Industrial and Domestic
Waste Management

Research Article
Volume 6(1), 2026, 167–180
https://doi.org/10.53623/idwm.v6i1.1076

Management of Urban Air Quality: Evaluating the Sequestration Potential of Green Infrastructure Against Domestic Transportation Emissions

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SUBMITTED: 25 February 2026; REVISED: 20 April 2026; ACCEPTED: 23 April 2026

ABSTRACT: Rapid urbanization escalated domestic vehicular CO_2 emissions, necessitating the optimization of urban green open spaces (GOS) as engineered biological sinks. However, urban planning practices frequently prioritized spatial area over species-specific sequestration capacity, leading to potential spatial inefficiencies. This study evaluated the efficacy of four GOS in Tanjung Redeb, Indonesia, by overlaying localized vehicular emission loads—calculated using the Vehicle Kilometer Traveled (VKT) model—with the biological sequestration capacities of the parks, quantified through species-specific allometric equations. The results indicated that all evaluated parks operated at a net positive carbon surplus, with absorption ratios ranging from 1,474.8% to 117,668.6%. Crucially, the empirical data exposed a severe source–sink decoupling. The primary emission hotspot, Taman Bukit Maritam (1,032.33 kg CO_2/year), relied on moderately performing vegetation, yielding the lowest relative surplus. Conversely, the highest sequestration capacity (37,010.96 kg CO_2/year) was located in Taman Sanggam, a low-stress corridor (92.33 kg CO_2/year), driven by the aggressive structural biomass of the hyper-accumulator *Samanea saman*. The analysis demonstrated that biological filtration performance was strictly dictated by species taxonomy and allometric structure, rather than stand age or total park area. The study concluded that mitigating urban vehicular emissions required a paradigm shift from passive aesthetic landscaping to active, data-driven biological engineering, deploying high-capacity hyper-accumulators strategically along high-emission transportation corridors.

KEYWORDS: Carbon sequestration; urban air quality; vehicular emissions; green open space; green infrastructure management

1. Introduction

Globally and nationally, rapid urbanization precipitated a significant environmental management challenge: the exponential increase in domestic vehicular emissions. In Indonesia, the transportation sector was a major contributor to urban pollution, accounting for over 23% of the nation's total CO_2 emissions [1]. This phenomenon was no longer confined to metropolitan hubs but rapidly expanded to regional growth centers. A prime example was Tanjung Redeb, Berau Regency, which experienced accelerated economic growth and rapid urbanization. This urban expansion led to a proportional surge in the volume of localized motorized traffic, consequently elevating the concentration of exhaust gas emissions in the ambient air [2, 3].

Within the framework of environmental engineering and sustainability, these vehicular CO_2 emissions were classified as a critical form of domestic gaseous waste. Unlike solid domestic waste, which could be collected and transported to specific treatment facilities, gaseous waste accumulated directly in the urban atmosphere. Furthermore, it frequently associated with other particulate pollutants such as PM2.5, acting as a medium that carried CO_2 and other pollutants directly into residential environments [4–6]. Therefore, managing this continuous influx of transportation emissions was fundamentally an urban waste management and public health challenge, requiring targeted and continuous remediation strategies to stabilize localized air quality and prevent long-term environmental deterioration.

To combat the continuous generation of vehicular gaseous waste, urban environmental management moved beyond conventional mechanical filtration and embraced localized biological remediation. Historically, urban green open spaces (GOS) were designed primarily for aesthetic enhancement, community recreation, and superficial microclimate regulation [7]. However, in the context of escalating transportation emissions, these spaces were critically reconceptualized as engineered biological sinks.

The core mechanism of this remediation relied on the photosynthetic capacity of urban vegetation, which actively absorbed atmospheric CO_2, the primary constituent of domestic vehicular exhaust, and permanently sequestered it as woody biomass [6]. In this framework, an urban park operated as a scalable biofiltration facility. However, the efficacy of this biological treatment system was not uniform. A park's sequestration capacity was heavily dictated by the specific morphological and physiological traits of its constituent vegetation. Variables such as total leaf surface area, canopy density, and species-specific allometric growth rates determined the volume of gaseous waste a given area could process [8]. Therefore, evaluating green infrastructure through the lens of carbon sequestration metrics allowed city planners to quantify the exact mitigation value of these spaces, transitioning urban forestry from a purely ecological discipline into a vital component of the urban waste management continuum.

