**NUSANTARA BIOSCIENCE**
Vol. 17, No. 2, pp. 337-353
November 2025

ISSN: 2087-3948
E-ISSN: 2087-3956
DOI: 10.13057/nusbiosci/n170215

# Diversity of urban street tree communities in Semarang District, Indonesia

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[2]Department of Biology, Faculty of Mathematics and Natural Sciences, Universitas Sebelas Maret. Jl. Ir. Sutami 36A, Surakarta 57126, Central Java, Indonesia
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Manuscript received: 20 November 2024. Revision accepted: 17 December 2025.

**Abstract.** *Madjid AA, Wulandari AA, Dzihni A, Simanjuntak MPD, Chairunisa S, Dewangga A, Himawan W, Buot Jr IE, Setyawan AD. 2025. Diversity of urban street tree communities in Semarang District, Indonesia. Nusantara Bioscience 17: 337-353.* Roadside vegetation plays an important role in maintaining ecological functions, microclimate regulation, and environmental quality in rapidly urbanizing tropical landscapes. This study examined the diversity, composition, and functional structure of urban street trees across five major 10-km roadside corridors in Semarang District, Central Java, Indonesia. Field surveys conducted in September 2024 recorded 2,091 individuals representing 53 species, 47 genera, and 26 families, and classified into functional categories based on ecological and management attributes. Species richness and abundance varied markedly among routes. The Bandungan-Kaloran corridor showed the highest richness and stability, while the Ungaran-Cangkiran corridor exhibited the strongest species dominance, and the Semarang-Bawen corridor had the lowest richness. Three species-*Swietenia mahagoni*, *Polyalthia longifolia*, and *Mangifera indica*-emerged as district-wide dominants. Functional composition was heavily skewed toward Ornamental Plant (OP) and Timber Plants (TP), with Frugivory-supporting species (Fr) providing secondary ecological roles. Diversity indices (Shannon, Simpson, Margalef, and Evenness) revealed substantial spatial heterogeneity: peri-urban routes showed balanced community structures, whereas highly built-up corridors exhibited low diversity and high dominance. These patterns highlight the influence of urbanization intensity, planting space limitations, and disturbance pressure on roadside vegetation structure. These findings highlight the need for more diversified and functionally balanced street tree planting strategies to enhance the sustainability and resilience of urban green infrastructure in Semarang District and other rapidly developing tropical cities.

**Keywords:** Functional diversity, Semarang District, tree diversity, tropical urban ecology, urban street trees

## INTRODUCTION

Urban vegetation plays an increasingly crucial role in maintaining ecological stability within rapidly expanding cities, particularly in tropical regions where land-use change and infrastructure development exert strong pressures on native biodiversity (Berry et al. 2008; Liu et al. 2024a). Street trees-woody plants intentionally or spontaneously occurring along transportation corridors-constitute one of the most visible components of urban green infrastructure (Choi et al. 2021; Wang et al. 2025). They contribute to biodiversity support, microclimate regulation, air pollution mitigation, stormwater attenuation, and visual landscape quality (Roy et al. 2012; Gherri 2023). In Southeast Asian cities, where urban expansion continues at an accelerating pace, understanding the diversity and ecological functions of street trees is essential for designing resilient and livable environments (Wiryono et al. 2018; Asanok et al. 2021).

Urban street tree communities represent unique vegetation assemblages shaped by ecological tolerance, planting preferences, species availability, and management regimes (Almas and Conway 2016; Pretzsch et al. 2017). Because street corridors are exposed to extreme environmental stressors-heat, drought, soil compaction, pollution, and limited rooting space-their floristic composition typically differs from that of parks or remnant natural forests (Rajoo et al. 2021; Liu et al. 2024b). Tree diversity along roadsides influences a city's overall ecological functioning by supporting pollinators, frugivores, and other wildlife groups that rely on scattered vegetation patches within fragmented urban mosaics (Dietzel et al. 2023; Graffigna et al. 2024). Maintaining diverse street-tree assemblages, therefore, contributes not only to aesthetic and cultural values but also to urban ecological resilience.

Although research on urban tree diversity has grown substantially during the past decade, significant gaps remain, particularly in tropical developing countries. Many studies have focused on urban parks (Wang and Zhang 2022), residential areas (Xie et al. 2024), and green belts (Nasrullah and Suryowati 2008), while roadside ecosystems-despite their linear continuity and large spatial extent-remain underexplored. In Indonesia, existing works have examined vegetation in urban forests, campuses, and parks, but comprehensive assessments of street-tree communities at the district scale are still limited. Most available studies address only partial aspects such as species lists, ornamental preferences, or community perceptions, without integrating taxonomic diversity, functional roles, and spatial variation across multiple road corridors. This knowledge gap restricts the capacity of planners and policymakers to design evidence-based urban greening strategies, particularly in regions experiencing rapid development such as Central Java, Indonesia.

Semarang District represents one of the most dynamic peri-urban areas in Indonesia, marked by accelerated transportation development, expansion of residential zones, and increasing traffic density (Aprillia and Pigawati 2018). Despite these transformations, the region retains substantial stretches of roadside vegetation that potentially function as biodiversity reservoirs within an otherwise intensively modified landscape (Pemerintah Kota Semarang 2010). Yet, systematic evaluations of street-tree diversity in Semarang District have not been documented, leaving uncertainties regarding the composition, functional attributes, and ecological roles of tree species distributed along major road networks. Understanding these patterns is critical because the resilience of urban ecological systems often depends on the diversity and distribution of vegetation along transportation corridors (Zhang and Jim 2014; Huff et al. 2020).

Given the research gaps, this study provides a comprehensive assessment of urban street-tree communities across five major road corridors in Semarang District, Indonesia. It aims to: (i) document taxonomic composition (species richness, abundance, family representation); (ii) analyze spatial distribution patterns across five 10-km routes; (iii) identify functional categories (edible, medicinal, ornamental, frugivory-supporting, pollution-mitigating species) and evaluate their ecological relevance; and (iv) assess route-level biodiversity stability using Shannon-Wiener, Simpson, Margalef, and Evenness indices. These integrated objectives enable a multidimensional understanding of how urban street trees contribute to ecological functioning in a rapidly urbanizing district.

By generating a district-scale baseline, this study fills a key knowledge gap in Indonesian urban ecology. The findings provide a scientific foundation for optimized tree-planting programs, enhanced habitat connectivity, and improved environmental quality along road networks. The results also serve as a reference for future biodiversity monitoring and guide local governments in selecting species that balance aesthetic appeal, ecological performance, and long-term resilience. Such evidence-based insights are essential for supporting sustainable urban planning and strengthening ecological infrastructure in Semarang and other tropical cities.

This study offers the first district-wide, route-explicit evaluation of street-tree diversity in Central Java by integrating taxonomic structure, functional composition, and multi-index ecological stability across continuous 10-km corridors. Unlike prior studies focusing on parks or isolated green spaces, it quantifies spatial heterogeneity and dominance patterns along linear transport networks. The integration of detailed taxonomic validation, functional categorization, and corridor-level diversity modeling provides a methodological advance for understanding how urbanization gradients shape vegetation structure in tropical cities. The dataset establishes a robust ecological baseline for evidence-based roadside greening and long-term biodiversity planning.

## MATERIALS AND METHODS

### Study area

*Administrative and biophysical setting of Semarang District*

Semarang District is situated in Central Java, Indonesia and encompasses a heterogeneous administrative landscape shaped by interactions between urban, peri-urban, and rural development zones. Urban expansion associated with the Greater Semarang metropolitan region has long been recognized as a driver of land-use restructuring and vegetation transformation in Java's rapidly developing districts (Firman 2004; Hudalah and Firman 2012). The district extends from lowland alluvial plains in the north to upland foothills exceeding 700 m in elevation, producing marked gradients in temperature, humidity, and cloud cover that influence species distribution patterns. These gradients align with broader monsoonal climatic characteristics of Central Java, featuring a pronounced wet season and dry season (Schmidt and Ferguson 1951; Aldrian and Susanto 2003). Such administrative-biophysical heterogeneity creates a mosaic of ecological conditions that shape roadside vegetation structure, consistent with urban ecological frameworks emphasizing spatial variation across metropolitan gradients (Pickett et al. 2013).

*Road corridors, land use, and traffic intensity*

The study focused on five major 10-km road corridors traversing diverse land-use settings: Bandungan-Kaloran, Salatiga-Kedungjati, Ungaran-Cangkiran, Ambarawa-Bawen, and Semarang-Bawen (Figure 1). These corridors intersect agricultural foothills, rural settlements, peri-urban zones, and dense commercial areas, reflecting the district's multilevel development pattern. Elevation shifts from ~200 to >700 m introduce substantial microclimatic variation, a factor known to influence roadside vegetation performance in tropical landscapes (Whitten et al. 1996; Corlett and Primack 2011). Traffic intensity also varies widely, with Semarang-Bawen receiving the highest vehicular load, producing elevated heat, dust, and pollution stressors that are characteristic drivers of urban tree performance (Jim and Liu 2001). Differences in land-use intensity, pollution, and shading conditions generate spatially distinct ecological filters along the routes, paralleling urbanization-gradient patterns reported in global roadside ecology (Morgenroth and Buchan 2009; Sjöman et al. 2015).

**Figure 1.** Geographical distribution of the five 10-km street-tree survey routes in Semarang District, Central Java, Indonesia

*Route selection criteria*

The selection of the five routes followed three primary criteria. First, each represents a major arterial or collector road under district jurisdiction, ensuring ecological relevance for assessing street-tree composition. Second, the routes collectively span strong gradients of elevation, land-use intensity, and traffic pressure, enabling examination of how environmental and anthropogenic factors shape vegetation patterns (McDonnell and Hahs 2008). Third, a uniform transect length of 10 km was adopted to enhance comparability among corridors and to ensure adequate sampling coverage, a practice consistent with long-distance roadside survey guidelines (Nowak et al. 2006; Jim and Chen 2008). Together, these criteria provide a representative cross-section of Semarang District's ecological and urban structural heterogeneity.

