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Scenario-based Forecasting of Carbon Sequestration and Oxygen Production in Urban Green Spaces Using I-tree Forecast: A Case Study of Sidoarjo, Indonesia

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SCENARIO-BASED FORECASTING OF CARBON SEQUESTRATION AND OXYGEN PRODUCTION IN URBAN GREEN SPACES USING I-TREE FORECAST: A CASE STUDY OF SIDOARJO, INDONESIA

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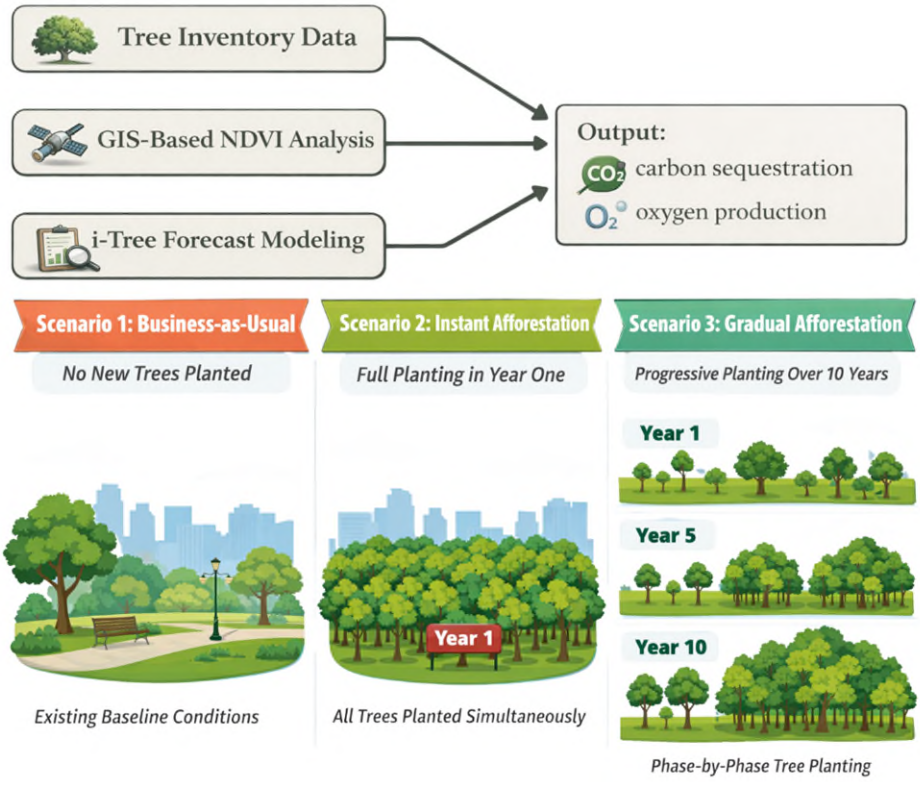
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Graphical abstract



Highlights

1. The transportation sector contributes approximately 60% of urban air pollution emissions.
2. Carbon sequestration is higher in Abhirama Park than in Apkasi Park (2.14 vs 0.92 t/year).
3. Greening scenarios enhance carbon sequestration and oxygen production.
4. Existing green open spaces remain insufficient to offset urban emissions.

Abstract
Transportation is the largest CO2 emission contributor in Indoneisa, followed by industries, waste management, and households. The major greenhouse gas has seen carbon offsetting attempts with varying proposals, one of which is by implementing Green Open Spaces (GOS), acting as ecological buffers, carbon sinks, and oxygen producers. This study evaluates existing greenery at Abhirama Park (urban core) and Apkasi Park (suburban area) in Sidoarjo Regency (East Java, Indonesia), Utilizing tree planting scenarios to assess CO2 sequestration and oxygen production changes. The methodology integrates field base inventories, vegetation density analysis (GIS-based NDVI), microclimate observations, and i-Tree Forecast modelling from three scenarios (existing conditions, instant greening, and gradual greening). Observations ran for two weeks on select days (Monday, Friday, Sunday) at specific times (Morning, Midday, and Evening) to observe diurnal variatons. The results show Abhirama Park having more complex vegetation structure with a higher tree count (159 trees vs 70 trees), greater carbon sequestration capacity (2.14 tons/year to 0.92 tons/year) compared to Apsaka park. Sequestration values reveal extremely limited capacity of carbon offset abilities from both parks for each respective locations, accounting only 1.33% and 0.5% of total emissions. Microclimate analysis observations found the lowest humidity to be during midday, and is inverse with temperature, driven by increased solar radiation and accelerating evapotranspiration (influencing photosynthetic efficiency). Greening scenarios show better carbon sequestration and oxygen production, yet still insufficient to be said meaningful carbon offset of growing vehicle emissions. While both parks contribute to climate resilience and sustainable urban development, their current capacity remains inadequate to balance urban emissions. Enhancing vegetation structure, Increasing tree biomass, and integrating green space planning with emission control strategies are crucial to optimize urban carbon mitigation.
Keywords : *Carbon Sequestration, i-Tree Forecast, NDVI, Oxygen Production, Urban Park*

1. Introduction

Various environmental issues, including air quality degradation and climate change [1] are caused by population growth and the intensification of human activities in urban areas. To mitigate these impacts, the availability and quality of green open spaces (GOS) are being improved as an effective strategy. Ecological sustainability in urban areas is supported, and the urban heat island effect is reduced by green open spaces through the provision of various ecosystem services, such as carbon sequestration and improved air quality [2]. Additionally, cooling of local temperatures, increase in biodiversity, and public health improvement are prevalent benefits observed in high population density areas with GOS. [3]. However, most studies still focus on large cities, while rapidly developing medium and secondary cities often receive less attention. As a result, green infrastructure planning in these areas is not yet fully based on comprehensive ecosystem service assessments [4]. This gap highlights the importance of local assessments to support more contextual and equitable urban planning.

In this context, modeling tools such as i-Tree Eco are important instruments for evaluating tree-based ecosystem services with detailed resolution. For example, a study in Taipei integrated i-Tree Eco with drone-based mapping to assess carbon stocks and sequestration rates in urban parks, with carbon storage ranging from 5–21 tC/ha, depending on tree density and canopy structure [3]. In China, the use of i-Tree Eco combined with national forest inventory data enables more accurate and efficient estimation of carbon sinks at the urban-rural scale compared to the conventional IPCC

approach [5]. The main advantages of this method lie in the flexibility of the study area coverage, ranging from yard to city scale, as well as the relatively high level of analysis accuracy [6].

The sustainability of urban forest planning is not only determined by the area of green space, but also by the selection of tree species that have high potential for carbon sequestration and oxygen production [7]. A study of 32 urban landscape species found that carbon storage capacity is heavily influenced by photosynthesis rate, canopy area, and leaf area index [8]. Another recent study of six varying mulberry trees also found that carbon storage and oxygen production varied during the summer, confirming important roles of species-specific characteristics in urban ecosystem optimization [9].

