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Ecological determinants and indicator-based analysis of *Aedes albopictus* expansion in a Central European metropolis: implications for urban sustainability

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ABSTRACT

The invasive bridge vector mosquito *Aedes albopictus* has been increasingly detected across Europe, posing potential risks for arboviral disease transmission. Urban-scale assessments of its expansion remain scarce in Central Europe. The establishment and spread of *Ae. albopictus* in Budapest were analysed between 2018 and 2025 using spatio-temporal mapping, seasonal observations, and indicator-based ecological modelling, complemented by ensemble machine learning approaches. Occurrence patterns followed a logistic growth trajectory ($R^2 = 0.995$), with colonization rising from sparse foci in 2020 to over 85% of districts by 2025. Seasonal activity extended from late April to mid-October, peaking in early September. Ensemble machine learning models consistently achieved high predictive performance, with key predictors included urban fabric, temperature, topography, and precipitation-related indices (bio18; Köppen Aridity Index) while other factors contributed variably. Ecological associations were strongest with urbanized land cover (discontinuous and continuous urban fabric, industrial areas), specific soil types such as fluvent entisols, and humid temperate climates (Köppen Cfa). K-means clustering and decision tree analyses distinguished seven ecological clusters across Budapest, ranging from warm, densely built urban cores to cooler, shaded peri-urban and forested zones. Conceptually linking ecological clusters to the Sustainable Development Goals highlighted spatially heterogeneous intersections with health (SDG 3), urban sustainability (SDG 11), water management (SDG 6), climate action (SDG 13), and biodiversity conservation (SDG 15). These findings provide a baseline for predicting urban vector expansion, informing early warning systems, and guiding public health interventions and vector control strategies in European metropolitan regions.

1. Introduction

Aedes albopictus (Skuse, 1894), commonly known as the Asian tiger mosquito, has expanded from a regional pest in Southeast Asia to a globally important vector of human and animal diseases (Battaglia et al., 2022). It transmits several medically significant arboviruses (Lwande et al., 2020), including Cache Valley, chikungunya, dengue, Eastern equine encephalitis, Keystone, La Crosse, West Nile, and Zika viruses—depending on the continent and the region (Bonizzoni et al., 2013; Garcia-Rejon et al., 2021)—as well as avian *Plasmodium* spp. (Veiga et al., 2024) and several filarial nematodes such as *Dirofilaria* spp. (Genchi et al., 2024).

Laboratory and field studies have confirmed its competence for many of these pathogens, and in some outbreaks, it has acted as the primary or sole vector, particularly in regions where the more efficient dengue vector *Aedes aegypti* is absent or scarce (Braks et al., 2004). Its growing epidemiological relevance results from a combination of ecological adaptability, broad vector competence, rapid global spread facilitated by human activities (Roche et al., 2015), and environmental changes that continue to expand its potential distribution (Proestos et al., 2015). Because *Ae. albopictus* bites aggressively during the daytime and readily feeds on humans (Unlu et al., 2021), in addition to other mammals (and in some cases birds), its opportunities as a "bridge vector" (connecting animal reservoirs and humans) are significant (Pereira-dos-Santos et al., 2020). When populations reach high density, even modest competence can translate into serious outbreak potential (Brass et al., 2024).

Originating in Southeast Asia and some Pacific Islands (Paupy et al., 2009), *Ae. albopictus* has, over the past decades, invaded every continent permanently inhabited by humans (Abbasi, 2025). It has expanded its range from its native tropical and subtropical zones into temperate and

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mild winter continental regions, including large portions of peri-Mediterranean Europe (Cunze et al., 2016). This global spread has been greatly facilitated by human activities—especially the transport of dormant eggs in used tires, shipments of plants, and other containerized transport systems (Mohammadi et al., 2022). Consequently, anthropogenic movement likely plays a more dominant role in its dispersal than natural spread or the mosquito's intrinsic flight capability (Trájer et al., 2017a).

Once introduced into new regions, *Ae. albopictus* exhibits remarkable ecological plasticity. Its adaptability allows it to exploit a wide variety of larval habitats in both natural and artificial containers (Bonizzoni et al., 2013), across urban, suburban, and rural settings, and even *peri*-forested zones (Dalpadado et al., 2022). Such adaptive phenotypic versatility means that despite the predominantly subtropical origin of this mosquito species, it can also relatively quickly adapt to the environmental conditions of continental, cooler winter areas (Kramer et al., 2021). Some strains show cold hardiness and capacity to survive winters, enabling establishment in temperate regions previously unsuitable for tropical-origin mosquitoes (Kress, 2016; Abbasi, 2025). Its ability to thrive in human-modified habitats further enhances human–mosquito contact, particularly in rapidly urbanizing areas (Kolimenakis et al., 2021).

The expansion of *Ae. albopictus* has been linked to increasing incidence of arboviral outbreaks in newly invaded or marginal areas (Gratz, 2004). For instance, in Central Africa, its invasion has raised concerns of enhanced chikungunya, dengue, and Zika transmission where such diseases were previously less common or under-recognized (Ngoagouni et al., 2015). Similarly, in continental and maritime Europe, its establishment in multiple countries has corresponded with autochthonous cases of dengue, chikungunya, and Zika—events (Brem et al., 2023; Menegale et al., 2025; Cattaneoet al., 2025) that would have been unlikely without this vector.

Currently, *Ae. albopictus* is rapidly invading climatically suitable areas in Europe (Radici et al., 2025). Further, climate change is projected to expand the range of suitable habitat for *Ae. albopictus* (Trájer et al., 2024; Barman et al., 2025), extend the seasonal windows for mosquito activity, and increase the likelihood of establishment at higher latitudes or altitudes (Dhimal et al., 2015). These environmental shifts act synergistically with globalization (trade, travel) and urban growth — especially where water storage and container habitats are abundant — to amplify the global burden of mosquito-borne diseases (Abbasi, 2025; Kress, 2016). The climate change-driven spread of invasive *Aedes* vectors and the potential emergence of a homodynamic situation in Southern Europe (Del Lesto et al., 2022) may therefore further facilitate the transmission of *Aedes* mosquito-borne viruses across the continent (Rezza et al., 2024).

Recent surveillance data indicate that *Ae. albopictus* is now established across many EU/EEA countries, including Hungary (Garamszegi et al., 2023a,b). In the North Balkans and adjacent Pannonian regions, its expansion has been particularly rapid: while the first Hungarian record came from Baja in 2014 (Sztikler et al., 2015), by 2022–2023 the species had become abundant in the Budapest metropolitan area (*Aedes albopictus*, GBIF.org, 2025).As of June 2025, the species was reported as established in 369 regions across Europe and is present in a total of 26 European countries (ECDC, 2025; ECDC and EFSA, 2025). In Hungary, *Ae. albopictus* has become an increasingly important invasive species with significant implications for public health and vector control (Garamszegi et al., 2023a), occurring in 16 counties and in the capital, and remaining absent from only three counties (ECDC, 2025).

Model projections reinforce this trend: whereas about 49 % of major European urban areas are currently suitable for *Ae. albopictus*, this could increase to around 83 % under future warming scenarios (Caminade et al., 2017). In Hungary, surveillance combining entomological and citizen science approaches has shown a strong association between urbanization and the presence of *Ae. albopictus*, with the species being more frequent in urbanized landscapes and transport hubs (Garamszegi et al., 2023a). Spatial patterns of detections show clusters along the southwest and southeast borders as well as around major traffic corridors leading into Budapest (Garamszegi et al., 2023b), suggesting that these hotspots function as both introduction sites and early colonization centers.

1.1. Aims

Although *Ae. albopictus* is increasingly reported across Europe, including Hungary, most studies focus on short-term seasonal activity, single sites, or individual environmental factors. Comprehensive analyses integrating spatio-temporal dynamics, climate, land cover, and predictive modelling are scarce in Central European cities like Budapest. The links between mosquito ecology, public health, and urban sustainability (e.g., SDGs) remain underexplored. This study aims to provide a spatio-temporal assessment of *Ae. albopictus* establishment and spread in Budapest and its surroundings between 2018 and 2025.

2. Materials and methods

2.1. Logical framework of the study

Specifically, the following tasks were examined:

(i) The spatio-temporal expansion of *Ae. albopictus* across the Budapest metropolitan area was evaluated.
(ii) Seasonal activity patterns in relation to meteorological drivers were analysed.
(iii) Weekly abundance of *Ae. albopictus* in Budapest was analysed using meteorological predictors, including average, maximum, and minimum temperature, precipitation, sea-level pressure, global radiation, and wind speed.
(iv) The influence of climatic and land cover characteristics on mosquito occurrence using Köppen–Geiger and CORINE Land Cover classifications was studied.
(v) To assess the relative importance of meteorological underlying the seasonal activity of *Ae. albopictus*, three machine learning methods were applied: Random Forest (RF), Gradient Boosting (GB), and eXtreme Gradient Boosting (XGB) following the concept of Sahin (2020).
(vi) Machine learning approaches, including Random Forest (RF), Gradient Boosting (GB), eXtreme Gradient Boosting (XGB), Extra Trees (ET), and a Voting Ensemble (VE), were applied, including Random Forest (RF), Gradient Boosting (GB), eXtreme Gradient Boosting (XGB), Decision Tree (DT), and Voting Ensemble (VE) algorithms were applied to identify key environmental determinants shaping the spatio-temporal distribution of *Ae. albopictus* within the studied urban environment.
(vii) K-means clustering was employed to characterize habitat types and evaluate their links to Sustainable Development Goals, thereby integrating ecological findings into a broader sustainability framework.

2.2. Conceptual indicator framework

This study applied a socio-ecological systems perspective, combining the indicator framework of Carlsen and Bruggemann (2022) with the DPSIR (Driver–Pressure–State–Impact–Response) model (Gupta et al., 2020). Integrating DPSIR with Sustainable Development Goals (SDGs) is increasingly used in urban sustainability assessments (Liu et al., 2020; Luo et al., 2025) and can be adapted to vector-borne disease research (Trájer, 2025). This approach treats environmental, climatic, and urban-structural variables as conceptual indicators influencing *Ae. albopictus* ecology and urban sustainability.

Within DPSIR, long-term environmental and urban-structural attributes (e.g., land use, land cover, regional climate) were drivers, while short-term meteorological variables (temperature, precipitation, radiation, pressure, wind) acted as pressures. The system state was described by spatial and seasonal patterns of *Ae. albopictus* and habitat indicators, including terrain and Köppen classifications (Köppen, 1923; Köppen et al., 2011). Impacts were the modelled spatio-temporal distribution and seasonal abundance identified via machine learning. Responses linked habitat clusters to SDGs, notably SDG 3, 11, and 13, framing *Ae. albopictus* as both an ecological invader and an urban sustainability challenge.

Fig. 1 illustrates this framework.

2.3. Study area and occurrence data

The analysis focused on the Budapest metropolitan area in Central Europe (47.32–47.67° N, 18.83–19.36° E). Occurrence data for *Aedes albopictus* were obtained from the Global Biodiversity Information Facility (Aedes albopictus, GBIF.org, 2025) and related biodiversity repositories. The datasets comprise records from both citizen-science platforms and institutional monitoring programs including AIMSurv (Miranda et al., 2022), EMBL-EBI INSDC (Cantelli et al., 2021), iBOL (Adamowicz, 2015), iNaturalist (Matheson, 2014), izeltlabuak . hu (2025), Mosquito Alert (Escobar et al., 2024), Observation.org (2025), OH_SURVector (2025), and VectorNet (Braks et al., 2022). After filtering out redundant records, a total of 1337 data points were used in the analysis. The dataset was further filtered to retain only valid georeferenced records without spatial errors, presence-only observations, and selected basis-of-record categories (Observation, Human Observation, Specimen, and related evidence). These GBIF data provided a broad spatio-temporal reference for *Ae. albopictus* presence in Central Europe, whereas detailed weekly abundance data (2018–2025) were separately obtained from systematic mosquito surveillance within the Budapest metropolitan area.