## Survey design and sampling framework

*Overall transect-based roadside survey design*

This study employed an observational survey using continuous 10-km transects along each road corridor, allowing systematic documentation of all trees present within the roadside zone. Transects are widely used in urban ecological assessments because linear sampling better captures vegetation patterns influenced by road geometry, land-use intensity, and microclimatic conditions than discrete plot-based designs (Forman et al. 2003; McDonnell and Hahs 2008). Continuous transects also minimize sampling gaps and yield more representative data for corridor-level vegetation heterogeneity (Morgenroth and Östberg 2017). Plot methods were not adopted because roadside vegetation is spatially linear, discontinuous, and strongly conditioned by traffic exposure, which often leads to underrepresentation when fixed-area plots are used (Pauleit et al. 2005; Kent 2012). Standardizing the 10-km length across all routes allowed comparability and produced sufficiently large sample sizes consistent with tropical roadside vegetation surveys (Jim and Chen 2008).

*Left-right sampling and definition of individual trees*

Field observations were conducted on both the left and right sides of each road corridor to ensure full coverage of roadside vegetation and reduce detection bias. Parallel scanning is recommended in urban tree surveys because opposite verges often differ in shading, slope, built-up density, and exposure to pollutants, leading to asymmetric vegetation patterns (Pauleit et al. 2005; Roy et al. 2012). The roadside boundary was defined as the area from the road shoulder to the edge of the planting strip or drainage channel. An "individual tree" was defined as a perennial woody plant ≥2 m tall rooted within this designated zone, following standard guidelines for urban tree inventories (Nowak et al. 2008; FAO 2016). Multi-stemmed clumps arising from a single root base were counted as one individual, while seedlings or saplings below the height threshold were excluded to avoid inflating abundance estimates. Trees within private compounds were omitted unless their canopy extended clearly into the roadside space. These criteria align with international urban forestry survey protocols (Konijnendijk et al. 2005).

*Survey period and temporal considerations*

The field survey was conducted in September 2024, corresponding to the late dry season in Central Java. Surveying during this period ensured high visibility of canopy structure and reproductive traits while minimizing rainfall-related obstruction, consistent with recommendations for tropical vegetation assessments (Corlett and Primack 2011). Because most roadside tree species in Java are evergreen, seasonal detectability biases are generally low (Whitmore 1998; Körner and Basler 2010). All transects were surveyed during daylight hours under comparable weather conditions to reduce temporal variability and ensure consistent identification accuracy (Sutherland 2006). This timing also aligns with best practices in urban tree monitoring, which emphasize minimizing phenological and climatic variation during fieldwork (Miller et al. 2015).

## Field data collection

### *Georeferencing and route mapping*

Each 10-km transect was established using predetermined start-end coordinates derived from district road maps and administrative boundaries. GPS tracking ensured the survey team remained aligned with the intended route, enabling consistent spatial coverage throughout the corridor. Coordinates were cross-checked with field conditions to avoid deviations caused by road curvature or construction. Mapping followed general ecological survey protocols emphasizing spatial precision (Sutherland 2006; Kent 2012). The spatial configuration of the five transects corresponds to the distribution presented in Figure 1, which illustrates their position across varying land-use and elevation zones (ESRI 2020).

### *Tree inventory and recorded attributes*

Tree inventories were conducted through continuous visual assessment along both sides of each corridor. Every individual tree within the roadside zone was identified to species level when possible, counted, and recorded in standardized forms. This direct-observation method is widely applied in roadside vegetation studies because it accommodates the linear, heterogeneous nature of urban planting strips (McDonnell and Hahs 2008; Nowak et al. 2008). Supplementary attributes-including height class, canopy density, and the presence of flowers or fruits-were documented when visible to support later verification and ecological interpretation. These attributes help distinguish similar taxa and provide context on growth performance under differing roadside conditions (FAO 2016; Pretzsch et al. 2017). Recording these morphological traits also aligns with best practices in tropical urban forestry, where environmental stressors often induce variable phenotypic expression (Sjöman and Nielsen 2010).

### *Photographs, vouchers, and rare species handling*

Representative photographs were taken for each species, especially when diagnostic structures were visible. When permissible, small non-destructive samples (twigs or fallen reproductive parts) were collected as voucher material following standard herbarium practices (Bridson and Forman 1998; Funk et al. 2017). Species that were rare, morphologically ambiguous, or difficult to confirm in the field were documented with additional notes and photographic angles and later verified through expert consultation. Functional traits of interest were also noted to aid subsequent categorization (Díaz et al. 2016).

## Species identification and taxonomic validation

### *Identification workflow and diagnostic characters*

Species identification followed a stepwise workflow beginning with field recognition based on readily observable vegetative and reproductive traits. Key diagnostic characters included leaf arrangement, blade shape, and venation, bark texture, crown architecture, latex presence, and flower or fruit morphology when available-criteria widely used in tropical tree identification (Kent 2012; Beentje 2016). Ambiguous taxa were documented through photographs and additional notes for subsequent verification. Post-field verification relied on comparison with authoritative floristic descriptions, ensuring that identifications were consistent with regional morphological variation. This workflow reflects best practices in botanical survey methodology (Hollingsworth et al. 2011), particularly for species commonly used in urban plantings that show substantial phenotypic variability under roadside stress.

### *Regional floras and online databases*

Verification employed major regional floras, including *Flora Malesiana* (van Steenis 1954-2006), *Flora of Java* (Backer and van den Brink 1963-1968), and the Tree Flora used by Indonesian botanical institutions. These references provided authoritative morphological keys for species distributed across Malesia. Digital taxonomic resources-including POWO, WFO, and GBIF-were used to confirm accepted names, synonymy, and geographic distribution, following global nomenclatural standards (Kew 2019; GBIF 2020). Integration of printed floras and online databases aligns with current taxonomic protocols in tropical biodiversity studies and supports consistency across datasets (Smith and Brown 2018).

### *Native vs introduced status and taxonomic consistency*

Species were classified as native, naturalized, or introduced based on distribution evidence from POWO, GBIF, and the CABI Invasive Species Compendium (https://www.cabi.org/isc). A species was considered native when at least one authoritative source confirmed historical distribution in Indonesia, and it was not listed as introduced or invasive (Richardson et al. 2000; Pyšek et al. 2004). Synonymy checks minimized misidentification among horticulturally common taxa (Govaerts 2001, 2003).

## Functional category classification

### *Functional groups and assignment criteria*

Each species was assigned to functional groups based on documented ecological roles and human uses, including Timber Plants (TP), Medicinal Plants (MP), Edible Plants (EP), Ornamental Plants (OP), Frugivory-supporting species (Fr), Pollen Producing (PP), Pollen Reducing (PR), and Toxic Plants (Tc). Assignments followed clear, literature-supported criteria emphasizing stable characteristics rather than occasional or anecdotal uses (Heyne 1987). Functional grouping was guided by trait-based frameworks widely used in plant ecology (Violle et al. 2007; Díaz et al. 2016). Species exhibiting ambiguous or inconsistent uses were excluded to maintain clarity and comparability across routes (Kendal et al. 2012).

### *Cross-validation of ethnobotanical and horticultural uses*

Functional categories were cross-validated using regional ethnobotanical references, horticultural databases, and complementary resources such as Useful Tropical Plants (https://tropical.theferns.info). Distributional and taxonomic checks using POWO (https://powo.science.kew.org) and GBIF (https://www.gbif.org) ensured accuracy and prevented misclassification (Zerega et al. 2005).

### Data processing and diversity analysis

*Data matrices, species frequency, and functional matrices*

Field records were organized into a species × route matrix capturing abundance across all five corridors, complemented by a species × functional-category matrix integrating ecological and ethnobotanical attributes. Species frequency was calculated using (i) the number of routes in which each species occurred and (ii) proportional abundance relative to total individuals, following standard vegetation ecology approaches (Curtis and McIntosh 1951; Kent 2012). These matrices facilitated comparison of compositional patterns and functional representation among routes. All taxa were standardized to accepted nomenclature prior to analysis through verification with POWO and GBIF (Kew 2019).

*Diversity indices and stability assessment*

Four diversity metrics were computed: Shannon-Wiener, Simpson, Margalef richness, and Pielou's Evenness, each representing complementary aspects of community structure (Shannon and Weaver 1949; Simpson 1949; Margalef 1958; Pielou 1966, 1975; Krebs 1999; Magurran 2004). Indices were calculated using established formulas and cross-validated with statistical software to minimize computational errors. Diversity values were compared among routes to assess how richness, dominance, and abundance distribution varied along environmental gradients (Legendre and Legendre 2012). Integration of multiple indices allowed a general appraisal of community stability, reflecting concepts used in urban vegetation assessment (Jost 2006; McDonnell and Hahs 2008; Pretzsch et al. 2017).

### Ethical considerations

All field activities followed non-destructive sampling principles, with no cutting or removal of vegetation. Observations were conducted exclusively in public roadside spaces without entering private property or obstructing traffic. Only naturally fallen materials were handled when needed for identification. No protected species were disturbed, and all procedures adhered to ecological fieldwork guidelines (Sutherland 2006) and best practices in urban ecology (McDonnell and Hahs 2008; Miller et al. 2015).