Extensive literature documented the carbon sequestration capabilities of various urban tree species and successfully established robust allometric models to quantify biomass and carbon storage [9]. However, a critical gap remained in the operationalization of these biological metrics for active urban air quality management. Urban planning frameworks frequently treated green infrastructure as a generalized, homogeneous environmental benefit and rarely correlated the highly variable, species-specific biological capacity of vegetation with localized and fluctuating loads of domestic vehicular emissions.

Global urban ecology literature suggested that this disconnect created a severe risk of "spatial mismatch" [3, 10], where high-emission traffic corridors relied on inadequate, low-capacity vegetation, while highly efficient biofiltration species were inadvertently relegated to low-emission zones. To effectively manage air quality, research moved beyond simple carbon inventorying and overlaid localized emission tracking with species-specific sequestration data to evaluate biological treatment systems precisely where the waste was produced.

To test the presence of this spatial mismatch locally, this study evaluated the functional efficiency of green infrastructure in the rapidly urbanizing municipality of Tanjung Redeb, Berau Regency. By integrating vehicular emission tracking with species-specific allometric carbon modeling across four prominent parks (Taman Cendana, Taman Sanggam, Taman Bukit Maritam, and Taman Singkuang), this research overlaid empirical pollution loads with biological sink capacities. Ultimately, this evaluation provided actionable data to guide future urban forestry policies, ensuring that subsequent green infrastructure was strategically deployed as an active biological treatment node to optimize urban air quality.

2. Materials and Methods

2.1. Study area and site characteristics.

The research was conducted in Tanjung Redeb, the administrative capital and commercial center of Berau Regency, East Kalimantan, Indonesia. As an emerging regional economic hub experiencing accelerated infrastructural development, Tanjung Redeb faced a proportional increase in motorized traffic volumes along its primary corridors. This made the municipality a highly representative model for assessing the accumulation and management of domestic vehicular gaseous waste. To evaluate the efficacy of localized biological remediation, four prominent green infrastructure sites were purposively selected: Taman Cendana, Taman Sanggam, Taman Bukit Maritam, and Taman Singkuang.

2.2. Quantification of domestic vehicular emissions.

The localized CO_2 emission loads surrounding the green infrastructure were quantified using a methodological framework that integrated empirical traffic volume data with the Vehicle Kilometer Traveled (VKT) mathematical model. Primary traffic volume data was acquired through direct field observation via manual counting conducted during peak mobility hours (06:30–08:00, 12:00–13:00, and 16:30–18:00). Observations were conducted on both weekdays and weekends to comprehensively capture urban traffic dynamics. Passing vehicles were classified into motorcycles, light vehicles (passenger cars), and heavy vehicles (buses and trucks). To standardize spatial and operational capacities, raw counts were converted into Passenger Car Equivalents (PCE) using national conversion factors of 0.2, 1.0, and 1.3, respectively. This standardized volume was then extrapolated to determine the total annual vehicle volume (Qji) traversing the road segments adjacent to the parks [10]. Subsequently, total annual CO_2 exhaust emissions were calculated by determining the total distance traveled by the vehicles and multiplying it by specific emission factors using the integrated VKT model, expressed as [11]:]:

$$VKT_{ji} = \sum_{i=1}^{n} \left(Q_{ji} \times l_i \right)$$

$$E_{cji} = VKT_{ji} \times EF_{cj}$$

Within these equations, VKT_{ji} represents the total distance traveled by vehicle category j on road segment i in kilometers per year, calculated using the physical length of the segment (l_i).

The variable E_{cji} denotes the total mass of $\mathrm{CO_2}$ generated by the vehicle category in kilograms per year. Furthermore, EF_{cj} is the category-specific $\mathrm{CO_2}$ emission factor converted into a distance-based metric (kg/km). This factor was derived from the baseline technical regulations in EMEP/EEA (2020) Emission Factors—established at 3,180 g/kg of fuel for gasoline-powered motorcycles and light vehicles, and 3,172 g/kg for diesel heavy vehicles—multiplied by respective vehicular fuel consumption rates [12]. For this evaluation, active vehicular emission control efficiencies were assumed to be zero to establish a baseline maximum pollution load.

