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ARTICLE

Urban Tree Health Assessment Using Forest Health Monitoring for Eco Forest City Planning in Medan, Indonesia

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ABSTRACT: Urban trees are a critical component of green infrastructure in tropical cities, yet city-scale evidence on tree health in Indonesia remains limited. This study assessed urban tree health in Medan City using the Forest Health Monitoring (FHM) protocol, Tree Level Index (TLI), GIS-based spatial analysis, and Normalized Difference Vegetation Index (NDVI) validation to support Eco Forest City planning. A total of 1184 trees, representing a 30% sample from 3947 inventoried trees across six sub-districts, were evaluated based on damage location, type, and severity. Average Nearest Neighbor (ANN) and Kernel Density Estimation (KDE) were applied to examine spatial clustering of health classes, while Sentinel-2 NDVI values were extracted as an indicator of vegetation greenness. Overall, 65.79% of trees were classified as healthy, 30.66% as lightly damaged, 3.04% as moderately damaged, and 0.51% as severely damaged. Tree health differed significantly among sub-districts (Kruskal-Wallis $\chi^2 = 82.31$, $p < 0.001$), with Medan Tuntungan showing the best condition, whereas Medan Marelan and Medan Amplas showed the poorest profiles. ANN and KDE results indicated that tree health classes were spatially clustered, supporting geographically targeted management. NDVI values differed significantly among health classes (Kruskal-Wallis $H = 49.144$, $p < 0.001$), although the weak Spearman correlation suggests that NDVI is more appropriate as supplementary validation than as a substitute for field assessment. These findings support risk-based tree management through routine FHM monitoring, priority inspection in vulnerable sub-districts, spatially explicit maintenance zoning, and gradual species diversification to strengthen Medan's Eco Forest City planning.

KEYWORDS: Urban tree health; forest health monitoring; tree level index; species vulnerability; risk-based urban tree management; eco forest city planning

1 Introduction

Rapid urban expansion in tropical cities such as Medan intensifies environmental pressures, including heat stress, declining air quality, soil sealing, and the progressive loss of green open space. Urban trees are therefore a critical component of green infrastructure because they regulate the microclimate, intercept pollutants, support hydrological stability, and provide broader ecological and public health benefits [1–3]. However, these benefits depend on the tree's condition. Declining tree health reduces ecological performance, weakens resilience, and may increase public safety risks through structural failure [4–7].

Within the Eco Forest City (EFC) framework, the quality of the urban tree stock is as important as the total extent of green space. In this sense, EFC implementation should not be limited to expanding vegetated area, but should also incorporate evidence-based monitoring of tree condition, structural risk, and species suitability as part of urban green-infrastructure governance [1,8–10]. Forest Health Monitoring (FHM) is relevant to this need because it provides a standardized field-based protocol for recording damage location, damage type, and damage severity in a way that supports repeated assessment and practical management [9,11–16].

Urban tree decline and failure are frequently associated with crown deterioration, stem injury, branch failure, and root-related damage, especially in dense urban environments where trees experience restricted growing space, repeated disturbance, and site-level stress [6,17–19]. Species also differ in their tolerance to urban conditions, making species-level evaluation important for risk-aware planting, maintenance, and replacement decisions [8,20–24].

In Indonesia, previous FHM-based studies have mostly been conducted at park or site scale and have rarely examined spatial variation at the city level [25]. For Medan City, no previous study has yet provided a statistically supported comparison of tree health across contrasting urban typologies, nor has any study clearly linked city-scale tree-health evidence to EFC-oriented management priorities. This gap is important because Medan faces heterogeneous urban pressures across suburban, residential, industrial, and coastal environments, which likely influence tree condition and management needs differently [26,27].

Accordingly, this study aimed to: (1) assess and compare tree health across six sub-districts of Medan City using the Tree Level Index (TLI); (2) describe dominant patterns of tree damage and the relative vulnerability of common species; (3) examine the spatial distribution of tree health classes using geographic information system-based spatial statistics and density mapping; (4) validate field-based tree health patterns using satellite-derived vegetation greenness; and (5) derive practical recommendations for risk-based urban tree management to support Eco Forest City planning in Medan.

2 Materials and Methods

2.1 Study Area

The study was conducted in Medan City, North Sumatra, Indonesia, a major metropolitan center covering 265.10 km^2 with a reported population of 2,498,293 in 2025 [28]. Medan is characterized by strong urbanization pressure, with built-up land covering the largest share of the city area. In contrast, mixed gardens and mangrove areas remain important components of the broader urban landscape. This pattern is relevant to tree-health assessment because growing conditions and disturbance pressures differ substantially across land-use settings. Medan also has a humid tropical climate and includes lowland urban, suburban, and coastal environments, which contribute to contrasting site conditions for urban tree growth and stress exposure.

Six sub-districts were selected to represent contrasting urban typologies and urbanization pressures: Medan Tuntungan and Medan Johor represent greener and more suburban settings; Medan Amplas and Medan Denai represent denser residential environments; and Medan Marelan and Medan Belawan represent industrial, port, and coastal settings [4,27]. Previous work on tree species distribution in Medan Belawan has also supported the relevance of this coastal sub-district for EFC development [29]. This combination allowed comparison of conditions across suburban, urban, and coastal areas within one city and provided a practical basis for examining whether tree health varies spatially under different urban pressures. Fig. 1 presents the spatial distribution of trees in Medan City in 2025.

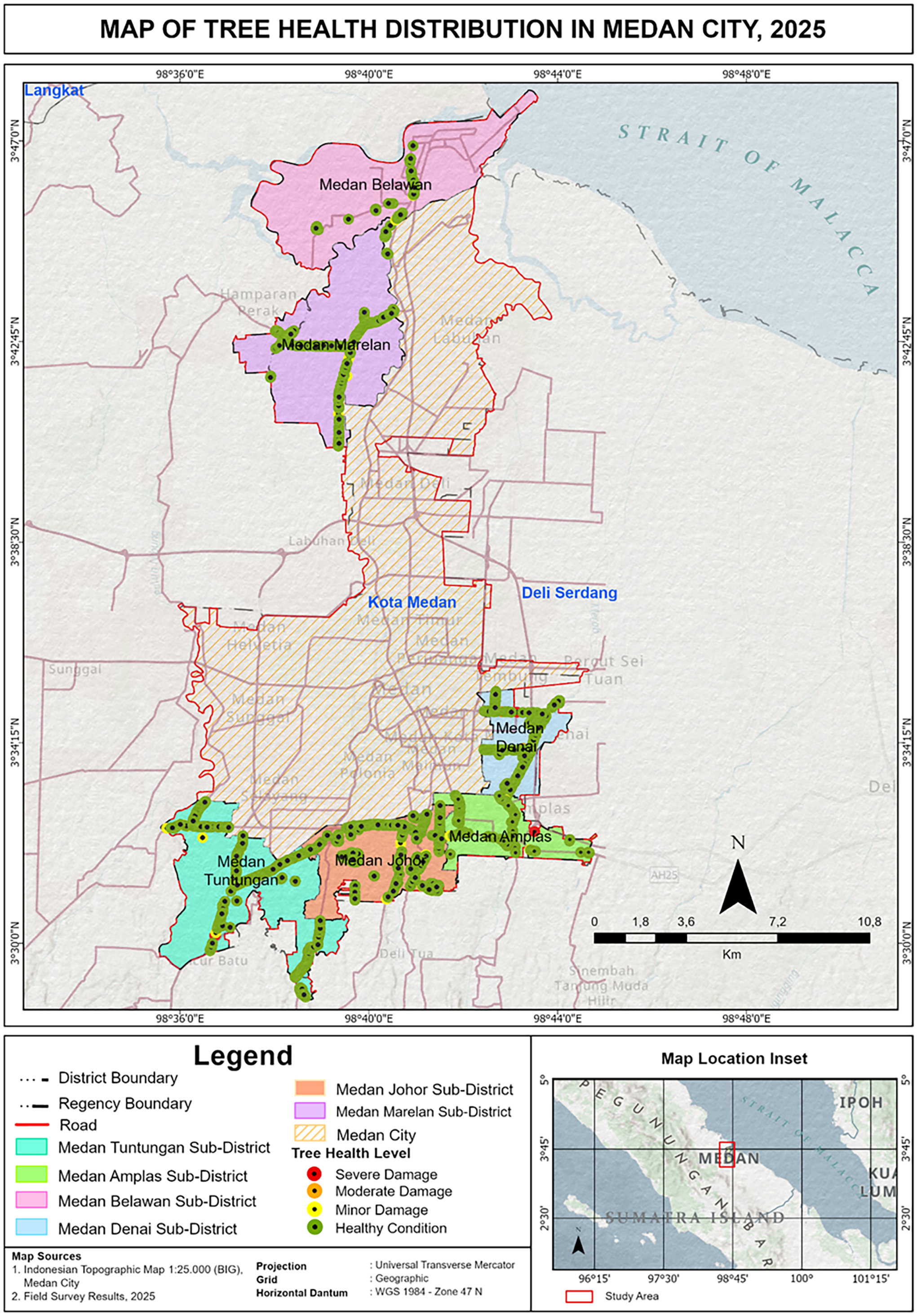


Figure 1: Map of tree distribution in Medan City in 2025.