## RESULTS AND DISCUSSION

### Overall species composition

*Total individuals, species, genera, and families recorded*

A total of 53 tree species, representing 47 genera and 26 families, were recorded along the five 10-km roadside corridors in Semarang District. These species collectively accounted for 2,091 individual trees distributed across all routes (Table 2). Of the total 2,091 individuals, Route 4 (Ambarawa-Bawen Street) contained the highest number of trees (635 individuals), followed by Route 1 (Bandungan-Kaloran Street, 539 individuals), Route 3 (Ungaran-Cangkiran Street, 465 individuals), Route 2 (Salatiga-Kedungjati Street, 299 individuals), and Route 5 (Semarang-Bawen Street, 153 individuals). Species richness varied among corridors but consistently reflected the presence of multiple taxa adapted to disturbed, high-traffic urban environments. The overall floristic composition demonstrates a structurally diverse assemblage dominated by widely planted ornamentals, shade-providing species, and a smaller subset of multipurpose trees. The species-family structure presented in Table 1 highlights the predominance of families commonly associated with urban greening initiatives in tropical Asia. The spatial distribution of these species followed the geographical layout of the five survey routes illustrated in Figure 1.

*Contribution of native vs introduced species*

Based on distributional verification using POWO, GBIF, and regional floras, roadside corridors in Semarang District were dominated by introduced species, which accounted for 32 species, exceeding the number of native species (21 species) recorded in the dataset (Table 1). Native species comprised a smaller proportion and were often represented by residual or conserved individuals, particularly within older urban and peri-urban sections. Several introduced species, including *Swietenia mahagoni* and *Tabebuia rosea*, were numerically prominent within specific corridors, reflecting long-standing urban planting preferences in Indonesian metropolitan landscapes rather than uniform distribution across all routes. In contrast, native species-although fewer in number-were frequently represented by large, mature individuals such as *Ficus benjamina* and *Pterocarpus indicus*, suggesting historical planting records and long-term persistence within the urban matrix. The disproportionate representation of introduced taxa (approximately 60% of total recorded species) indicates strong human-mediated selection as a key driver shaping the taxonomic structure of street-tree communities across Semarang District.

*Dominant families in Semarang roadside corridors*

Analysis of taxonomic composition (Table 1) indicates that a limited number of plant families dominate roadside tree assemblages across the five surveyed corridors in Semarang District. Fabaceae contributed the highest number of species (9 species), reflecting its wide ecological tolerance, frequent use in urban roadside planting, and representation by both shade-providing and ornamental trees. This family's prominence is consistent with its well-documented adaptability to highlight, compacted-soil, and disturbance-prone urban environments.

**Table 1.** Roadside tree species in the urban area of Semarang District, Indonesia and their benefits

| Scientific name | Family | Origin | Functional groups | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | TP | MP | EP | PP | PR | OP | Fr | Tc |
| *Albizia julibrissin* | Fabaceae | I | ✓ | - | - | - | - | ✓ | - | - |
| *Alstonia scholaris* | Apocynaceae | N | - | ✓ | - | - | - | ✓ | - | - |
| *Anacardium occidentale* | Anacardiaceae | I | - | - | ✓ | - | - | - | ✓ | - |
| *Artocarpus communis* | Moraceae | N | - | - | ✓ | - | - | - | ✓ | - |
| *Artocarpus heterophyllus* | Moraceae | N | - | - | ✓ | - | - | - | ✓ | - |
| *Averrhoa carambola* | Oxalidaceae | N | - | - | ✓ | - | - | - | ✓ | - |
| *Carica papaya* | Caricaceae | I | - | - | ✓ | - | - | - | ✓ | - |
| *Casuarina equisetifolia* | Casuarinaceae | I | ✓ | - | - | - | - | ✓ | - | - |
| *Cerbera manghas* | Apocynaceae | N | - | - | - | - | - | ✓ | - | ✓ |
| *Chrysophyllum cainito* | Sapotaceae | I | - | - | ✓ | - | - | ✓ | ✓ | - |
| *Citrus maxima* | Rutaceae | I | - | - | ✓ | - | - | - | ✓ | - |
| *Cocos nucifera* | Arecaceae | N | - | - | ✓ | - | - | - | ✓ | - |
| *Cordyline australis* | Asparagaceae | I | - | - | - | - | - | ✓ | - | - |
| *Dalbergia latifolia* | Fabaceae | N | ✓ | - | - | - | - | - | - | - |
| *Delonix regia* | Fabaceae | I | - | - | - | ✓ | - | ✓ | - | - |
| *Diospyros blancoi* | Ebenaceae | I | - | - | ✓ | - | - | ✓ | ✓ | - |
| *Durio zibethinus* | Malvaceae | N | - | - | ✓ | - | - | - | ✓ | - |
| *Elaeis guineensis* | Arecaceae | I | - | - | ✓ | - | - | - | - | - |
| *Erythrina crista-galli* | Fabaceae | I | - | - | - | - | - | ✓ | - | - |
| *Erythrina variegata* | Fabaceae | I | - | - | - | - | - | ✓ | - | - |
| *Ficus benjamina* | Moraceae | N | - | ✓ | - | - | ✓ | ✓ | ✓ | ✓ |
| *Filicium decipiens* | Sapindaceae | I | - | - | - | - | - | ✓ | - | - |
| *Gnetum gnemon* | Gnetaceae | N | - | - | ✓ | - | - | - | - | - |
| *Gossypium hirsutum* | Malvaceae | I | - | - | - | - | - | ✓ | - | - |
| *Lagerstroemia speciosa* | Lythraceae | I | - | - | - | - | - | ✓ | - | - |
| *Lansium domesticum* | Meliaceae | N | - | - | ✓ | - | - | - | ✓ | - |
| *Leucaena leucocephala* | Fabaceae | I | - | - | ✓ | - | - | - | - | - |
| *Malus domestica* | Rosaceae | N | - | - | ✓ | - | - | - | ✓ | - |
| *Mangifera indica* | Anacardiaceae | N | ✓ | - | ✓ | - | - | ✓ | ✓ | - |
| *Manilkara zapota* | Sapotaceae | N | - | - | ✓ | - | - | - | ✓ | - |
| *Mimusops elengi* | Sapotaceae | N | - | - | - | - | ✓ | ✓ | - | - |
| *Morinda citrifolia* | Rubiaceae | N | - | - | ✓ | - | - | - | - | - |
| *Moringa oleifera* | Moringaceae | N | - | - | ✓ | - | - | - | - | - |
| *Muntingia calabura* | Muntingiaceae | I | - | - | - | - | - | - | ✓ | - |
| *Nephelium lappaceum* | Sapindaceae | N | - | - | ✓ | - | - | - | ✓ | - |
| *Pinus merkusii* | Pinaceae | I | ✓ | - | - | - | - | ✓ | - | - |
| *Pithecellobium dulce* | Fabaceae | I | - | - | ✓ | - | - | - | ✓ | - |
| *Plumeria rubra* | Apocynaceae | I | - | - | - | - | - | ✓ | - | ✓ |
| *Plumeria acuminata* | Apocynaceae | I | - | - | - | - | - | ✓ | - | ✓ |
| *Polyalthia longifolia* | Annonaceae | I | - | - | - | - | ✓ | ✓ | - | - |
| *Pometia pinnata* | Sapindaceae | N | - | - | ✓ | - | - | - | ✓ | - |
| *Pouteria campechiana* | Sapotaceae | I | - | - | ✓ | - | - | - | ✓ | - |
| *Psidium guajava* | Myrtaceae | N | - | - | ✓ | - | - | - | ✓ | - |
| *Pterocarpus indicus* | Fabaceae | I | ✓ | ✓ | - | - | - | ✓ | ✓ | - |
| *Roystonea regia* | Arecaceae | I | - | - | - | - | - | ✓ | - | - |
| *Swietenia mahagoni* | Meliaceae | I | ✓ | - | - | ✓ | - | ✓ | - | - |
| *Syzygium myrtifolium* | Myrtaceae | I | - | - | - | - | - | ✓ | - | - |
| *Syzygium polyanthum* | Myrtaceae | N | - | - | ✓ | - | - | - | - | - |
| *Tabebuia rosea* | Bignoniaceae | I | - | - | - | - | - | ✓ | - | - |
| *Tabebuia roseo-alba* | Bignoniaceae | I | - | - | - | - | - | ✓ | - | - |
| *Tamarindus indica* | Fabaceae | I | - | - | ✓ | - | - | - | - | - |
| *Terminalia catappa* | Combretaceae | I | - | - | - | - | - | ✓ | - | - |
| *Terminalia mantaly* | Combretaceae | I | - | - | - | - | - | ✓ | - | - |
| **Total: 53 species** | **26 families** | **N:21; I: 32** | **7** | **3** | **26** | **2** | **3** | **28** | **22** | **4** |

Note: Origin Status: Native tree (N), Introduced (I) based on: POWO, CABI, GBIF. Functional categories: TP: Timber; MP: Medicinal; EP: Edible; PP: Pollen Producing; PR: Pollen Reducing; OP: Ornamental Plant; Fr: Frugivory-supporting; Tc: Toxic

Apocynaceae and Sapotaceae followed as the next most represented families, each comprising four species. Members of these families are commonly selected for roadside environments due to their structural resilience, relatively stable growth forms, and tolerance to urban stressors such as heat, limited rooting space, and air pollution. The repeated occurrence of these three families across multiple corridors suggests a degree of consistency in municipal planting preferences and long-term greening practices at the district scale. In contrast, families with lower species representation-such as Anacardiaceae, Arecaceae, and Myrtaceae-were more unevenly distributed among routes and often restricted to specific corridors. This localized occurrence likely reflects differences in planting history, land-use context, or micro-environmental conditions along individual road segments, rather than uniform district-wide planting strategies.