2.4. Software

All curve fitting and machine learning methods were performed in Python 3.10 (64-bit). Spatial mapping, data sampling, and visualization were conducted in QGIS 3.34.11 with GRASS GIS 8.4.0.

2.5. Methodological rationale for environmental predictors

Environmental and climatic variables were selected to represent key drivers of *Ae. albopictus* development, survival, and distribution in Budapest. Temperature regulates development and survival, enabling multiple generations per season, while mismatches between larval and adult habitats can reduce fitness (Delatte et al., 2009; Phanitchat et al., 2017; Ezeakacha and Yee, 2019). Precipitation provides temporary aquatic habitats, with dry periods limiting their duration (Dieng et al., 2012; Trájer, 2018; Alto and Juliano, 2001a; Tran et al., 2013), and aridity indices, such as the Köppen Aridity Index, integrate hydrothermal balance for mosquito development (Paz, 2019; Sinka et al., 2016; Musah et al., 2023).

Global radiation influences container water temperature, evaporation, and larval stress (Haider et al., 2017; Paaijmans et al., 2010; Steinhoff et al., 2016; Villena et al., 2018), while wind and sea-level pressure affect dispersal and seasonal activity (Trájer, 2018; Waldock et al., 2013; Adeleke et al., 2022; Trájer and Trájer, 2022). Köppen–Geiger zones contextualize long-term climatic constraints (Trájer, 2024; Shaikevich et al., 2023).

Land cover defines habitat availability and dispersal corridors

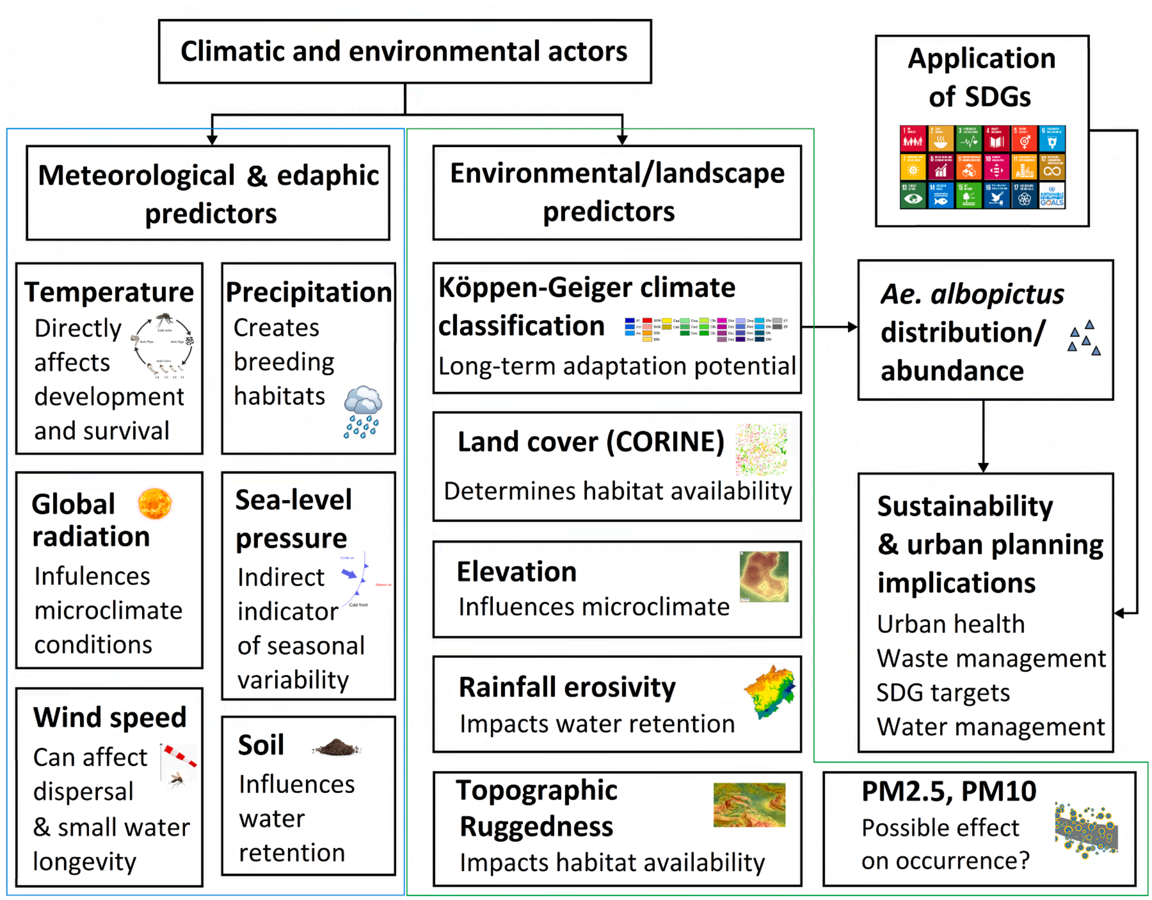

Fig. 1. Visualization of the logical framework of the study.

(Baldacchino et al., 2017; Leisnham et al., 2021; Tsuda et al., 2006; Hiscox et al., 2013; Lacroix et al., 2009), while topography and microhabitat heterogeneity affect thermal gradients, water accumulation, and breeding-site formation (Eisen et al., 2008; Dhimal et al., 2015; Palaniyandi et al., 2020; Cao et al., 2025; Wimberly et al., 2020). Rainfall erosivity and soil properties influence container refilling, water persistence, and larval survival (Di Lena et al., 2021; Pautzke et al., 2024; Youssefi et al., 2022; Reiskind and Lounibos, 2013; Yee and Juliano, 2006).

Finally, $PM_{2.5}$ and PM_{10} were included as proxies for urban air pollution, affecting breeding-site quality and mosquito physiology (Duval et al., 2024; Phanitchat et al., 2021).

2.6. Sources of climatic and environmental predictors

Climatic and meteorological variables were compiled from multiple complementary sources. To characterize long-term climatic conditions of occurrence sites, data were obtained from the WorldClim 2.1 database (Cerasoli et al., 2022). Daily meteorological records (temperature, precipitation, global radiation, wind speed, and sea-level pressure) used for seasonality analysis were sourced from the KNMI Climate Explorer database (Trouet et al., 2013). These values were aggregated into weekly means (or sums for precipitation) to match the temporal resolution of mosquito sampling intervals. The Köppen–Geiger climate classification (Köppen, 1884; Beck et al., 2018) was extracted from 1-km resolution global maps, providing categorical descriptors consistent with long-term climatic zones of the Budapest region. Land cover was characterized using the CORINE Land Cover dataset (Büttner et al., 2014), which describes urban, agricultural, and natural habitats.

Supplementary Table S1 shows the summary of datasets used in the study and Supplementary Table S2 summarizes the CORINE Land Cover classes present in the Budapest metropolitan area.

The Global Rainfall Erosivity Index was obtained from the Global Rainfall Erosivity Database (GloREDa) of the European Soil Data Centre (Panagos et al., 2023). Elevation were derived from the NOAA seamless topography-and-bathymetry bare earth surface elevation dataset (ETOPO) (MacFerrin et al., 2022). Topographic ruggedness was calculated in QGIS using the specific terrain analysis GDAL tools.

Supplementary Table S3 summarizes the Köppen–Geiger climatic classes identified in the Budapest metropolitan area. Five main types were recognized, belonging to three broader climatic groups.

2.7. Mapping of annual mean $PM_{2.5}$ and PM_{10} concentrations

Annual mean $PM_{2.5}$ and PM_{10} concentrations in Budapest for 2020–2025 were compiled from the World Air Quality Index Project (WAQI, https://aqicn.org/station/hungary), which aggregates quality-controlled data from 105 official and partner monitoring stations. Only stations with consistent, reliable records were included, while irregular or outlier data were excluded. Annual means were calculated from daily values and georeferenced using station coordinates. Spatial patterns were mapped in QGIS 3.x using Inverse Distance Weighting (IDW), a standard method for urban-scale air-pollution interpolation (De Mesnard, 2013). Maps, projected in WGS 84 / UTM Zone 34 N, illustrate long-term mean distributions of $PM_{2.5}$ and PM_{10} in Budapest and surrounding areas, highlighting potential urban pollution hotspots.

Supplementary Fig. S1 a–b show the IDW-interpolated $PM_{2.5}$ and PM_{10} concentration layers.

2.7.1. Aridity factor

In addition to standard climatic and land cover predictors, an aridity factor was calculated using the Köppen Aridity Index (KAI), defined as (Quan et al., 2013):

$$KAI = \frac{P_{sum}}{T_{avg} + 33}$$

where P_{sum} represents the annual or seasonal precipitation sum (mm), and T_{avg} denotes the mean air temperature (°C). The denominator incorporates an empirical constant (+33) to normalize the influence of temperature on evapotranspiration demand, as originally proposed in the Köppen framework.

The KAI provides a dimensionless measure of hydrothermal balance, differentiating humid, sub-humid, and arid environments. For this study, KAI values were computed at seasonal and annual scales for all sites and time intervals, thereby capturing long-term water availability conditions relevant to *Ae. albopictus* ecology (Fukui et al., 2022). The KAI was subsequently incorporated as a continuous predictor in clustering, classification, and machine learning models.

Supplementary Table S4 summarizes the climatic and environmental factors used.

2.8. K-means clustering

An unsupervised clustering procedure (Suyal and Sharma, 2024) was used to identify characteristic environmental conditions associated with *Ae. albopictus* presence.

2.8.1. Environmental data used

The categorical variables included Köppen climatic class and Corine land cover type. The numerical variables included elevation a.s.l., topographical ruggedness, Köppen Aridity Index, rainfall erosivity index, annual mean temperature (bio1), mean temperature of wettest quarter (bio8), mean temperature of driest quarter (bio9), mean temperature of warmest quarter (bio10), mean temperature of coldest quarter (bio11), annual precipitation sum (bio12), precipitation of warmest quarter (bio18), and precipitation of coldest quarter (bio19).

2.8.2. Data preprocessing

Categorical predictors were transformed using one-hot encoding (Yu et al., 2022). Numerical variables were standardized (zero mean, unit variance). Missing meteorological values were imputed via time-series interpolation. To capture lagged ecological responses, predictors were expanded to include 1- and 2-week lags.

2.8.3. Clustering process

The optimal number of clusters was identified using the elbow method (minimizing within-cluster sum of squares) and the silhouette index (Saputra et al., 2020). Cluster solutions with $k = 2$–10 were tested, and the primary silhouette peak was observed at $k = 2$, indicating the broadest separation of the data. A secondary peak was identified at $k = 7$, reflecting finer-scale spatial structure. Although the first peak represented the most distinct statistical separation, the second peak was selected to capture biologically and ecologically more meaningful spatial substructures. The silhouette and elbow plots are provided in Supplementary Fig. S2 to document the decision-making process. Cluster centroids were inspected to identify influential variables. PCA was used to visualize clustering results, and loadings of environmental variables on principal components were analysed.

2.8.4. Classification and variable importance

To interpret the environmental differentiation among the identified clusters, a Decision Tree classifier (Kushwah et al., 2022) was applied to the full predictor set, using the cluster labels as categorical targets. The tree depth was constrained to six levels to avoid overfitting and to enhance interpretability. The model identified which environmental factors best distinguished clusters rather than predicting species presence. Variable importance was measured via Gini impurity reduction (Laber and Murtinho, 2019) and confirmed with permutation-based analysis. Rankings and visualizations highlighted each climatic and topographic variable's contribution to cluster separation, summarizing key environmental gradients. The tree structure is provided in

Supplementary text S1 Decision_tree_structure.txt.Temporal evaluation of *Aedes albopictus* abundance.