2.2 Sampling Design and Tree Inventory

Tree inventory and health assessment were conducted in public green open spaces, including roadside green belts, urban parks, public cemeteries, urban forest areas, and other accessible public open spaces. Trees with a diameter at breast height (DBH) ≥ 20 cm were inventoried following the practical threshold commonly used in urban FHM-based assessments [1,12,30,31].

A total of 3947 trees were inventoried across the six sub-districts. From this inventory, 1184 trees were selected as a 30% proportional sample so that each sub-district remained represented in line with its tree population [25,32]. The 30% sampling intensity was adopted to maintain broad spatial representation while keeping field assessment operationally feasible, consistent with previous urban tree-health studies [32,33]. Within each sub-district, a sample was selected using purposive sampling from the inventory list to maintain proportional representation of the local tree population.

Purposive sampling was used because the assessment focused on inventoried trees located in accessible public green open spaces that were directly relevant to urban tree management, while still maintaining proportional representation across sub-districts. This approach allowed operationally feasible field assessment across contrasting urban settings without excluding priority locations such as roadside green belts, parks, public cemeteries, and urban forest areas.

For each sampled tree, species identity, number of individuals, DBH, tree height where feasible, and field coordinates were recorded. DBH was measured at approximately 1.3 m above ground using a DBH measuring tape. Tree height was measured in the field using a clinometer based on trigonometric principles. The measurement involved recording the horizontal distance from the observer to the tree and the angles to the tree's top and base to calculate the total tree height or, where applicable, the clear bole height. Location data were recorded using handheld GPS supported by Avenza Maps and verified during field mapping [8,34]. Field photographs were also taken to document visible damage symptoms and surrounding site conditions. The spatial distribution of assessed urban tree health levels across the selected sub-districts is shown in Fig. 2.

2.3 Forest Health Monitoring (FHM) Evaluation Protocol

Tree health was evaluated using the FHM protocol developed by the USDA Forest Service [9,35]. In this study, the assessment focused on three indicators recorded for each sampled tree: (1) damage location, (2) damage type, and (3) damage severity. For each tree, up to three most significant observed damages were recorded. The damage location codes used in the FHM assessment are presented in Fig. 3.

The corresponding descriptions of damage locations are provided in Table 1.

Damage severity was scored on a 1–9 scale, where higher values indicate greater severity [30,35]. The FHM approach was selected because it enables consistent field recording of visible structural and physiological damage across trees and sites, making it suitable for routine urban tree-risk evaluation and repeated monitoring [9,11–16].

2.4 Tree Health Classification and Index Calculation

Tree health was quantified using the Tree Level Index (TLI), which aggregates the three most important recorded damages for each tree. For each damage record, a damage index value was calculated from the combination of location weight (X), damage-type weight (Y), and severity weight (Z). In the original field worksheet, this damage index value is referred to as NIK.

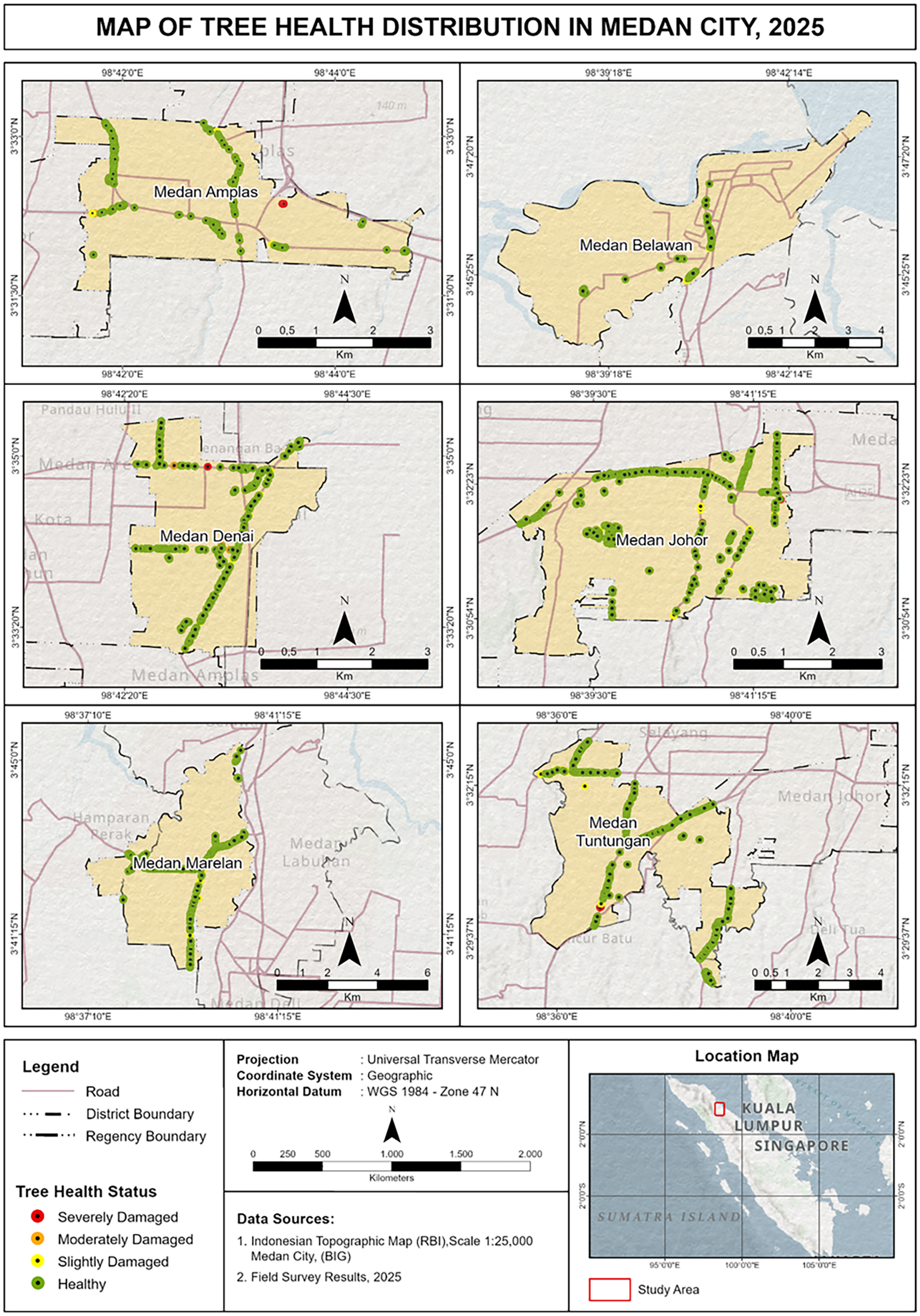


Figure 2: Spatial distribution of urban tree health levels in Medan City by sub-district in 2025.