### Spatial distribution of roadside trees across routes

#### *Distribution of individuals along the five 10-km routes*

The abundance of roadside trees varied substantially among the five 10-km survey routes (Table 2). In total, 2,091 individuals were recorded across all routes. Ambarawa-Bawen Street recorded the highest abundance (635 trees), followed by Bandungan-Kaloran Street (539 trees), indicating relatively continuous roadside vegetation along these corridors. Ungaran-Cangkiran Street showed moderate abundance (465 individuals), albeit with fragmented distribution in certain sections, while Salatiga-Kedungjati Street represented a corridor with lower tree density (299 individuals). The fewest trees were recorded along Semarang-Bawen Street (153 individuals), consistent with its highly urbanized character and limited planting space.

#### *Identification of routes with the highest and lowest abundance*

Based on the total counts, Route 4 (Ambarawa-Bawen Street) was the most abundant corridor, while Route 5 (Semarang-Bawen Street) contained the lowest number of trees (Table 2). These contrasts highlight the divergent structural conditions across the district's roadside environments, where some corridors maintain extensive vegetative cover, while limited planting space, intensive built-up zones, or discontinuous canopy structure characterize others.

#### *Species occurring only as singletons or rare occurrences*

Several species appeared as singletons, being recorded only once across the entire dataset (Table 2). In total, six species were represented by a single individual: *Artocarpus communis*, *Gnetum gnemon*, *Lansium domesticum*, *Leucaena leucocephala*, *Manilkara zapota*, and *Pometia pinnata*. Although limited in abundance, these rare occurrences contribute to route-level differences in species richness and reflect localized planting decisions or isolated retention of individual trees rather than widespread planting patterns. The presence of these singleton species, while numerically minor, is ecologically noteworthy as it increases overall floristic heterogeneity within Semarang District's urban roadside vegetation.

### Functional categories of roadside trees

#### *Proportion and number of species in each functional group*

Roadside tree assemblages in Semarang District exhibited a diverse distribution of functional categories (Table 1). Edible plants (26 species), frugivory-supporting species (22 species), and ornamental plants (28 species) dominated the composition, reflecting a landscape shaped by both legacy fruit trees from agro-urban mosaics and intentional ornamental planting by local authorities. Timber plants formed a smaller group (7 species), while medicinal plants were limited (3 species), i.e. *Alstonia scholaris, F. benjamina,* and *P. indicus*. Pollen-related categories showed minimal representation, with only 2 Pollen Producing (PP) species (i.e. *Dalbergia latifolia, S. mahagoni*) and 3 Pollen Reducing (PR) species (i.e. *F. benjamina, Mimusops elengi, Polyalthia longifolia*), indicating a generally low contribution to airborne pollen loads along the corridors. Toxic species were also few (4 species), i.e. *Cerbera manghas, F. benjamina, Plumeria rubra,* and *Plumeria acuminata.* The distribution pattern is illustrated in Figure 2, which shows the clear numerical dominance of EP, Fr, and OP, whereas TP, MP, PP, PR, and Tc collectively represent a much smaller fraction of the roadside flora.

#### *Functional overlap and multifunctional species*

Several species occupied more than one functional category (Table 1), highlighting the multifunctionality of many tree taxa in the district. Species such as *Mangifera indica*, *Artocarpus* spp., and *P. pinnata* contributed simultaneously to the edible and frugivory-supporting groups, while *P. indicus* combined timber value with ecological functions related to shade provision and wildlife support. *Ficus benjamina* was among the most multifunctional species, appearing in medicinal, PR, OP, Fr, and Tc categories.

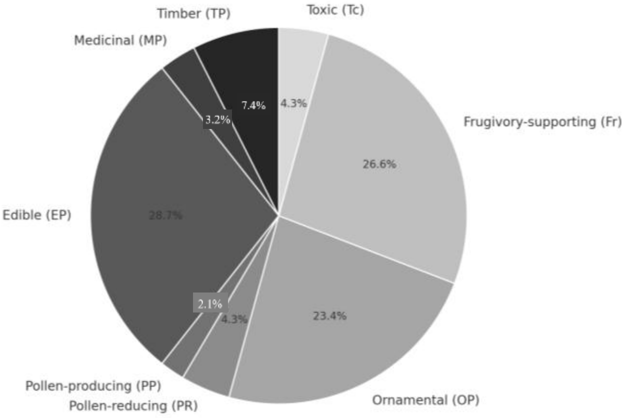

**Figure 2.** Functional categories of roadside tree species in the urban area of Semarang District, Indonesia. Note: TP: Timber Plant; MP: Medicinal Plant; EP: Edible Plant; PP: Pollen Producing Plant; PR: Pollen-Reducing Plant; OP: Ornamental Plant; Fr: Frugivory-supporting plant; Tc: Toxic plant (after Thothathri et al. 1985)

**Table 2.** Species frequency counts by point in Semarang District, Indonesia

| Scientific name | Family | Route |  |  |  |  |
|---|---|---|---|---|---|---|
|  |  | **1** | **2** | **3** | **4** | **5** |
| *Albizia julibrissin* | Fabaceae | 0 | 0 | 0 | 0 | 2 |
| *Alstonia scholaris* | Apocynaceae | 4 | 0 | 2 | 0 | 0 |
| *Anacardium occidentale* | Anacardiaceae | 0 | 4 | 2 | 0 | 0 |
| *Artocarpus communis* | Moraceae | 0 | 0 | 0 | 1 | 0 |
| *Artocarpus heterophyllus* | Moraceae | 9 | 7 | 52 | 9 | 0 |
| *Averrhoa carambola* | Oxalidaceae | 5 | 1 | 7 | 1 | 0 |
| *Carica papaya* | Caricaceae | 9 | 9 | 6 | 0 | 0 |
| *Casuarina equisetifolia* | Casuarinaceae | 19 | 2 | 0 | 5 | 0 |
| *Cerbera manghas* | Apocynaceae | 4 | 0 | 0 | 0 | 0 |
| *Chrysophyllum cainito* | Sapotaceae | 7 | 0 | 0 | 0 | 0 |
| *Citrus maxima* | Rutaceae | 0 | 0 | 6 | 0 | 0 |
| *Cocos nucifera* | Arecaceae | 13 | 10 | 29 | 3 | 0 |
| *Cordyline australis* | Asparagaceae | 7 | 1 | 0 | 0 | 0 |
| *Dalbergia latifolia* | Fabaceae | 0 | 0 | 0 | 71 | 1 |
| *Delonix regia* | Fabaceae | 0 | 0 | 0 | 19 | 0 |
| *Diospyros blancoi* | Ebenaceae | 0 | 8 | 0 | 0 | 0 |
| *Durio zibethinus* | Malvaceae | 1 | 16 | 18 | 0 | 0 |
| *Elaeis guineensis* | Arecaceae | 0 | 1 | 0 | 0 | 3 |
| *Erythrina crista-galli* | Fabaceae | 53 | 0 | 0 | 0 | 0 |
| *Erythrina variegata* | Fabaceae | 0 | 0 | 0 | 0 | 5 |
| *Ficus benjamina* | Moraceae | 8 | 0 | 2 | 5 | 0 |
| *Filicium decipiens* | Sapindaceae | 3 | 2 | 0 | 9 | 0 |
| *Gnetum gnemon* | Gnetaceae | 0 | 0 | 0 | 1 | 0 |
| *Gossypium hirsutum* | Malvaceae | 0 | 0 | 2 | 0 | 0 |
| *Lagerstroemia speciosa* | Lythraceae | 1 | 0 | 0 | 15 | 28 |
| *Lansium domesticum* | Meliaceae | 1 | 0 | 0 | 0 | 0 |
| *Leucaena leucocephala* | Fabaceae | 0 | 0 | 1 | 0 | 0 |
| *Malus domestica* | Rosaceae | 4 | 0 | 0 | 0 | 0 |
| *Mangifera indica* | Anacardiaceae | 110 | 86 | 41 | 43 | 7 |
| *Manilkara zapota* | Sapotaceae | 1 | 0 | 0 | 0 | 0 |
| *Mimusops elengi* | Sapotaceae | 0 | 0 | 0 | 0 | 4 |
| *Morinda citrifolia* | Rubiaceae | 2 | 0 | 0 | 0 | 0 |
| *Moringa oleifera* | Moringaceae | 2 | 0 | 0 | 0 | 0 |
| *Muntingia calabura* | Muntingiaceae | 38 | 38 | 9 | 11 | 4 |
| *Nephelium lappaceum* | Sapindaceae | 1 | 0 | 0 | 1 | 5 |
| *Pinus merkusii* | Pinaceae | 0 | 0 | 13 | 1 | 0 |
| *Pithecellobium dulce* | Fabaceae | 0 | 0 | 0 | 0 | 20 |
| *Plumeria rubra* | Apocynaceae | 5 | 0 | 1 | 1 | 20 |
| *Plumeria acuminata* | Apocynaceae | 6 | 6 | 8 | 1 | 0 |
| *Polyalthia longifolia* | Annonaceae | 53 | 47 | 0 | 67 | 0 |
| *Pometia pinnata* | Sapindaceae | 1 | 0 | 0 | 0 | 0 |
| *Pouteria campechiana* | Sapotaceae | 0 | 0 | 0 | 0 | 28 |
| *Psidium guajava* | Myrtaceae | 1 | 4 | 14 | 56 | 0 |
| *Pterocarpus indicus* | Fabaceae | 16 | 0 | 9 | 0 | 0 |
| *Roystonea regia* | Arecaceae | 87 | 0 | 0 | 0 | 0 |
| *Swietenia mahagoni* | Meliaceae | 13 | 4 | 229 | 222 | 0 |
| *Syzygium myrtifolium* | Myrtaceae | 20 | 11 | 14 | 0 | 0 |
| *Syzygium polyanthum* | Myrtaceae | 0 | 0 | 0 | 17 | 0 |
| *Tabebuia rosea* | Bignoniaceae | 4 | 5 | 0 | 49 | 0 |
| *Tabebuia roseo-alba* | Bignoniaceae | 0 | 0 | 0 | 0 | 21 |
| *Tamarindus indica* | Fabaceae | 2 | 2 | 0 | 0 | 0 |
| *Terminalia catappa* | Combretaceae | 28 | 35 | 0 | 3 | 0 |
| *Terminalia mantaly* | Combretaceae | 1 | 0 | 0 | 24 | 5 |
| Total: 2,091 individuals |  | 539 | 299 | 465 | 635 | 153 |

Notes: Route 1: Bandungan-Kaloran Street; Route 2: Salatiga-Kedungjati Street; Route 3: Ungaran-Cangkiran Street; Route 4: Ambarawa-Bawen Street; Route 5: Semarang-Bawen Street

This functional overlap enhances ecological resilience by supporting multiple ecosystem services-shade, food provisioning, pollination benefits, and cultural value-within a relatively limited number of planted species. Such multifunctionality strengthens the structural and functional complexity of roadside vegetation along the five surveyed routes.