2.3. Biological sequestration estimation.

The biological sequestration capacity of the green infrastructure was quantified by integrating structural vegetation sampling with species-specific allometric modeling. A comprehensive non-destructive inventory of all arboreal and understory vegetation was conducted at each site. For tree species, Diameter at Breast Height (DBH) was measured at 1.3 meters above the ground using calipers. To ensure maximum precision for tall or inaccessible mature canopies, an aerial drone sensors was utilized. Understory vegetation, specifically shrubs, was measured by overall plant height (*H*), while grassland coverage was mapped spatially in square meters ($\mathrm{m^2}$) [13]. This physical structural data was converted into total permanent $\mathrm{CO_2}$ sequestration capacity by calculating the total biomass, extracting the carbon fraction, and applying a stoichiometric conversion to $\mathrm{CO_2}$. This process was executed using the integrated equation[14, 15]:

$$\mathrm{CO}_{2(Total)} = \left(\sum AGB + \sum BGB + \sum B_{shrub} + \sum B_{grass}\right) \times CF \times 3.67$$

In this formulation, $\mathrm{CO}_{2(Total)}$is the absolute mass of carbon dioxide permanently sequestered by the vegetation in kilograms. The parameters AGB (Above-Ground Biomass) and BGB (Below-Ground Biomass) for trees were calculated using established species-specific allometric power models[16,17]:

$$AGB = a \times D^b \times T,$$

$$BGB = AGB \times R,$$

with coefficients derived from tropical forestry literature, listed on Table 1, while BGB was estimated using a standard root-to-shoot ratio of $R = 0.24$. The variables B_{shrub} and B_{grass} represent the biomass of understory vegetation, calculated via height-dependent models:

$$B_{shrub} = a \times H^b,$$

$$B = \text{Area}\ (\mathrm{m^2}) \times \text{BFactor}\ ,$$

and standard areal biomass factors, BFactor ($0.3\ \mathrm{kg/m^2}$), respectively. The constant CF in first equation acts as the universally accepted Carbon Fraction multiplier for plant biomass (0.47), and 3.67 represents the molar mass conversion ratio of carbon to carbon dioxide, $\mathrm{CO_2}$. Finally, to align the biological sequestration data with the annual vehicular emission data, the total stored $CO_2$was divided by the estimated age of the vegetation stand (t) at each site, represented as:

$$CO_{2(\text{Annual})}=\frac{CO_{2(\text{Total})}}{t}$$

Table 1. Species-specific allometric coefficients used for biomass estimation [13].

No	Local Name	Scientific Name	Type of Canopy	*a* (Koef.)	*b* (Koef.)
1	Trembesi	*Samanea saman*	Umbrella	0.1242	2.34
2	Angsana	*Pterocarpus indicus*	Rounded	0.062	2.53
3	Ketapang Kencana	*Terminalia mantaly*	Flat Shade	0.069	2.47
4	Jati	*Tectona grandis*	Towering	0.0509	2.466
5	Mahoni	*Swietenia macrophylla*	Straight Upright	0.0826	2.442
6	Tabebuya	*Tabebuia spp.*	Towering	0.07	2.42
7	Beringin	*Ficus benjamina*	Dragging	0.085	2.41
8	Akasia	*Acacia auriculiformis*	Semi-pyramidal	0.0343	2.775
9	Kamboja	*Plumeria spp.*	Low	0.06	2.3
10	Sawo Kecik	*Manilkara kauki*	Densely Rounded	0.078	2.44
11	Pohon Bintaro	*Cerbera manghas*	Rounded	0.168	2.47
12	Pohon Mangga	*Mangifera indica*	Rounded	0.083	2.148
13	Pohon Glodokan tiang	*Polyalthia longifolia*	Towering	0.053	2

2.4. Analytical framework.

To evaluate the spatial environmental management efficiency of the parks, an Absorption Balance Ratio was calculated. This ratio divides the annual CO_2 sequestered by the green open spaces by the total annual CO_2 emitted by the adjacent vehicular traffic. Ratios exceeding 100% indicate a surplus sequestration capacity, signifying the infrastructure's active role as a net positive bio-filter for the urban environment. The resulting spatial mismatch data was further evaluated using a SWOT (Strengths, Weaknesses, Opportunities, Threats) matrix to formulate localized management strategies for future urban infrastructure and air quality improvement.

3. Results and Discussion

3.1. Vehicular emission profile and atmospheric waste load.

To evaluate the localized gaseous waste load around the green infrastructure, domestic vehicular emissions were quantified by analyzing traffic volumes, spatial travel distances, and their corresponding carbon outputs. The foundational metric for this assessment was the standardized volume of vehicles, expressed as Passenger Car Equivalents (PCE), traversing the corridors adjacent to each park. Empirical observations revealed a stark contrast in traffic density and vehicle composition across the study areas. The road segments surrounding Taman Bukit Maritam (Jl. Pulau Sambit and Jl. Raja Alam 2) experienced an intense traffic burden, recording 2,266,992.00 PCE annually. During weekdays, this location was heavily dominated by light vehicles (passenger cars), peaking at 5,785 PCE per day, firmly establishing it as the primary pollution hotspot. In contrast, Taman Sanggam (Jl. Pangeran Diguna) recorded 592,051.20 PCE annually, with a distinct shift in composition where motorcycles dominated weekday traffic at 1,305.6 PCE/day. Taman Cendana exhibited a moderate annual volume of 558,194.00 PCE, while Taman Singkuang operated in a highly tranquil zone, registering a minimal annual traffic volume of only 44,210.40 PCE.