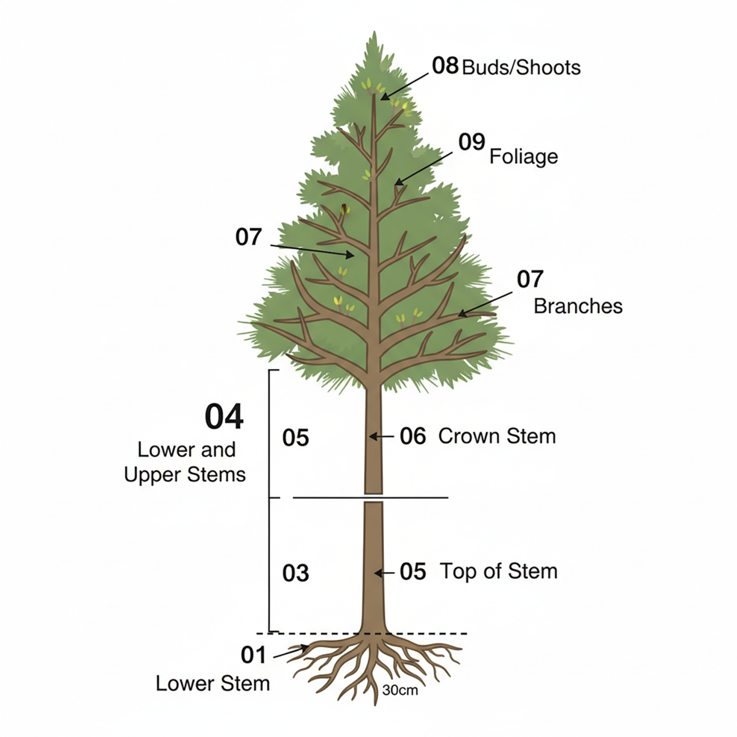


Figure 3: Tree part location code for damage indicators.

Table 1: Codes and descriptions of tree damage locations.

Code	Description
0	Healthy (no damage)
1	Roots (exposed) and stumps (12 inches/30 cm above ground level)
2	Roots and lower Stem
3	Lower Stem (lower half of the Stem between the stump and the base of the living crown)
4	Lower and upper stems
5	Top of Stem (top half of the Stem between stump and base of living crown)
6	Crown stem (main Stem within the living canopy area above the base of the living crown)
7	Branches (greater than 2.54 cm at the branching point relative to the main Stem or crown stem within the living crown area)
8	Buds and shoots (last year's growth)
9	Foliage

The weighting system followed the FHM-based approach used in the dissertation dataset. Location weights ranged from 1.0 to 2.0, with the highest weights assigned to root and lower-stem damage. Damage-type weights ranged from 1.0 to 2.0, and severity weights ranged from 1.1 to 1.9. This weighting structure gives greater influence to damages that are structurally more critical. Fig. 4 summarizes the workflow from field recording to health-class assignment.

The damage index value (NIK) for each recorded damage was calculated as:

$$\text{NIK} = X \times Y \times Z \tag{1}$$

where X is the location weight, Y is the damage-type weight, and Z is the severity weight.

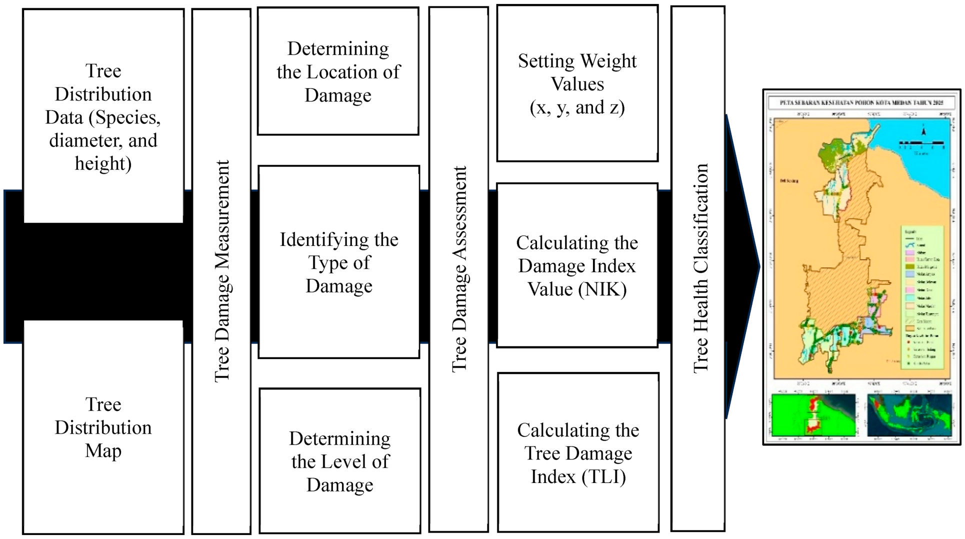


Figure 4: Flowchart of tree health data processing stages.

The Tree Level Index (TLI) for each tree was then calculated by summing the NIK values of the three most significant recorded damages:

$$TLI = NIK1 + NIK2 + NIK3 \quad (2)$$

Following Muslihudin et al. [25], trees were classified into four health classes:

- Healthy: TLI < 5
- Light damage: 5 ≤ TLI < 10
- Moderate damage: 10 ≤ TLI < 15
- Severe damage: TLI ≥ 15

2.5 *Statistical Analyses*

Statistical analysis was used to describe tree health patterns and to test whether health status varied among sub-districts, species, and diameter classes. Analyses were conducted in IBM SPSS Statistics version 31.0 (IBM Corp., Armonk, NY, USA), with a significance threshold of $p < 0.05$.

Descriptive statistics were used to summarize frequencies, percentages, means, and standard deviations of tree health classes across the six sub-districts. Because TLI values were not treated as normally distributed continuous data for all comparisons, non-parametric and categorical tests were used where appropriate.

The Kruskal-Wallis test was used to evaluate whether TLI values differed significantly among sub-districts. Chi-square tests were used to examine the association between TLI health classes and two categorical variables: tree species and DBH class. These analyses were used to identify spatial variation and broad vulnerability patterns within the urban tree population.

2.6 *Spatial Analysis of Tree Health Conditions*

To strengthen the geospatial contribution of the study, spatial analyses were conducted in ArcMap 10.8 (Esri, Redlands, CA, USA) using the mapped tree coordinates and the corresponding FHM-based health classes. The analyses were designed to evaluate whether the spatial distribution of tree health conditions was clustered, random, or dispersed across the six sub-districts of Medan City. All tree points were processed in a projected coordinate system to ensure that distance-based calculations were interpreted in metric units.

Average Nearest Neighbor (ANN) analysis was applied separately to the healthy, light damage, moderate damage, and severe damage categories. The ANN statistic compares the observed mean nearest-neighbor distance with the expected mean distance under complete spatial randomness and produces a Nearest Neighbor Ratio (NNR), z-score, and p-value. An NNR below 1 indicates clustering, an NNR close to 1 indicates a random distribution, and an NNR above 1 indicates dispersion [36,37].

Kernel Density Estimation (KDE) was then used to visualize the spatial intensity of each tree health class. KDE converts point observations into a continuous density surface, allowing areas with high concentrations of healthy or damaged trees to be identified visually and compared across sub-districts [38]. In this study, KDE was used as a descriptive spatial visualization tool to complement ANN statistics and to support management zoning for Eco Forest City planning.

2.7 Vegetation Condition Assessment Using Sentinel-2 NDVI

Satellite-derived vegetation greenness was used as a supplementary validation layer for the field-based tree health assessment. Sentinel-2 MultiSpectral Instrument (MSI) imagery was selected because it provides high-resolution multispectral observations that are widely used for land and vegetation monitoring [39]. Cloud-screened imagery for the 2025 observation period was processed in Google Earth Engine, and the resulting raster was exported as GeoTIFF for point-based extraction [40].

The Normalized Difference Vegetation Index (NDVI) was calculated from the near-infrared and red bands using the standard formula $\text{NDVI} = (\text{NIR} - \text{Red})/(\text{NIR} + \text{Red})$. NDVI is sensitive to canopy greenness and photosynthetically active vegetation, and therefore provides a useful remote-sensing indicator for comparing vegetation condition [41,42]. NDVI values were extracted at mapped tree observation points and linked with the corresponding FHM health classes.

Descriptive statistics were used to summarize NDVI values for each health class, including mean, standard deviation, and range. Because NDVI values were not normally distributed across all categories, the Kruskal-Wallis test was used to test differences among health classes, followed by Dunn's post-hoc test with Bonferroni correction where pairwise comparisons were required [43]. Spearman's rank correlation was also used to examine the monotonic relationship between NDVI values and tree health scores. NDVI was interpreted as supplementary validation because a single Sentinel-2 pixel may contain mixed urban surfaces and may not fully represent individual tree-level structural damage.