Sidoarjo (East Java, Indonesia) is a prime example of a medium-sized city facing rapid urbanization, increased traffic volume, and rising anthropogenic emissions. With the current issue at hand, there are limited studies assessing GOS's contribution in solving said problem. Such this study utilize the i-Tree forecast model to assess carbon sequestration and oxygen production potential in Sidoarjo. Three management scenarios were conducted: (1) simulating existing vegetation conditions with no alterations, (2) simultaneous tree planting in the first year, and (3) gradual tree planting over several years. Through this research, a deeper understanding of the role of small-scale urban parks in climate change mitigation and the implementation of green infrastructure strategies in sustainable urban planning can be enhanced.

2. Material & Methods

Conducted in Sidoarjo (East Java, Indonesia), Abhirama Park represents the urban core and APKASI Park as the suburban area. Observations were carried out over six consecutive days. Measurements were taken in the morning (07:00–08:00), midday (12:00–13:00), and evening (17:00–18:00). Measurements of carbon sequestration, oxygen production, alongside air temperature and relative humidity, were done in triplicates to ensure reproducibility and data reability. Tree inventory and GIS-based analysis will be integrated using the Normalized Difference Vegetation Index (NDVI), and modelled with the i-Tree Forecast. Carbon sequestration and oxygen production under three scenarios were evaluated using this approach, supporting the assessment of ecosystem services in urban green spaces.

2.1 Tree Inventory and Data Collection

Tree species were identified using the PlantNet application based on leaf, stem, and other vegetative morphological characteristics. Each identified species are recorded as a distinct inventory unit. Tree biometric measurements were conducted in situ following standardized urban forestry protocols. Stem diameter was measured as diameter at breast height (DBH) at 1.3 m above ground level. When stem circumference (C) was recorded, DBH was derived using:

$$D = \frac{C}{\pi}$$

where D is stem diameter (cm), C is stem circumference (cm), and $\pi = 3.1416$. Tree height was estimated using a smartphone-based clinometer applying trigonometric principles:

$$H = d \times \tan(\theta)$$

where H is tree height (m), d is the horizontal distance from observer to tree (m), and θ is the elevation angle (°). Canopy width was measured along two perpendicular directions (north–south and east–west), with the average value used to represent canopy diameter. Tree health condition was

visually assessed using PlantNet image-based classification, categorizing individuals as healthy (H) or less healthy (LH) from leaf quality and crown structure.

A comprehensive inventory was made from both study sites, having entries of species, DBH, height, and canopy dimensions. All measurements followed established urban forestry assessment protocols [10]. The inventory was used as the primary input for ecosystem structure and service analysis using the i-Tree Forecast model [11]. Figure 1 details the methodology and inventory procedures.

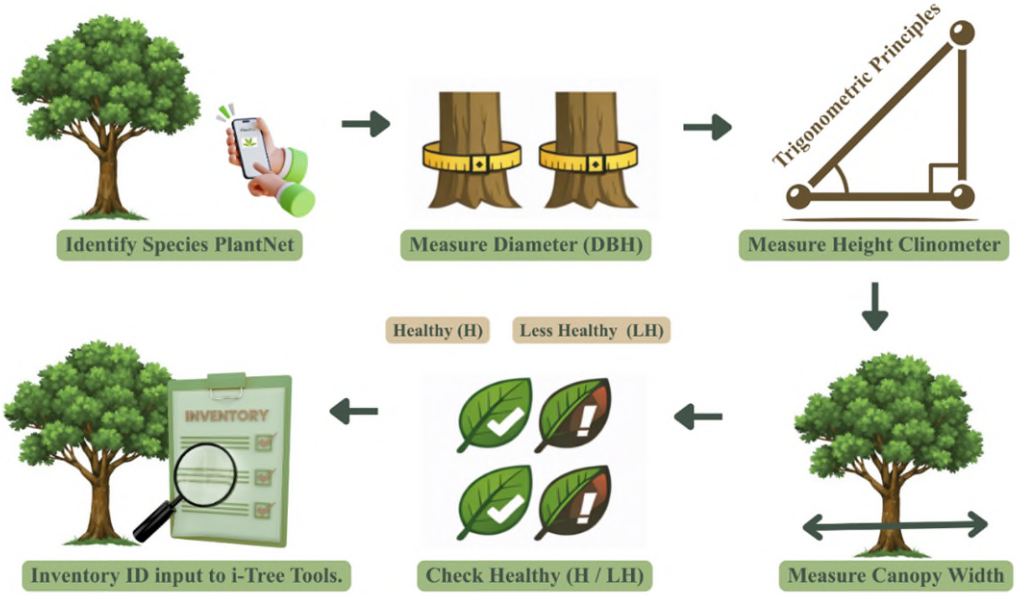


Figure 1. Tree Inventory and Data Collection

2.2 Carbon Sequestration Capacity Analysis

Carbon sequestration capacity were estimated based on vegetation inventory data (species, number of trees, DBH, height, and canopy) analyzed with i-Tree Eco to produce gross carbon sequestration (ton/year). Carbon values were converted to CO_2 using:

$$CO_2 = C \times 3.67$$

Furthermore, the values were converted into kg/hour for comparison purposes:

$$CO_2 \text{ (kg/h)} = \frac{CO_2\ (ton/year)\ x\ 1000}{8760}$$

Which was used to compare carbon sequestration capacity between study sites.

2.3 Geospatial Quantification of Vegetation Density Using NDVI

Remote sensing and GIS were employed to quantify vegetation cover within the study areas. Landsat 8 OLI/TIRS imagery (30 m spatial resolution) was obtained from the USGS Earth Explorer database. Pre-processing steps include atmospheric correction and image clipping from shapefile boundaries of Abhirama and APKASI Parks. The Normalized Difference Vegetation Index (NDVI), known to estimate vegetation cover [12], is then calculated to identify and classify surfaces with and without vegetation cover from following equation :

$$NDVI = \left(\frac{NIR\text{-}Red}{NIR+Red}\right)$$

$$NDVI = \frac{Float\ ("Band5" - "Band4")}{Float\ ("Band5\ + Band4")}$$

This principle is used to assess vegetation coverage [12], where Higher NDVI values indicate better vegetation cover [13], and values approaching +1 are associated with denser and healthier

vegetation (vigor) [14]. The range from −1 to +1 is used to represent NDVI values, with interpretations determined by the type of land cover or land use. Higher vegetation density is indicated by high NDVI values, while areas with sparse or no vegetation are characterized by low NDVI values. Negative NDVI values are typically associated with clouds, bodies of water, and surfaces without vegetation.

NDVI then gets classified into three categories. Low-density vegetation (NDVI 0.1–0.2) describing roads, buildings, settlements, and open lands with sparse vegetation cover. Medium-density vegetation (NDVI 0.2–0.3) indicating residential areas with large yards, gardens, shrubs, undergrowth, and scattered tree species. High-density vegetation (NDVI 0.3–0.4) for areas dominated by densely growing trees [12].