Weekly mosquito abundance data from Budapest (2018–2025) were used to assess temporal patterns in *Ae. albopictus* activity. Temporal mosquito observation data were merged with weekly aggregated meteorological variables, including mean, maximum, and minimum temperature, precipitation, sea-level pressure, global radiation, and wind speed. Missing meteorological values were imputed through temporal interpolation, and 1-week and 2-week lagged predictors were generated to account for delayed population responses to climatic conditions. To investigate environmental drivers of seasonal mosquito dynamics, three ensemble regressors—Random Forest (RF), Gradient Boosting (GB), and XGBoost (XGB)—were trained on concurrent-week, 1-week lagged, and 2-week lagged meteorological predictors. Model performance was assessed via five-fold cross-validation using RMSE (Rougier, 2016; Sahin, 2020).

Variable importance was evaluated using internal (mean decrease in Gini impurity; Elsayad et al., 2025; Xie et al., 2023) and model-agnostic (permutation) approaches (Disha and Waheed, 2022; Hodson, 2022). Permutation-based reductions in accuracy identified the most influential predictors, providing a robust assessment of climatic factors shaping seasonal and interannual *Ae. albopictus* abundance in Budapest.

2.9. Spatial ensemble analysis

Machine learning was used to identify environmental determinants of *Ae. albopictus* distribution. Algorithms included RF, GB, XGB, ET, and a Voting Ensemble of RF, GB, and XGB. Model performance was assessed with accuracy and weighted F1-score, and feature importance highlighted key climatic, land cover, and soil predictors. Pseudo-absence points ($n = 2000$; 1.5:1 ratio to 1337 presences) were randomly generated within the study area, excluding points within 500 m of presences. Spatial operations were performed in EOV (EPSG:23700) and transformed to WGS84 for environmental data extraction (CORINE, WorldClim). Residuals were checked for spatial autocorrelation using Moran's I (Epperson and Li, 1996).

3. Results

3.1. Territorial spread of Aedes albopictus in Budapest (2020–2025)

The mapped data reveal a clear and progressive expansion of *Ae. albopictus* across the Budapest metropolitan area over the period 2020–2025. In 2020, occurrence points were sparse and highly localized, with only a few known sites exhibiting a sparse distribution. These were concentrated in the central region and the southern and south-western margin of the city and in Budaörs, very close to the south-western part of the capital. By 2021, the number of sites showed a burst, occurrences concentrated along the Danube and in southern districts. About one-quarter of the city's districts (26 %) reported detections, showing the first signs of local clustering. In 2022, expansion accelerated and around 43 % of districts had reported the species by this stage, confirming that *Ae. albopictus* was no longer confined to isolated hotspots but actively spreading into the urban core. By 2023, the mosquito exhibited widespread dispersal. At least 65 % of districts reported established populations. New detections in the eastern and northern parts of the city illustrate how the species had moved beyond its initial foci to colonize diverse urban and peri-urban environments. By 2024–2025, more than 85 % of districts were colonized, and the distribution pattern showed both infilling of central districts and expansion into the western suburban hills (Fig. 2).

The above-described colonization patterns mark the transition toward near saturation of suitable habitats in the capital. The fitted sigmoid curve accurately described the expansion, with an upper asymptote of ~2653 occurrences and an inflection point in mid-2021, indicating the period of fastest spread ($R^2 = 0.995$, adjusted $R^2 = 0.989$, $p < 0.001$). The standard error of the estimate was 108, confirming the robustness of the model fit (Fig. 3).

3.2. Ecological and indicator analyses

3.2.1. Seasonal analysis

The continuous *Ae. albopictus* season in the Budapest metropolitan area starts in the 18th calendar week, around late April to early May. However, the increase of observations remains slow until the 29th week.

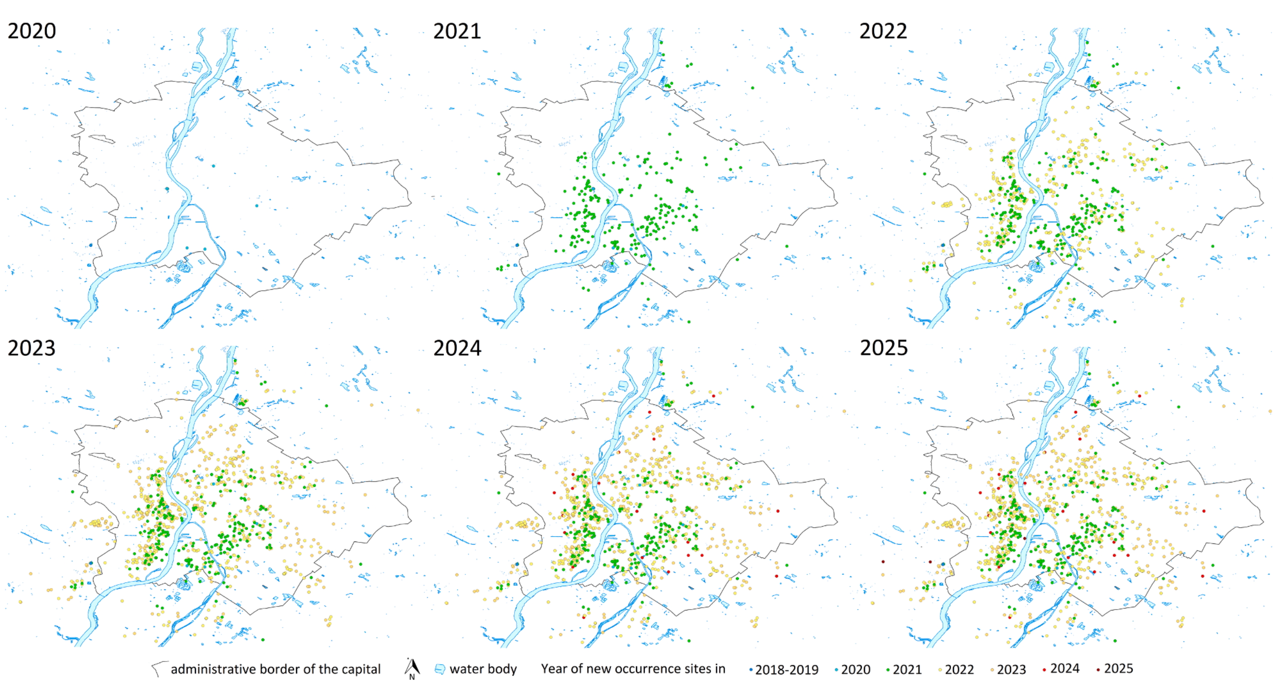

Fig. 2. The territorial spread of *Aedes albopictus* in the Budapest metropolitan area in 2018–2025. The boundary coordinates of the maps are: 47.32–47.67° N, 18.83–19.36° E.

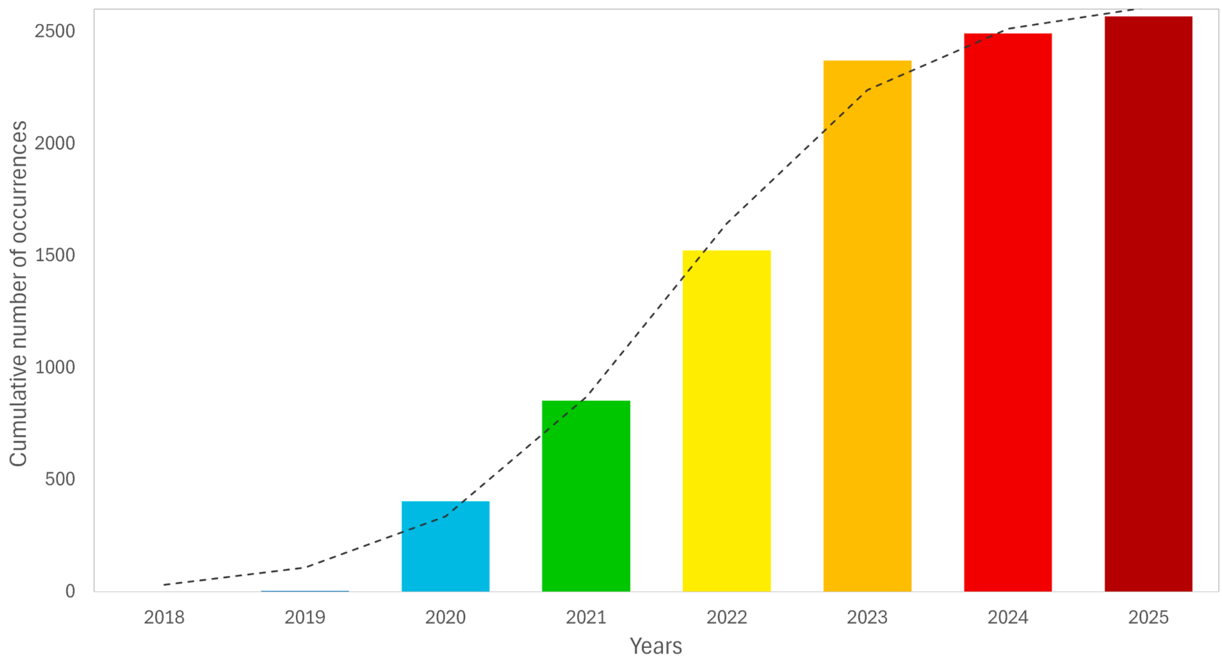

Fig. 3. The cumulative number of *Aedes albopictus* occurrences in 2018–2025 and the fitted sigmoid curve.

After that, in mid-July, the number of observations exhibits a rapid increase which peaks in the 36th week in early September. In the next week, the number of observations decrease rapidly, and it is followed by a slower decline from late September to mid-October (Fig. 4).

For the same-week predictors (0-week lag), model performance was generally similar, with RF and XGB achieving the lowest cross-validated RMSE (mean: 9.7), while GB slightly higher (mean: 10.3). Across all machine learning models, maximum temperature (Tmax) and global radiation (GlobRad) were consistently the most influential variables, followed by minimum temperature (T_{min}) and average temperature (T_{avg}). Precipitation and wind speed contributed the least to weekly occurrence prediction. Permutation importance further highlighted the dominance of T_{max} and GlobRad in RF and GB, indicating strong short-term effects on mosquito activity (Fig. 5, weekly lag: 0 week).

For predictors lagged by one week (-1 week), RMSE increased modestly (mean: 11.2), reflecting weaker predictive power from past-week meteorology. Feature importance shifted slightly, with T_{min} and T_{max} remaining important, while global radiation maintained moderate influence. Permutation importance highlighted T_{min} as particularly relevant in GB and XGB models, suggesting that conditions from the previous week partially affect mosquito abundance (Fig. 5, weekly lag: -1 week).

Two-week lagged predictors (-2 weeks) showed similar or slightly higher RMSE values (mean: 11.5–12.3), indicating that meteorological conditions older than one week are less informative. Gini and permutation importances indicated a greater relative contribution of T_{avg} and T_{min}, while T_{max} and GlobRad still contributed notably in some models. Overall, precipitation, sea-level pressure, and wind speed remained minor predictors at all lags (Fig. 5, weekly lag: -2 weeks).