3 Results

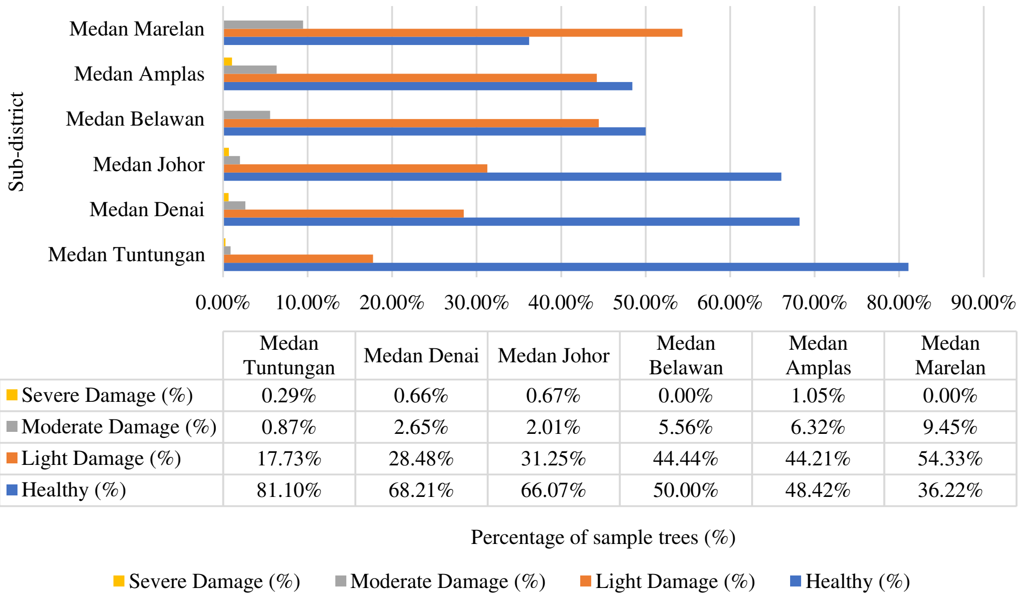
3.1 Distribution of Tree Health Conditions by District

Analysis of 1184 sampled trees showed that Medan City's urban tree stock was generally in good condition, with a mean TLI of 4.21 ± 2.55. At city level, 65.79% of the trees were classified as healthy, 30.66% as lightly damaged, 3.04% as moderately damaged, and 0.51% as severely damaged. These values indicate that most trees were still functionally viable, although a substantial proportion had already entered the early stages of decline.

The Kruskal-Wallis test showed significant differences in TLI values among sub-districts ($\chi^2 = 82.31$; $p < 0.001$), indicating that tree health was unevenly distributed across the city. Medan Tuntungan had the best health profile (mean TLI 3.51 ± 1.88; 81.10% healthy trees), whereas Medan Marelan and Medan Amplas showed the highest TLI values and the least favorable health distributions. Table 2 summarizes tree health by sub-district, and Fig. 5 visualizes the spatial variation in health classes.

Table 2: Tree health status by sub-district based on TLI (N = 1184).

Sub-District	Total Trees (N)	Healthy (%)	Light Damage (%)	Moderate Damage (%)	Severe Damage (%)	TLI Mean ± SD	Relative Health Status
Medan Tuntungan	344	81.10%	17.73%	0.87%	0.29%	3.51 ± 1.88	Highest health status
Medan Denai	152	68.21%	28.48%	2.65%	0.66%	4.12 ± 2.40	Generally healthy
Medan Johor	448	66.07%	31.25%	2.01%	0.67%	4.38 ± 2.65	Generally healthy
Medan Belawan	18	50.00%	44.44%	5.56%	0.00%	4.91 ± 2.80	Intermediate
Medan Amplas	95	48.42%	44.21%	6.32%	1.05%	5.03 ± 3.10	Vulnerable
Medan Marelan	127	36.22%	54.33%	9.45%	0.00%	5.78 ± 4.51	Most vulnerable
Total	1184	65.79%	30.66%	3.04%	0.51%	4.21 ± 2.55	



	Medan Tuntungan	Medan Denai	Medan Johor	Medan Belawan	Medan Amplas	Medan Marelan
■ Severe Damage (%)	0.29%	0.66%	0.67%	0.00%	1.05%	0.00%
■ Moderate Damage (%)	0.87%	2.65%	2.01%	5.56%	6.32%	9.45%
■ Light Damage (%)	17.73%	28.48%	31.25%	44.44%	44.21%	54.33%
■ Healthy (%)	81.10%	68.21%	66.07%	50.00%	48.42%	36.22%

Figure 5: Tree health distribution by sub-district.

Fig. 5 confirms that healthy trees were concentrated in Medan Tuntungan, whereas the distribution in Medan Marelan and Medan Amplas contained a larger share of lightly and moderately damaged trees. This spatial contrast supports the use of sub-district level prioritization in urban tree management.

3.2 *Susceptibility of Predominant Species*

Species composition analysis showed that *Pterocarpus indicus* was the most common species in the sampled dataset (330 individuals; 27.9%). The chi-square test indicated a significant association between species and tree health class ($p < 0.05$), suggesting that damage distribution differed among species.

Among the two focal species presented in Table 3, *Pterocarpus indicus* had the larger damaged proportion (47.27%), whereas *Swietenia mahagoni* showed a lower damaged proportion (24.46%). The broader dataset also included other common species, such as *Samanea saman*, but the clearest contrast in health distribution was observed between the two species highlighted here.

Table 3: Health distribution of two dominant urban tree species (N = 1184).

Species	Total Individuals (N)	Healthy (%)	Light Damage (%)	Moderate Damage (%)	Severe Damage (%)	Damaged (%)
Pterocarpus indicus (Angsana)	330	52.73%	41.82%	5.45%	0.00%	47.27%
Swietenia mahagoni (Small-leaf mahogany)	139	75.54%	22.30%	1.44%	0.72%	24.46%

The species pattern suggests that reliance on a single dominant and relatively vulnerable species may reduce the resilience of Medan's urban tree population.

3.3 Patterns of Damage Location and Type

A total of 2218 damage records were documented in the 2025 field assessment. Most damage locations were recorded in buds and shoots (628 cases), branches (416 cases), and the lower stem (338 cases), indicating that crown components and lower-stem structures were the most frequently affected parts of the urban tree stock.

The most frequently recorded damage type was dieback or loss of the dominant leader (623 cases; 28.09%), followed by open wounds (537 cases; 24.21%) and broken or dead branches (284 cases; 12.80%).

Less frequent but still recurrent damage expressions included epicormic shoots, cankers, foliage injury, and leaf discoloration.

Table 4 summarizes the distribution of recorded damage types across the sampled trees.

Table 4: Distribution of recorded tree damage types of six sub-districts of Medan City, 2025.

No	Code	Description	Total Cases	Percentage
1	1	Canker	150	6.76%
2	2	Conks, fruiting bodies, and others	16	0.72%
3	3	Open wounds	537	24.21%
4	4	Resinosis/Gummosis	12	0.54%
5	12	Epicormic Shoots (Brum)	175	7.90%
6	20	Liana	16	0.72%
7	21	Dieback, loss of the dominant leader	623	28.09%
8	22	Broken/Dead branches	284	12.80%
9	23	Excessive Sprouting/Brum	144	6.47%
10	24	Damaged leaves, buds/shoots	102	4.59%
11	25	Discolored leaves	72	3.25%
12	31	Miscellaneous	55	2.48%
–	–	Felled	5	0.23%
Total			2218	100%

Overall, the FHM record indicates that crown-related symptoms and lower-stem injuries were the dominant observed damage expressions in the Medan dataset.

Fig. 6 summarizes the dominant combinations of damage location and damage type recorded during the field assessment.

