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ORIGINAL PAPER

Unveiling the bee pollinators interaction with *Muntingia calabura*: implications for urban biodiversity conservation in tropical cityscapes

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Abstract Pollinators provide crucial role in sustaining ecosystem functioning, supporting plant reproduction, and ensuring food security, however, their populations are increasingly threatened by urbanisation. Habitat loss, fragmentation, and reduced floral diversity in urban environments pose significant challenges to pollinator survival. Despite these challenges, well-managed urban green spaces, such as parks and urban grasslands, can provide critical habitats and resources to sustain diverse pollinator populations. Understanding how specific tree species, such as *Muntingia calabura*, influence pollinator communities, particularly bees, in tropical urban environments remains limited. This study investigates the interactions between bees and *M. calabura*, a common ornamental tree, in urban landscapes of Peninsular Malaysia. We quantified bee visitation patterns in relation to floral abundance, microclimatic conditions (air temperature and light intensity), season, tree distribution pattern, and urban land-use type. Our final model showed that bee visitation increased strongly with floral abundance and light intensity, while higher air temperatures were associated with reduced visitation rates. Seasonal effects were not significant. Tree distribution pattern significantly influenced visitation, with individually occurring trees receiving more visits than clustered trees. Urban land-use also had a pronounced effect, with trees located in commercial areas supporting higher bee visitation than those in residential and green areas. These findings highlight the ecological importance of *M. calabura* as a consistent floral resource for urban bees in tropical environments. From a management perspective, we argue that enhancing urban green spaces by prioritising the planting of pollinator-friendly tree species, such as *M. calabura*, can play a pivotal role in sustaining pollinator populations.

Implications for insect conservation Our study highlights the conservation value of strategically planted, pollinator-friendly urban trees, demonstrating that species such as *Muntingia calabura* can sustain a continuous supply of floral resources, mitigate the impacts of habitat loss, and promote ecological resilience in rapidly urbanising tropical landscapes.

Keywords Pocket habitats · Green spaces · Urban trees · Naturalised species

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Introduction

Pollinators are vital to maintaining ecological balance, making them essential components of both natural and human-modified environments (Peixoto et al. 2022). Pollinators facilitate the reproduction of flowering plants in terrestrial ecosystems, ensuring the survivability of diverse plant species (Ashman et al. 2004; Aguilar et al. 2006). This animal-mediated pollination process also underpins the productivity of ecosystems and ensures the availability of food resources, such as fruits, nuts, and seeds, which are critical for both wildlife and human consumption. For humans, pollinators such as bees, butterflies, and flies provide indispensable ecological services by pollinating commercial crops (Khalifa et al. 2021). Approximately 75% of global food crops rely on animal pollination, underscoring their importance for food security and agricultural sustainability (Genersch 2010). Pollinators are directly responsible for the production of 87 major global crops (Klein et al. 2007), and recent bioeconomic analyses estimate that 17% of the global crop production value is pollination-dependent, representing 28% of the global agricultural trade value (Siopa et al. 2024). These figures highlight the ecological and economic significance of pollinators, emphasising the urgent need for their conservation to safeguard both biodiversity and human livelihoods.

Globally, urbanisation is a major driver influencing the composition and structure of biodiversity community assemblages (Puan et al. 2019; Hadi et al. 2024; Atikah et al. 2025; Bichi et al. 2025), interactions (Buchholz and Kowarik 2019; Theodorou 2022), and individual physical traits (Badiane et al. 2024). Similar to other wildlife, pollinator agents face significant threats from urbanisation, primarily due to the loss of natural habitats, which often results in increased habitat isolation and fragmentation (Potts et al. 2010; Ye et al. 2021). Moreover, the homogenisation and decline of floral plant diversity caused by urbanisation reduces pollinator diversity by limiting the availability of diverse and specialised floral resources essential for supporting a wide range of pollinator species such as bees (Theodorou et al. 2020a, b). Additionally, the widespread use of pesticides particularly herbicides (e.g. glyphosate) and insecticides (e.g. neonicotinoids) can severely disrupt the behaviour and physiology of pollinating species, leading to impaired foraging efficiency, navigation, reproduction, and immune responses (Goulson et al. 2015; Woodcock et al. 2017; Tosi et al. 2017). These effects can accumulate over time, increasing pollinator vulnerability and contributing to long-term population declines, particularly in urban and agricultural landscapes where pesticide exposure is common (Siviter et al. 2021; Arce et al. 2018).