The spatial emission load generated by these vehicles was contextualized through the Vehicle Kilometer Traveled (VKT) model, which integrated the annual traffic volume with the physical length of the adjacent road networks [18]. Driven by its massive traffic volume and a road length of 1.790 km, Taman Bukit Maritam generated a VKT of 4,057,915.68 km/year. Notably, although Taman Cendana had a lower raw traffic volume than Taman Sanggam, its significantly longer adjacent road segment (1.839 km compared to 0.613 km) resulted in a higher spatial load, yielding a VKT of 1,026,518.77 km/year. By applying the converted national emission factor (0.0002544 kg/km) to the VKT data, the definitive annual CO_2 emission profiles for each location were established [17,19,20]. As synthesized in Table 1, Taman Bukit Maritam was subjected to an intense pollution load of 1,032.33 kg CO_2/year, demanding substantial biological buffering. Taman Cendana experienced a moderate emission burden of 261.15 kg CO_2/year. Conversely, the shorter travel distances at Taman Sanggam generated only 92.33 kg CO_2/year, while the minimal traffic at Taman Singkuang produced a nearly negligible 7.54 kg CO_2/year. These disparate pollution profiles in Table 2 were critical for understanding the spatial mismatch in the city's urban forestry management. The biological treatment capacities of these parks were then evaluated against these specific gaseous waste loads to determine their localized efficiency.

Table 2. Spatial assessment of domestic vehicular emissions: Integrating annual traffic volume, Vehicle Kilometer Traveled (VKT), and localized CO_2 emission loads around urban green infrastructure.

Location (Green Open Space)	Annual Traffic Volume (PCE/Year)	Road Segment Length (Km)	Annual Vkt (Km/Year)	Emission Factor (Kg/Km)	Total Annual Co2 Emission (Kg/Year)
Taman bukit maritam	2,266,992.00	1.790	4,057,915.68	0.0002544	1,032.33
Taman cendana	558,194.00	1.839	1,026,518.77	0.0002544	261.15
Taman sanggam	592,051.20	0.613	362,927.39	0.0002544	92.33
Taman singkuang	44,210.40	0.670	29,620.97	0.0002544	7.53

3.2. Species-specific sequestration capacities.

A critical evaluation of the biological systems within these parks demonstrated a profound disparity in biofiltration efficiency. The most significant biological sink in the study area was observed in Taman Sanggam, which contained a massive total vegetation biomass of 278,939.35 kg (comprising 277,492.67 kg of trees, 14.48 kg of shrubs, and 1,432.20 kg of grass), as shown in Figure 1. This extraordinary mass was largely driven by mature *Samanea saman* (Trembesi) stands, validating the species as a highly optimized, high-capacity biological filter suitable for mitigating intense urban emissions. In stark contrast, the vegetative profile of Taman Singkuang relied heavily on *Mangifera indica* (mango) populations, resulting in the lowest total park biomass of only 30,820.73 kg. While *Mangifera indica* provided localized aesthetic and shading benefits, its allometric structural properties yielded a limited sequestration capacity, generating only 151.53 kg CO_2/year per tree [13, 21]. As presented in Table 3, the comprehensive biological sequestration profiles highlighted clear inter-park differences in biomass distribution and carbon storage capacity. Crucially, the evaluation of these green open spaces reveals that absolute sequestration efficiency is dictated primarily by species composition rather than stand age or mere spatial area. Taman Sanggam emerges as the most productive biological filter, sequestering an estimated 37,010.96 kg CO_2/year for the entire park, despite its relatively young stand age of 13 years. In contrast, Taman Cendana, despite operating as a mature, 19-year-old park with a total biomass of 87,087.71 kg, yields a substantially lower total sequestration rate of only 7,906.19 kg CO_2/year.