These categories are mapped geospatially using ArcGIS Spatial Analyst tools, to find the total green area of each park, by overlaying the NDVI classification with shapefile boundaries. This analysis provides base estimation of vegetated land proportions, identifying spaces for planting, and assessing park compliance with the Indonesian Ministry of Public Works and Housing (PUPR) standards, which require at least 85% of urban park areas to be covered by vegetation [15].

2.4 Scenario-Based Ecosystem Service Modeling Using i-Tree Forecast

Public awareness and policy support for conservation and sustainable management efforts can be enhanced through an assessment of the ecosystem services provided by trees in urban areas. The regulating ecosystem services provided by urban forests, including carbon sequestration and improved air quality, are often measured using the i-Tree Eco software [16]. The processed tree inventory data in this study were analysed with the i-Tree Forecast model, simulating annual tree growth, carbon sequestration, and oxygen production in a 10-year period. To ensure consistency and comparability across all scenarios, all Basic Options (e.g., tree mortality rate, pest impacts, and management interventions) were set to 0%. This approach allows the model outputs to reflect solely the effects of different tree planting strategies, without introducing additional external assumptions. Previous studies have also implemented akin methodological approaches, by fixing baseline parameters to establish a neutral reference condition for scenario-based analaysis [17].

2.5 Scenario Design for Urban Greening and Ecosystem Service Projections

Based on the availability of plantable open space in Abhirama Park and Apkasi Park, three scenario-based simulations were developed to evaluate future carbon sequestration and oxygen production under different urban greening strategies [18]:

1. Scenario 1, Business-as-usual (BAU): Keeps existing vegetation structure with no additions of planting occurrences, maintained throughout the simulation period to represent baseline conditions.
2. Scenario 2, Instant afforestation scenario: Plantable areas are fully utilized during the initial year, with tree planting conducted simultaneously to maximize early-stage ecosystem service gains.
3. Scenario 3, Gradual afforestation scenario: Tree planting is incrementally implemented over a 10-year period, distributing a realistic annual and adaptive urban greening strategy.

Figure 2 provides details in scenario development and planting strategies. Species composition assumptions and site-specific planting capacity were kept consistent throughout the simulations to ensure comparability across scenarios. The results were then split into projected carbon sequestration and oxygen production over the simulation period.

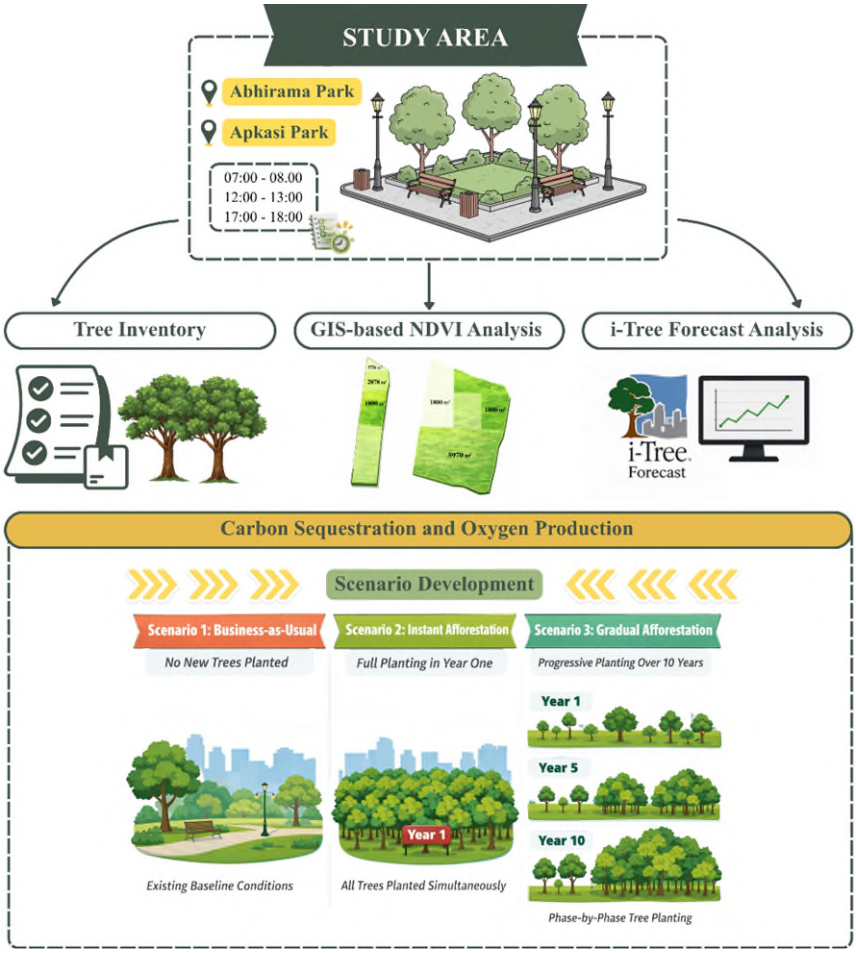


Figure 2. Scenario Development

3. Results and Discussions

3.1 Vegetation Composition and Structural Characteristics in Urban Green Spaces

Abhirama Park contains 160 trees that exhibit high species diversity and structural variation, as evidenced by the presence of large-diameter trees (DBH >100 cm) and a wide diameter range (0.2–155 cm) from Table 1. This condition reflects a vertically stratified and relatively stable vegetation structure to support urban ecological function [19]. Field observation indicates a large portion of trees were in good condition (±80–85%), and the presence of young plants (e.g., code 44; DBH 0.2 cm) indicates ongoing regeneration. However, the younger plants were excluded from the i-Tree Eco analysis as it falls under the minimum DBH threshold.

Table 1. Structural Characteristics of Vegetation in Abhirama Park

Tree Code	Local Name	DBH (cm)	Tree Height (m)	Canopy Width (m)	Tree Condition	Tree Code	Local Name	DBH (cm)	Tree Height (m)	Canopy Width (m)	Tree Condition
1	Saribus	20.4	8	1.5	H	81	Ketapang Biola	24.5	3.5	3.3	H
2	Kiacret	94	10.5	4.2	H	82	Tabebuia	23	3.2	1.6	H
3	Kamboja Merah	4.5	2.1	0.6	LH	83	Pulai	39.7	3.5	4.2	H
4	Srikaya	12.5	3	1.8	H	84	Belimbing	11	2.2	1.9	H