However, urban green spaces, such as public parks, home gardens and streetscapes may play a crucial role in mitigating the ecological impacts of urbanisation by providing refuge and resources for biodiversity (Aida et al. 2016; Threlfall et al. 2015; Persson et al. 2020). These green spaces contribute to habitat heterogeneity, enhance ecological connectivity, and offer foraging and nesting opportunities for a variety of taxa, including pollinators (Baldock et al. 2015; Aronson et al. 2017; Ranalli et al. 2025). Yet, not all urban green spaces equally support biodiversity; high-quality habitats like urban grasslands can sustain more diverse and abundant pollinator populations (Dylewski et al. 2019). Urban green spaces can be strategically managed to enhance their capacity to support pollinators by incorporating diverse flowering plants and maintaining structural complexity (Harrison and Winfree 2015; Turo and Gardiner 2019). A crucial step in this process involves identifying and promoting tree species that provide consistent floral resources for urban pollinators. Understanding these interactions can inform the selection of tree species for urban planting schemes and urban tree conservation program, ensuring a continuous supply of nectar and pollen throughout the year (Fortel et al. 2014). Quantifying pollinator-plant interactions, particularly the rate and frequency of floral visits, provides a key insight into the quantity component of pollination effectiveness, which reflects the functional intensity of these mutualistic interactions (Herrera 1989).

Muntingia calabura L. (Muntingiaceae), commonly known as Jamaican cherry or Panama berry, is a versatile and fast-growing medium-sized trees which are commonly found along urban fringes across many countries (Upadhye et al. 2021). Its adaptability to poor soil conditions and rapid germination enables it to thrive in urbanised landscapes (Figueiredo et al. 2008). However, this pioneer species is unable to thrive in shady habitats such as closed-canopy rainforests (Nghiem et al. 2015). *M. calabura* is extensively associated with a diverse assemblage of insects (Srikumar and Bhat 2013; Hanapi et al. 2023), birds (Yuliawati et al. 2021; Mokhter et al. 2022) and mammals (Singaravelan and Marimuthu 2006; Kassim et al. 2017), attributable to its continuous year-round production of nectar, pollen, and fruits (Fleming et al. 1985; Upadhye et al. 2021). Despite its common occurrence, however, little is known about how *M. calabura*, influence pollinator populations, such as bees in tropical urban environments. This gap in knowledge is particularly relevant in urban areas with varying levels of urbanisation, where the microhabitat characteristics of these trees may play a crucial role in supporting pollinator activity. Understanding these dynamics is essential for informing urban biodiversity conservation strategies and guiding urban planning efforts to enhance the ecological benefits of green spaces for pollinators and other wildlife.

Here, we assessed the relationship between *M. calabura* trees and pollinators in tropical urban environments, focusing primarily on bee taxa from the tribe Apini (honey bees: *Apis* spp.), Meliponini (stingless bees: *Heterotrigona* spp.) and Xylocopini (carpenter bees: *Xylocopa* spp.). These tribe represent a diversity of foraging behaviours and ecological roles within urban ecosystems. *M. calabura*, with its persistent flowering and nectar availability, is frequently visited by bees, yet little empirical evidence highlights how its presence contributes to pollinator activity across different urban settings. To address this gap, we examined the subsequent research questions: (1) Do *M. calabura* trees promote the distribution of bees in urban environments characterised by three distinct urban land-uses (i.e. commercial zones, residential zones, and green spaces)? and (2) Do the microhabitat characteristics of *M. calabura* trees affect the frequency of bee visits? Understanding *M. calabura* interaction with pollinator communities is vital for informing urban biodiversity conservation, particularly in tropical cities where green spaces are often fragmented and under pressure from development. By identifying the conditions under which this species supports pollinator presence and activity, our study provides insights for enhancing pollinator friendly habitats within urban landscapes. Comprehending the role of *M. calabura* trees in sustaining bee populations also enables conservation stakeholders to formulate successful urban biodiversity conservation plans. In addition, findings from this study may assist urban town planners in creating landscapes that optimise the advantages of existing green spaces for bees and other wildlife species.

Methodology

Study area

This study was conducted in Seri Kembangan (3°00′57″N 101°42′02″E), located within the Petaling District (Fig. 1). Situated within Malaysia's Klang Valley urban region, Seri Kembangan has experienced significant urban expansion since its establishment in the 1950s, largely due to its proximity to the capital cities, Kuala Lumpur and Putrajaya. The area is currently home to an estimated population of 130,000. Seri Kembangan has a typical tropical climate, characterised by warm temperatures throughout the year, ranging from 22 °C to 33 °C. The region also experiences distinct heavy rainfall during the northeast monsoon season, which usually occurs between October and December. The urbanisation of Seri Kembangan has led to the fragmentation of natural habitats and green spaces, posing challenges to local biodiversity, including pollinator populations. However, pockets of greenery, such as urban parks and community gardens, persist within the urban matrix, offering potential refuges for various species.