3.2.2. *Environmental analysis of occurrences*

Aedes albopictus observation sites in the Budapest metropolitan area occur across five Köppen climate classes: steppe climate (Köppen BSk), humid subtropical climate (Köppen Cfa), oceanic climate (Köppen Cfb),

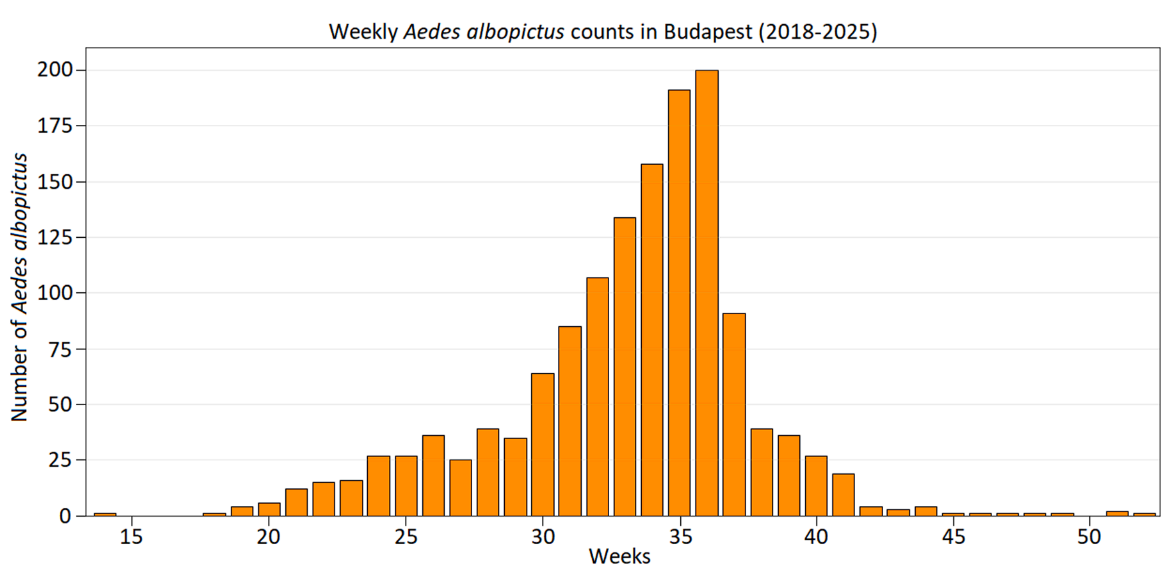

Fig. 4. The weekly number of *Aedes albopictus* observation events in 2018–2025.

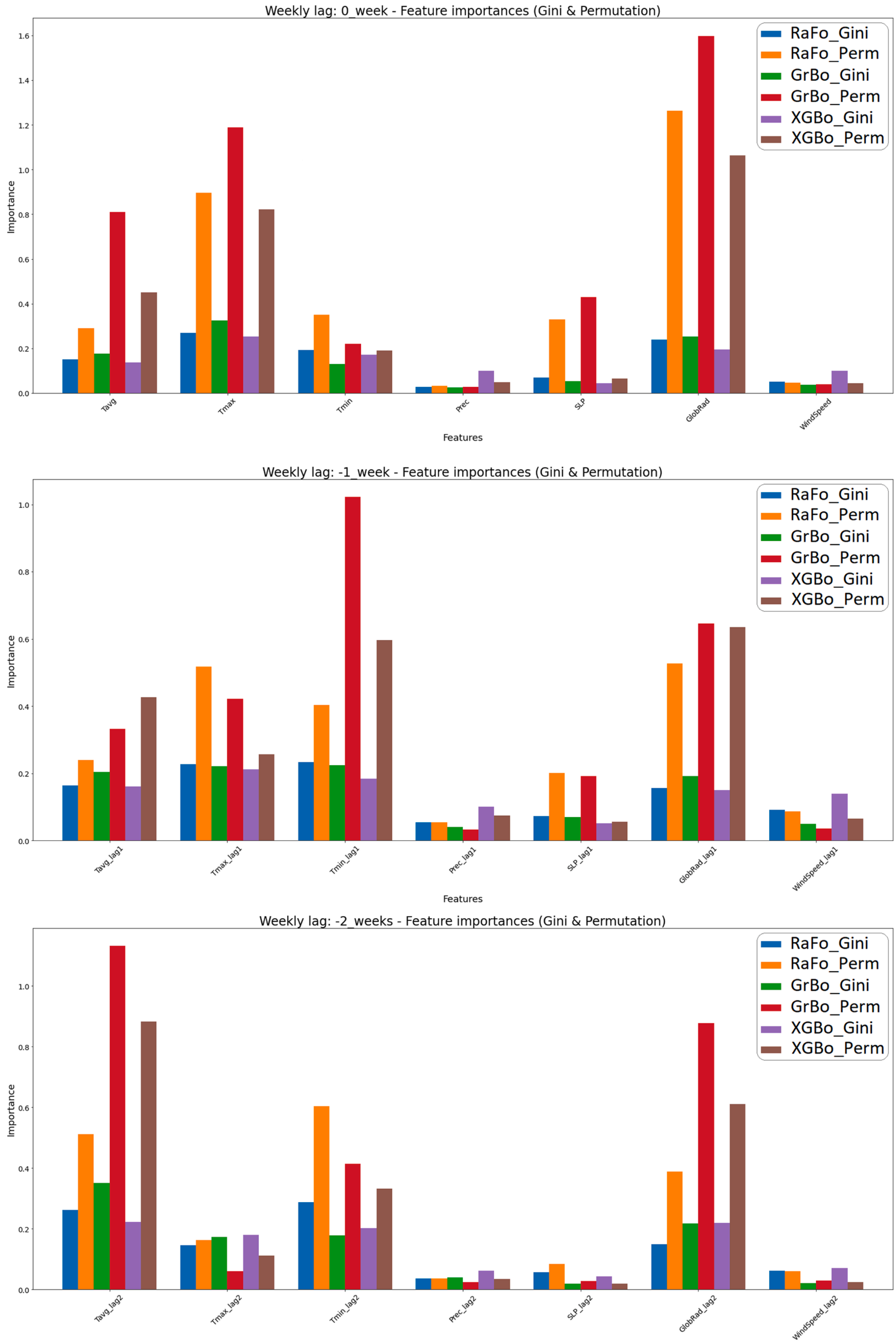

Fig. 5. The importances of different meteorological factors shaping the weekly *Aedes albopictus* observation events based on Random Forest (RaFo), Gradient Boosting Machine (GrBo), and eXtreme Gradient Boosting (XGBo) learning methods using Gini and permutation feature importance techniques.

hot summer humid continental climate (Dsa), and warm summer humid continental climate (Dsb) (Fig. 6a).

Based on the CORINE Land Cover model, most occurrences are concentrated in highly urbanised regions, predominantly within discontinuous urban fabric, industrial or commercial units, and areas covered by continuous urban fabric (Fig. 6b).

Analysis of *Ae. albopictus* occurrences in the Budapest metropolitan area revealed distinct patterns related to both climate and land cover. Based on Köppen–Geiger classifications, the species was most frequently observed in cold, no dry season climates with warm summers (Dfb, 49.0 %) and cold, no dry season climates with hot summers (Dfa, 23.1 %), while occurrences were lower in temperate climates with hot (Cfa, 16.0 %) or warm summers (Cfb, 4.1 %) and arid steppe cold climates (BSk, 7.8 %) (Fig. 7a1).

When adjusted for the relative abundance of these Köppen climatic classes within the metropolitan area, *Ae. albopictus* showed a strong preference for temperate climates with hot summers (Cfa, 48.5 %), whereas cold climates (Dfa, 0.7 %; Dfb, 0.8 %) were underrepresented, indicating a disproportionately preference for warmer temperate conditions (Fig. 7b1).

Analysis of CORINE Land Cover types further highlighted the species' association with urban and semi-urban habitats. The highest absolute occurrences were found in discontinuous urban fabric (81.5 %), followed by industrial or commercial units (9.3 %) and continuous urban fabric (3.0 %), whereas natural and agricultural areas such as green urban spaces (1.1 %), complex cultivation patterns (2.1 %), and non-irrigated arable land (0.7 %) contributed less to overall observations (Fig. 7a2).

When normalized by land cover availability, the relative occurrence frequencies confirmed the species' preference for human-modified landscapes, with continuous urban fabric (3.8 %), discontinuous urban fabric (3.3 %), and green urban areas (1.5 %) exhibiting the strongest associations. Conversely, natural and less intensively used areas, including non-irrigated arable land (0.02 %) and miscellaneous land covers (0.01 %), were markedly underrepresented (Fig. 7b2).

3.2.3. Spatial feature importance analysis results

The predictive performance of five machine learning models for *Ae. albopictus* presence in Budapest was consistently high. RF, XGB, GB, ET, and a Voting Ensemble achieved strong accuracy (0.952–0.972) and weighted F1-scores, with the Voting Ensemble performing best (Fig. 8).

Feature importance analyses consistently highlighted discontinuous urban fabric (CLS 2), annual mean temperature (bio1), rainfall erosivity, topographic ruggedness, and elevation. RF prioritized discontinuous urban fabric, wind, elevation, rainfall erosivity, and topographic ruggedness; XGB emphasized discontinuous urban fabric, annual mean temperature, industrial/commercial units (CLS 3), complex cultivation patterns (CLS 20), and Aquept Inceptisol (USDA code 90); GB prioritized discontinuous urban fabric, rainfall erosivity, annual mean temperature, topographic ruggedness, and elevation; ET identified discontinuous urban fabric, topographic ruggedness, Fluvent Entisol (USDA code 98), rainfall erosivity, and elevation; the Voting Ensemble highlighted discontinuous urban fabric, annual mean temperature, rainfall erosivity, topographic ruggedness, and elevation. These results indicate the combined importance of land cover and climatic variables in shaping Ae. albopictus distribution.

Spatial dependence assessed via Moran's I showed raw presence points were strongly clustered, while residuals were near zero for most models (RF: −0.0002; XGB: 0.0012; ET: 0.0008; Voting Ensemble: 0.0013), indicating minimal spatial autocorrelation. GB residuals were slightly higher (0.0741), reflecting model sensitivity to spatially structured predictors. Predictor correlations were visualized in a heatmap (Supplementary Fig. S3), and spatial residuals are in Supplementary Figs. S4–S8.

Overall, high predictive performance combined with minimal residual spatial autocorrelation shows that these machine learning approaches robustly identified key environmental determinants of *Ae. albopictus* occurrence in Budapest.

3.2.4. K-means clustering results

K-means clustering analysis identified seven distinct environmental clusters within the Budapest metropolitan area (Fig. 9a-b), each representing characteristic climatic and habitat conditions that influence the potential distribution of *Ae. albopictus*, which can be further interpreted using the decision tree results (Supplementary Fig. S9).

Cluster 1 is primarily located in the eastern and southeastern periphery of the Pest region (districts X, XIV-XIX), in suburban areas with family houses and residential parks on the Pest Plain., This region is characterized by warmer, relatively wetter microclimates and dense urbanization with abundant artificial water-holding containers, such as garden ponds, rain barrels, and discarded waste, highlighting the suburban periphery where high human density coincides with mosquito habitat opportunities.