Tree Code	Local Name	DBH (cm)	Tree Height (m)	Canopy Width (m)	Tree Condition	Tree Code	Local Name	DBH (cm)	Tree Height (m)	Canopy Width (m)	Tree Condition
5	Kamboja Merah	5	2.2	0.9	H	85	Nusa Indah	11.5	2.7	2	H
6	Kamboja Merah	10	1.8	1.4	H	86	Dracaena Draco	32	2.1	0.3	H
7	Kamboja Obtusa	11	1.5	0.9	H	87	Megaskepasma	11	2.1	0.3	H
8	Kamboja Putih	13	1.7	1.2	H	88	Dracaena Draco	11.5	1.7	0.1	H
9	Srikaya	10.5	3.5	1.6	LH	89	Bunga Betawi	16.5	1.9	0.75	H
10	Kamboja Merah	12.5	2.1	1.6	H	90	Belimbing	13.5	3.2	1.3	H
11	Kamboja Merah	16.5	2.4	1.6	H	91	Nyanyian Dari India	12	0.9	0.05	H
12	Kamboja Merah	16	2.1	1.7	H	92	Pucuk Merah	11	0.7	0.1	H
13	Kamboja Merah	14.5	1.8	0.7	LH	93	Eupatorium	10.1	1.6	0.1	H
14	Kamboja Merah	9.5	2.2	1.3	H	94	Pucuk Merah	10.1	2.2	0.6	H
15	Kamboja Merah	10	2.2	1.1	H	95	Adonidia	10.1	3.2	0.5	H
16	Kamboja Merah	16.5	3.1	2.6	H	96	Pucuk Merah	8	0.9	0.4	H
17	Palem Putri	18	3.4	1.8	H	97	Tabebuia	22.1	2.6	2	H
18	Tabebuia	12	3.2	2.1	H	98	Adonidia	14.5	2.4	1.1	H
19	Tabebuia	6.5	2.6	3	H	99	Kamboja Merah	13.1	2.5	1	H
20	Tabebuia	7	3.3	2.4	H	100	Pucuk Merah	4.1	1.6	0.3	H
21	Tabebuia	5.5	2.8	1.1	H	101	Pucuk Merah	6.1	1.3	0.05	H
22	Tabebuia	13.5	2.2	2.1	H	102	Adonidia	15	3.2	0.5	H
23	Tabebuia	15	2.8	1.4	H	103	Pucuk Merah	6	0.8	0.1	H
24	Tabebuia	9.5	3.2	0.9	H	104	Dracaena Draco	14.5	2.4	0.25	H
25	Pisang Kipas	39.5	2.3	1.8	H	105	Cusonia	18.1	3.2	1	H
26	Tabebuia	9.5	3.6	1.3	H	106	Tabebuia	21.1	2.5	0.3	H
27	Pisang Kipas	51.5	2.3	0.6	H	107	Palem Kuning	14.1	2.4	1	H

Tree Code	Local Name	DBH (cm)	Tree Height (m)	Canopy Width (m)	Tree Condition	Tree Code	Local Name	DBH (cm)	Tree Height (m)	Canopy Width (m)	Tree Condition
28	Pohon Hujan	22.5	5.5	1	H	108	Palem Kuning	12.5	3.1	1	H
29	Kamboja Merah	34.5	2.5	1.6	H	109	Theobroma	12	3.3	3	H
30	Kamboja Merah	5.5	1.8	0.25	H	110	Beringin Cina	8	1.8	0.05	LH
31	Srikaya	9.5	2.2	0.8	H	111	Beringin Cina	7.5	1.7	0.05	LH
32	Saribus	23.5	7	0.9	LH	112	Dracaena Draco	18	2.2	0.3	H
33	Kiacret	45	7.2	4.5	H	113	Ketapang Biola	20	3.4	2	H
34	Kamboja Merah	7	1.7	0.2	LH	114	Dracaena Draco	5.2	2.1	0.3	H
35	Kamboja Obtusa	10.5	2.1	0.1	LH	115	Pisang Kipas	17	3.5	0.7	H
36	Srikaya	11.5	2.1	0.3	H	116	Pepaya	5.5	2.1	0.5	H
37	Kiacret	58	6.2	3	H	117	Dracaena Draco	17	2.2	0.3	H
38	Srikaya	6	2.3	1	H	118	Dracaena Draco	26	3.3	0.4	H
39	Kamboja Obtusa	12	1.6	0.2	LH	119	Ketapang	22	1.8	0.4	H
40	Trembesi	71	5.8	4	H	120	Mengkudu	2.1	1.85	0.35	H
41	Kiacret	60	4.6	3	H	121	Ketapang Biola	19.5	3.6	3	H
42	Agave Kuning Putih	28	1.2	1.1	H	122	Elneis	82	4.2	4	H
43	Kamboja Merah	11	3	1.1	H	123	Ketapang Biola	21	4.4	3	H
44	Pucuk Merah	0.2	1.6	0.3	H	124	Srigading	3.5	1.9	0.3	H
45	Ketapang Biola	32	4	1.2	H	125	Jambu Air	2.1	0.9	0.3	H
46	Agave Kuning Putih	25	0.8	2.3	H	126	Soga	143	4.5	5	H
47	Agave Kuning Putih	24	0.6	2.3	H	127	Ketapang	83	4.1	4	H
48	Nusa Indah	11	1.8	1.3	H	128	Beringin Cina	155	5.5	7.5	H
49	Nusa Indah	7.5	1.8	1.5	H	129	Prunus	1.5	1.6	0.3	H

Tree Code	Local Name	DBH (cm)	Tree Height (m)	Canopy Width (m)	Tree Condition	Tree Code	Local Name	DBH (cm)	Tree Height (m)	Canopy Width (m)	Tree Condition
50	Ketapang Biola	3.5	5.1	4.5	H	130	Ketapang	74	4.3	4	H
51	Ketapang Biola	22.5	3.3	1.5	H	131	Ketapang	68	4.3	6	H
52	Dracaena Draco	9	2.5	0.3	H	132	Ketapang Biola	32	7.3	4	H
53	Ketapang Biola	24	3.6	1	H	133	Ketapang Biola	26	3.3	3	H
54	Kamboja Merah	12	1.8	1	H	134	Ketapang	22	3.1	2.8	H
55	Kelengkeng	14	3.1	1.1	H	135	Ketapang Biola	26	3.4	3.1	H
56	Enterolobium	66	3.3	1.8	H	136	Theobroma	4.5	2.2	1	H
57	Pucuk Merah	5.5	0.8	0.1	H	137	Ketapang Biola	19	3.3	1.2	H
58	Modokaski	7	1.6	0.3	LH	138	Ketapang Biola	19	3.3	1	H
59	Pucuk Merah	4	1.7	0.15	H	139	Ketapang	22.3	3.4	4.5	H
60	Ketapang	42.5	4.4	6	H	140	Beringin Cina	9	1.9	0.05	H
61	Ketapang Biola	29.5	4.2	2	H	141	Srikaya	7	3.3	1	H
62	Pucuk Merah	5	1.7	0.08	H	142	Ketapang Biola	22.5	3.6	3	H
63	Ketapang Biola	21.5	3.2	0.3	H	143	Tabebuia	21	3.7	0.7	H
64	Pucuk Merah	7	2.1	0.35	H	144	Pucuk Merah	9	1.9	0.1	H
65	Pucuk Merah	4.5	0.9	0.05	H	145	Pucuk Merah	6	2.1	0.5	H
66	Pucuk Merah	17	2.3	0.3	H	146	Pulai	40	3.5	4.5	H
67	Kamboja Merah	11	2.2	0.3	H	147	Kamboja Obtusa	11	3.2	1	H
68	Ketapang Biola	11	2.2	0.9	H	148	Tabebuia	19	3.5	2.1	H
69	Pucuk Merah	9	2.1	0.5	H	149	Kamboja Merah	8.5	2.1	0.3	H
70	Pucuk Merah	10.5	1.9	0.5	H	150	Dracaena Draco	11	2.3	0.4	H
71	Pucuk Merah	11	1.9	0.1	H	151	Kelengkeng	4.5	2.4	1	H