Study design

The study was conducted across three distinct urban land-uses: (1) commercial zones, (2) residential zones, and (3) green spaces (Fig. 1). These land-uses were selected to represent varying levels of anthropogenic disturbance and intensity, which may influence pollinator activity and floral resource availability. Commercial zones are designated zones for business activity and establishments, including retail shops, banks, and restaurants characterised by impervious surfaces and minimal vegetation cover. Residential zones include housing developments such as terraced homes

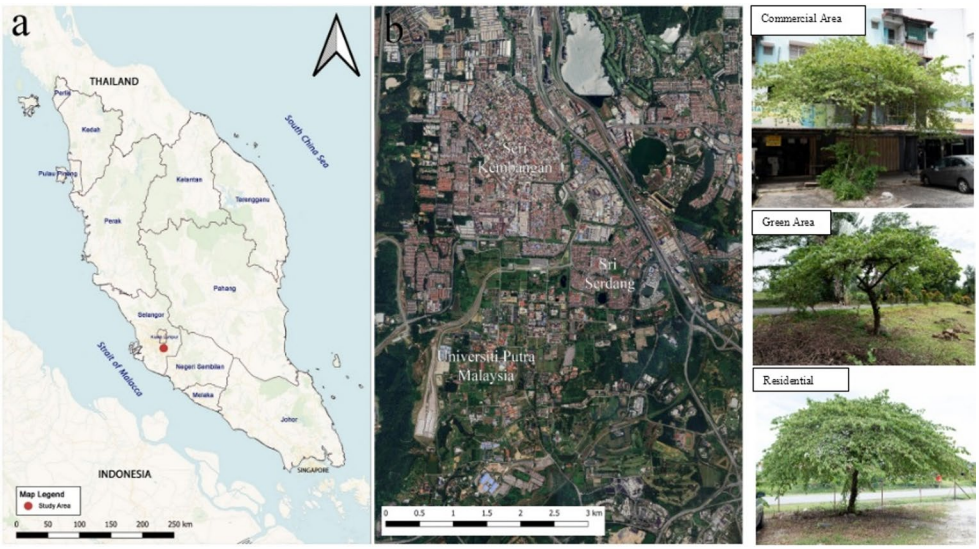

Fig. 1 Map (**a**) depicts the geographical location of the study area within Peninsular Malaysia, whereas Map (**b**) presents a satellite image providing a detailed view of the study area. Representative photographs illustrate three major urban land-use types: commercial area (top), green space (middle), and residential area (bottom)

representing moderately urbanised settings with mixed vegetation types and ornamental plantings. Green spaces encompass public open areas such as urban parks, community gardens, and other vegetated recreational zones. These areas are generally characterised by lower development intensity and greater plant diversity and are often managed for amenity. Sampling points were distributed based on the existing locations of *M. calabura* trees within these three land-uses. A total of 80 sampling points were established: 24 in commercial zones, 10 in residential zones, and 46 in green spaces. Each sampling point represented by a single *M. calabura* tree either categorised as single or cluster. In total, 80 trees were surveyed across the three urban land-use types, comprising 75 individual trees and 5 clusters. Trees located within a 10 m radius of each other were categorised as a cluster. Treating each tree (or cluster) as an independent sampling unit allowed for consistent standardisation across sites and ensured that pollinator observations could be reliably attributed to the focal tree. This design enabled robust assessment of bee visitation patterns in relation to both urbanisation intensity and local microhabitat characteristics associated with *M. calabura*.

Bee sampling

Bee activity was monitored using standardised point count observations at each of the 80 sampling locations. At each site, eight 10-min point counts were conducted to systematically record bee visitation to *M. calabura* trees. During each session, observers recorded bee activity visually within a 10 m radius around each focal tree or tree cluster. Each instance of floral contact by a bee was counted as one visit, even if made by the same individual, to represent foraging frequency rather than individual abundance. The frequency of bee visits was thus defined as the total number of bees visit events recorded per tree or tree cluster per 10-min session and used as a proxy for visitation activity, following the quantity component framework of Herrera (1989). Four observations were carried out during the wet season (November–December 2019) and the remaining four during the dry season (January–February 2020), allowing for the assessment of seasonal variation in pollinator activity. All observations were conducted between 1100 and 1500 h, which corresponds to peak foraging times for tropical bees (Corlett 2004). Sampling was conducted only on days with favourable weather conditions to minimise the influence of climatic variability on bee activity. During each point count, observers recorded bee visits from three target tribe: Apini (honey bees: *Apis* spp.), Meliponini (stingless bees: *Heterotrigona* spp.) and Xylocopini (carpenter bees: *Xylocopa* spp.). Bees were identified to the genus level in the field, as species-level identification was not feasible due to morphological similarity among stingless bees. These genera represent a functional diversity of bee taxa commonly found in urban environments in Peninsular Malaysia, encompassing social, stingless, and solitary species. Observations focused exclusively on individuals interacting directly with *M. calabura* flowers, such as those collecting nectar or pollen, to ensure that only relevant pollination interactions were considered. All observations were performed by the same trained observer to minimise inter-observer variability, and bees were identified visually using field guides and supported by photographic documentation where necessary.