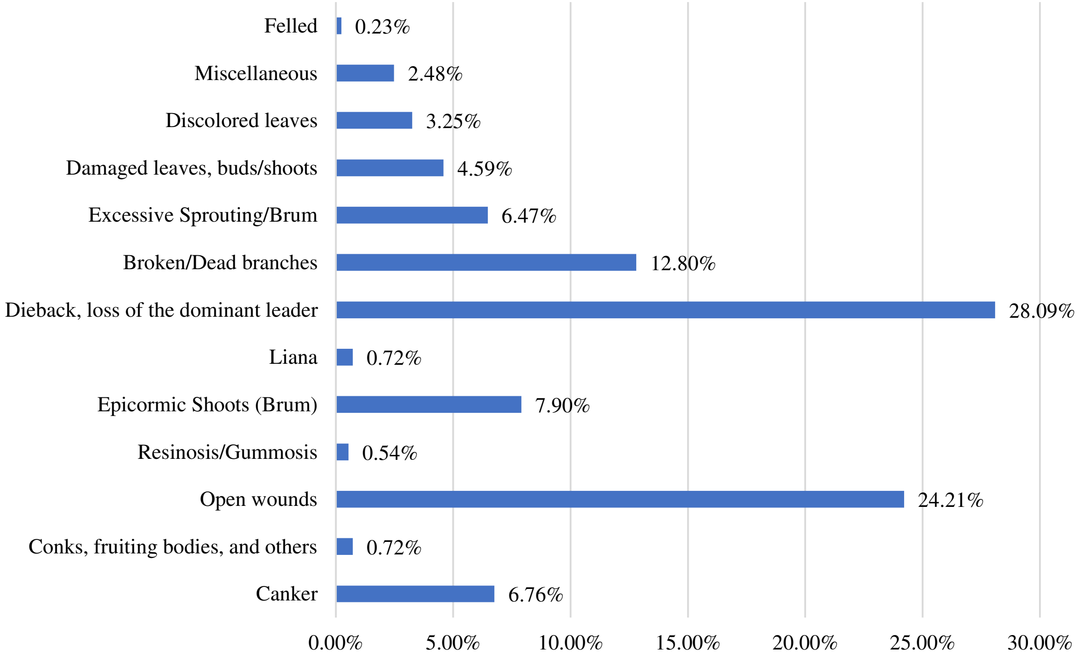


Figure 6: Distribution of the highest damage frequency based on location and type.

3.4 *Vulnerability Based on Diameter Class (DBH)*

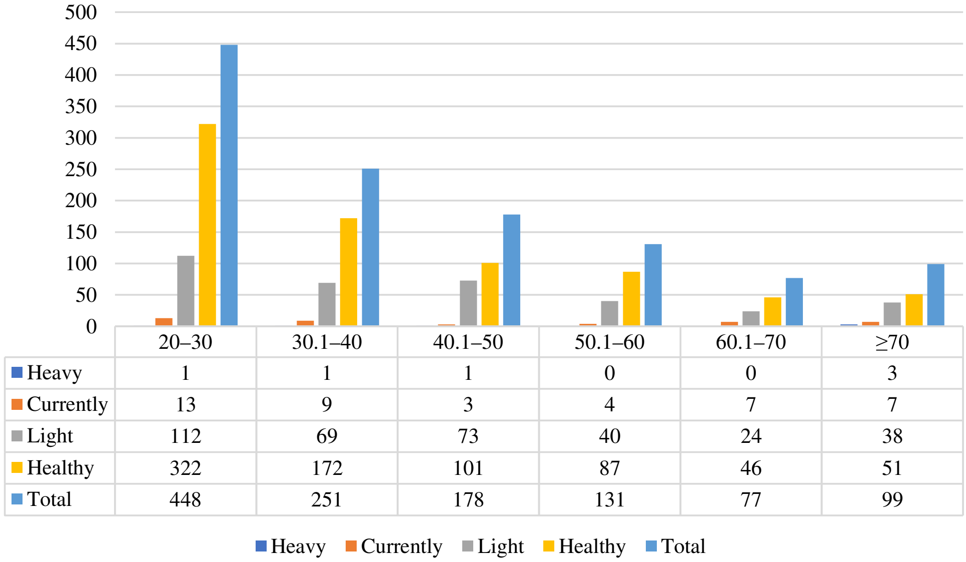
The distribution by diameter class showed that severe damage was uncommon overall (n = 6), but large trees still warranted attention. Three of the six severe cases occurred in the DBH ≥ 70 cm class, and moderate damage was also present in the 60.1–70 cm and ≥70 cm classes.

Because the number of trees differed across DBH classes, this pattern should be interpreted as an indicator of inspection priority rather than as direct evidence that all larger trees were less healthy than smaller trees. Table 5 presents the distribution of tree health conditions across DBH classes.

Table 5: Tree health distribution by diameter class.

DBH Class (cm)	Severe	Moderate	Light	Healthy	Total
20–30	1	13	112	322	448
30.1–40	1	9	69	172	251
40.1–50	1	3	73	101	178
50.1–60	0	4	40	87	131
60.1–70	0	7	24	46	77
≥70	3	7	38	51	99

Fig. 7 illustrates that the 20–30 cm class was dominated by healthy trees, whereas larger diameter classes contained a greater relative share of moderate and severe cases.



	20–30	30.1–40	40.1–50	50.1–60	60.1–70	≥70
■ Heavy	1	1	1	0	0	3
■ Currently	13	9	3	4	7	7
■ Light	112	69	73	40	24	38
■ Healthy	322	172	101	87	46	51
■ Total	448	251	178	131	77	99

Figure 7: Distribution of tree health based on diameter class (DBH).

3.5 Tree Damage by Type and Location (Visual FHM)

Figs. 8 and 9 present representative field photographs of the main damage symptoms recorded during the survey, including cankers, conks, open wounds, gummosis, stem fractures, root damage, dead branches, liana infestation, and foliage discoloration. These figures are provided as visual references to support consistent interpretation of FHM observations in future monitoring.

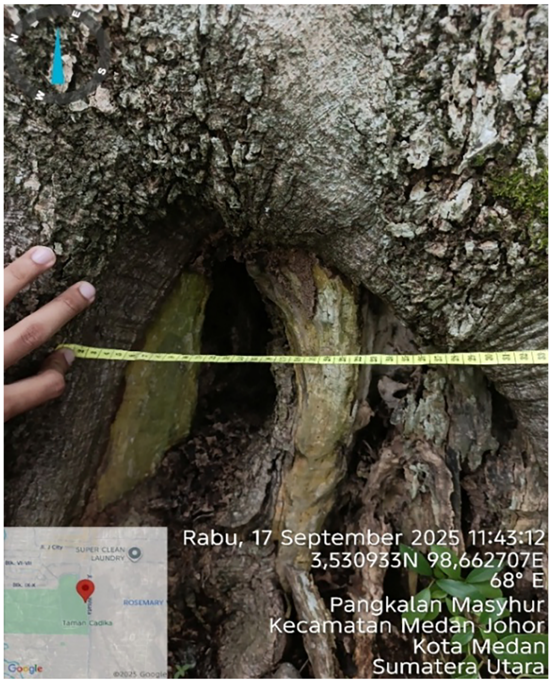


Figure 8: Structural damage to large diameter trees (DBH ≥ 70 cm) in Medan Johor District.

Canker Conks Open Wound on Root Open Wound on the Trunk

Open Wound on the Trunk Open Wound on the Trunk Resinosis/Gummosis Broken Stem

Broken Roots < 3 Feet from the Stem Brum on the Roots Brum on the Stem Broken Stems/Roots > 3 Feet from the Stem

Liana Dead Top Broken/Dead Branch Brum/Excessive Branching

Damaged Leaves, Shoots/Buds Leaf discoloration Tunnel Mold

Figure 9: Tree damage and health condition.

Together, these visual examples illustrate the range of structural and physiological symptoms encountered during the assessment.

The field photographs also confirm that many of the observed symptoms were externally visible and therefore suitable for routine visual screening under the FHM protocol.

3.6 Spatial Distribution Patterns of Tree Health Conditions

The Average Nearest Neighbor (ANN) analysis was conducted to evaluate whether the spatial distribution of tree health classes was clustered, random, or dispersed. The results are expressed through the Nearest

Neighbor Ratio (NNR), z-score, and p-value, which indicate both the direction and statistical significance of the observed spatial pattern. The ANN outputs for each tree health class are presented in Fig. 10.