Tree Code	Local Name	DBH (cm)	Tree Height (m)	Canopy Width (m)	Tree Condition	Tree Code	Local Name	DBH (cm)	Tree Height (m)	Canopy Width (m)	Tree Condition
72	Mahoni	43	4.1	1.1	H	152	Tabebuia	23	3.5	3	H
73	Cusonia	33	4.3	1.5	H	153	Viburnum	2.3	1.3	0.05	H
74	Nanas	12	0.7	0.1	H	154	Ketapang	44	4.4	4	H
75	Kamboja Merah	9.5	1.9	0.5	H	155	Jatropa	8.7	2.3	0.3	H
76	Pucuk Merah	4	0.9	0.1	H	156	Callophylum	4.5	2.3	0.5	H
77	Jambu Biji	13	2.1	1	LH	157	Trembesi	151	4.8	4.2	H
78	Jambu Biji	9	2.4	1	LH	158	Dracaena Draco	19	2.3	0.5	H
79	Duit	26	3.8	3	H	159	Theobroma	12.5	2.6	2.3	H
80	Dracaena Draco	26.3	2.3	0.3	H	160	Ketapang Biola	23	2.6	1	H

Note: Healthy (H) or Less Healthy (LH) classifications were based on leaf quality and crown structure of trees.

In contrast, Apkasi Park contains only 70 trees with a more restricted size distribution and is dominated by small to medium diameter classes. Although the overall tree health is relatively similar (±85%), less complex stand structures were observed compared to Abhirama Park. The difference indicates vegetation composition and development being influenced by management intensity and green open space utilization efforts [20]. Additionally, the park's being located farther from the city center may cause reduced intensity of vegetation planting and maintenance [21].

Table 2. Structural Characteristics of Vegetation in Akasi Park

Tree Code	Local Name	DBH (cm)	Tree Height (m)	Canopy Width (m)	Tree Condition	Tree Code	Local Name	DBH (cm)	Tree Height (m)	Canopy Width (m)	Tree Condition
1	Glodokan	25	3.6	0.7	H	36	Glodokan	27	2.4	0.5	H
2	Asam Kandis Laut	9	2.1	0.7	H	37	Palem Phoenix	8	2.5	1	H
3	Jarak Pager	23.5	0.9	0.4	H	38	Asam Buto	61	7	2	LH
4	Waru	8	3.5	1	H	39	Adonidia	13	3.2	0.6	H
5	Pulai	8.5	3.3	0.05	LH	40	Palem Phoenix	8	2.4	0.7	H
6	Sempu	7	1.5	0.3	S	41	Tabebuia	40	5	1.5	LH
7	Pulai	3.7	2.5	0.4	LH	42	Pucuk Merah	16	2.2	0.7	H

Tree Code	Local Name	DBH (cm)	Tree Height (m)	Canopy Width (m)	Tree Condition	Tree Code	Local Name	DBH (cm)	Tree Height (m)	Canopy Width (m)	Tree Condition
8	Nangka	10.5	1.4	0.6	H	43	Pucuk Merah	11	3	1	H
9	Mangga	11.2	3	0.4	H	44	Tabebuia	24.5	4	2	H
10	Kamboja	6.1	3.2	0.2	H	45	Tabebuia	21	7	1	H
11	Srikaya	15	0.9	0.5	H	46	Tabebuia	21	5	1	H
12	Duit	12	2.3	0.7	H	47	Pucuk Merah	11	2	0.7	H
13	Pulai	8.5	3.3	0.6	H	48	Tabebuia	20.5	5.3	1	H
14	Kemuning Cina	8.5	1.8	0.6	H	49	Tabebuia	20	4.5	1.2	H
15	Pulai	8.2	3.1	0.3	LH	50	Beringin	8.5	1.1	0.4	H
16	Pulai	6	3.4	0.4	H	51	Pulai	44	4.3	1.2	H
17	Karet Merah	124	5	2	H	52	Pulai	43	5	1.5	H
18	Duit	11	3.2	0.6	H	53	Pulai	35	4.3	1	H
19	Palem Raja	21	4	1	H	54	Duit	27	4.3	1.1	H
20	Palem Raja	19.8	3.8	1	H	55	Pulai	21.5	2.4	1.5	LH
21	Pulai	16	2.8	0.4	H	56	Pulai	67	5	1.5	H
22	Bismarckia	60	2	0.6	LH	57	Beringin Cina	18	0.9	0.5	H
23	Pucuk Merah	4	1.8	0.7	H	58	Wodietya	17	3.4	0.6	LH
24	Pucuk Merah	5	2.7	0.7	H	59	Pulai	58	5.2	1.3	H
25	Pucuk Merah	7	2.2	0.6	H	60	Kamboja Merah	27.4	3	1.4	H
26	Pucuk Merah	8	2.1	0.7	H	61	Tabebuia	16.4	3.3	1	LH
27	Pucuk Merah	99	2.3	0.8	H	62	Bichofia	38	3.5	1.2	LH
28	Pucuk Merah	5.5	2.2	0.7	H	63	Kelapa	17	2.3	0.6	LH
29	Beringin Cina	11.5	1.2	0.4	H	64	Pulai	7	2.5	0.4	LH
30	Palem Phoenix	8	1.7	0.3	H	65	Tabebuia	19.8	4	0.8	LH

Tree Code	Local Name	DBH (cm)	Tree Height (m)	Canopy Width (m)	Tree Condition	Tree Code	Local Name	DBH (cm)	Tree Height (m)	Canopy Width (m)	Tree Condition
31	Adonidia	8.8	2.4	0.6	H	66	Pulai	11	2.8	0.7	H
32	Wodietya	19.8	4.5	0.7	H	67	Beringin	43	1.4	0.6	H
33	Wodietya	18.5	4.3	0.6	H	68	Mimba	40	1.3	0.6	H
34	Beringin India	51.5	4.5	1.9	H	69	Pulai	46	4.3	1.3	H
35	Glodokan	27.5	5.5	0.8	H	70	Garcinia	6.8	1.5	0.6	H

Note: Healthy (H) or Less Healthy (LH) classifications were based on leaf quality and crown structure of trees.

Comparisons in Table 3 reveals the number of trees in Abhirama Park (159 trees; 69.4%) to be higher than in Apkasi Park (70 trees; 30.6%). The difference directly influence a gap in carbon sequestration capacity, as a greater number of trees and larger tree sizes provide higher biomass and increased carbon sequestration rates [22].