Measurement of tree microhabitat characteristics

At each sampling point, we recorded seven parameters related to vegetation structure and microclimatic conditions to evaluate their potential influence on bee visitation patterns. The vegetation structure variables included: (1) diameter at breast height (DBH) of the tree, measured in centimetres (cm); (2) tree height (TH), measured in metres (m); (3) number of inflorescences (NFL); and (4) number of ripe fruits (NRF). In addition, three microclimatic conditions measured beneath the tree canopy were: (5) relative humidity (RH), expressed as a percentage (%); (6) air temperature (AT) in degrees Celsius (°C); and (7) light intensity (LI) in Lux (lx). All microclimatic measurements were taken at a standard height of 1.1 m above the ground and recorded during solar noon (between 1200 and 1400 h) on non-overcast days. RH and AT were measured using a Skywatch Atmos device (sensor accuracy: RH ± 3%, AT ± 0.4 °C), while LI was recorded with a silicon pyranometer (sensor accuracy: ± 5%). For each microclimatic parameter, four readings were taken, and the average value was used to represent the conditions at each sampling point.

Data analysis

We employed generalised linear mixed models (GLMMs) using the glmmTMB package (Brooks et al. 2017) and the lme4 package (Bates et al. 2015) to evaluate the relationships between bee visitation frequency, *M. calabura*, and habitat attributes. Before conducting the modelling analysis, we assessed multicollinearity among the predictive variables representing habitat attributes using Spearman's rank correlation coefficient. Variables with a correlation modulus (|r|) exceeding 0.7 were excluded to avoid multicollinearity (Dormann et al. 2013) (Supplementary Table S1). Strong correlations were detected between relative humidity and air temperature; therefore, only air temperature was retained among microclimatic predictors for subsequent analyses. To improve interpretability and address right-skewed

distributions, the number of inflorescences and light intensity were log-transformed prior to analysis, following recommendations for ecological count data (Bolker et al. 2009; Zuur et al. 2010).

Bee visitation frequency was treated as count data and initially analysed using a GLMM with a Poisson error distribution and log link function. Fixed effects included floral abundance (number of inflorescences), air temperature, light intensity, season (wet: November–December 2019; dry: January–February 2020), tree distribution pattern (individual or clustered), and urban land-use type (commercial, residential, or green area). Sampling month (November-February) was included as a random intercept to account for temporal non-independence. Model adequacy was evaluated using simulation-based residual diagnostics implemented in the DHARMa package (Hartig 2016). Diagnostic tests revealed substantial overdispersion and excess zeros in the Poisson GLMM, indicating violation of distributional assumptions (Cameron and Trivedi 2013).

To address overdispersion, we refitted the model using a negative binomial error structure (nbinom2), which substantially improved model fit. Residual diagnostics further indicated the presence of structural zeros, consistent with ecological situations where bee visitation may be entirely absent under certain conditions. Consequently, a zero-inflated negative binomial (ZINB) GLMM with a constant zero-inflation term was fitted. The ZINB GLMM model showed no residual overdispersion, improved residual uniformity, and the lowest Akaike's Information Criterion (AIC) among alternative model structures, and was therefore selected for inference (Zuur et al. 2009; Warton 2018), with model selectionprocedures facilitated by the MuMIn package (Bartoń 2023)

Statistical significance of fixed effects was assessed using Wald z-tests. Model-based predictions for significant continuous predictors were visualised using bias-corrected marginal effects to account for Jensen's inequality in nonlinear mixed models (Korner-Nievergelt et al. 2015). Differences among categorical predictors (season, tree distribution pattern, and urban land-use) were evaluated using estimated marginal means (EMMs) (Lenth 2023), with Tukey-adjusted pairwise comparisons conducted on the log scale and back-transformed to the response scale for presentation. These comparisons were averaged across remaining predictors in the model to facilitate interpretation of level-specific effects. Visualisation of model predictions was conducted using ggeffects (Lüdecke 2018). All analyses were conducted in R version 4.3.0 (R Core Team 2024).

Results

A total of 2559 interactions between *M. calabura* and bees (Fig. 2; Table 1) were recorded across all point counts. The majority of visits were made by honey bees (*Apis* spp.), which accounted for 2079 encounters. Stingless bees (*Heterotrigona* spp.) and carpenter bees (*Xylocopa* spp.) contributed significantly fewer visits, with 485 and 4 visits, respectively. Of the total observations, 1357 interactions were recorded during the dry season, while 1202 occurred in the wet season (Table 1).