Cluster 2 occurs mainly in the central parts of the Buda region

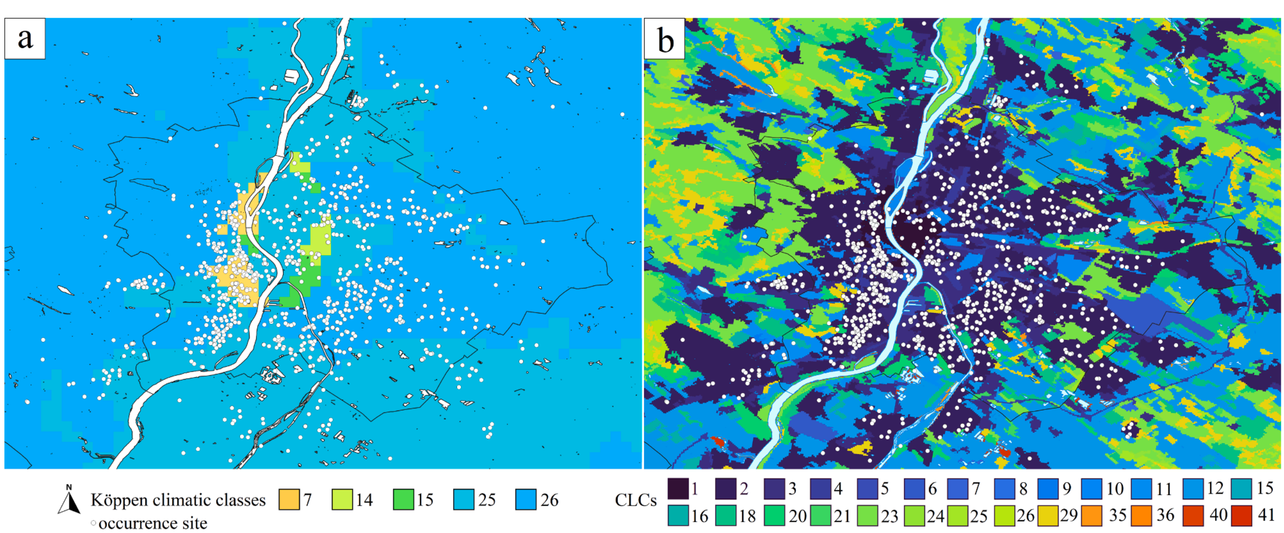

Fig. 6. The distribution of *Aedes albopictus* occurrences in the Budapest metropolitan area in 2018–2025 is projected to the Köppen-Geiger climatic classification map (a) and the CORINE Land Cover model (b). The boundary coordinates of the maps are 47.32–47.67° N, 18.83–19.36° E. Köppen climatic classes are 7: BSk, 14: Cfa, 15: Cfb, 25: Dfa, and 26: Dfb. The explanations of Köppen climate classes and CORINE Land Cover categories are given in Supplementary Tables S1 and S2.

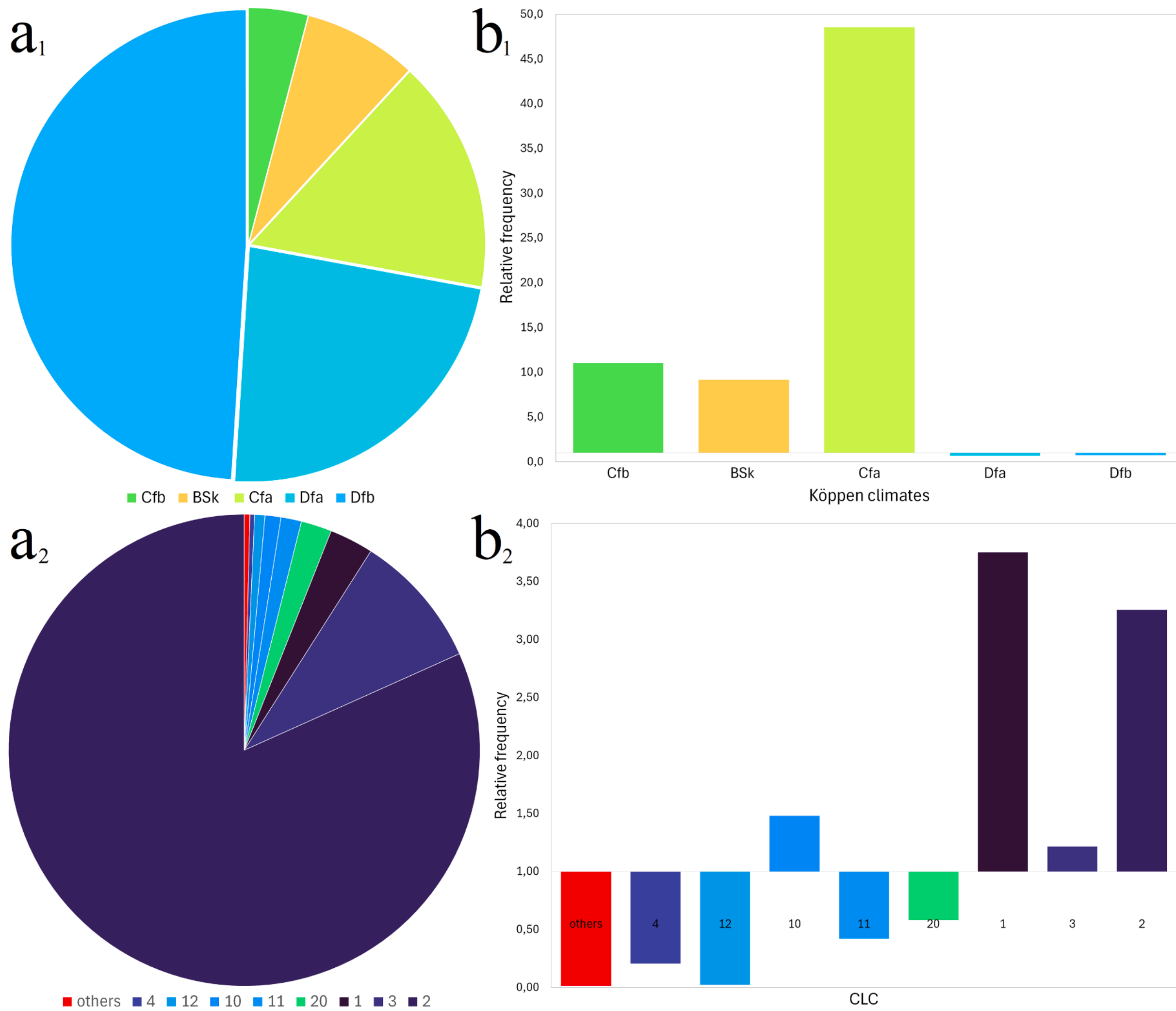

Fig. 7. Pie charts showing the distribution of *Aedes albopictus* occurrences across Köppen–Geiger climate classes (1) and CORINE Land Cover (CLC) types (2). The charts display both the proportion of each class/type at mosquito occurrence sites (a) and the relative frequency of occurrences normalized by the availability of the same classes/types (b) within the study area (47.32–47.67° N, 18.83–19.36° E).

(districts I, XI-XII), extending onto the eastern slopes of the Buda Hills. This cluster reflects cooler, more seasonally variable environments where droughts may limit mosquito proliferation, but temporary water bodies after rainfall can still provide breeding opportunities.

Cluster 3 is found mainly west of Budapest, in neighbouring towns and suburban zones (Budaörs, Budakeszi), characterized by park-like or family-house areas closer to the Buda hills, and occurs in some points of the western part of districts I and XI-XII. Although, rugged topography and garden water management systems (ponds, rain tanks) contribute to the persistence of localized breeding habitats here, the cooler micro-climates of the hills may limit overwintering success compared to low-land areas.

Cluster 4 is situated in the Budafok-Tétény area (the southern part of District XI and the northern part of District XXII), a limestone plateau lower than the Buda Hills, with primarily gardened residential zones. This region with dense tree and bush vegetation and its moderately warm and humid climate max provide appropriate conditions for *Ae. albopictus*.

Cluster 5 is distributed along the Danube, encompassing heterogeneous land covers, including suburban areas with family houses and floodplains on the margins (districts XXI-XXII), densely built-up down-town areas (districts V-IX), and even industrial sites (in the northern part of District XXI). It is the warmest, driest, and generally the most anthropogenically modified region. Although this cluster occurs within highly urbanized and heterogeneous environments, it can still provide suitable conditions for *Ae. albopictus*, primarily due to the abundance of artificial breeding sites, such as construction areas, disturbed soils, and temporary water accumulations.

Cluster 6 is widespread across the Pest side (e.g., districts IV, XIV, XIX-XX, XXIII), mostly encompassing large suburban, residential park, and smaller apartment-block neighbourhoods, as well as certain industrial or infrastructure-dominated zones. These dry, flat environments are associated with high human activity and artificial water storage, such as tire depots, construction yards, and neglected containers, which can serve as key mosquito breeding sites.

Cluster 7 is localized mainly in the eastern part of District II which, is characterized by villas with large gardens and extending onto the eastern slopes of the Buda Hills. Currently, these areas represent less suitable habitats for *Ae. albopictus* (Fig. 9b).

Cluster 6 was the most frequent, representing 36.8 % of all cases, followed by Clusters 5 (17.1 %) and 1 (13.5 %). Clusters 2 (12.9 %) and 4 (11.5 %) were less common, while Clusters 7 (4.7 %) and 3 (3.0 %) were the rarest (Fig. 10). The three dominant clusters were concentrated along the Danube riverbanks and across the alluvial plain of Pest, whereas the rarest habitats occurred mainly on the eastern foothills of the Buda Mountains (Figs. 9–10).

The decision tree analysis identified the main predictors shaping the clusters. While temperature-related bioclimatic factors—annual mean

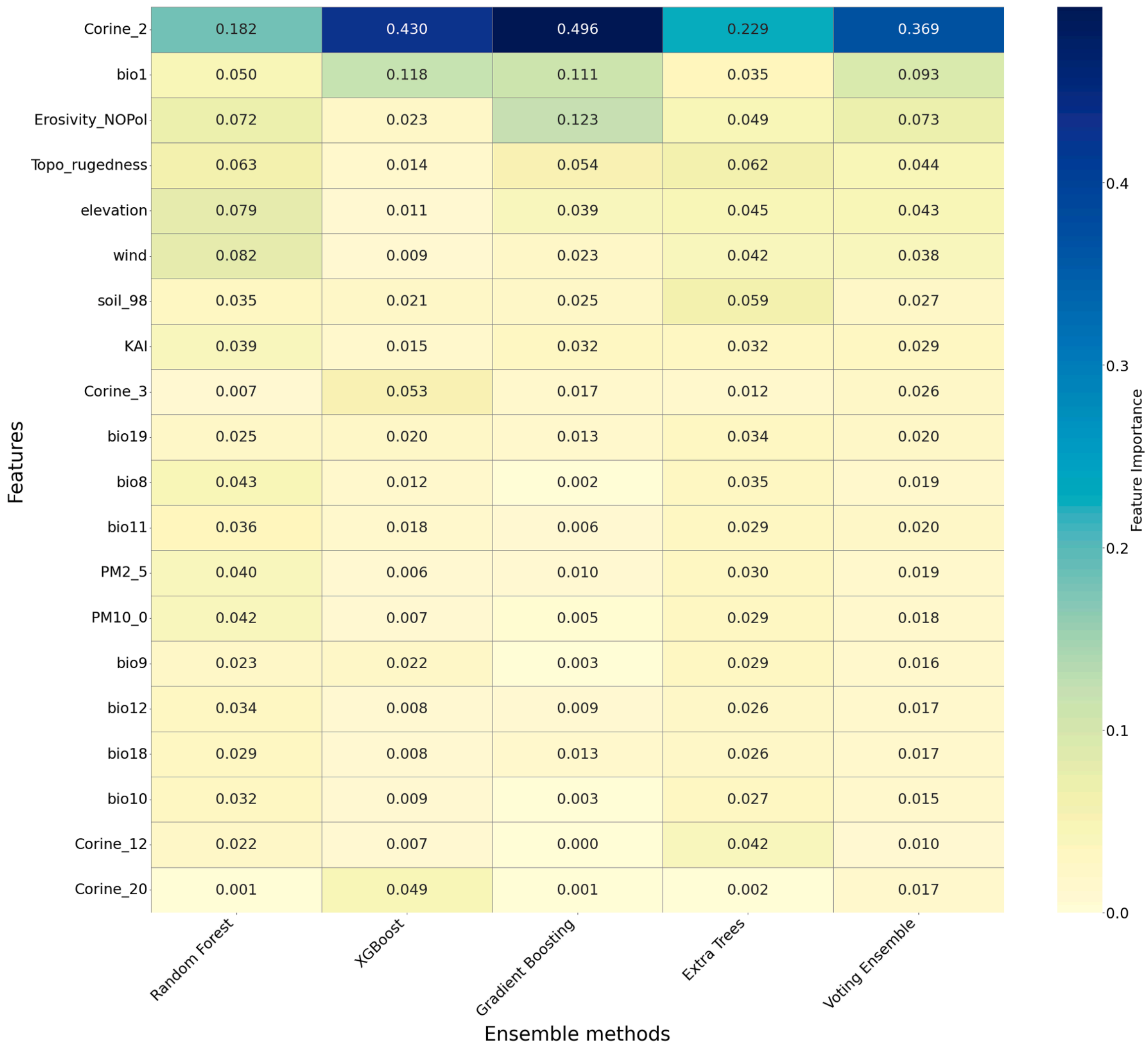

Fig. 8. Importance of environmental and climatic factors estimated using an ensemble of five factor importance analyser models. Only the top 20 variables were displayed.