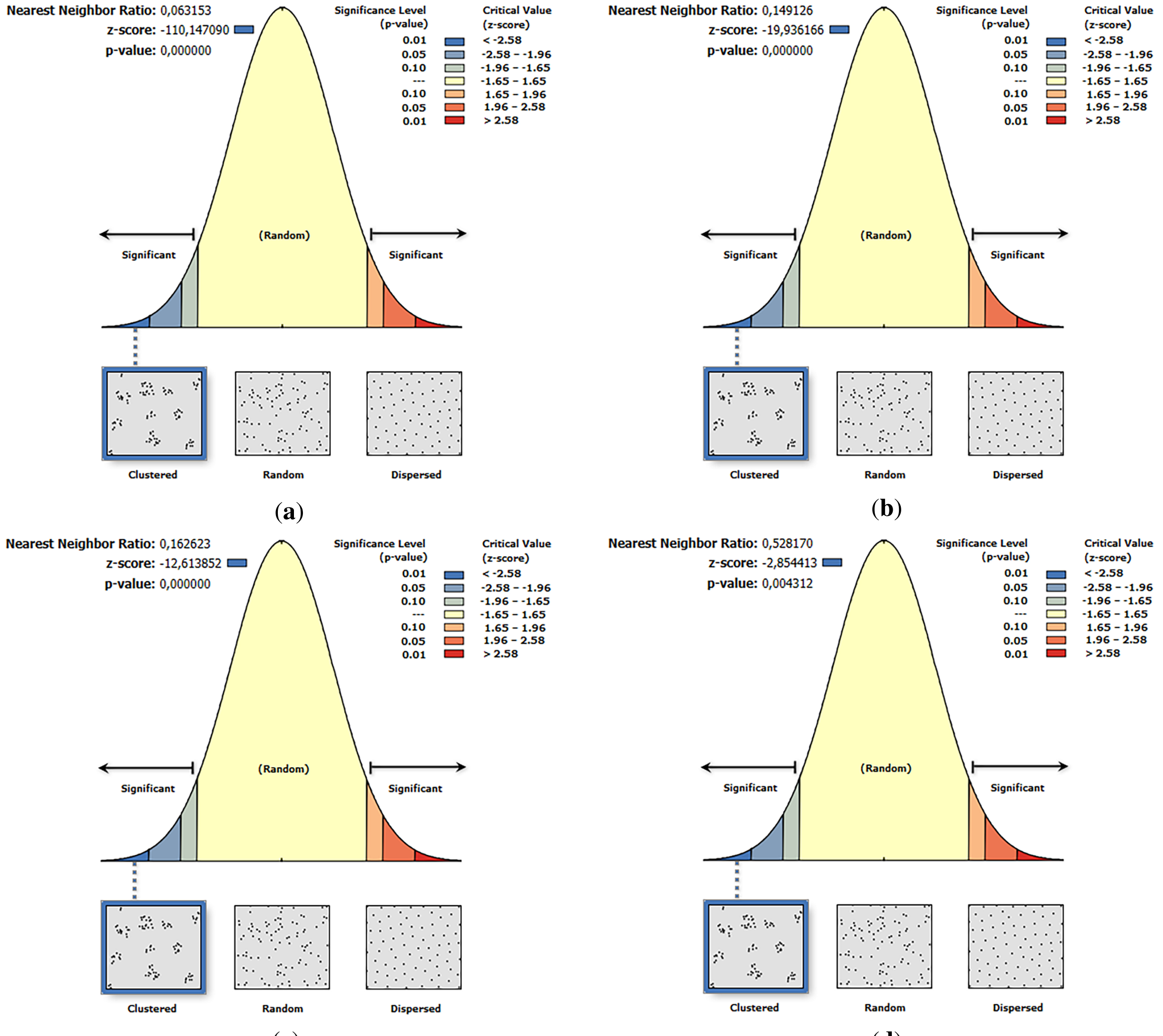
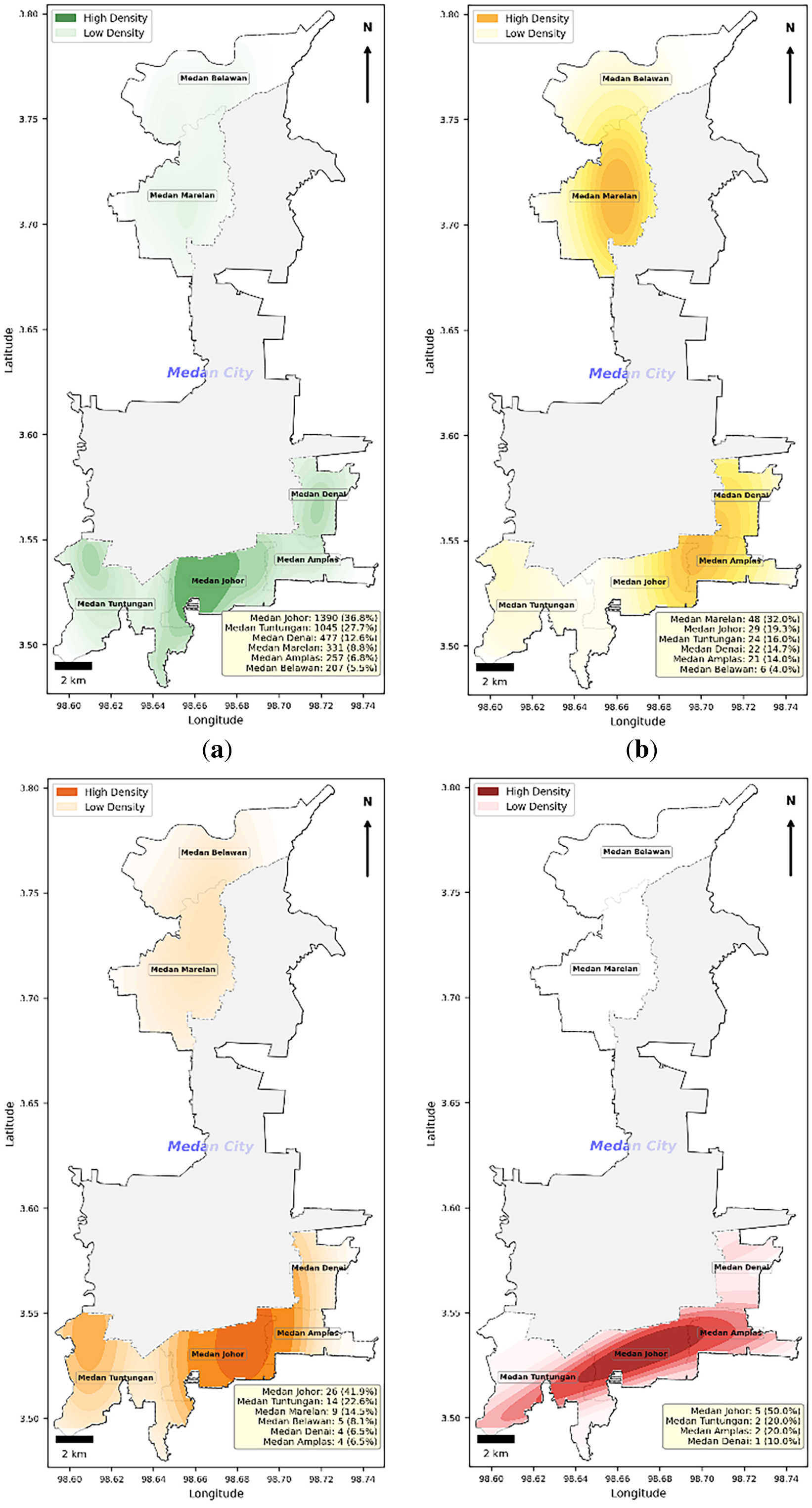


Figure 10: ANN results and z-score distribution of tree conditions in Medan City: (**a**) healthy condition; (**b**) light damage; (**c**) moderate damage; and (**d**) severe damage.

The ANN results indicate that all tree health categories exhibited statistically significant clustered spatial patterns. Healthy trees showed the strongest clustering tendency, with an NNR of 0.063, z = −110.147, and $p < 0.001$. Trees with light damage (NNR = 0.149, z = −19.936, $p < 0.001$) and moderate damage (NNR = 0.163, z = −12.614, $p < 0.001$) also showed clustered distributions. Severely damaged trees had a weaker but still significant clustered pattern (NNR = 0.528, z = −2.854, $p = 0.004$). These results indicate that both healthy and damaged trees were not randomly distributed across Medan, but were spatially concentrated in particular areas (Fig. 11).



(**a**) (**b**)

(**c**) (**d**)

Figure 11: Kernel density estimation of tree distribution based on health condition in Medan City (**a**) healthy condition; (**b**) minor damage; (**c**) moderate damage (**d**) severe damage.

The Kernel Density Estimation (KDE) maps further confirmed spatial variation in tree health conditions across the six sub-districts. Healthy trees were concentrated mainly in Medan Johor and Medan Tuntungan, which is consistent with the high number and proportion of healthy trees recorded in these areas. In contrast, damaged trees formed more localized clusters. Medan Marelan had the highest within-sub-district proportion of light and moderate damage, whereas the small number of severe cases was concentrated mainly in Medan Johor, followed by isolated cases in Medan Tuntungan, Medan Amplas, and Medan Denai. This distinction between absolute concentration and within-sub-district proportion is important because sub-districts with larger tree populations may show higher absolute counts even when their relative health status remains generally favorable.