Table 3. Tree Inventory Summary using i-Tree Eco

Stratum	Number of Trees	Percent of Population
Abhirama Park	159	69.4%
Apkasi Park	70	30.6%
Study Area	229	100%

Carbon sequestration estimation using i-Tree Eco is based on parameters such as species type and DBH as primary data, alongside tree height, canopy size and condition, health status, and location to improve accuracy [23]. Areas with higher tree density and larger tree dimensions tend to have greater biomass, and consequently higher carbon sequestration capacity [3]. The results in Table 4 show that Abhirama Park has a gross carbon sequestration of 2.14 tons/year (7.85 tons CO_2/year), higher than Apkasi Park at 0.92 tons/year (3.39 tons CO_2/year). Their differences were influenced by tree size and density, where Abhirama Park contains more large-diameter trees, while Apkasi Park is dominated by smaller trees, resulting in lower sequestration capacity. This finding is consistent with studies observing the correlation between tree size, density, and vegetation management, with carbon density in urban parks [24].

Table 4. Annual Carbon Sequestration and CO_2 Equivalent in Urban Green Spaces

Stratum	Gross Carbon Sequestation (metric ton/yr)	CO_2 Equivalent (metric ton/yr)
Abhirama Park	2.14	7.85
Apkasi Park	0.92	3.39
Study Area	3.07	11.24

3.2 Spatial Assessment of Vegetation Density Using NDVI

The three level NDVI classification of Apkasi Park was used to observe low, medium, and dense vegetation. This threshold-based approach is widely used to distinguish spatial variations in land cover or land use, including vegetation health in urban areas [25]. Spatial distribution mapping of

vegetation density in both Abhirama Park and Apkasi Park provided an overview of existing green cover conditions, presented in Figure 3.

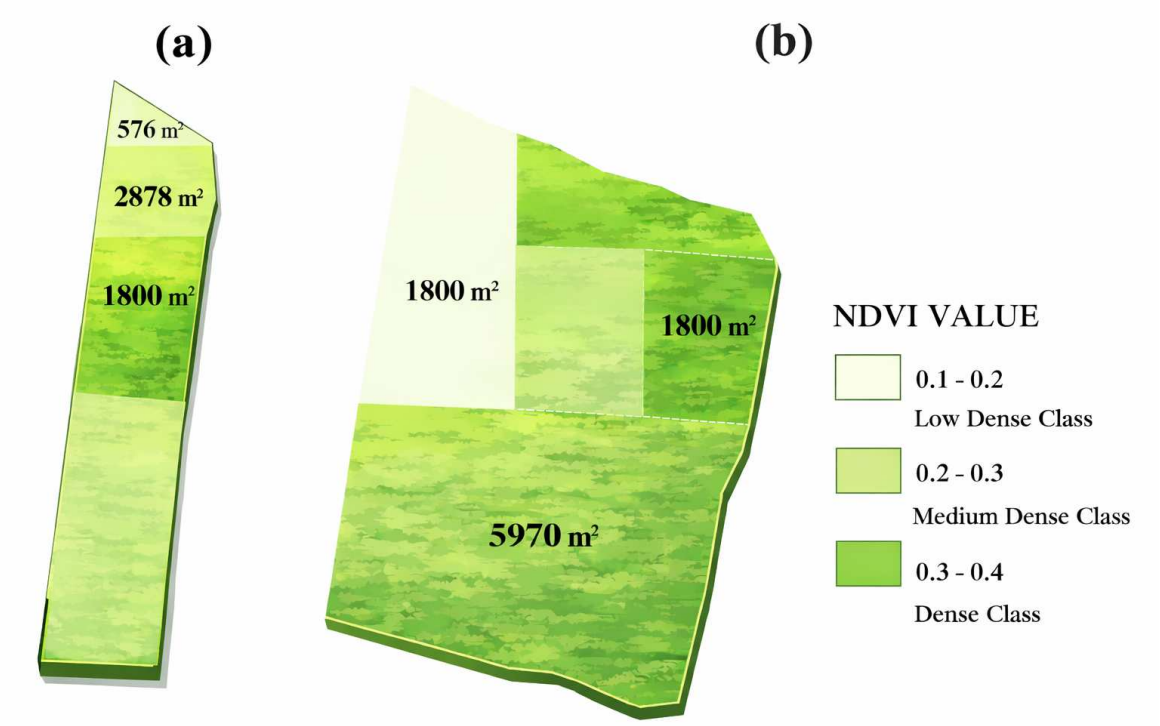


Figure 3. Spatial Assessment of Vegetation Density Using NDVI in (a) Abhirama Park and (b) Apkasi Park

From a total area of approximately 5254 m² at Abhirama Park, 576 m² (±11%) consisted of low-density vegetation, 2878 m² of medium-density vegetation, and 1800 m² of high-density vegetation. Limited spread of low-density vegetation was observed alongside the northern and southern area of the park, while medium-density vegetation dominated the area. This indicates that most of the park is already covered by relatively dense vegetation, limiting the space for additional planting. Therefore, focusing on rejuvenation and improving the condition of existing vegetation as to expansion could create better results during park management [26].

In contrast, Apkasi Park has an area of 9570 m² that consists of 1800 m² (±19%) low-density vegetation, 5970 m² of medium-density vegetation, and 1800 m² of high-density vegetation. Low density-vegetation dominated a larger portion of the park's area compared to Abhirama Park, indicating a larger potential for increasing vegetation coverage, and should be the priority of development strategies in its park management [27].

3.3 Microclimate Influence on Carbon Sequestration Capacity

Microclimate analysis presented in Figure 4 and 5 show air temperature and humidity as key factors influencing the ecological function of urban green spaces, particularly in supporting vegetation growth and carbon sequestration capacity. From Figure 4, air temperature in Abhirama Park and Apkasi Park coincides a typical diurnal pattern, increasing from morning to midday (peaking at 12:00–13:00) and declining in the afternoon. Abhirama Park reached a maximum temperature of 32.57 ± 0.23°C (Sunday, 13 July 2025), with Apkasi Park recording a higher temperature value of 33.70 ± 0.17°C (Friday, 4 July 2025). This gap is likely influenced by the canopy density, vegetation structure, and surface characteristics [23, 28].