The final model (ZINB GLMM) included floral abundance (number of inflorescences), air temperature, light intensity, season, tree distribution pattern, and urban land-use as fixed effects, with sampling month included as a random effect (Table 2, Table 3). Bee visitation frequency increased strongly with floral abundance, showing a pronounced positive association with the log-transformed number of inflorescences ($\beta = 1.102 \pm 0.062$ SE, $p < 0.001$; Fig. 3A). Light intensity also had a significant positive effect on visitation rates ($\beta = 0.278 \pm 0.127$ SE, $p = 0.029$; Fig. 3C). In contrast, air temperature exhibited a significant negative relationship with bee visitation ($\beta = -0.086 \pm 0.042$ SE, $p = 0.042$; Fig. 3B), indicating reduced visitation at higher temperatures. Seasonal effects were not significant ($\beta = 0.051 \pm 0.080$ SE, $p = 0.53$), with similar predicted visitation rates between the dry and wet seasons. In contrast, tree distribution pattern significantly influenced bee visitation, with individually occurring trees receiving more visits than clustered trees (pairwise ratio = 0.723, $p = 0.036$; Fig. 4A). Urban land-use exerted a strong influence on bee visitation frequency (Fig. 4B). Trees located in commercial areas received significantly more bee visits than those in green areas (ratio = 1.36, $p = 0.002$) and residential areas (ratio = 1.83, $p < 0.001$). Visitation rates in green areas were marginally higher than in residential areas ($p = 0.049$) (Supplementary Table S2). These results suggest that urban habitat heterogeneity, particularly the floral-rich environments within commercial zones, promotes higher pollinator activity compared to greener or residential surroundings.

Discussion

Our data revealed a positive relationship between bee visitation and the number of *Muntingia calabura* inflorescences, suggesting that trees with a more prominent floral display are more likely to attract foraging bees. This pattern is consistent with Optimal Foraging Theory (OFT), which suggests that foragers tend to prioritise resources that maximise energetic returns relative to their foraging effort (Pyke 1984). In resource-fragmented urban landscapes,

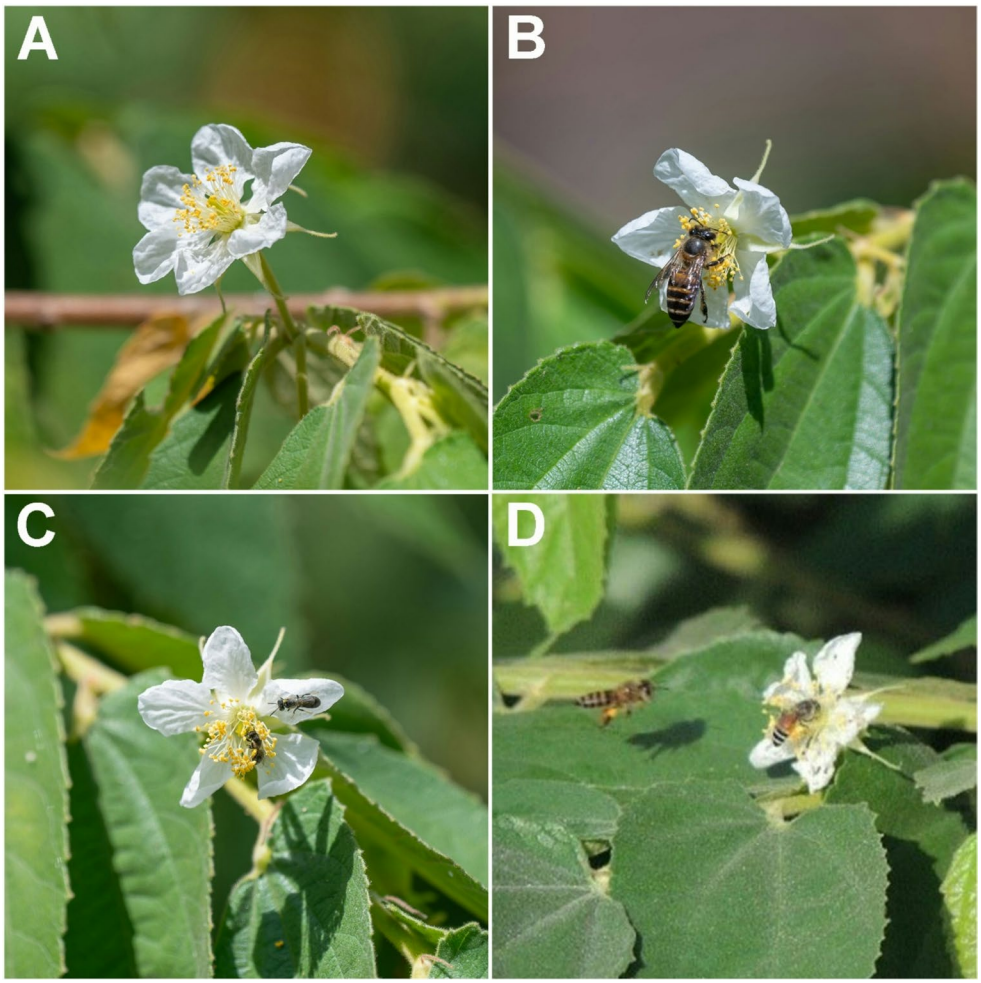

Fig. 2 **A** Individual flower of *Muntingia calabura*; **B**–**D** various bee species including *Apis cerana* (**B**), *Heterotrigona* spp. (**C**), and *Apis florea* (**D**) visiting the flowers for foraging