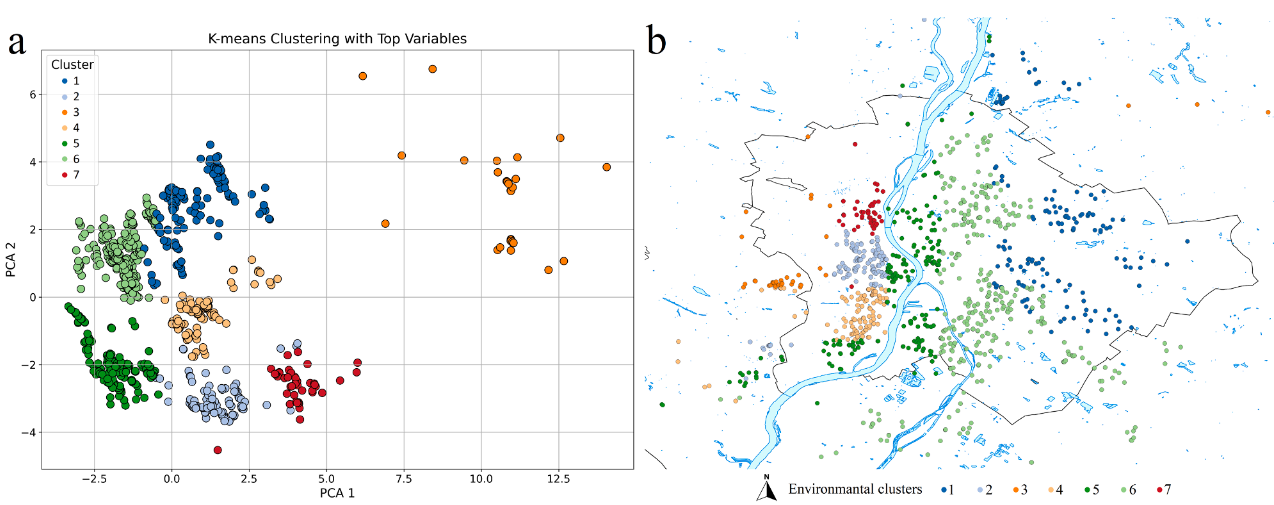

Fig. 9. K-means clustering-based environmental clusters (ECs) of *Aedes albopictus* habitats (a) and their projection to the in the Budapest metropolitan area (b). The boundary coordinates of the map are: 47.32–47.67° N, 18.83–19.36° E.

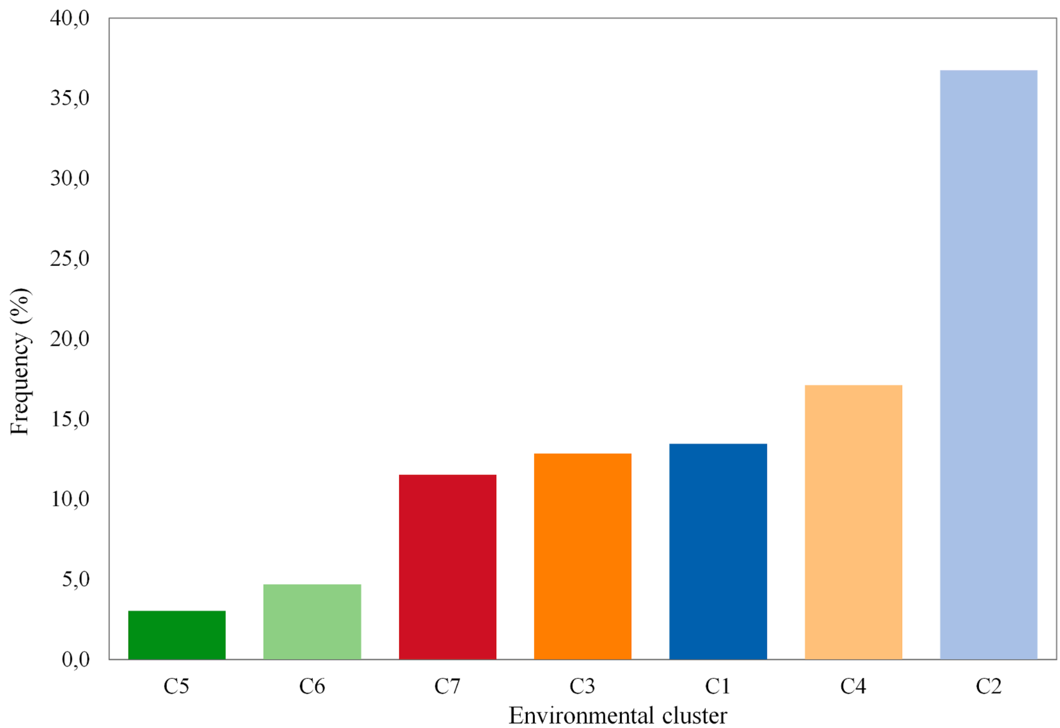

Fig. 10. Relative frequencies of the identified environmental clusters of *Aedes albopictus* in the Budapest metropolitan area.

temperature (bio1), mean temperature of the driest quarter (bio9), and mean temperature of the wettest quarter (bio8)—strongly differentiated clusters, the most important variable was precipitation of the warmest quarter (bio18), highlighting its decisive role (Fig. 11).

The tree achieved very high classification accuracy, with precision, recall, and F1-scores near 1.00 for all clusters. Cluster 2 represents the most favorable conditions for *Ae. albopictus*, characterized by humid microclimates, moderate aridity, and stable precipitation. Key factors include bio18, Köppen Aridity Index (KAI), annual precipitation (bio12), precipitation of the coldest quarter (bio19), and rainfall erosivity, reflecting humid, erosion-prone, and water-stable environments such as landscaped villa neighbourhoods, shaded urban parks, and vegetated margins.

Clusters 5 and 6 provide moderately suitable environments (suburban gardens, peri-urban habitats, shaded microclimates), whereas clusters 1, 3, 4, and 7 correspond to cooler, drier, or thermally extreme conditions less suitable for the species (Fig. 11).

3.3. Linking clusters to sustainable development goals (SDGs)

The distribution of environmental clusters across Budapest metropolitan area provides a framework for integrating mosquito management into broader sustainability and resilience strategies aligned with the UN Sustainable Development Goals, synthesizing the results of K-means clustering (Fig. 9 a-b) and decision tree analyses results (Supplementary Fig. S9).

Cluster 1 (urban, warm, wet, and polluted) directly relates to SDG 3 (Good Health and Well-Being) due to the combined impacts of vector-borne disease risk and degraded air quality (PM10 and PM2.5). It also ties to SDG 11 (Sustainable Cities and Communities) by calling for improved drainage, green infrastructure, and air quality management, as well as SDG 6 (Clean Water and Sanitation) through safe water storage and runoff control.

Cluster 2 (cooler peri-urban, moderately polluted) highlights water and air quality management challenges linked to SDG 6 (Clean Water) and SDG 11 (Sustainable Cities). Rainwater harvesting and drought-adaptation strategies must avoid creating mosquito habitats, while also addressing particulate pollution sources. SDG 13 (Climate Action) remains relevant for monitoring how climatic and environmental variability alter habitat suitability.

Cluster 3 (forested and shaded areas) underscores the intersection of biodiversity and public health. Actions under SDG 15 (Life on Land) should focus on managing urban green spaces to balance biodiversity conservation with vector control, while SDG 3 (Health) requires public awareness campaigns in recreational areas where mosquito exposure is likely. In addition to SDG 3 and 15, SDG 11 (Sustainable Cities and Communities) should also be considered to manage urban green infrastructure effectively, ensuring that biodiversity conservation and vector control are balanced in recreational and park-like areas.

Cluster 4 (construction and disturbed soils with high rainfall erosivity) illustrates the indirect role of urban development and soil disturbance in mosquito ecology, as increased surface runoff and the accumulation of artificial water-holding structures can create suitable breeding habitats for container-breeding species such as *Ae. albopictus*. Here, SDG 11 (Sustainable Cities) is critical for regulating construction runoff, erosion, and water management, while SDG 12 (Responsible Consumption and Production) calls for sustainable practices that minimize unintended mosquito habitats. SDG 13 (Climate Action) and SDG 15 (Life on Land) are also relevant for mitigating rainfall-induced soil erosion and maintaining ecosystem stability in rapidly developing areas. SDG 6 (Clean Water and Sanitation) should also be highlighted to emphasize safe water storage and runoff management, reducing opportunities for artificial container-breeding of *Ae. albopictus*.

Cluster 5 (hilly Buda side) links biodiversity-rich suburban areas to mosquito risks. SDG 15 (Life on Land) should guide conservation of hillside ecosystems, while SDG 6 (Clean Water) emphasizes secure storage in residential gardens and small-scale water systems. In addition to SDG 6 and 15, SDG 3 (Good Health and Well-Being) should be included, given that these biodiversity-rich suburban areas may still pose localized vector-borne disease risks, particularly in gardens and small-scale water systems.

Cluster 6 (dry peri-urban/industrial, high wind exposure) shows the importance of waste, air and infrastructure management. Actions fall under SDG 12 (Responsible Consumption) for better waste handling (e.