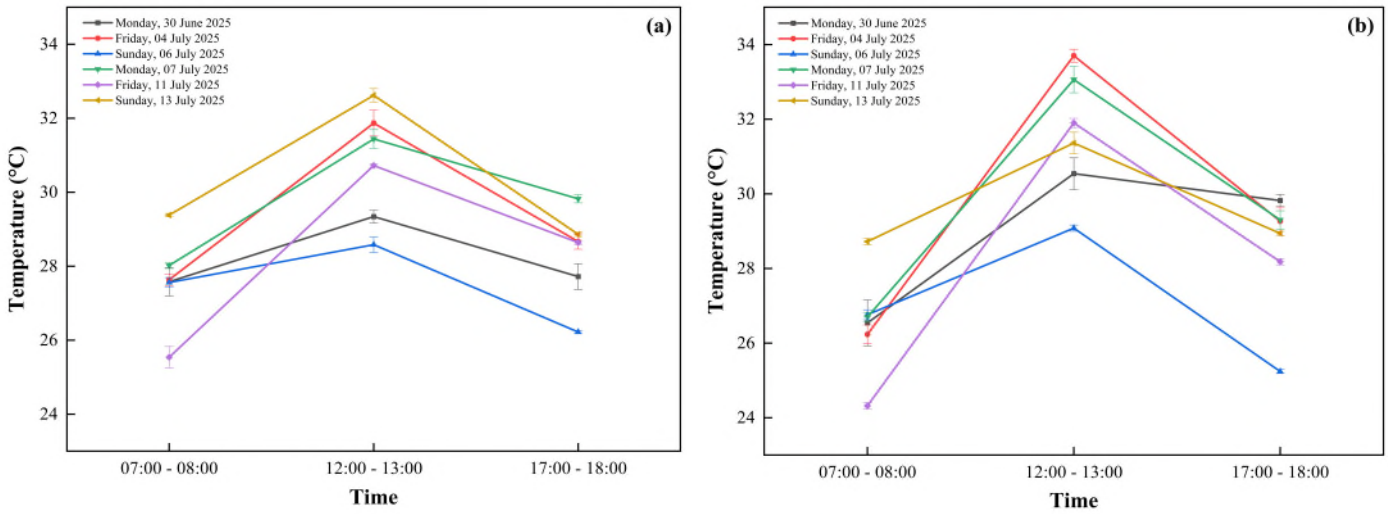


Figure 4. Existing Temperature in (a) Abhirama Park (b) Apkasi Park

Contrasting to temperature patterns, air humidity (Figure 5) shows an inverse pattern to temperature, with the lowest values occurring at midday. On Friday, 11 July 2025, at 12:00–13:00, a recorded minimum humidity at 59.33 ± 0.58% was observed at Abhirama Park, and a humidity of 61.67 ± 0.58% in Apkasi Park. These values are known to be affected by increased photosynthetically active radiation (PAR), air temperature, and wind speed, that enhance transpiration rates and consequently reduce relative humidity around vegetation [29]. Furthermore, the environmental conditions also influence stomatal responses, as plants must regulate the balance between photosynthesis and water-use efficiency, which is controlled by light intensity, CO_2 concentration, temperature, and relative humidity [30].

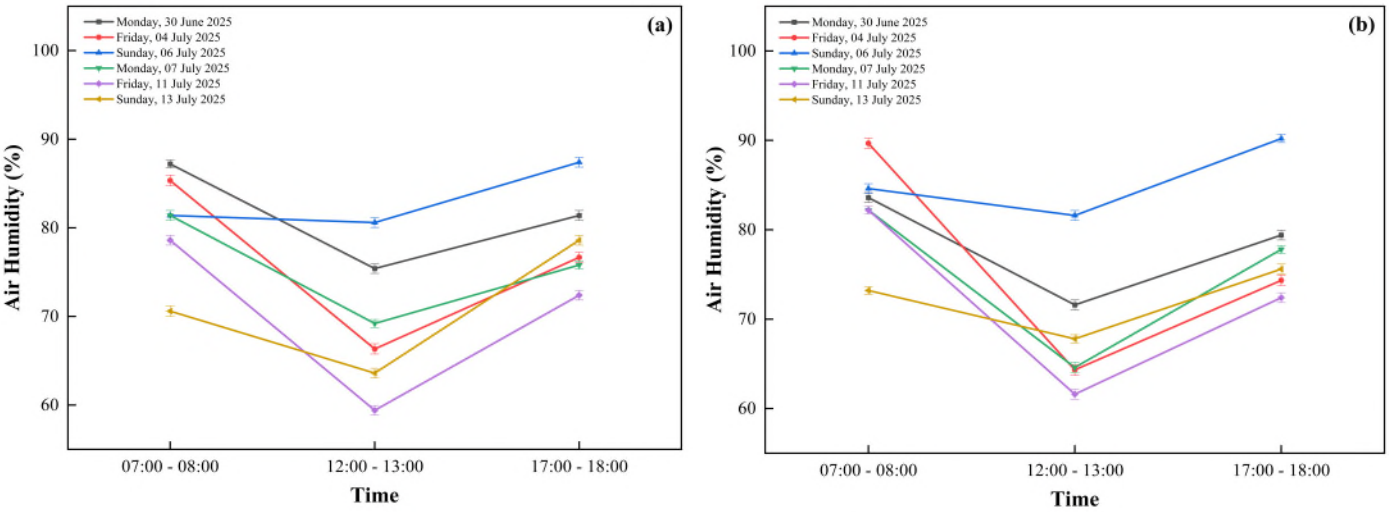


Figure 5. Existing Air Humidity in (a) Abhirama Park (b) Apkasi Park

Differences in microclimate conditions between the two parks are closely related to vegetation structure. Higher tree density at Abhirama Park tend to create a cooler and more stable microclimate compared to Apkasi Park. Denser canopy cover reduces leaf thermal stress, which improves photosynthetic efficiency [31, 32]. Vegetation density, microclimate conditions, and CO_2 uptake rates, are known to relate with denser vegetation as it provides the favorable environment for carbon assimilation per unit biomass [22].

In Table 5, Transportation-related CO_2 emissions were calculated using the IPCC Tier 2 method, and carbon sequestration utilized the i-Tree Eco model. The existing vegetation in Abhirama Park

exhibits a sequestration capacity of only 0.90 kg/h, equivalent to 1.33% of the total emissions (67.32 kg/h). On the contrary, Apkasi Park show a lower capacity of 0.39 kg/h, about 0.50% of its total emissions (77.33 kg/h). Even with the varying microclimatic conditions affecting photosynthetic activity, current vegetation provides extremely limited contribution to carbon sequestration compared to the magnitude of emissions. This discrepancy is not solely linked to tree abundance, but also influenced by vegetation characteristics, including trunk diameter, canopy area, and overall structural composition [23, 28].

Table 5. Existing CO_2 Emission and Absorption rates

Parameter	Unit	Abhirama Park	Apkasi Park
Year	-	2025	2025
Average CO_2 Emissions	kg/h	67.32	77.33
Average CO_2 Sequestration	kg/h	0.90	0.39
CO_2 Sequestration Efficiency	%	1.33	0.50

Differences in sequestration capacity between the two parks are therefore governed by both microclimatic conditions and vegetation attributes. Structural factors such as tree size, canopy extent, and species composition play a critical role in determining total biomass and carbon uptake efficiency. Accordingly, effective mitigation strategies should not only consider microclimate optimization but also prioritize the establishment of high-biomass tree species, appropriate planting density, and vegetation composition that can maximize the utilization of local environmental conditions to enhance CO_2 sequestration in urban areas [22].

3.4 Estimation of Vehicular CO_2 Emissions in Urban Areas

Current 10-year projections of motor vehicle counts in Indonesia visualizes the challenges Indonesia faces to achieve its greenhouse gas emission reduction targets under the Paris Agreement. A 29% reduction independently, or up to 41% with international support by 2030, was ratified through Law No. 16 of 2016. Transportation remains one of several big contributors to CO_2 emissions that is expected to be the last sector to reach peak carbon emissions in the future [33]. In line with this, Figure 6 show increasing trends in yearly vehicle counts based on data from the Central Statistics Agency of Sidoarjo Regency during the 2021–2024 period, indicating growing emission pressure in the coming years.