*Interpretation of dominant functional roles in the urban landscape*

The functional profile shown in Figure 2 suggests that a combination of aesthetic, microclimatic, and agro-ecological considerations shapes roadside tree composition in Semarang District. Ornamental species remain important for aesthetic continuity and urban image, while fruit-bearing and frugivory-supporting species contribute substantially to urban wildlife resources and reflect long-standing planting traditions. Timber species, though less numerous, play essential structural roles in providing shade and canopy cover. Conversely, the relatively small representation of EP-only utilitarian plants, medicinal taxa, pollen-related groups, and toxic species indicates a shift toward multifunctional and ecologically favored species rather than culturally utilitarian or specialized taxa.

The dominance of edible, frugivory-supporting, and ornamental groups underscores the hybrid character of Semarang's roadside vegetation, balancing ecological benefits with cultural and aesthetic functions.

## Species abundance and dominant taxa

*Top five most abundant species per route*

Species abundance varied markedly across the five surveyed corridors (Table 2). On Bandungan-Kaloran Street, the leading species were *S. mahagoni*, *P. longifolia*, *T. rosea*, and *P. indicus*, together comprising a substantial portion of the total individuals on this route. Salatiga-Kedungjati Street showed a different abundance profile, with *S. mahagoni* remaining dominant, accompanied by *M. indica*, and several ornamental taxa with moderate representation. Along Ungaran-Cangkiran Street, overall abundance was lower, but *S. mahagoni* and *P. longifolia* again emerged as the most frequently recorded species. Ambarawa-Bawen Street and Semarang-Bawen Street displayed similar trends, each characterized by a small set of high-abundance ornamentals and shade species dominating the community structure.

*City-wide dominant species*

Across the entire Semarang District dataset, several tree species emerged as both numerically abundant and spatially widespread across multiple corridors (Table 2). *Ficus benjamina* was the most widely distributed species, occurring across all five surveyed routes, indicating strong tolerance to varied roadside conditions in both urban and peri-urban environments. *Mangifera indica* and *P. indicus* were each recorded in four routes, reflecting their multifunctional roles as shade-providing, fruit-bearing, and structurally resilient trees commonly retained along major roads. In contrast, *S. mahagoni*, although highly abundant within certain corridors, was present in only three routes, demonstrating that numerical dominance does not necessarily correspond to the widest spatial distribution at the district scale. *P. longifolia* was frequently encountered along densely built-up segments, consistent with its widespread use as an avenue tree characterized by a narrow, vertical crown structure. Collectively, these species form the structural backbone of roadside vegetation in Semarang District, contributing substantially to overall canopy cover and shaping the abundance patterns of the surveyed urban tree assemblages.

*Species with intermediate and low abundance classes*

A substantial number of species occurred at intermediate abundance, typically represented by 5-20 individuals per route (Table 2). These included widely planted but not overwhelmingly dominant ornamentals such as *T. rosea*, *D. regia*, and *P. indicus*. Species with low abundance-represented by fewer than five individuals-were numerous and contributed to route-level richness without strongly influencing overall dominance patterns. Several of these, such as *L. domesticum*, *M. zapota*, and *G. gnemon*, were restricted to single or isolated occurrences. Although limited in numbers, these low-abundance species enhanced the spatial heterogeneity and complemented the rich ornamental matrix observed across the road corridors.

### Route-specific community profiles

*Bandungan-Kaloran Street (Route 1)*

Route 1 exhibited the highest species richness and total abundance among all surveyed corridors, forming the most structurally stable assemblage in Semarang District (Table 2). The roadside vegetation along this corridor was dominated by *S. mahagoni*, followed by *P. longifolia*, *T. rosea*, and *P. indicus*, which together produced a relatively dense and continuous canopy along much of the route. The dominance of these taxa reflects a combination of long-established planting practices and favorable planting space typical of peri-urban environments. In addition to dominant species, several taxa occurred only as singletons, including *L. domesticum*, *M. zapota*, and *G. gnemon*, indicating localized planting decisions or isolated retention of individual trees rather than systematic planting. Although numerically infrequent, these rare occurrences contributed to the overall species richness of Route 1 and reinforced its status as the most diverse corridor in the district. The coexistence of dominant and rare species suggests that Route 1 benefits from wider roadside verges, lower disturbance intensity, and more heterogeneous microhabitats, resulting in a comparatively balanced and ecologically robust community structure.

*Salatiga-Kedungjati Street (Route 2)*

Route 2 exhibited moderate species richness and total abundance, forming a structurally mixed assemblage dominated by *S. mahagoni* (Table 2). Other relatively frequent taxa included *M. indica* and *P. longifolia*, creating a corridor characterized by a combination of shade-providing and ornamental species commonly selected for inter-urban roadside planting. This composition reflects regular planting interventions along transport routes where visual uniformity and canopy function are prioritized. Several additional species occurred at low frequencies, typically represented by one to three individuals, indicating localized planting decisions or residual trees retained from earlier land-use phases rather than systematic planting schemes. Although these low-abundance taxa contributed minimally to overall tree density, their presence increased compositional heterogeneity along the corridor. Overall, Route 2 represents a moderately diverse and moderately stable assemblage shaped by mixed land-use influence and intermediate levels of disturbance.

*Ungaran-Cangkiran Street (Route 3)*

Route 3 (Ungaran-Cangkiran Street) displayed the strongest dominance pattern, with *S. mahagoni* overwhelmingly shaping the structure of the corridor. This created a heavily skewed community composition where a single taxon accounted for a disproportionate share of total individuals. The prevalence of *Swietenia* along this route likely reflects limited planting space, high levels of disturbance, and the common municipal practice of selecting vertically oriented species for narrow roadside verges. Low-frequency taxa occurred sporadically, with several species recorded only once or twice, indicating limited species turnover and reduced canopy heterogeneity (Table 2). Although these rare species marginally increased richness, their presence did not significantly alter the overall dominance-driven structure. The resulting assemblage is considered the least stable among all routes due to low diversity, strong dominance, and fragmented canopy cover.

*Ambarawa-Bawen Street (Route 4)*

Route 4 displayed a moderately dense and moderately rich assemblage dominated by *S. mahagoni*, *P. longifolia*, and *D. regia*, which together formed the bulk of roadside vegetation along the corridor (Table 2). The coexistence of ornamentals and large shade trees produced a mixed but not highly diverse structure, indicative of standardized planting strategies typical of regional highways. In contrast to Route 3, this corridor retained a more balanced distribution of secondary species, contributing to a more evenly distributed canopy. Several taxa were recorded almost exclusively along this route, including isolated individuals not observed in other corridors, suggesting distinct planting histories or localized microhabitats that favor certain species. Such route-specific taxa highlight the varying management approaches employed across districts and contribute to the intermediate stability observed in Route 4.

*Semarang-Bawen Street (Route 5)*

Route 5 presented a species composition broadly comparable to that of Routes 2 and 4, with *S. mahagoni* emerging as the dominant species along the corridor (Table 2). Secondary dominant taxa included *M. indica*, reflecting the widespread selection of multifunctional and aesthetically preferred trees in urban and peri-urban roadside environments. The total tree abundance on this route was lower than that recorded in less urbanized corridors, consistent with higher levels of built-up land cover, increased traffic intensity, and reduced planting space in more densely urbanized segments. These conditions resulted in a comparatively homogenized community structure, a lower number of rare species, and reduced canopy continuity. The abundance patterns observed along Route 5 indicate that urbanization intensity acts as a key driver shaping roadside tree community structure, limiting opportunities for diversified planting and constraining ecological heterogeneity.

## Biodiversity indices across routes

### *Species richness (Margalef Index) comparison*

Species richness, as reflected by the Margalef Index, varied markedly among the five surveyed routes (Table 3). Bandungan-Kaloran Street (Route 1) recorded the highest richness value, consistent with its large number of species and relatively high individual counts, indicating a more heterogeneous community structure than the other corridors. Intermediate richness values were observed on Salatiga-Kedungjati Street (Route 2) and Ambarawa-Bawen Street (Route 4), both of which maintained a moderate species pool supported by mixed land-use patterns. In contrast, Ungaran-Cangkiran Street (Route 3) had the lowest richness level, reflecting both the limited number of species and the markedly low abundance recorded along the corridor. These patterns mirror the spatial distribution of individuals across routes and highlight the influence of planting space, disturbance intensity, and land-use type on species richness in urban roadside environments.