Table 1 Total number of bee visits to *Muntingia calabura* flowers during wet (November–December) and dry (January–February) seasons across all sampling points

No.	Species	Wet	Dry	Total
1	Asian Honey Bee (*Apis cerana*)	539	665	1204
2	Giant Honey Bee (*Apis dorsata*)	184	253	437
3	Dwarf Honey Bee (*Apis florea*)	263	166	429
4	Stingless Bee (*Heterotrigona* spp.)	215	270	485
5	Carpenter bee (*Xylocopa* spp.)	1	3	4

Five pollinator taxa were observed, including three *Apis* species, one stingless bee genus (*Heterotrigona* spp.), and one carpenter bee genus (*Xylocopa* spp.)

Table 2 Comparison of alternative generalised linear mixed models (GLMMs) used to model bee visitation to *Muntingia calabura*

Model type	logLik	AIC	ΔAIC
Poisson GLMM	−641.96	1283.92	349.42
Negative binomial GLMM	−486.98	993.95	59.45
Zero-inflated negative binomial GLMM	**−456.23**	**934.46**	**0**

Models share identical fixed and random effects and differ only in their assumed error structure. Model selection was based on akaike's information criterion (AIC), with the best-supported model highlighted in bold

All models included log-transformed number of inflorescences, air temperature, log-transformed light intensity, season, tree distribution pattern, and urban land-use as fixed effects, with sampling month included as a random intercept

floral abundance becomes a key determinant of pollinator presence and activity (Garbuzov and Ratnieks 2014). These findings emphasise the vital role of floral abundance, exemplified by *M. calabura*, in influencing pollinator foraging behaviour within urban landscapes. The prolific characteristics of *M. calabura*, including its production of bright, open, star-shaped flowers year-round in tropical climates, provide a continuous resource for pollinators. Such traits make it especially suitable for sustaining pollinator activity in tropical urban environments, where seasonal gaps in floral availability can limit pollinator populations (Harrison and Winfree 2015). Consistent with our findings, previous studies in tropical regions have demonstrated that *M. calabura* trees attract a variety of native and non-native pollinator species, including honey bees and stingless bees (Cunanan-Deyto et al. 2012; Hawkeswood and Sommung 2016; Hanapi et al. 2023). Beyond bees, *M. calabura* is also associated with a diverse range of other insect species

Table 3 Summary of coefficients from the final zero-inflated negative binomial generalised linear mixed model (ZINB GLMM) describing the effects of floral abundance, environmental, and habitat variables on bee visitation frequency to *Muntingia Calabura*

Predictor	Estimate	SE	z value	*p* value	Significance
Log(Number of inflorescences)	1.102	0.0619	17.81	< 0.001	***
Air temperature (°C)	−0.086	0.0423	−2.04	0.042	*
Log(Light intensity)	0.278	0.1273	2.18	0.029	*
Season (wet)	0.051	0.0802	0.63	0.527	n.s.
Tree distribution pattern (individual)	0.324	0.1541	2.10	0.036	*
Urban land-use (green area)	−0.309	0.0915	−3.38	< 0.001	***
Urban land-use (residential area)	−0.605	0.1308	−4.62	< 0.001	***

n.s. not significant

Coefficients are derived from the conditional component of a zero-inflated negative binomial generalized linear mixed model. Number of inflorescences and light intensity were log-transformed prior to analysis. The zero-inflation component models the probability of structural zero visitation events. Significance codes: ***$p < 0.001$; ** $p < 0.01$; *$p < 0.05$