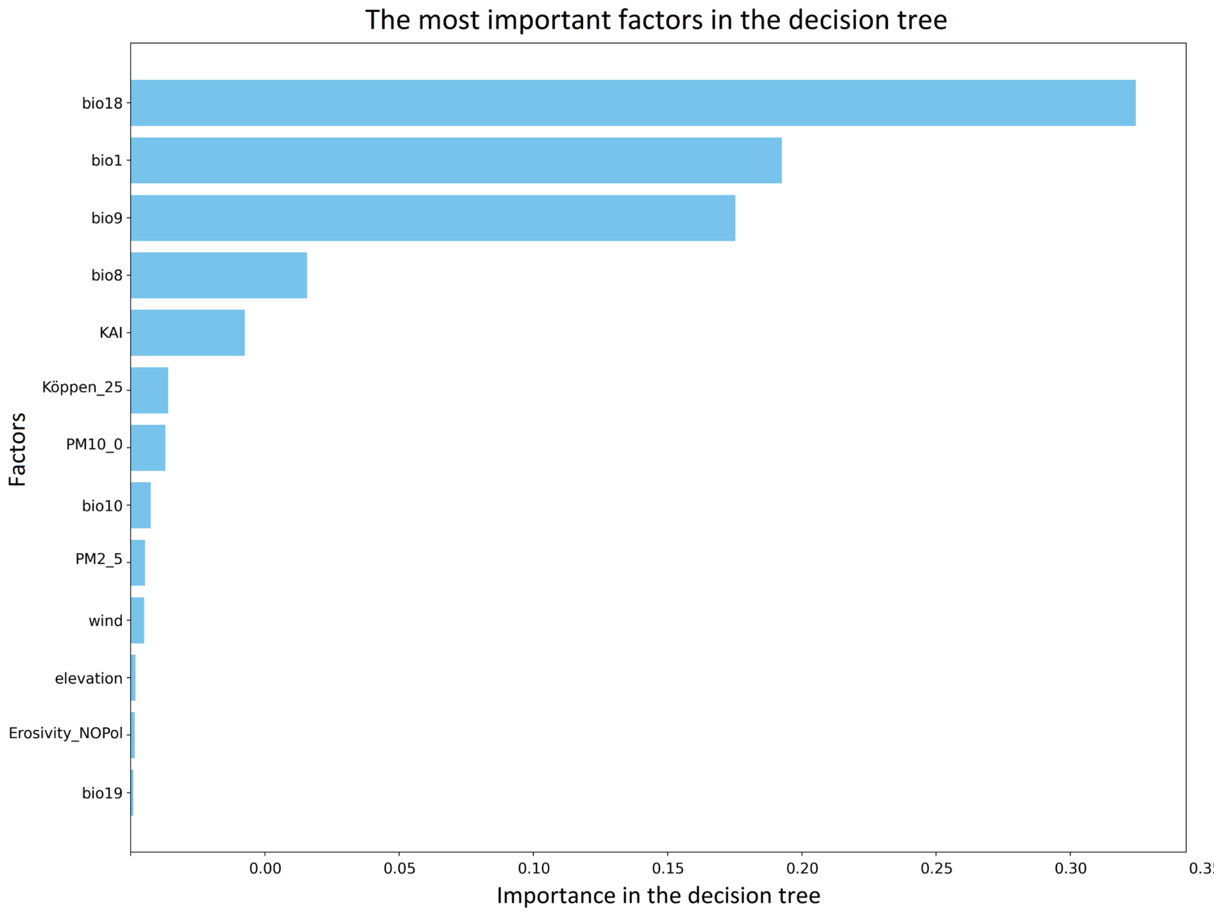

Fig. 11. The most important environmental factors distinguishing the identified clusters of *Aedes albopictus* in the Budapest metropolitan area based on decision tree results. Factor abbreviations: bio1: annual mean temperature, bio8: mean temperature of wettest quarter, bio9: mean temperature of driest quarter, bio10: mean temperature of warmest quarter, bio18: precipitation of warmest quarter, bio19: precipitation of coldest quarter, KAI: Köppen Aridity Index, Köppen_25: Köppen Dfb (humid continental with warm summers) climate, elevation: topographic elevation a.s.l., Erosivity_NoPol: rainfall erosivity, PM2_5: PM 2.5, PM10_0: PM10.0, wind: wind speed.

g., tires, plastics), emission control, and SDG 11 (Sustainable Cities) to improve infrastructure planning that avoids stagnant water formation. Although rainfall erosivity is low, SDG 6 (Clean Water) remains relevant to ensure sustainable stormwater management under increasingly variable precipitation.

Cluster 7 (cooler, wind-influenced outskirts) represents areas with currently limited suitability but potential future expansion under changing wind and temperature regimes. Long-term SDG 13 (Climate Action) monitoring, including climatic and atmospheric dynamics, and SDG 3 (Health) early-warning systems will be crucial to prepare for the northward and upward spread of *Ae. albopictus* (Fig. 12).

4. Discussion

This study aimed to characterize the ecological and climatic drivers shaping the distribution and seasonal dynamics of *Ae. albopictus* in the Budapest metropolitan area between 2020 and 2025. The results revealed a rapid territorial expansion of the species, following a sigmoid invasion pattern with an inflection point around 2021, and a clear seasonal activity peaking in early September. Machine learning analyses identified temperature and global radiation as the dominant predictors of weekly occurrence, while precipitation and wind speed had minor influence. The clustering and decision tree analyses further showed that the species prefers humid, shaded, and moderately warm urban and peri-urban environments, particularly along riparian corridors and densely built-up areas. These findings provide the basis for interpreting the broader ecological, urban, and sustainability implications discussed below.

While previous studies on this invasive mosquito in Europe have often focused on short-term monitoring, isolated urban sites, or individual environmental drivers (Roche et al., 2015; Georgiades et al., 2023; Steindorf et al., 2025), more recent approaches have begun to integrate long-term spatio-temporal expansion with multiple environmental determinants and machine learning methods (Da Re et al., 2025). However, comprehensive frameworks that simultaneously account for meteorological influences, climatic and land-cover characteristics, and advanced modelling strategies remain limited, as highlighted in recent systematic reviews (Lippi et al., 2023). This holistic assessment offers novel insights into how ecological and anthropogenic factors interact to shape the colonization dynamics of *Ae. albopictus* in a complex Central European metropolis.

The rapid territorial expansion observed in Budapest is consistent with broader patterns of *Ae. albopictus* spread in Europe, where the species has established stable populations in the Mediterranean and has been moving northward into temperate regions in the last few decades (Medlock et al., 2012, 2015; Kraemer et al., 2019). The sigmoid pattern of colonization identified in this study suggests that *Ae. albopictus* undergoes a typical invasive trajectory of mosquito vectors (Bruzzone and Utgés, 2022). A): initial establishment in a few localized hotspots, followed by exponential spread across suitable habitats, and finally approaching saturation as available ecological niches are filled. On a larger spatial scale, the territorial invasion characteristic trends of *Ae.*

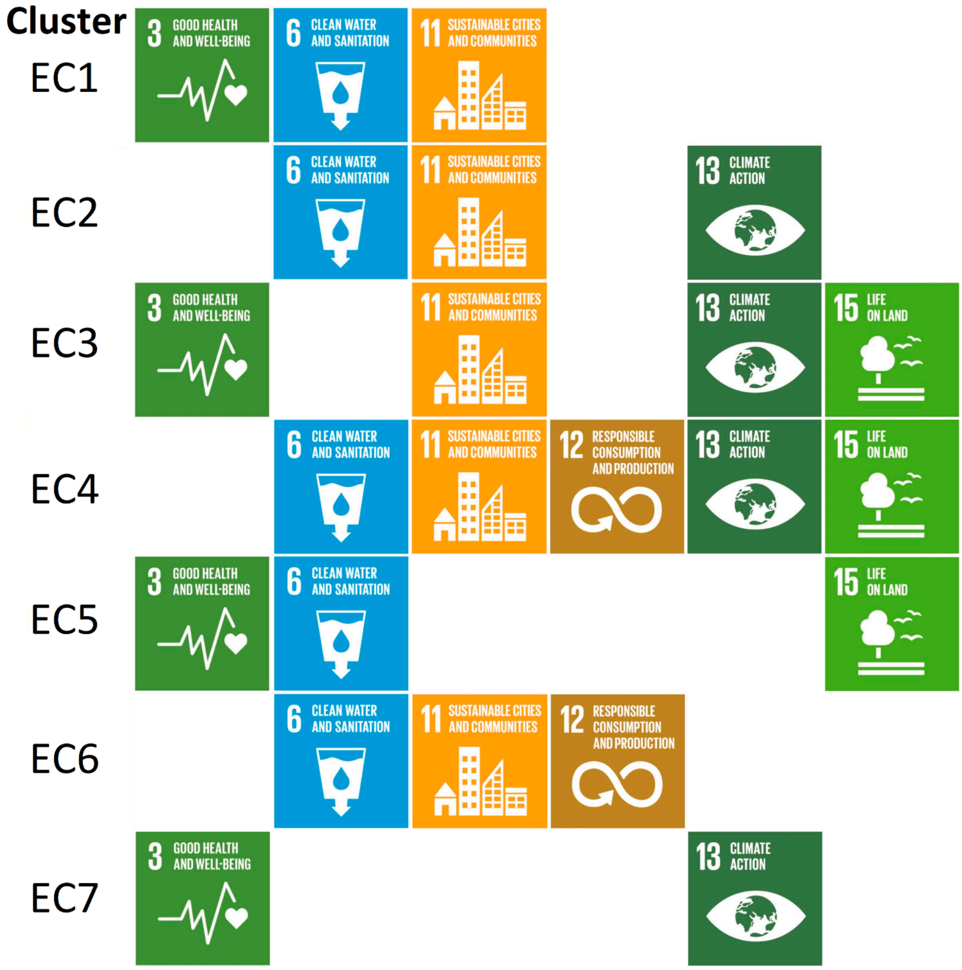

Fig. 12. Linked environmental clusters of *Aedes albopictus* habitats in the Budapest metropolitan area to Sustainable Development Goals. EC= environmental cluster. ECs are equal to the clusters of Fig. 9.

albopictus in Florida and Italy followed very similar trends in the 1990s and the early 2000s (Trájer et al., 2017a). The inflection point in June of 2021 closely aligns with similar tipping points reported in other Central and Eastern European urban centers (Pluskota et al., 2016). This highlights that Budapest is no longer in the early detection phase but has transitioned into a stage of widespread establishment requiring integrated management.

This study revealed a clear seasonal pattern in *Ae. albopictus* activity, beginning in late April and peaking in early September, before declining into October. These findings mirror the phenology described in other European studies (e.g., in Northern Italy; Carrieri et al., 2023), where the species' activity is tightly linked to thermal thresholds and summer photoperiods (Roiz et al., 2011; Neteler et al., 2011). Machine learning analyses confirmed that temperature variables, particularly maximum temperature and global radiation, were the strongest predictors of weekly occurrence. These results are consistent with physiological studies showing that development rates, survival, and biting activity of *Ae. albopictus* increase under warmer and sunnier conditions (Delatte et al., 2009; Alto and Juliano, 2001b). Interestingly, precipitation and wind speed showed variable influence on *Ae. albopictus* abundance, reflecting the species' adaptability to urban environments with artificial water sources such as rain barrels, discarded containers, and infrastructure-associated water retention (Reinbold-Wasson and Reiskind, 2021; You-xiang et al., 2017). While weekly abundance patterns were not solely dictated by rainfall, our analysis revealed that precipitation-related factors—particularly precipitation of the warmest quarter (bio18), annual precipitation (bio12), and the Köppen Aridity Index—were among the most important predictors of the species' preferred microhabitats, highlighting the role of stable water availability in shaded and vegetated urban areas. Additionally, *Ae. albopictus* showed a clear association with discontinuous urban fabric and moderately warm microclimates, often corresponding to humid temperate regions with hot summers (Cfa). This combination of urbanization and microclimatic warmth likely buffers populations against harsher winter conditions, supporting both mosquito abundance and the potential prevalence of transmitted diseases (Ravasi et al., 2022; Kraemer et al., 2015; Sureshkumar and Shekhar, 2025).

In Budapest, *Ae. albopictus* activity starts in late April–early May (week 18), rising slowly until week 29, then sharply increasing to peak in early September (week 36), followed by a rapid decline through mid-October. This unimodal pattern aligns with central European observations (Petrić et al., 2021; Luciano et al., 2003; Lacour et al., 2015) but contrasts with Mediterranean bimodal patterns (Torina et al., 2023; Manica et al., 2016). Cluster-specific microhabitats—humid, shaded areas with stable warm-season precipitation—create localized abundance hotspots, echoing urban "green islands" in Rome (Manica et al., 2016).