### *Shannon-Wiener diversity patterns*

Shannon-Wiener Index values (H′) indicated moderate to high diversity across most routes, with Route 1 showing the highest H′-a pattern consistent with its rich species pool and balanced abundance distribution (Table 3). Routes 2, 4, and 5 shared similar H′ ranges, reflecting structurally mixed but not heavily dominated communities typical of suburban-urban transition zones. The lowest H′ value occurred on Route 3, driven primarily by the strong dominance of *S. mahagoni* and the scarcity of secondary species, which reduced overall species balance. The contrast between the routes underscores how dominance, species evenness, and total richness interact to shape the composite diversity of roadside trees in Semarang District.

### *Evenness distribution across routes*

Evenness (E) values further revealed inter-route variation in species balance (Table 3). Semarang-Bawen Street (Route 5) exhibited the highest evenness score, indicating a more equitable distribution of individuals among constituent species, despite having fewer total individuals compared to Route 1. Moderate evenness values on Routes 1, 2, and 4 point to mixed dominance structures, where several species contribute substantially to total abundance. In contrast, Route 3 showed the lowest evenness, congruent with its strong skew toward *S. mahagoni*. Across the district, evenness generally reflected the interaction between planting uniformity and disturbance levels, with more urbanized routes tending toward slightly homogenized species distributions.

### *Simpson Diversity Index and dominance levels*

Simpson Index values (1-D) were relatively high on most routes, indicating low to moderate dominance and generally stable multi-species assemblages (Table 3). Route 1 again recorded the highest Simpson (1-D) value, aligning with its diverse and relatively evenly distributed community. Simpson values on Routes 2, 4, and 5 remained within comparable ranges, signifying moderate dominance pressure and the presence of multiple co-dominant taxa. Route 3 showed the lowest Simpson value, reflecting its highly skewed structure dominated by a single species and limited contribution from rare taxa. Overall, Simpson patterns reinforce the conclusion that dominance-driven corridors exhibit reduced ecological balance and are more vulnerable to disturbance.

### *Identification of the most stable vs the least stable communities*

Integration of Margalef, Shannon, Simpson, and Evenness indices collectively indicates that Bandungan-Kaloran Street (Route 1) represents the most stable tree assemblage within Semarang District, characterized by high richness, high diversity, and a relatively balanced distribution of individuals. On the opposite end, Ungaran-Cangkiran Street (Route 3) emerged as the least stable corridor due to its low richness, low evenness, and strong species dominance. The remaining routes showed intermediate levels of stability, shaped by mixed dominance structures, moderate species pools, and varying disturbance conditions. Together, these multi-index comparisons illustrate how roadside vegetation stability in Semarang is shaped by the interaction of species diversity, structural balance, planting history, and urbanization pressure.

**Table 3.** Species diversity indices at five roadside routes in Semarang District, Central Java, Indonesia

| Route | Region | Margalef (G) | Shannon-Wiener (H') | Evenness (E) | Simpson (1-D)* |
|---|---|---|---|---|---|
| 1 | Bandungan-Kaloran Street | 5.404 | 2.725 | 0.766 | 0.899 |
| 2 | Salatiga-Kedungjati Street | 3.508 | 2.322 | 0.763 | 0.854 |
| 3 | Ungaran-Cangkiran Street | 3.093 | 1.936 | 0.646 | 0.728 |
| 4 | Ambarawa-Bawen Street | 3.564 | 2.247 | 0.707 | 0.831 |
| 5 | Semarang-Bawen Street | 2.584 | 2.260 | 0.856 | 0.873 |

Note: Diversity indices were calculated as follows: Margalef's Richness Index (G) = (S − 1)/ln(N); Shannon-Wiener Index (H'); Evenness (E) = H'/ln(S); and Simpson's Diversity Index $1-D=1-\sum p_i^2$, where p = $n_i$/N

## Summary of key ecological findings

### *Integration of species counts, abundance, and indices*

Synthesis of the dataset (Table 1) shows that Semarang District's roadside corridors support 53 species, 47 genera, and 26 families, forming a taxonomically diverse yet unevenly distributed assemblage. A total of 2,091 individual trees were documented across all five corridors. Abundance patterns reveal clear contrasts among routes, with Ambarawa-Bawen Street (Route 4) recording the highest number of individuals (635), while Semarang-Bawen Street (Route 5) hosts the lowest (153). Diversity indices further demonstrate substantial route-level variation: Route 1 exhibits consistently high Margalef, Shannon, and Simpson values, indicating greater richness and structural balance, whereas Route 3 shows the lowest diversity and evenness, reflecting strong dominance and reduced community stability. Together, these metrics illustrate a mosaic-like distribution of roadside tree communities shaped by corridor-level differences in planting history, urbanization intensity, and local environmental conditions.

### *Emergent patterns of urban tree diversity*

Urban roadside vegetation in Semarang is characterized by a strong dominance of widely planted ornamentals and timber species, as evidenced by their high abundance and frequent occurrence across routes (Tables 1 and 2). Functional diversity is skewed toward a few major groups, with ornamental plants forming the largest component, followed by shade-providing timber species and frugivory-supporting taxa. Introduced species constitute a substantial portion of the flora, while native species remain present but comparatively limited. Species richness and community balance are highest in less urbanized corridors, while built-up routes show reduced richness and stronger dominance patterns.

### *Ecological implications of current roadside vegetation structure*

The observed patterns indicate that Semarang's roadside tree communities provide structural diversity but are functionally concentrated in a few dominant roles. High dominance by species such as *S. mahagoni* and *P. longifolia* contributes to consistent canopy structure but may reduce resilience to pests, diseases, or climatic extremes. Conversely, the presence of multiple rare and low-abundance species enhances route-level richness and contributes to spatial heterogeneity. Overall, current roadside vegetation reflects a blend of ecological function, aesthetic preference, and urban planting practice, forming a community structure that supports moderate biodiversity while revealing opportunities for greater functional diversification in future urban greening strategies.

## Discussion

### *Urban roadside tree diversity in the context of tropical cities*

The diversity patterns observed across the roadside corridors of Semarang District highlight the ecological complexity of vegetation in rapidly expanding tropical cities. The combination of moderate-high Shannon diversity, substantial species richness, and marked route-specific variability indicates that the interaction of ecological filtering and long-term management decisions drives community assembly. In tropical metropolitan regions, roadside vegetation commonly functions as a semi-managed mosaic where environmental stress and human intervention jointly shape species composition (Luck and Smallbone 2010; Cariñanos and Casares-Porcel 2011). Similar to findings from Jakarta, Manila, Kuala Lumpur, and Bangkok, Semarang's corridors support heterogeneous mixtures of native and introduced taxa, with diversity declining predictably in locations characterized by stronger heat-island effects, narrower planting strips, and higher disturbance intensities (Lourdes et al. 2021; Maruthaveeran et al. 2011; Sholihah et al. 2022).

Short-distance compositional turnover-a hallmark of tropical roadside systems-reflects the interplay between heterogeneous planting histories and disturbance-driven selection (Roman et al. 2016; Sjöman et al. 2016). The variation recorded across Semarang's five routes aligns with broader urban ecological theory, which posits that fine-scale environmental gradients in built-up density, shading, and soil compaction create distinct ecological niches along linear corridors. These gradients, documented in Guangzhou (Jim and Liu 2001) and Colombo (Wells et al. 2017), promote localized filtering and generate route-specific vegetation signatures. Under the limited availability of larger green spaces, such linear elements often act as ecological "refuge corridors," retaining species otherwise excluded from more heavily sealed urban matrices (Aronson et al. 2017).

Several interacting mechanisms explain the richness and heterogeneity observed in Semarang. Elevated temperatures and extensive impervious surfaces act as strong abiotic filters, selecting for taxa with high heat and drought tolerance and shifting community assembly toward resilient ornamentals such as *S. mahagoni*, *D. regia*, and *P. longifolia* (Oke et al. 2017; Zandler and Samimi 2024; Hwang et al. 2025). Restricted rooting spaces along arterial roads impose below-ground constraints that suppress growth of sensitive taxa, reinforcing dominance by species with efficient water-use strategies and compact root systems (Pretzsch et al. 2017; Sun et al. 2024). Additionally, chronic disturbances-including pruning, pollution, and mechanical damage-reduce survival of species lacking structural or physiological adaptations, producing the low richness and depressed evenness commonly observed along highly urbanized segments (Sarwadi et al. 2019; Siqueira et al. 2022; Pratiwi et al. 2025).

Patterns from other Southeast Asian cities corroborate these mechanisms. Bangkok's dominance by fast-growing ornamentals (Soonsawad 2013), Manila's dependence on introduced shade species (Moriwake et al. 2020), and Singapore's persistence of non-native ornamentals even under high management standards (Hwang et al. 2025) all point to convergent ecological outcomes: environmental filtering under urban stress narrows the functional pool, while historical planting decisions maintain certain taxa over decades. Semarang's moderate richness, substantial representation of introduced species, and recurrent dominance of heat- and disturbance-tolerant taxa therefore reflect regionally consistent assembly rules across tropical Asia.

Despite these constraints, the presence of 53 species from 26 families demonstrates that roadside vegetation-when effectively maintained-can sustain ecologically meaningful diversity. The variation observed across corridors suggests that linear green spaces can serve not only as visual and climatic buffers but also as functional ecological components, provided species selection and management practices align with the environmental realities of tropical urban landscapes.