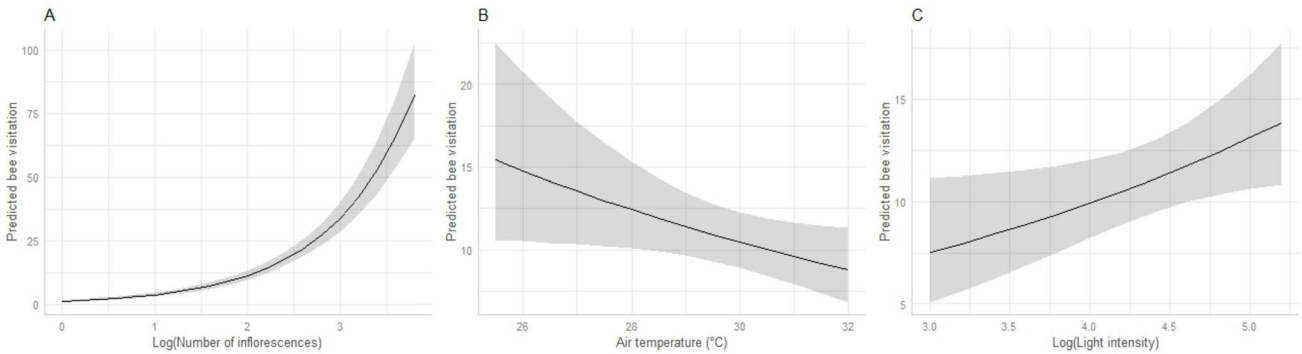

Fig. 3 Model-based relationships between bee visitation frequency to *Muntingia calabura* and significant continuous predictors derived from the conditional component of the final zero-inflated negative binomial generalised linear mixed model (ZINB GLMM). Solid lines represent predicted bee visitation rates, and shaded areas indicate 95% confidence intervals. Panels show the effects of **A** log-transformed number of inflorescences, **B** air temperature, and **C** log-transformed light intensity. The model accounts for overdispersion and excess zero counts in visitation data and includes sampling month as a random effect

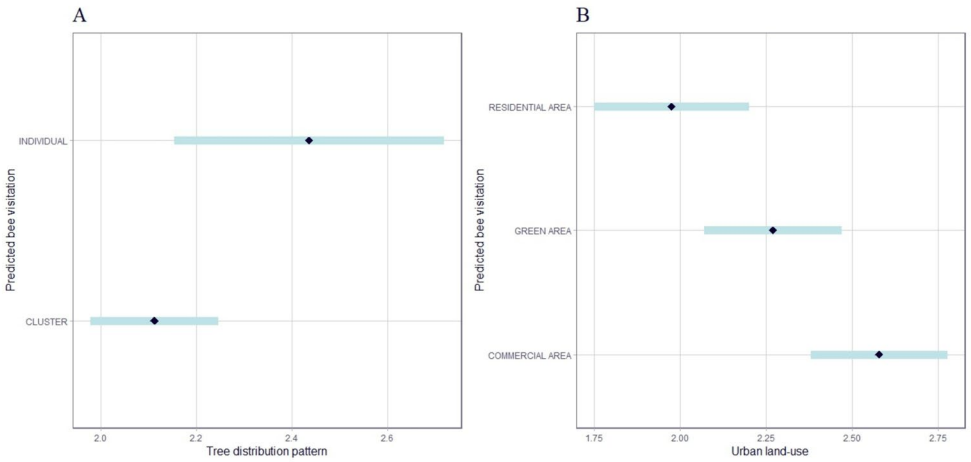

Fig. 4 Model-based differences in predicted bee visitation frequency to *Muntingia calabura* across significant categorical predictors derived from the conditional component of the zero-inflated negative binomial generalised linear mixed model (ZINB GLMM). Points represent estimated marginal means and horizontal bars indicate 95% confidence intervals. Panels show the effects of **A** tree distribution pattern (clustered vs. individual trees) and **B** urban land-use categories. Predictions account for overdispersion and excess zero counts in visitation data and include sampling month as a random effect

(Bandeira et al. 2013; Srikumar and Bhat 2013), underscoring its role as a keystone floral species in disturbed and urbanised habitats.

In addition to the availability of inflorescences, our data highlight the complex interplay between urban landscape features and pollinator activity. Urban environments often suffer from limited floral continuity and reduced habitat quality, both of which are major drivers of pollinator decline (Hall et al. 2017). Specifically, *M. calabura* trees located in commercial areas received significantly higher bee visitation rates than those in green or residential areas. Similar patterns have been reported in other urban systems, where pollinator activity concentrates on isolated, resource-rich plants in highly built-up environments due to reduced availability of alternative floral resources (Baldock et al. 2019; Theodorou et al. 2020a, b). This finding may suggest that commercial areas, often typified by reduced vegetation diversity and limited floral resources, may funnel pollinators towards a restricted number of floral sources, such as *M. calabura*. Conversely, green patches and residential areas, which typically contain a wider range of vegetation including those native florals, may dilute pollinator activity due to the greater availability of alternative resources. Incorporating *M. calabura* into urban planting schemes could help mitigate these limitations by enhancing floral resource availability and supporting pollinator persistence. This aligns with previous research highlighting the importance of integrating pollinator-friendly trees into urban green infrastructure to improve habitat quality, ecosystem resilience, and ecological connectivity (Turo and Gardiner 2019).