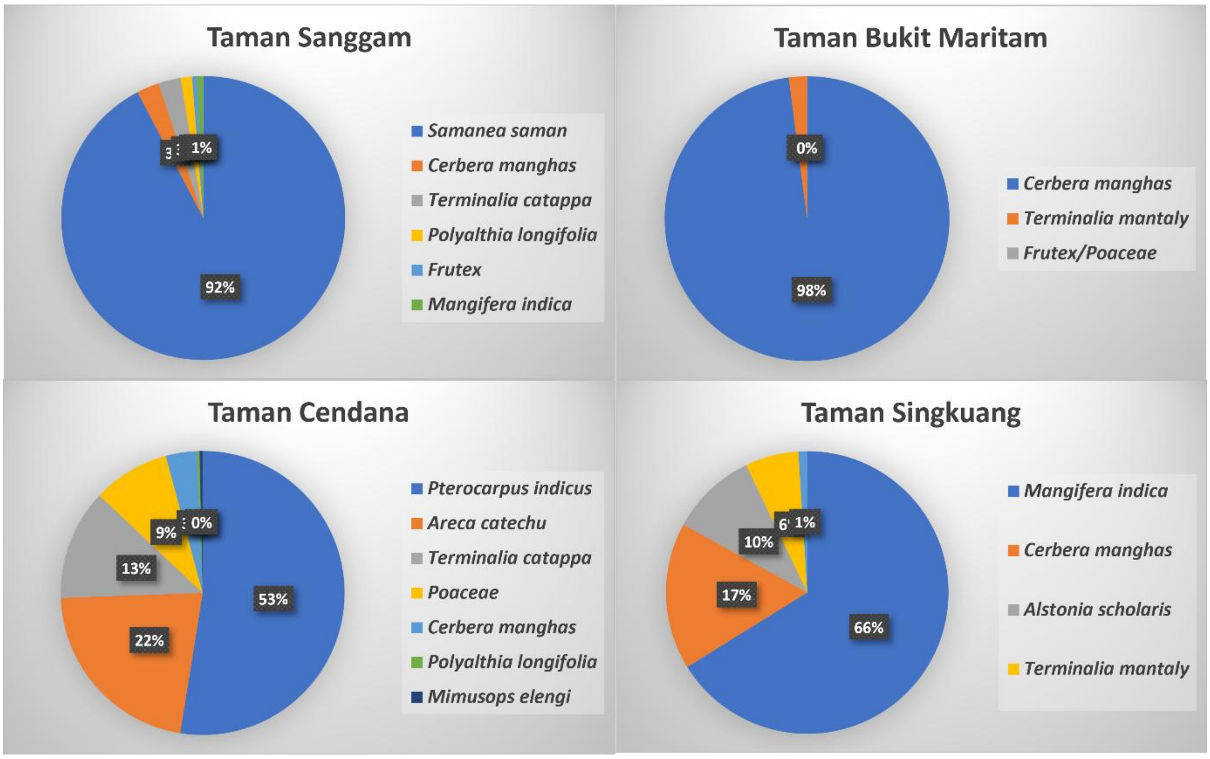

Figure 1. Comparison of total vegetation biomass in four parks.

Table 3. Comprehensive biological sequestration profiles of the evaluated green infrastructure.

Location (Green Open Space)	Dominant Tree Species	Total Park Biomass (kg)	Dominant Species Biomass (kg)	Species Contribution to Park (%)	Total Park Stored CO_2 (kg)
Taman Bukit Maritam	*C. manghas*	52,956.28	51,789.74	97.80%	91,344.29
Taman Cendana	*P. indicus*	87,087.71	45,278.29	51.99%	150,217.59
Taman Sanggam	*S. saman*	278,939.35	249,085.10	89.30%	481,142.48
Taman Singkuang	*M. indica*	30,820.73	20,029.39	64.99%	53,162.68

This operational inefficiency in older parks is directly traceable to the reliance on species with limited woody biomass potential. The contrast is sharpest at the individual tree level: while the *Samanea saman* in the younger Taman Sanggam demonstrates an exceptional individual absorption capacity of 2,148.23 kg CO_2/tree/year, the *Mimusops elengi* prevalent in the older Taman Cendana sequesters a mere 0.72 kg CO_2/tree/year. This extreme quantitative contrast definitively proves that urban parks cannot be treated as homogenous environmental assets. Their functional utility as active gaseous waste treatment facilities is strictly governed by the biological mechanics of their constituent trees, indicating that strategic species selection is paramount in optimizing urban environmental infrastructure.

