors influencing *Aedes aegypti* and *Aedes albopictus* (Diptera: Culicidae), with emphasis on natural infection and dissemination: Implications for an emerging vector in Colombia. *PLoS Negl. Trop. Dis.* **19**(4), e0012605 (2025).
3. Singh, H., Akhtar, N. & Gupta, S. K. Biology of Mosquitoes. In *Mosquitoes: Biology, Pathogenicity and Management* 141–163 (Singapore, Springer Nature Singapore, 2024).
4. AbuBakar, N. et al. The dengue disquisition: A low-cost public housing conundrum in Klang Valley, Malaysia. *PLoS ONE* **20**(1), e0317349 (2025).
5. Telle, O. et al. Dengue dynamics beyond biological factors: Revealing the nexus between urbanisation planning, and mobilities in Vientiane, Lao PDR. *PLOS Negl. Tropic. Diseases* **19**(6), e0011990 (2025).
6. Joseph, N. K. et al. Mosquito-borne diseases in urban East African Community region: a scoping review of urban typology research and mosquito genera overlap, 2000–2024. *Front. Tropic. Diseases* **5**, 1499520 (2024).
7. Islam, S., Haque, C. E., Hossain, S. & Hanesiak, J. Climate variability, dengue vector abundance and dengue fever cases in Dhaka, Bangladesh: a time-series study. *Atmosphere* **12**(7), 905 (2021).
8. Xu, Z. et al. Spatiotemporal patterns and climatic drivers of severe dengue in Thailand. *Sci. Total Environ.* **656**, 889–901 (2019).
9. Alam, K. E. et al. Time series analysis of dengue incidence and its association with meteorological risk factors in Bangladesh. *PLoS ONE* **20**(8), e0323238 (2025).
10. Tayebi, S. et al. A neighborhood-based urban water carrying capacity assessment: analysis of the relationship between spatial-demographic factors and water consumption patterns in Tehran. *Iran. Land* **11**(12), 2203 (2022).
11. Ghavidelfar, S., Shamseldin, A. Y. & Melville, B. W. A multi-scale analysis of single-unit housing water demand through integration of water consumption, land use and demographic data. *Water Resour. Manage* **31**(7), 2173–2186 (2017).
12. Mohd Hardy Abdullah, N. A., Dom, N. C., Pradhan, B., Salleh, S. A. & Dapari, R. Temporal associations between microclimate, adult Aedes mosquito indices, and dengue cases at the residence level in Malaysia: Implications for targeted interventions. *PLoS ONE* **20**(2), e0316564 (2025).
13. Dickin, S. K., Schuster-Wallace, C. J. & Elliott, S. J. Mosquitoes & vulnerable spaces: Mapping local knowledge of sites for dengue control in Seremban and Putrajaya Malaysia. *Appl. Geogr.* **46**, 71–79 (2014).
14. Woods O, & Randle S. Ecological responsibility in the city: the surfaces and volumes of urban mosquito management. *Urban Geography*, 1–23 (2025).
15. Seidahmed, O. M., Lu, D., Chong, C. S., Ng, L. C. & Eltahir, E. A. Patterns of urban housing shape dengue distribution in Singapore at neighborhood and country scales. *GeoHealth* **2**(1), 54–67 (2018).
16. Rahman, M. S. et al. Ecological, social, and other environmental determinants of dengue vector abundance in urban and rural areas of Northeastern Thailand. *Int. J. Environ. Res. Public Health* **18**(11), 5971 (2021).
17. Ngugi, H. N. et al. Characterization and productivity profiles of Aedes aegypti (L.) breeding habitats across rural and urban landscapes in western and coastal Kenya. *Parasites Vectors* **10**(1), 331 (2017).
18. Abdullah, M. S. et al. Impact of waste management on infectious disease control: Evaluating strategies to mitigate dengue transmission and mosquito breeding sites: A systematic review. *Integ. Biomed. Res.* **8**(8), 1–12 (2024).
19. Fernandez, S. A. et al. Features of the urban environment associated with *Aedes aegypti* abundance in high-rise public apartments in Singapore: An environmental case-control study. *PLoS Negl. Trop. Dis.* **17**(2), e0011075 (2023).
20. Sairi, F. A. M., Dom, N. C. & Camalxaman, S. N. Infestation profile of Aedes mosquitoes in multi-storey buildings in Selangor, Malaysia. *Procedia Soc. Behav. Sci.* **222**, 283–289 (2016).
21. Roslan, M. A. et al. A study on Wolbachia-dengue-carrying Aedes mosquitoes (Diptera: Culicidae) focuses on the sustainability and frequency of Wolbachia in high-rise buildings in Selangor, Malaysia. *Appl. Entomol. Zool.* **59**(3), 225–236 (2024).
22. Jin, S. et al. Vertical dispersal of Aedes albopictus within multi-story buildings in downtown Shanghai, China. *Parasites Vectors* **16**(1), 176 (2023).
23. Kolimenakis, A. et al. The role of urbanisation in the spread of Aedes mosquitoes and the diseases they transmit: A systematic review. *PLoS Negl. Tropic. Diseases* **15**(9), e0009631 (2021).
24. Sarfraz, M. S. et al. Analyzing the spatio-temporal relationship between dengue vector larval density and land-use using factor analysis and spatial ring mapping. *BMC Public Health* **12**(1), 853 (2012).
25. Aris NAM, Fathi MS, Harun AN, & Mohamed Z. Spatial Pattern of Affordability and Overhang in Selangor. In *IOP Conference Series: Earth and Environmental Science*. 012057. (IOP Publishing 2025)
26. Jaafar HZ, & Ashraf MA. 1 Climate, Ecosystem, Flora, and Fauna. *Soils of Malaysia* (2017)
27. Herath, J. M. K., De Silva, W. P. P., Weeraratne, T. C. & Karunaratne, S. P. Breeding habitat preference of the dengue vector mosquitoes Aedes aegypti and Aedes albopictus from urban, semiurban, and rural areas in Kurunegala District, Sri Lanka. *J. Trop. Med.* **2024**(1), 4123543 (2024).
28. Hossain, K. et al. Spatio-temporal patterns of dengue in Bangladesh during 2019 to 2023: Implications for targeted control strategies. *PLoS Negl. Trop. Dis.* **18**(9), e0012503 (2024).
29. Zhaki, Z. A., Dom, N. C. & Alhothily, I. A. Study on the distribution and abundance of *Aedes aegypti* and *Aedes albopictus* in different environment settings for high-rise buildings. *Malaysian J. Med. Health Sci.* **15**, 102–108 (2019).