### *Patterns of taxonomic structure and dominant species*

The strong dominance of *S. mahagoni*, *P. longifolia*, and *M. indica* across Semarang's roadside corridors reflects the convergence of ecological tolerance, functional traits, and long-standing municipal planting regimes that shape tree-community assembly in tropical cities. Under urban ecological filtering, species capable of maintaining physiological performance under heat stress, soil compaction, and pollution tend to monopolize available niches, thereby reducing the effective species pool (Sjöman et al. 2016; Sun et al. 2024; Zandler and Samimi 2024). *Swietenia mahagoni*, for instance, possesses deep-rooted architecture, drought-tolerant foliage, and high structural uniformity-traits that enhance survival in thermally extreme corridors. Its recurrent dominance in Manila, Colombo, and Yangon (Esperon-Rodriguez et al. 2025; Wells et al. 2017) indicates that this species often occupies a "core functional niche" in tropical urban forests, where environmental constraints narrow community composition toward a few physiologically robust taxa.

*Polyalthia longifolia* dominates for complementary mechanistic reasons. Its columnar crown and narrow lateral spread represent a classic "urban-tolerant architecture" optimized for limited rooting volumes, heavy pedestrian traffic, and overhead cables-conditions that frequently eliminate species with broader, structurally complex canopies (Maruthaveeran et al. 2011; Soonsawad 2013). This architectural predictability, combined with moderate pollution tolerance and rapid early growth (Hwang et al. 2025), creates a competitive advantage in spatially constrained corridors. Comparable dominance in Guangzhou, Bangkok, and Dhaka (Jim and Liu 2001; Kjelgren et al. 2011; Uddin et al. 2021) suggests that *P. longifolia* is repeatedly selected through both environmental filtering and institutional preference.

The persistence of *M. indica* follows a different mechanism: legacy effects. Many large individuals are retained through road-widening cycles due to their cultural familiarity, shade value, and established root systems (Sarwadi et al. 2019; Pratiwi et al. 2025). In urban ecological theory, such legacy trees serve as "structural anchors," exerting disproportionate influence on canopy stratification and microclimate while shaping successional trajectories by limiting available space for replacement species. Their drought tolerance and broad crowns reinforce their ecological persistence-even when newly planted cohorts shift toward ornamentals.

Dominance by a narrow suite of species is a well-documented feature of tropical urban vegetation (Cariñanos and Casares-Porcel 2011; Aronson et al. 2017). Ecologically, such dominance emerges from two overlapping processes: (i) Abiotic filtering, where heat, compaction, and pollution reduce niche breadth; and (ii) Planting inertia, where municipalities repeatedly select "safe" species with predictable performance (Luck and Smallbone 2010; Pretzsch et al. 2017).

While dominant taxa stabilize canopy cover and offer reliable ecosystem services in the short term, they simultaneously reduce functional redundancy. This creates vulnerability to pests, physiological decline, or climate-driven stress, as evidenced by pest-induced canopy loss in Singapore and Guangzhou (Jim and Liu 2001) and the decline of dominant ornamentals in Jakarta and Surabaya (Nidah and Mukhlison 2013). When a community's functional capacity is concentrated in a few taxa, stochastic shocks can trigger system-level instability, accelerating canopy degradation and reducing urban resilience (Roman et al. 2016; Siqueira et al. 2022).

In Semarang, the strong dominance of *S. mahagoni*, *P. longifolia*, and *M. indica* therefore represents a structurally efficient but ecologically vulnerable community architecture. Although these species currently support essential canopy functions, the long-term resilience of the roadside vegetation system will depend on diversifying species pools, increasing functional redundancy, and reducing the ecological risks inherent in dominance-led community structures-recommendations increasingly emphasized in contemporary tropical urban forestry research (Luck and Smallbone 2010; Sjöman et al. 2016; Hwang et al. 2025).

### *Functional composition and ecosystem services of roadside trees*

The functional composition of Semarang's roadside vegetation reflects a community structured by both environmental filters and the functional priorities of urban management. The dominance of Ornamental Plant (OP), Edible Plant (EP), and Frugivory-supporting (Fr) species (Table 1; Figure 2) indicates that functional assembly is not random but driven by a combination of physiological tolerance, service provisioning, and historical planting regimes. In tropical cities, environmental harshness and design constraints tend to favor species with high thermal plasticity, stable architectural forms, and predictable maintenance requirements-traits aligning closely with the functional groups most abundant in Semarang (Cariñanos and Casares-Porcel 2011; Sun et al. 2024).

Ornamental species, including *D. regia*, *T. rosea*, and *P. longifolia*, exemplify "urban-tolerant" phenotypes that combine high photosynthetic resilience under elevated temperatures with canopy architectures suited to constrained spatial environments. Their visual appeal is often cited, but ecologically, their dominance arises from a strategic advantage under low-soil-volume, high-radiation, and pollution-heavy conditions (Thaiutsa et al. 2008;

Kjelgren et al. 2011). Through shading and transpiration cooling, these species help modulate microclimates, lowering surface temperatures and mitigating heat-island effects-ecosystem services that become increasingly critical as tropical cities warm (Wells et al. 2017; Zandler and Samimi 2024).

Timber Plants (TP) such as *S. mahagoni* and *P. indicus* represent another functional axis: structural robustness. With dense wood, deep-rooting systems, and large crowns, these species operate as "ecosystem-service anchors," capturing particulate matter, stabilizing soil along roadside banks, and providing a more persistent canopy under hydrological or thermal stress (Pretzsch et al. 2017; Hwang et al. 2025). Their presence enhances carbon storage, but more importantly, contributes to structural heterogeneity-a key determinant of ecological resilience in linear habitats.

The ecological significance of frugivory-supporting species becomes evident when interpreted through a trophic-interaction lens. Species such as *M. indica*, *F. benjamina*, and other fruiting taxa provide continuous or seasonal resources for birds, bats, and small mammals. These interactions help maintain urban food webs, sustain pollinator and seed-disperser presence, and support the connectivity of wildlife across fragmented landscapes (Wells et al. 2017; Lourdes et al. 2021). In tropical urban systems, such frugivory pathways often act as "ecological bridges," preventing the collapse of species interactions under increasing urban stress.

In contrast, the limited representation of Medicinal Plants (MP), Toxic plants (Tc), Pollen Producers (PP), and Pollen Reducers (PR) highlights trade-offs inherent in roadside environments. High-disturbance corridors impose sanitation, safety, and allergenicity constraints that reduce the suitability of utilitarian fruit crops and allergenic species (Jianan et al. 2007; Cariñanos et al. 2016, 2019). Pollen Producers (PP) species are minimized to prevent respiratory-health risks, while PR species remain underutilized due to limited horticultural availability and poor public familiarity (D'Amato et al. 2010). These patterns reveal that functional traits related to human health and public safety act as secondary filters shaping community composition.

Overall, Semarang's functional profile reflects a structure in which a few key functional groups-primarily ornamentals, timber plants, and frugivory-supporting species-provide the majority of regulatory, aesthetic, and ecological services. While effective in delivering microclimate regulation, shading, and habitat support, this configuration also reveals a degree of functional homogenization. The overrepresentation of similar service-provision pathways reduces the redundancy needed to withstand long-term disturbances, echoing global concerns that tropical urban forests dominated by narrow functional spectra may be less adaptable to climatic or pest-driven shocks (Aronson et al. 2017; Pretzsch et al. 2017). Expanding the diversity of functional groups, therefore, remains essential for enhancing ecological performance and stabilizing ecosystem-service delivery across Semarang's roadside corridors.

### *Spatial heterogeneity across corridors*

The five roadside corridors in Semarang District exhibit pronounced spatial heterogeneity in species richness, abundance distribution, and diversity indices, reflecting the combined influence of urbanization intensity, microclimatic variation, and corridor-specific management histories. From a landscape ecology perspective, linear road networks function as environmental gradients where temperature regimes, soil volumes, shading patterns, and disturbance pressures change continuously across space, generating distinct ecological niches even over short distances. These fine-scale gradients help explain why Route 1-characterized by broader planting strips, lower sealed-surface cover, and more favorable microclimates-supports richer and more evenly structured assemblages, a pattern consistent with peri-urban corridors documented in Kuala Lumpur, and Colombo (Maruthaveeran et al. 2011; Wells et al. 2017).

Conversely, Route 3 functions as a high-disturbance ecological filter. Narrow planting zones, restricted rooting volumes, and persistent vehicular stress limit the recruitment and survival of species lacking strong physiological stress tolerance. Under such conditions, environmental filtering promotes the dominance of a few urban-tolerant taxa-typically drought-resistant ornamentals-while reducing the functional and taxonomic diversity of the community (Jim and Liu 2001; Soonsawad 2013; Moriwake et al. 2020). These patterns align with ecological theory predicting that intense and chronic disturbances narrow community composition toward species with traits that minimize hydraulic failure, mechanical instability, and pollutant sensitivity (Rodrigues et al. 2021; Siqueira et al. 2022). As a result, Route 3 exhibits low richness, strong dominance, and depressed evenness, characteristic of structurally homogenized vegetation typical of dense urban fabrics.

The substantial beta diversity across routes indicates that these corridors do not form a continuous ecological unit but instead function as discrete habitat patches embedded in a heterogeneous urban matrix. Differences between the well-vegetated, peri-urban Route 1 and the more urbanized Routes 3 and 5 resemble patterns of functional turnover documented in Singapore and Jakarta, where microclimatic contrasts and localized planting regimes create spatially segregated communities (Sholihah et al. 2022; Hwang et al. 2025). High compositional turnover reinforces the idea that roadside vegetation outcomes depend not merely on species selection but on the interaction between biophysical constraints and the historical layering of management decisions.