Seasonal dynamics are shaped by overwintering egg diapause, with late-April hatching consistent with extended dormant stages (20–26 weeks) described in southern France (Lacour et al., 2015). Meteorological drivers primarily affect short-term abundance: same-week maximum temperature (T_{max}) and global radiation (GlobRad) are strongest predictors, followed by T_{min} and T_{avg}, while precipitation and wind have little influence. Lagged 1–2-week predictors reduce model performance slightly, shifting importance toward T_{min} and T_{avg}, reflecting immediate responses to current conditions (Torina et al., 2023), unlike rainfall-driven secondary peaks in Rome (Manica et al., 2016; Luciano et al., 2003). Overall, Budapest exhibits a unimodal peak in early September, controlled by diapause, photoperiod, and temperature, with urban microhabitats modulating local abundance. These findings highlight critical periods for surveillance and early-season vector control in temperate regions.The observation that *Ae. albopictus* is somewhat underrepresented in the continental regions of Budapest aligns with previous findings that *Ae. albopictus* is sensitive to harsh, cold continental winters (Trájer et al., 2017b). This limitation can be mitigated by the pronounced urban heat island effect, which creates locally warmer microclimates within the Hungarian capital (Dian et al., 2020). The species is most often found in microhabitats characterized by warm and humid conditions, generally corresponding to the Köppen Cfa type, suggesting that stable, wet conditions are critical for its persistence in an urban environment. Short-term climatic fluctuations, including temperature and radiation, appear to elicit rapid responses in mosquito abundance, highlighting *Ae. albopictus*' opportunistic ecology. Although high wind speeds can inhibit population establishment in Europe (Adeleke et al., 2022), this effect is not observed in Budapest, where the average annual wind velocity has remained relatively moderate (2.3 m/s in 2018–2024, wind speed category 2 in the Beaufort scale; KNMI Climate Explorer data). The urban landscape further buffers wind through building structures, reducing potential negative effects.

Land cover analysis revealed that urban habitats are the primary determinants of *Ae. albopictus* occurrences. Discontinuous and continuous urban fabric, along with industrial and commercial units, dominate, whereas natural habitats such as forests and agricultural lands are comparatively underrepresented. These patterns confirm the species' synanthropic nature thriving in densely populated urban and peri-urban areas with abundant container habitats and human hosts (Fischer et al., 2011; Canelas et al., 2023).

The identification of seven ecological clusters provides a detailed view of environmental heterogeneity shaping mosquito ecology in Budapest. In contrast to the findings of Dickens et al. (2018), annual minimum temperature was not consistently among the strongest predictors of *Ae. albopictus* presence. However, it should not be forgotten that Budapest's east-west and north-south extent is 31 × 30 km. This relatively small area exhibits no notable zonal climatic differences. The spatial heterogeneity of clusters well-reflect the geographical differences of the two sides of the Hungarian metropolitan area (Lóczy, 2022). While the left bank of the Danube consists of an alluvial plain (100–150 m a.s.l.), the right bank is characterized by the rising Buda Mountains (highest peak: Nagy Kopasz, 559 m a.s.l.) and the Tétény Plateau (185–225 a.s.l.), creating a striking topographic contrast across the river. The prominence of temperature-related bioclimatic factors (bio10, bio11) and precipitation stability (bio18, Köppen Aridity Index) highlights the dual role of thermal and hydrological conditions in defining habitat suitability.

Cluster 2, characterized by humid, shaded, and precipitation-stable microhabitats, emerged as the most favourable for *Ae. albopictus*, consistent with its requirement for reliable water availability for larval development (Sauer et al., 2021). In contrast, clusters associated with cooler, drier, or topographically rugged areas were less suitable, although they may serve as marginal or transitional habitats. The high classification accuracy of the decision tree models further reinforces the ecological distinctiveness of these clusters.

Importantly, these results show that *Ae. albopictus* is not uniformly distributed across the metropolitan landscape but instead occupies a mosaic of favourable niches embedded in urban and peri-urban settings. Similar spatially heterogeneous patterns have been reported in Spain, where the species showed higher presence in suburban municipalities compared to peri-urban areas (Cevidanes et al., 2023), in the United States, where densities varied significantly between urban and rural land-use types (Westby et al., 2021), and in China, where hotspots of abundance were identified within the urban matrix of Shanghai (Zhou et al., 2021). In Hungary, community science data have also revealed a positive association between urbanization and *Ae. albopictus* occurrence, confirming that the species thrives in favourable microhabitats rather than being evenly spread across cities (Garamszegi et al., 2023).

Aedes albopictus distribution in urban areas is influenced by human-modified environments, vegetation, and microclimate, though the relative importance of these factors varies regionally. In U.S. cities, abundance is linked to infrastructure decay and sparse vegetation, with abandoned buildings and containers providing larval habitats (Little et al., 2017). In contrast, in Budapest, most occurrences were in densely urbanized areas—discontinuous urban fabric, industrial/commercial units, continuous urban fabric, and suburban gardens—showing that urban morphology, land cover, and artificial containers, rather than building abandonment, drive local populations. Many observations in Budapest occurred in landscaped residential areas, highlighting complex interactions between urban design and mosquito ecology. Vegetation influences abundance rather than presence (Bartholomée et al., 2025), while temperature, humidity, and larval density regulate seasonal dynamics (Evans et al., 2019). Socioeconomic factors and impervious surfaces can affect spatial clustering, though container characteristics are unreliable predictors (Shragai and Harrington, 2019). Trees increase egg numbers, grass reduces them, and solar radiation can unexpectedly enhance oviposition, reflecting the nuanced roles of urban microhabitats (Cianci et al., 2015).

Urban greening improves biodiversity and thermal comfort but may create shaded, water-retaining habitats suitable for mosquitoes (Bartholomée et al., 2025; Evans et al., 2019; Xianci et al., 2015). Poorly managed water storage or runoff further promotes proliferation (Shragai and Harrington, 2019). Rigorous, expert-supervised sampling is essential, as trap placement and vegetation management can influence abundance estimates (Baldacchino et al., 2017). Highly anthropized habitats with small vegetated "green islands" act as abundance hotspots, while humid, shaded microclimates with stable warm-season precipitation provide the most suitable environments in Budapest (Manica et al., 2016). Overall, Ae. albopictus thrives in human-modified landscapes, with local abundance shaped by the interplay of urban structure, vegetation, microclimate, and rainfall, highlighting the need for integrated, site-specific management strategies.

A major contribution of this study is its explicit coupling of ecological clusters with the United Nations Sustainable Development Goals (SDGs), offering a systems-level framing in which *Ae. albopictus* functions not only as a biological invader or public health threat, but also an indicator of broader urban sustainability challenges (Contreras Velásquez et al., 2024). Cluster analysis demonstrates how spatially explicit environmental conditions correspond to distinct sustainability and management priorities. Cluster 1 (urban, warm, wet and polluted) links strongly to SDG 3 (Good Health and Well-Being), SDG 11 (Sustainable Cities and Communities) and SDG 6 (Clean Water and Sanitation), reflecting the combined pressures of vector-borne disease risk, air pollution (PM10/PM2.5), inadequate drainage, and water retention. Cluster 2 relates to SDG 6 and SDG 11 through the need for improved water and air quality management, while SDG 13 (Climate Action) remains essential for monitoring climatic variability influencing habitat suitability. Cluster 3 (forested and shaded areas) emphasizes trade-offs between biodiversity and public health, aligning with SDG 15 (Life on Land), SDG 3, and SDG 11 for managing green infrastructure in recreational zones. Construction-disturbed Cluster 4 highlights how soil erosion, runoff, and artificial water-holding structures increase breeding habitat availability, implicating SDG 11, SDG 12 (Responsible Consumption and Production), SDG 13, SDG 15, and SDG 6 in mitigating development-related mosquito risks. Cluster 5 (hilly, biodiversity-rich suburban areas) further underscores the interplay of SDG 15 and SDG 6, with SDG 3 relevant due to localized risks in gardens and small residential water systems. Dry peri-urban/industrial Cluster 6 connects SDG 12 and SDG 11 through waste and infrastructure management, with

SDG 6 remaining pertinent for stormwater handling. Finally, Cluster 7 (cooler, wind-influenced outskirts) illustrates areas of emerging future suitability, underscoring the importance of SDG 13 and SDG 3 for long-term surveillance and early-warning systems.

These findings offer actionable guidance for city planners and public health officials. Cluster-specific interventions—including adaptive drainage design, runoff and erosion control, targeted monitoring of artificial containers, sustainable waste management (especially tires and plastics), and ecologically informed green-space planning—can support integrated mosquito management while advancing SDG 3, SDG 11, and SDG 13. By linking ecological patterns with urban sustainability frameworks, the study provides a practical basis for anticipatory planning that strengthens both public health preparedness and long-term urban resilience.

The vector's biological traits complicate both surveillance and control. Egg dormancy allows survival through dry periods, and cryptic breeding in small, often hidden containers (e.g. gutters, discarded tires, buckets) hampers source reduction. Moreover, increasing insecticide resistance is documented in many invaded regions (Zhou et al., 2024; Li et al., 2021). For example, Zhou et al. (2024) found field populations in Beijing resistant to several pyrethroids and a carbamate, with multiple detoxification genes overexpressed. Li et al. (2021) reported widespread resistance to many synthetic insecticides in Hainan Province, China, involving both knock-down resistance (kdr) mutations and metabolic detoxification. These patterns necessitate multi-faceted surveillance (entomological, ecological, climatic), early detection (e.g. at ports of entry), and adoption of novel control methods (e.g. Wolbachia, genetic tools), combined with careful resistance monitoring and alternative insecticides (Carrera et al., 2024; Bellver-Arnau et al., 2025).

Climate change will further exacerbate challenges. Modelling shows that under future emission scenarios, habitat suitability for *Ae. albopictus* will expand in many temperate regions, both via increased temperature and changing rainfall patterns (Georgiades et al., 2023; Bellver-Arnau et al., 2025). In La Réunion Island, for example, both local climate variation and typology of breeding sites modulate the vector's sensitivity to change in precipitation and temperature under future scenarios (Lamy et al., 2023). Thus, *Ae. albopictus* functions simultaneously as a product of unsustainable urban practices, a driver of disease risk, and a harbinger of climate-related risk. Addressing its spread requires integrated urban planning, ecological health strategies, continuous resistance monitoring, and forward-looking climate adaptation and mitigation measures.

The findings underscore the urgent need for proactive vector surveillance and management in Budapest and similar Central European cities. As *Ae. albopictus* approaches habitat saturation, the likelihood of arbovirus transmission events, including dengue, chikungunya, and Zika, will increase (Leta et al., 2018; Ciota and Keyel, 2019). Urban planners and public health authorities should integrate ecological knowledge into infrastructure design, waste management, and climate adaptation strategies. Future research should expand beyond occurrence records to include vector competence and pathogen surveillance, which will determine the actual epidemiological risk posed by *Ae. albopictus*. In addition, coupling citizen science initiatives with machine learning models may enhance early detection and community-level awareness (Palmer et al., 2017).

5. Conclusions

This study demonstrates the rapid establishment and near-saturation of Aedes albopictus across the Budapest metropolitan area in under a decade, with the species expanding from scattered foci in 2020 to over 85 % of districts by 2025, following a sigmoid growth trajectory indicative of successful long-term colonization. Seasonal activity was strongly influenced by temperature and solar radiation, with peak occurrence in early September, highlighting short-term climatic predictors that are likely to shape invasion dynamics across temperate Europe. Integration of Köppen–Geiger and CORINE classifications revealed a clear preference for urbanized, human-modified environments in hot summer temperate climates, while machine learning and clustering analyses identified temperature extremes and climatic water balance as primary drivers of ecological suitability.

By linking ecological clusters to the Sustainable Development Goals, the study underscores the importance of embedding vector surveillance within broader frameworks of urban planning, water and waste management, and climate adaptation. Although centred on Budapest, the patterns observed—rapid colonization, climate-driven seasonal dynamics, and strong associations with urban environments—mirror invasion trajectories documented in other European cities. These findings therefore provide a transferable, spatio-temporally explicit framework for anticipating Ae. albopictus expansion across Central and continental Europe and contribute to the development of targeted public health interventions to mitigate the risks posed by invasive mosquito vectors in temperate urban regions.

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Data availability

All freely available datasets which were used during the performance of the study were cited on the adequate parts of the materials and methods. Any other data used in the preparation of the manuscript can be found in the supplementary material.

CRediT authorship contribution statement

Attila J Trájer: Writing – review & editing, Writing – original draft, Visualization, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

The author declares that he has no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.actatropica.2025.107937.

Data availability

Data will be made available on request.

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