3.7 NDVI-Based Validation of Tree Health Conditions

To validate the field-based tree health assessment using remote-sensing data, Normalized Difference Vegetation Index (NDVI) values were extracted from Sentinel-2 imagery at mapped tree locations. The NDVI raster was processed in Google Earth Engine and exported as a GeoTIFF, allowing vegetation greenness values to be linked with field-based health classes.

The Kruskal-Wallis test showed significant differences in NDVI values among the four health classes (H = 49.144, $p < 0.001$), indicating that satellite-derived greenness varied with field-based tree condition. Healthy trees had the highest mean NDVI (0.534 ± 0.211), followed by moderate damage (0.516 ± 0.203), severe damage (0.450 ± 0.187), and light damage (0.410 ± 0.205). Although healthy trees generally exhibited higher NDVI values than damaged trees, the class means were not strictly monotonic, indicating overlap among health categories and the influence of mixed urban pixels, surrounding vegetation, and canopy background effects.

Spearman's rank correlation showed a statistically significant but weak negative relationship between NDVI and health score ($\rho = -0.098$, $p < 0.001$), as shown in Fig. 12. This result suggests that NDVI can support the interpretation of field-based tree health patterns at the spatial scale, but it should not be interpreted as a stand-alone diagnostic measure for individual tree damage. Overall, the NDVI analysis strengthens the geospatial component of the study by providing an independent vegetation-greenness layer that complements the FHM field assessment. The spatial distribution of urban tree health levels based on NDVI is shown in Fig. 13.

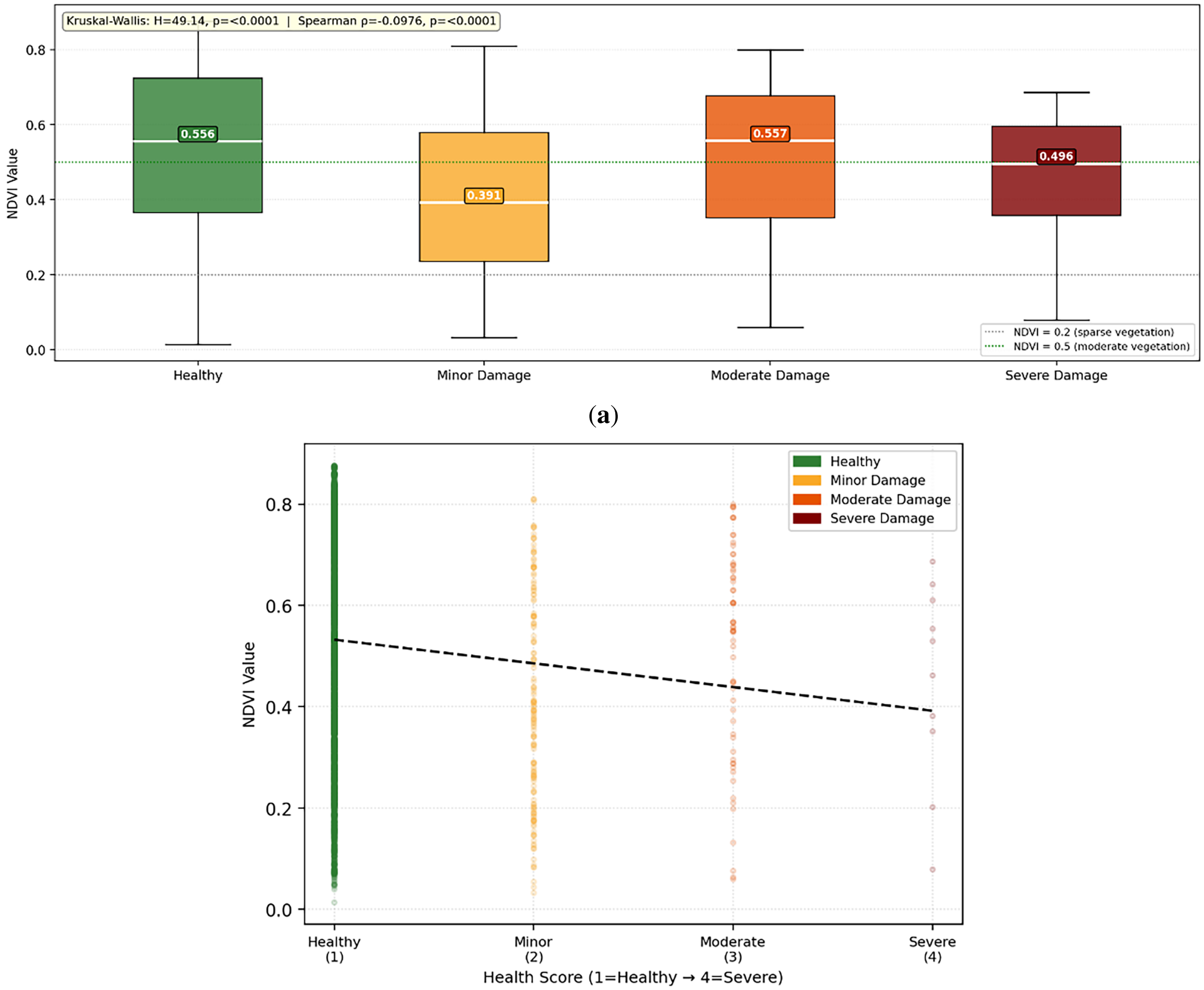
4 Discussion

4.1 Spatial Inequities and the Need for Management Zoning

The significant differences in TLI among sub-districts, together with the ANN and KDE results, indicate that urban tree health in Medan is spatially uneven rather than city-wide uniform. Medan Tuntungan consistently showed the healthiest profile, whereas Medan Marelan and Medan Amplas showed poorer health distributions and therefore higher management urgency. This finding is important because it suggests that urban tree management in Medan should be prioritized geographically rather than applied uniformly across the city.

The spatial pattern is also consistent with the broader dissertation framework, which identified non-homogeneous management needs across the six sub-districts and highlighted Medan Marelan as a higher-priority intervention area, while lower-priority maintenance zones dominated Medan Tuntungan. Taken together, the FHM results and the broader spatial planning perspective support a tiered management approach in which vulnerable sub-districts receive earlier inspection, site improvement, and maintenance intervention, while healthier areas focus on preventive maintenance and protection of existing ecological functions.

This spatially uneven pattern is also consistent with broader urban forestry literature showing that tree condition and management needs vary across urban typologies, land-use intensity, and site constraints rather than being evenly distributed across entire cities [4,8,27,44]. In this sense, the Medan results reinforce the importance of sub-district-based prioritization in tropical urban tree management, where coastal, residential, and suburban settings may expose trees to different levels of mechanical disturbance, growing-space limitation, and maintenance pressure.



(**a**)

(**b**)

Figure 12: NDVI distribution and correlation with tree health classification in Medan City: (**a**) boxplot of NDVI by health class; and (**b**) scatter plot of NDVI against health score using Spearman correlation.