Viewed more broadly, Semarang's roadside vegetation mirrors regional ecological trajectories in tropical Asian cities. Route 1 parallels semi-natural greenways with high ecological buffering capacity, whereas Routes 3 and 5 resemble engineered corridors shaped by structural confinement, elevated heat loads, and disturbance-dominated environmental filters (Roloff et al. 2009; Kjelgren et al. 2011). This spatial heterogeneity underscores the necessity of differentiated greening strategies: peri-urban corridors should be prioritized as biodiversity reservoirs and ecological connectors, while inner-urban corridors require interventions that expand soil volume, enhance species heterogeneity, and mitigate microclimatic extremes.

*Biodiversity indices and ecological stability*

Interpretation of the Shannon, Simpson, Margalef, and Evenness indices across the five Semarang corridors reveals not only differences in richness and dominance but also the underlying stability regimes governing these urban vegetation systems. From an ecological-theory perspective, these four indices collectively represent complementary dimensions of community organization: Margalef captures species pool size; Shannon integrates richness and entropy; Simpson emphasizes dominance resistance; and evenness reflects the distributional balance that allows communities to buffer stochastic disturbance. Their combined patterns show that Semarang's roadside assemblages operate along a gradient from structurally resilient to dominance-driven and disturbance-sensitive configurations.

Route 1 exemplifies a high-stability community where richness, moderate dominance, and strong evenness interact to produce a functionally redundant assemblage-an attribute repeatedly associated with enhanced resistance to environmental shocks in urban ecosystems (Aronson et al. 2017; Sun et al. 2024). The concurrence of high Shannon and high Simpson values indicates that no single species monopolizes the community, allowing ecological functions such as shading, particulate interception, and cooling to be distributed across multiple taxa. Comparable stability profiles have been reported for resilient roadside greenways in Singapore and Kuala Lumpur, where diverse species assemblages mitigate heat-island stress and maintain canopy continuity despite chronic disturbance (Maruthaveeran et al. 2011; Hwang et al. 2025). Under ecological theory, such communities possess higher "response diversity," enabling them to maintain functionality even when individual species decline.

In contrast, Route 3 represents a low-stability system marked by reduced richness, low evenness, and dominance by *S. mahagoni*. The clustering of low Shannon and low Margalef values alongside only moderate Simpson diversity indicates a system where functional pathways are concentrated within a narrow suite of taxa. Dominance-driven communities are known to exhibit weak redundancy, meaning that ecological functions are more vulnerable to collapse if key species experience stress or decline (Rodrigues et al. 2021; Siqueira et al. 2022). Such assemblages also show diminished capacity to absorb thermal or hydrological extremes, a pattern observed in Guangzhou, Manila, and other densely urbanized cities where roadside communities with low evenness rapidly degrade under drought or pest outbreaks (Roloff et al. 2009). In this context, the persistence of *S. mahagoni* functions as a stabilizing anchor but simultaneously creates single-species dependence, increasing systemic fragility.

Intermediate patterns-such as the moderate richness but relatively high Evenness in Route 5-illustrate an important insight from contemporary stability theory: richness alone does not determine resilience. Communities with modest species pools can still exhibit functional persistence if abundance is evenly distributed, as balanced representation reduces the risk of synchronized decline across dominant taxa (Pretzsch et al. 2017; Hwang et al. 2025). Evenness, therefore, acts as a stabilizing mechanism, shaping temporal resistance and recovery potential even in species-light systems.

Taken together, these results reveal that Semarang's corridors fall into two broad ecological regimes: (i) High-stability assemblages (e.g., Route 1), where high richness and balanced abundance support strong functional redundancy; and (ii) Low-stability assemblages (e.g., Route 3), where dominance and low evenness produce vulnerability to stress, disturbance, and species-specific shocks. This duality reflects broader patterns in tropical and subtropical urban forests, where resilience is shaped not only by species counts but by the internal distribution of ecological roles and abundances (Luck and Smallbone 2010; Hernández and Villaseñor 2018).

Ultimately, the biodiversity indices indicate that several corridors in Semarang rely heavily on dominant taxa rather than diversified ecological networks, underscoring the need for management strategies that increase redundancy, dilute dominance, and reinforce long-term ecological stability across the city's roadside vegetation systems.

*Implications for urban green-space management in Semarang District*

The taxonomic structure, functional composition, and stability gradients documented across Semarang's corridors offer clear insights into how urban green-space management can increase ecological resilience under intensifying tropical urban pressures. The most immediate implication concerns species diversification. Dominance by *S. mahagoni*, *P. longifolia*, and *M. indica* reflects effective short-term performance under heat stress, compaction, and pollution, yet such dominance also creates *systemic fragility* by concentrating ecological functions within a narrow set of physiological strategies (Pretzsch et al. 2017; Wells et al. 2017). A more diversified species pool would expand functional redundancy, reducing vulnerability to pests, drought events, or climate-amplified stressors-a principle widely emphasized in tropical urban forestry (Sjöman et al. 2016; Hwang et al. 2025).

Integrating more native, drought-tolerant, and multifunctional taxa into roadside plantings is therefore critical. Species such as *P. indicus*, *F. benjamina*, *Syzygium polyanthum*, and *A. scholaris* exhibit traits that support enhanced ecological interaction networks and increased habitat quality for urban wildlife (Wells et al. 2017; Lourdes et al. 2021). Their inclusion helps counterbalance the functional homogenization generated by long-term reliance on ornamentals. This aligns with growing evidence that native species often sustain richer trophic interactions and provide more stable ecosystem-service flows than their non-native counterparts (Maruthaveeran et al. 2011; Aronson et al. 2017).

The management risks associated with "urban monocultures" are further illustrated by case studies from Singapore and Guangzhou, where pest outbreaks targeting dominant street-tree species triggered rapid canopy decline at the city scale (Roloff et al. 2009; Hwang et al. 2025). To mitigate similar vulnerabilities, Semarang can adopt the widely endorsed 10-20-30 rule, limiting any single species, genus, or family to 10%, 20%, and 30% of total plantings. This approach embeds genetic and functional buffers into urban vegetation planning, lowering the probability of synchronous failure under climate extremes.

Beyond diversification, the study highlights the need to optimize the spatial configuration of ecosystem services. Increasing canopy cover through broad-crowned species such as *Samanea saman* and *P. indicus* would strengthen heat mitigation, especially along densely built corridors where temperature amplification is most severe (Sholihah et al. 2022). Meanwhile, the targeted addition of frugivory-supporting species enhances ecological connectivity by reinforcing food webs that sustain birds, bats, and other urban wildlife. These interventions reflect a shift toward landscape-functional planning, where roadside vegetation is treated not just as ornamental infrastructure but as active ecological corridors linking parks, riparian zones, and residential green spaces.

Improving planting-pit design, increasing soil volumes, and reducing mechanical disturbance (e.g., overly frequent pruning) are also essential for maintaining long-term performance. Evidence from Singapore, Hong Kong, and Kuala Lumpur shows that structural soil systems, heat-exposure mapping, and microhabitat-specific planting guidelines significantly improve survival and functional stability in roadside environments (Luck and Smallbone 2010; Hwang et al. 2025). Semarang can draw from these models to develop corridor-specific strategies that match species traits with microclimatic and spatial constraints.

The findings underscore the need to transition from a visually oriented planting paradigm to an ecologically informed management framework. Strengthening species diversity, enhancing functional redundancy, and spatially tailoring interventions offer a viable pathway toward resilient, multifunctional, and climate-adaptive roadside vegetation capable of supporting environmental quality, biodiversity conservation, and urban livability across Semarang District.

### *Limitations and future research directions*

This study relied on a linear roadside survey, which-while effective for capturing compositional patterns-may underrepresent understory layers and irregular plantings, limiting inferences about vertical structure and fine-scale habitat complexity. The absence of structural metrics (e.g., diameter, canopy geometry, rooting constraints) also restricts interpretation of stability mechanisms, particularly those related to mechanical vulnerability and long-term growth trajectories. The single-season sampling (September 2024) further constrains the ability to assess phenological dynamics, seasonal stress responses, and temporal variability in canopy performance.

Future research should integrate multi-season surveys with detailed structural and physiological measurements to better capture the ecophysiological mechanisms driving community assembly along urban corridors. Microclimate modelling-especially heat exposure, shading simulations, and vapor-pressure deficits-would strengthen the interpretation of functional performance under heterogeneous urban conditions. Soil-root environment assessments and long-term monitoring of survival, pest susceptibility, and growth rates are also essential for refining species-suitability guidelines and informing evidence-based urban greening policies in Semarang District.

In conclusion, this study recorded 2,091 roadside trees comprising 53 species, 47 genera, and 26 families across five 10-km road corridors in Semarang District, Central Java. Community composition differed markedly among corridors, with Bandungan-Kaloran exhibiting the highest species richness and overall ecological stability, while Ungaran-Cangkiran showed the lowest diversity and strongest dominance. Across the district, *S. mahagoni, P. longifolia,* and *M. indica* consistently dominated tree abundance, indicating a strong reliance on a limited number of urban-tolerant species. At the family level, Fabaceae (9 species) was the most represented, followed by Apocynaceae and Sapotaceae (each with 4 species). Biodiversity indices consistently show that peri-urban corridors support the most stable and balanced assemblages, whereas heavily urbanized corridors exhibit lower evenness and higher dominance, indicating reduced ecological stability. These patterns underscore the need to diversify planting compositions, enhance the proportion of native species, and reduce reliance on a small number of dominant taxa to improve functional redundancy and long-term resilience. Integrating these ecological insights into urban tree-management planning-through species diversification, native-species prioritization, and improved planting design-can strengthen the sustainability, ecosystem-service performance, and adaptive capacity of roadside vegetation throughout Semarang District.

## ACKNOWLEDGEMENTS

The authors thank the Semarang District Environmental Agency, Central Java, Indonesia, for field access support and all stakeholders who contributed to data collection and species verification. Appreciation is extended to colleagues who provided insights during manuscript preparation.

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