30. Ab Hamid, N. et al. Vertical infestation profile of Aedes in selected urban high-rise residences in Malaysia. *Tropic. Med. Infect. Disease* **5**(3), 114 (2020).
31. Montgomery, M. R., Pinchoff, J. & Chuang, E. K. Cities and their environments. In *International handbook of population and environment* 349–374 (Springer International Publishing, 2021).
32. Marti, R. et al. A mapping review on urban landscape factors of dengue retrieved from earth observation data, GIS techniques, and survey questionnaires. *Remote Sensing* **12**(6), 932 (2020).
33. Dom, N. C. et al. Barriers and opportunities for community engagement in UAV-based dengue management in rural Malaysia. *PLoS ONE* **20**(4), e0322321 (2025).
34. Samsudin, N. A., Othman, H., Siau, C. S. & Zaini, Z. I. I. Exploring community needs in combating aedes mosquitoes and dengue fever: a study with urban community in the recurrent hotspot area. *BMC Public Health* **24**(1), 1651 (2024).

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Author contributions
N.C.D., A.N.S.H., M.N.S., N.A.A.L., M.I.R. and R.D conceived the study, supervised overall execution, and verified the underlying data. N.C.D., Z.A.M.F., and N.M.Y. designed the analytical framework and performed data validation. N.C.D. and M.A.O. conducted the statistical and spatial analyses, and prepared the figures. N.C.D., S.A.S., and R.D. interpreted the results and drafted the initial manuscript. All authors reviewed, revised, and approved the final version prior to submission.

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Declarations

Competing interests
The authors declare no competing interests.

Ethical approval
This study utilized secondary surveillance data obtained with formal approval from the Medical Research and Ethics Committee (MREC), Ministry of Health Malaysia (NMRR ID: 25–02921-CR1). Ethical clearance was granted on 1 October 2025, valid until 1 October 2026. All procedures were conducted in accordance with national data protection regulations and institutional ethical standards. No human subjects were directly involved, and all data were anonymized prior to analysis. Data were used solely for research purposes under strict confidentiality.

Additional information
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