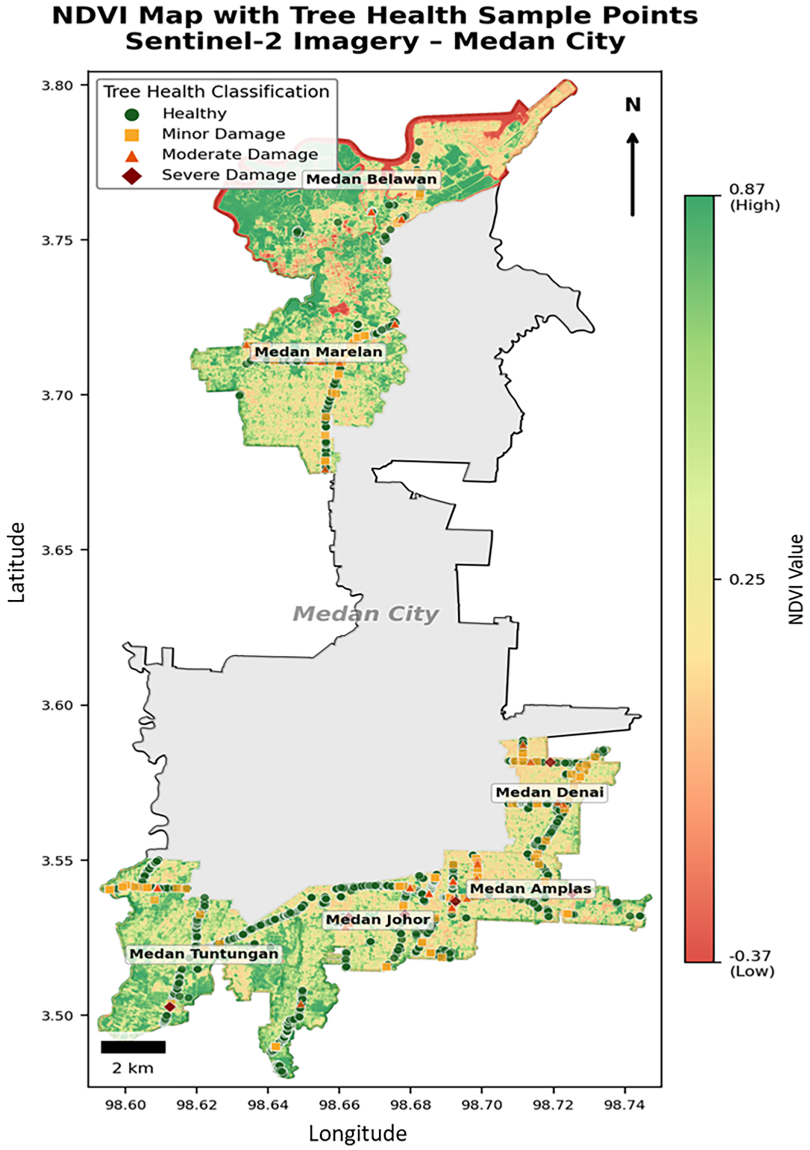


Figure 13: Spatial distribution of urban tree health levels based on NDVI in Medan City.

4.2 Duality of Threat: Physiological Versus Mechanical Damage

The damage profile suggests two broad management concerns: crown-related decline and lower-stem mechanical injury. Dieback and loss of the dominant leader were the most frequent recorded damage expressions, while open wounds and broken branches represented the most prominent structural injuries. Because this study used a visual FHM protocol, these patterns should be interpreted as observed damage expressions rather than direct causal diagnoses.

This pattern is broadly consistent with previous urban forestry studies showing that crown deterioration, stem injury, and branch failure are common symptoms in trees exposed to repeated urban disturbance, restricted growing space, and site-level stress [4,6,23]. In the present study, factors such as pruning practices, mechanical disturbance, and traffic exposure were not directly measured as explanatory variables; therefore, such factors should be interpreted as plausible contextual explanations supported by the literature rather than as direct causal findings from this dataset.

For management purposes, these results indicate that Medan requires both preventive maintenance to reduce recurrent crown damage and protective measures to reduce avoidable stem and root injury in high-traffic public spaces.

4.3 Susceptibility of Predominant Species and the Need for Diversification

Species composition is another important management issue. *Pterocarpus indicus* was both the most common species in the sampled dataset and the more damaged of the two focal species compared in detail, whereas *Swietenia mahagoni* showed a more favorable health distribution. This does not mean that *Pterocarpus indicus* should be excluded from future planting, but it does suggest that dependence on a narrow species base may amplify future vulnerability if dominant species are repeatedly exposed to similar urban stress conditions.

This interpretation is consistent with urban forestry studies emphasizing that species diversification improves resilience by distributing ecological and structural risk across a wider range of species, growth forms, and tolerance traits [8,20–23,45,46]. In practical terms, diversification should be treated as a long-term risk-reduction strategy rather than as a simple replacement measure, especially in cities where a small number of dominant species account for a large share of the urban tree population.

4.4 Structural Vulnerability of Large-Diameter Trees

Large-diameter trees deserve particular attention because they combine high ecological value with greater management consequences when they fail. In this study, severe damage was uncommon overall, but three of the six severe cases occurred in the DBH ≥ 70 cm class. This pattern does not by itself prove that all large trees are less healthy, but it does indicate that large trees should receive closer structural inspection, particularly when crown decline, lower-stem injury, or suspected internal decay is observed.

This interpretation is in line with previous urban tree-risk studies showing that mature trees often require more careful structural assessment because the ecological benefits of large trees are high, while the consequences of failure in public urban space are also greater [4,21,23]. In practice, this means that large trees in vulnerable sub-districts should be included in a routine audit program supported by follow-up inspection where necessary.

4.5 Evidence-Based EFC Management Recommendations

Based on the present findings, four practical directions emerge for EFC planning in Medan. First, routine FHM-based monitoring should be institutionalized so that tree condition is evaluated using the same protocol across sub-districts and over time. Second, management resources should be prioritized spatially, with earlier intervention in Medan Marelan and Medan Amplas and maintenance-oriented programs in healthier areas such as Medan Tuntungan. Third, preventive pruning standards, trunk and root protection in public spaces, and gradual species diversification should be integrated into routine urban forestry practice [8,20,23]. Fourth, GIS-based clustering maps and NDVI layers should be used as decision-support tools to identify inspection zones, prioritize maintenance, and communicate urban tree-risk patterns to city planners.

Together, these measures link field-based tree health evidence to a more operational EFC agenda by improving ecological resilience, reducing avoidable tree-failure risk, and supporting better long-term planning of urban green infrastructure.

4.6 Contribution of GIS and NDVI Integration to EFC planning

The integration of GIS-based spatial statistics and Sentinel-2 NDVI strengthens the contribution of this study to the geomatics domain and aligns with recent advances in urban forest assessment using remote sensing and field-based monitoring integration [47,48]. ANN analysis provides statistical evidence that tree health classes are spatially clustered, while KDE maps translate these patterns into practical management surfaces that can be used for inspection zoning. This is directly relevant to Eco Forest City planning because tree maintenance can be targeted toward areas where damage clusters are most evident rather than being distributed uniformly across administrative units.

The NDVI results further support the field assessment by showing that vegetation greenness differs significantly among health categories. However, the weak correlation between NDVI and health score also shows that satellite-derived greenness cannot replace field-based FHM observations. In heterogeneous urban settings, a Sentinel-2 pixel may include tree canopy, grass, bare soil, pavement, roof surfaces, and shadows, which can weaken the relationship between NDVI and individual tree damage. Therefore, the most appropriate use of NDVI in this study is as a supplementary spatial validation layer and a screening tool for broader vegetation-condition patterns.

Together, the FHM, ANN, KDE, and NDVI results provide a multi-source evidence base for urban tree management in Medan. This combined approach supports a more spatially explicit Eco Forest City strategy by linking field diagnosis, spatial clustering, remote-sensing validation, and management prioritization in one analytical framework.

4.7 Study Limitations

A key limitation of the present study is that some sub-district sample sizes were highly uneven, especially between Belawan and Johor. The study also relied primarily on visual FHM indicators and did not include more comprehensive explanatory variables, such as detailed site conditions, soil properties, pruning history, or repeated temporal measurements. Although Sentinel-2 NDVI provided useful supplementary validation, its spatial resolution can be affected by mixed urban pixels and may not fully capture individual tree-level structural damage. Future work should therefore combine repeated FHM monitoring, higher-resolution imagery or UAV data, fuller site-condition variables, and finer-scale spatial analysis to strengthen causal interpretation and management targeting.

5 Conclusion

This study shows that most sampled urban trees in Medan remained in healthy condition, but their health status varied markedly across sub-districts. Medan Tuntungan showed the best overall condition, whereas Medan Marelan and Medan Amplas emerged as the most vulnerable areas.

The most frequently recorded damage expressions were dieback, open wounds, and branch damage, while the focal species comparison showed greater damage in *Pterocarpus indicus* than in *Swietenia mahagoni*. Large-diameter trees also require closer inspection because severe cases were concentrated in the upper diameter classes.

The added geospatial and remote-sensing analyses strengthen the relevance of the study to geomatics. ANN and KDE results demonstrated that tree health classes were spatially clustered, while NDVI analysis provided supplementary validation that vegetation greenness differed significantly among field-based health categories. However, the weak NDVI-health correlation confirms that remote sensing should complement, rather than replace, field-based FHM assessment.

For Medan City, these findings support a risk-based urban tree management strategy that combines routine FHM monitoring, GIS-based priority zoning, NDVI-assisted vegetation-condition screening, priority inspection in vulnerable sub-districts, improved maintenance standards, and gradual diversification of planting composition. Future research should integrate repeated monitoring, higher-resolution spatial data, and site-condition indicators to link urban tree health more directly to management decisions within the Eco Forest City framework.

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