3.3. The sequestration-emission balance and spatial mismatch.

To determine the functional efficacy of the existing urban green infrastructure, the localized domestic vehicular emission loads were superimposed onto the annualized biological sequestration capacities of each respective park. This overlay revealed the functional balance of the system by determining whether a green open space operated at a carbon deficit or surplus. While macro-scale urban studies frequently demonstrated severe offset deficits where standard greenery neutralized as little as 0.1% to 4.4% of total city greenhouse gas emissions [22, 23], the localized evaluation in Tanjung Redeb revealed a highly functional dynamic. As presented in Table 4, empirical data indicated that all four evaluated green open spaces operated at a net positive carbon surplus, with biological absorption ratios significantly exceeding the 100% threshold required for baseline mitigation. However, a deeper analysis of this overlay exposed a pronounced spatial and operational mismatch in the existing environmental management strategy. The deployment of the city's biological assets was severely misaligned with the spatial distribution of its gaseous waste generation. This source–sink decoupling has been frequently identified as a primary barrier to effective urban climate mitigation [24, 25].

Table 4. Annual vehicular emission loads versus biological sequestration capacities.

Location (Green Open Space)	Annual CO_2 Emission (kg/year)	Annual CO_2 Sequestration (kg/year)	Absorption Balance Surplus (kg/year)	Absorption Ratio (%)
Taman Bukit Maritam	1,032.33	15,224.96	+ 14,192.63	1,474.8%
Taman Cendana	261.15	7,906.19	+ 7,645.04	3,027.4%
Taman Sanggam	92.33	37,010.96	+ 36,918.63	40,085.5%
Taman Singkuang	7.53	8,860.45	+ 8,852.92	117,668.6%

As shown in Table 4, the comparison between annual vehicular emission loads and biological sequestration capacities highlighted substantial imbalances across locations. The most striking manifestation of this mismatch was observed in the contrast between Taman Sanggam and Taman Bukit Maritam. Taman Sanggam operated within a low-stress traffic corridor, generating a minimal emission load of only 92.33 kg CO_2/year. However, it was equipped with the most intensive biological remediation system in the study. Driven by dominant *Samanea saman* stands, it sequestered 37,010.96 kg CO_2/year, resulting in an absorption ratio of 40,085.5%. This created a substantial, underutilized biofiltration surplus in an area that did not require such a high mitigation capacity.

Conversely, the spatial data established Taman Bukit Maritam as the primary vehicular emission hotspot, subjecting the localized environment to an annual load of 1,032.33 kg CO_2/year—more than eleven times the pollution burden of Taman Sanggam. Despite experiencing the highest environmental stress, this corridor relied on a relatively young, 6-year-old stand dominated by *Cerbera manghas*, yielding an absorption ratio of 1,474.8%. Although this remained a net positive balance, it revealed a critical vulnerability: the municipality's most polluted zone lacked the most efficient high-capacity biological filtration system.

This pattern reflected a broader global tendency in which standard aesthetic landscaping proved quantitatively insufficient to counteract continuous adjacent road emissions [25]. Although the overall system maintained a carbon surplus, future municipal spatial planning required explicit alignment between high-emission corridors and high-efficiency biological sinks. Such alignment, supported by dense spatial aggregation of high-capacity species, would be essential to ensure long-term urban resilience as traffic volumes continued to increase [24].

3.4. Implications for urban spatial and air quality management.

As regional infrastructural development accelerated and motorized traffic volumes inevitably expanded, high-stress corridors were projected to exceed the localized absorption limits of moderately performing vegetation. To ensure long-term urban environmental resilience, city administrators were required to transition from passive aesthetic landscaping to active, data-driven biological engineering [23, 26]. To contextualize the management implications of the identified gaseous waste source–sink decoupling, the biological performance of each site was evaluated against its physical spatial metrics and establishment timeline. As summarized in Table 5, the empirical data revealed that spatial area and stand age alone were unreliable predictors of environmental efficacy in Tanjung Redeb.

Table 5. Spatial profile, establishment timeline, and absorption balance of evaluated Green Open Spaces in Tanjung Redeb.

Location (Green Open Space)	Establishment Year	Stand Age (Years)*	Total Designated Area (m²)	Absorption Balance (Surplus kg/year)
Taman Cendana	2006	19	8,139.05	+ 7,645.04
Taman Sanggam	2012	13	8,436.32	+ 36,918.63
Taman Singkuang	2023	6	2,380.78"	+ 8,852.92
Taman Bukit Maritam	2023	6	1,986.60	+ 14,192.63

As presented in Table 5, the spatial profile, establishment timeline, and absorption balance of the evaluated green open spaces highlighted substantial variation in performance despite comparable physical attributes. To visualize the relationships among key variables across the four evaluated green open spaces, the data were mapped into a comparative analysis, as shown in Figure 2. This analysis demonstrated a pronounced decoupling between a park's physical metrics, its designated spatial footprint and stand age, and its actual environmental performance. This paradox was most clearly illustrated by comparing Taman Cendana and Taman Sanggam. Despite occupying nearly identical large-scale areas (>8,100 m²) and possessing mature stands (19 and 13 years, respectively), their functional performance differed substantially. Taman Cendana yielded a relatively low surplus, constrained by the limited sequestration capacity of its ornamental dominant species, *Mimusops elengi*. In contrast, Taman Sanggam generated a significantly higher biofiltration surplus, attributable to the superior allometric traits and woody biomass accumulation of the hyper-accumulator *Samanea saman*.