Native bee species are thought to have relatively restricted flower preferences, tending to favour native floral species over non-native ones (Prendergast et al. 2022, 2023). However, the availability of floral resources from naturalised tree species such as *M. calabura* may still support certain pollinators, such as native Asian Honey Bee (*A. cerana*), which was identified was the most frequently observed species in this study. *A. cerana* is known for its generalist foraging behaviour and adaptability to urban environments, traits that contribute to its dominance in many urban pollinator communities (Soh and Ngiam 2013; Lee 2023). Additionally, urban environments tend to favour bees with specific traits, such as smaller body sizes, social structures, and extended flight periods (Villalta et al. 2022). These characteristics enable species like *A. cerana* to thrive in fragmented and resource-variable urban landscapes. Our study also revealed that tree distribution patterns significantly affected frequency of visits, with individually distributed trees attracting more visits than clustered trees. This pattern likely results from diminished competition for pollinators among flowers in isolated trees, potentially enhancing the probability of individual trees being identified and visited. Such observations align with studies suggesting that the spatial arrangement of floral resources can affect pollinator foraging efficiency and plant–pollinator interactions (Eckerter et al. 2022; Kortsch et al. 2023).

Our model revealed that microclimatic variables, particularly air temperature and light intensity, significantly influenced bee visitation to *M. calabura*. Visitation rates declined at higher air temperatures, indicating that excessively warm conditions may constrain bee foraging activity in tropical urban environments. Although bees are heterothermic and depend on external heat sources to initiate flight, elevated ambient temperatures can impose thermal stress, reduce foraging efficiency, and increase energetic costs associated with thermoregulation (Willmer and Stone 2004; Heinrich 2013). Such thermal constraints are especially relevant in urban landscapes, where heat accumulation associated with urban heat island effects can reduce wild bee activity and abundance (Hamblin et al. 2018). In contrast, bee visitation increased with light intensity, consistent with the reliance of bees on visual cues for flower detection, navigation, and assessment of floral rewards (Kevan and Baker 1983), as well as enhanced nectar visibility under brighter conditions (Corbet et al. 1993; Dyer and Chittka 2004).

In addition to microclimatic conditions, our analysis also suggested a seasonal trend in visitation frequency, with slightly higher numbers of visits observed during the wet season compared to the dry season, although this difference was not statistically significant. This pattern could potentially relate to ecological and climatic factors typically associated with the wet season, including greater floral availability, extended flowering periods, and increased nectar or pollen production (Souza et al. 2018). Such factors may coincide with the phenology of *M. calabura*, which in some systems has been reported to exhibit seasonal alignment between floral resource production and pollinator activity (Bawa and Hadley 1990). While our findings do not provide strong evidence for a seasonal effect, they are consistent with broader literature highlighting the role of phenological synchrony in shaping plant–pollinator interactions.

Conservation implications

The findings underscore the critical role of urban landscapes in supporting pollinator populations, particularly through the strategic conservation of floral resources, including those from naturalised tree species such as *M. calabura*. Scattered urban trees, exemplified by *M. calabura*, serve as keystone floral resources for pollinators, offering consistent and accessible floral resources amidst urban fragmentation. Although *M. calabura* is a naturalised, non-native species, its consistent floral output and attractiveness to a variety

of pollinators highlight its potential utility in biodiversity-supportive urban planting. We believe that these trees are particularly valuable in highly developed areas, such as commercial zones, where alternative floral resources are often scarce. Incorporating such tree species into urban planning can improve functional habitat connectivity, acting as ecological stepping stones that support pollinator movement across heterogeneous cityscapes (Beninde et al. 2015). We emphasise the pivotal role of urban planning in integrating pollinator conservation into cityscapes by prioritising strategies that focus on planting and maintaining scattered trees, thereby enhancing habitat quality and connectivity for pollinators.

Conclusion

Overall, this study demonstrates that *M. calabura* visitation by bees is governed by a multifaceted interaction of floral traits, environmental variables, and landscape characteristics. Trees with greater floral abundance especially in resource-scarce commercial areas attract significantly more pollinator visits. Moreover, our findings indicate that the spatial arrangement of flowering trees plays a critical role, with individually distributed trees receiving higher bee visitation than clustered plantings, underscoring the importance of maintaining dispersed floral resources to maximise pollinator use in urban environment. Specifically, we recommend targeted interventions such as increasing floral resource availability in urban landscapes, maintaining scattered trees like *M. calabura*. By recognising the ecological value of certain naturalised species and leveraging them within urban planning, cities can promote pollinator persistence and enhance the delivery of ecosystem services in rapidly urbanising tropical regions.

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Author contributions N.F.Z, N.A.R. and B.A. conceived and planned the experiments. N.F.Z. executed the field experiments and data collections. N.F.Z., M.S.Y., and B.A. performed the data analysis. M.S.Y., N.A.R., R.S., and B.A. took lead in writing the manuscript. All authors contributed significantly to the research and gave their approval for the submission.

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Data availability The dataset that supports the findings of this article is available in the Supplementary Information files. Additional data not publicly archived are available from the corresponding author upon request.

Declarations

Conflict of interest The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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