Furthermore, Taman Bukit Maritam, despite being the youngest and smallest park evaluated, outperformed the larger and older Taman Cendana due to its reliance on a moderately efficient species, *Cerbera manghas*. Figure 2 demonstrated that maximizing urban land allocation alone did not guarantee improvements in air quality. Instead, strategic species selection emerged as the dominant factor determining the capacity of green infrastructure to mitigate vehicular emissions. Future urban forestry and waste management initiatives must strictly align the deployment of biological assets with projected Vehicle Kilometer Traveled (VKT) data, an established metric for tracking primary urban carbon loads [27], [28]. This requires the strategic establishment of targeted buffer zones along primary transportation arteries, such as the corridors surrounding Taman Bukit Maritam. In these high-emission hotspots, policy must mandate the exclusive planting of high-capacity, climate-adaptive hyper-accumulators. Species that demonstrate massive woody biomass generation and extensive canopy architecture, specifically *Samanea saman* (Trembesi), must be purposefully deployed to serve as heavy-duty biological filters, paralleling findings that large arbors exhibit vastly superior photosynthetic rates and structural carbon sequestration compared to small arbors and shrubs [26]. Conversely, the use of ornamental or fruit-bearing species with restricted sequestration profiles, such as *Mangifera indica*, should be strictly limited to tranquil, low-emission residential or pedestrian zones where aesthetic value can be prioritized without compromising critical air quality standards.

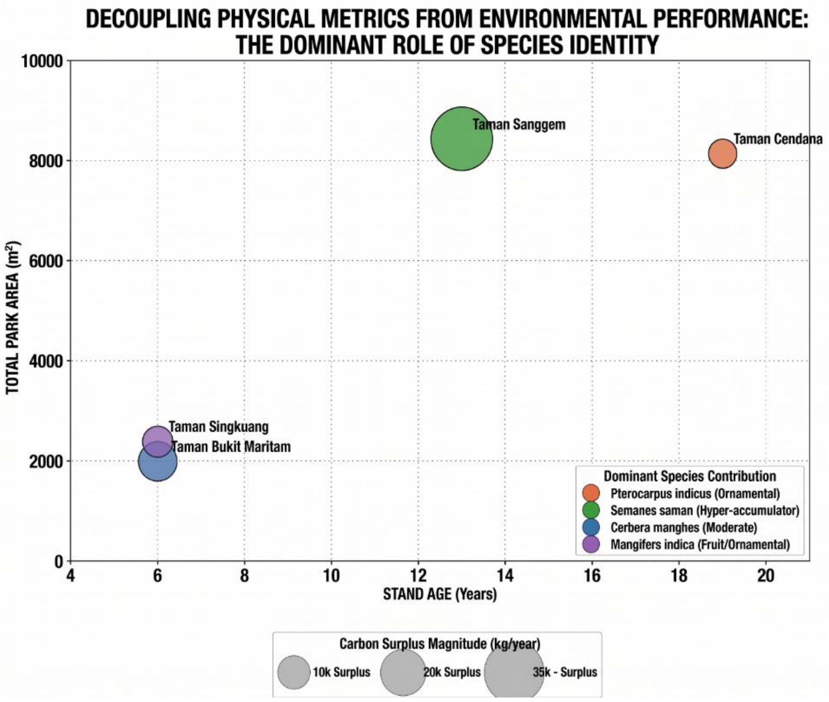

Figure 2. Decoupling physical metrics from environmental performance across evaluated Green Open Spaces.

3.5. Biological determinants of sequestration efficiency.

The observed disparity in sequestration performance among the evaluated green open spaces was governed by the divergent physiological traits of their dominant species. A comparative analysis of these structural and metabolic characteristics specifically canopy architecture, leaf morphology, and growth rates, revealed the biological mechanisms driving the identified spatial mismatch [26]. When comparing the primary high-capacity arbors, *Samanea saman* (Trembesi) and *Pterocarpus indicus* (Angsana), both benefited from their taxonomy as large, fast-growing species. However, *S. saman* exhibited a superior carbon sequestration profile due to its massive, spreading hemispherical crown [29]. This horizontal, umbrella-like structure maximized its Leaf Area Index (LAI) and canopy density, providing an extensive photosynthetic surface for continuous CO_2 adsorption [26,29]. While *P. indicus* also demonstrated substantial woody biomass accumulation and dense foliage, its more domed, weeping canopy generally achieved a slightly lower overall volume of gaseous exchange per mature tree compared to the aggressive lateral structural spread of *S. saman* [32]. Both species, however, exhibited significantly higher net carbon sequestration than lower-stratum vegetation.

A similar physiological divergence governed the performance of moderate-capacity species, as observed in the comparison between *Mangifera indica* (mango) and *Cerbera manghas* (bintaro). *M. indica* was a large evergreen tree that developed a dense, dome-shaped canopy with heavy foliage [31], providing a high absolute leaf area. However, its carbon allocation was inherently less efficient for dedicated air quality management, as a significant portion of its metabolic energy was diverted from permanent woody structural growth toward reproductive processes and fruit production [25,31]. Conversely, *C. manghas* was a resilient, fast-growing tropical tree highly tolerant of urban stress, but its naturally compact, ovoid canopy (typically reaching 12–15 m in height) inherently limited its maximum LAI and total photosynthetic surface area [30]. Consequently, despite its rapid growth, its restricted canopy spread resulted in lower absolute carbon sequestration compared to the larger canopy of *M. indica*, and it significantly underperformed relative to large-canopy species such as *S. saman* [30]. This biological reality indicated that while fruit-bearing or compact shade trees provided valuable socio-ecological benefits, their limited woody biomass accumulation and specialized canopy structures rendered them insufficient as primary filtration buffers in high-emission vehicular corridors.

These findings provided a critical framework for updating municipal spatial plans in Berau Regency. Existing regulations frequently evaluated the adequacy of green open spaces based solely on total land area percentages. However, this study and contemporary urban ecosystem assessments demonstrated that spatial area alone was a functionally inadequate metric. It failed to account for the specific ecological demands of the surrounding built environment [32], often assuming environmental efficacy even when the constituent species lacked strong biofiltration capacity and optimal spatial connectivity [25]. To resolve the spatial mismatch identified in this study, policymakers were required to transition from static area-based minimums to a dynamic, multi-indicator approach for characterizing green infrastructure [32]. Municipal regulations needed to incorporate species-specific carbon sequestration targets designed to offset the precise gaseous waste profiles of the surrounding urban environment. By aligning high-capacity, hyper-biomass accumulator species with localized emission hotspots, local governments could transform passive public parks into active infrastructure for domestic gaseous waste management.

4. Conclusions

This study confirmed that the green open spaces in Tanjung Redeb operated as high-efficiency biological sinks, maintaining net-positive carbon balances with absorption ratios ranging from 1,475% to 117,668.6%. However, their overall efficacy was constrained by a pronounced spatial mismatch. Empirical evidence revealed a clear source–sink decoupling: the primary emission hotspot (Taman Bukit Maritam, 1,032.33 kg CO_2/year) relied on moderately performing vegetation, whereas the most intensive biological remediation system (Taman Sanggam, 37,010.96 kg CO_2/year) was located within a low-stress traffic corridor. The analysis demonstrated that biofiltration performance was governed primarily by species taxonomy and allometric structure rather than stand age or total park area. High-biomass hyper-accumulator species, particularly *Samanea saman*, showed substantially greater sequestration capacity compared to older ornamental stands. Consequently, municipal planning required a transition from passive aesthetic landscaping to data-driven urban silviculture. Future policies should incorporate species-specific sequestration targets and prioritize the strategic placement of high-capacity species along high-emission corridors, integrated with complementary systems such as bioretention to support broader environmental resilience. Although this study focused specifically on domestic vehicular emissions, it provided a practical and scalable framework for municipal environmental management. By isolating transportation-related emission loads, the methodology demonstrated how urban planning could evolve to transform passive green spaces into engineered, high-capacity environmental remediation systems.

Author Contribution

The authors specified their contributions as follows. Conceptualization was carried out by Susana Elmira Uba Lamadoken. The methodology was developed by Muhammad Mahfuzh Huda and Dwi Fitrianingsih. Data collection was conducted by Susana Elmira Uba Lamadoken. Data analysis was performed by Wahyu Atiq Widiantoro and Raelly Harza Wiltianza. The manuscript was written by Muhammad Mahfuzh Huda, while supervision was provided by Wahyu Atiq Widiantoro.

Competing Interest

The authors declared that there were no competing financial or non-financial interests that could have influenced the work reported in this study.

Data Availability

The datasets generated and/or analyzed during the current study are available from the corresponding author upon reasonable request.

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