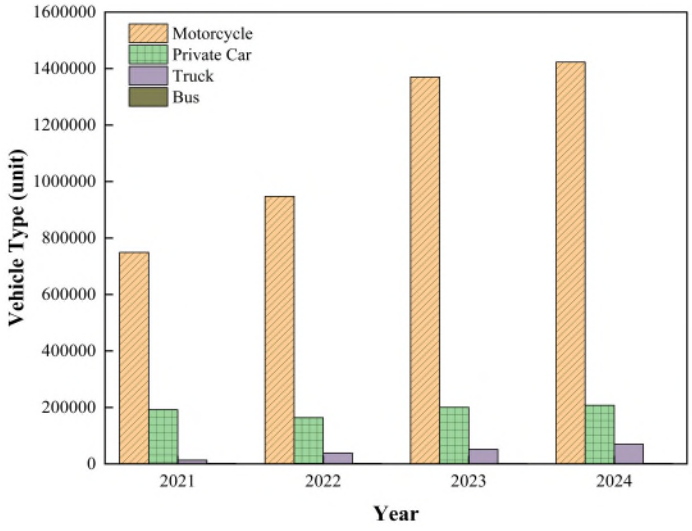


Figure 6. Vehicle Type Growth in Sidoarjo Regency (2021–2024) Based on Data from the Central Statistics Agency of Sidoarjo Regency

The correlation coefficient (r) for each vehicle type was found from arithmetic, least squares, and geometric calculation, where the method yielding an r value closest to 1 was selected as the basis for prediction. As shown in Figure 7, the projected number of motor vehicles were accumulated annually and used to estimate CO_2 emissions, following the IPCC Tier 2 emission calculation approach, enabling the identification of vehicle growth trends as well as the projected CO_2 emission impacts over the next ten years.

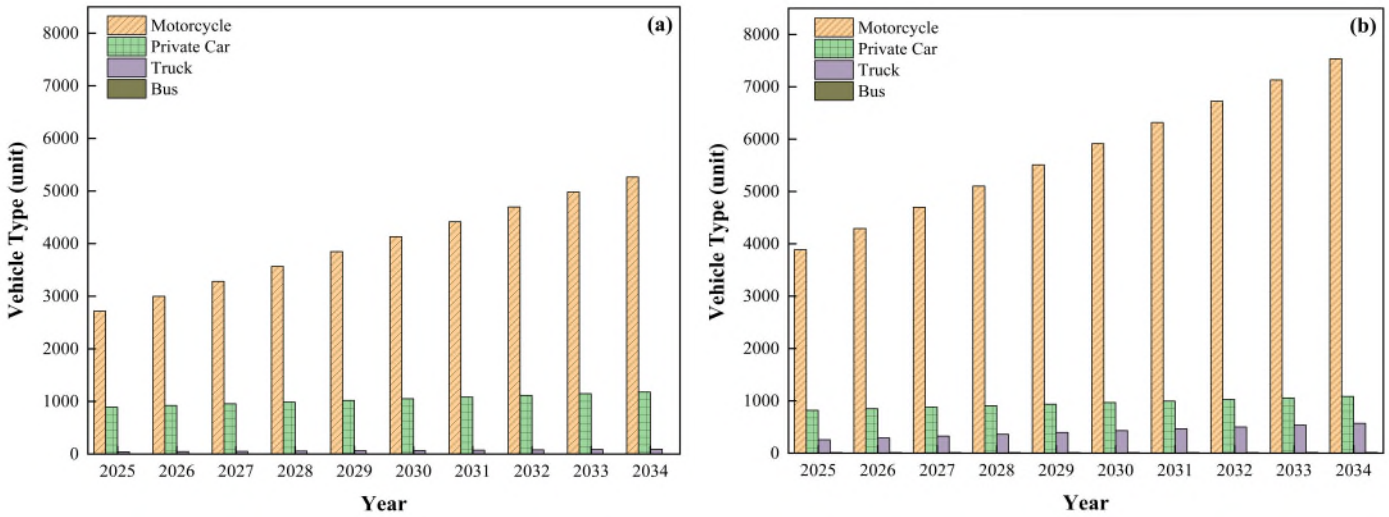


Figure 7. Projected Vehicle Type Growth (2025–2035) in (a) Abhirama Park and (b) Apkasi Park

The rise in the number of motorcycles and private cars is the main factor driving the increase in CO_2 emissions, from 67.32 kg/h in 2025 to 112.05 kg/h in 2035. The trend also reflects a linear relationship between traffic volume and carbon emissions, confirming the road transportation sector as one of the main contributors to greenhouse gas emissions driving global warming [34].

Figure 8 show Apkasi Park projecting higher increase in emissions compared to Abhirama Park, from 77.33 kg/h in 2025 to 141.23 kg/h in 2035 or about 82.6%. This increase is driven by the dominance of motorcycles as the most numerous vehicles, contributing the largest share of total emissions even though their emissions per unit are lower than those of heavy vehicles. This trend is also consistent with the continued rise in emissions from the transportation sector over time [35].

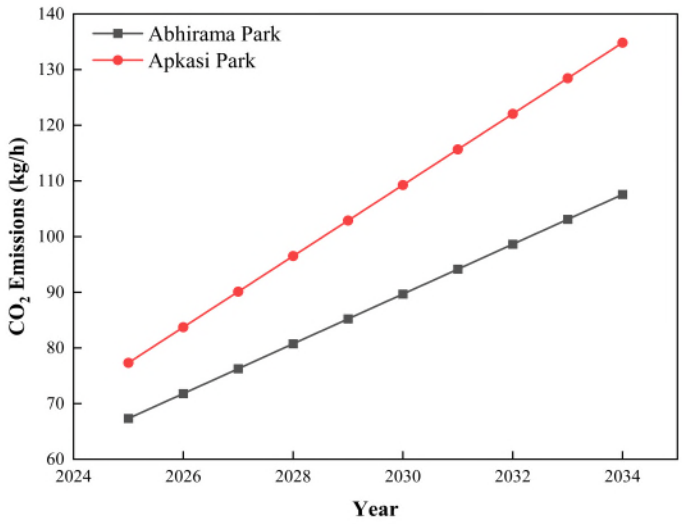


Figure 8. CO_2 Emissions in Abhirama and Apkasi Parks (2025–2035)

While both parks show increasing emission rates, the difference show a higher growth rate in Apkasi Park, indicating larger traffic pressure in suburban areas compared to the city center. The

condition is explained by urban sprawl patterns, as suburban areas fill with increasing use of private vehicles and logistical activities. Inadequate management may result in elevated air pollution levels and deterioration of urban environmental quality.

3.5 Integrated Scenario-Based Modeling of Carbon Sequestration and Oxygen Production Using i-Tree Forecast

3.5.1 Carbon Sequestration Using i-Tree Forecast

in Figure 9, projections of tree growth and health were used for i-Tree Forecast analysis, alongside environmental variables to predict future carbon storage [36].

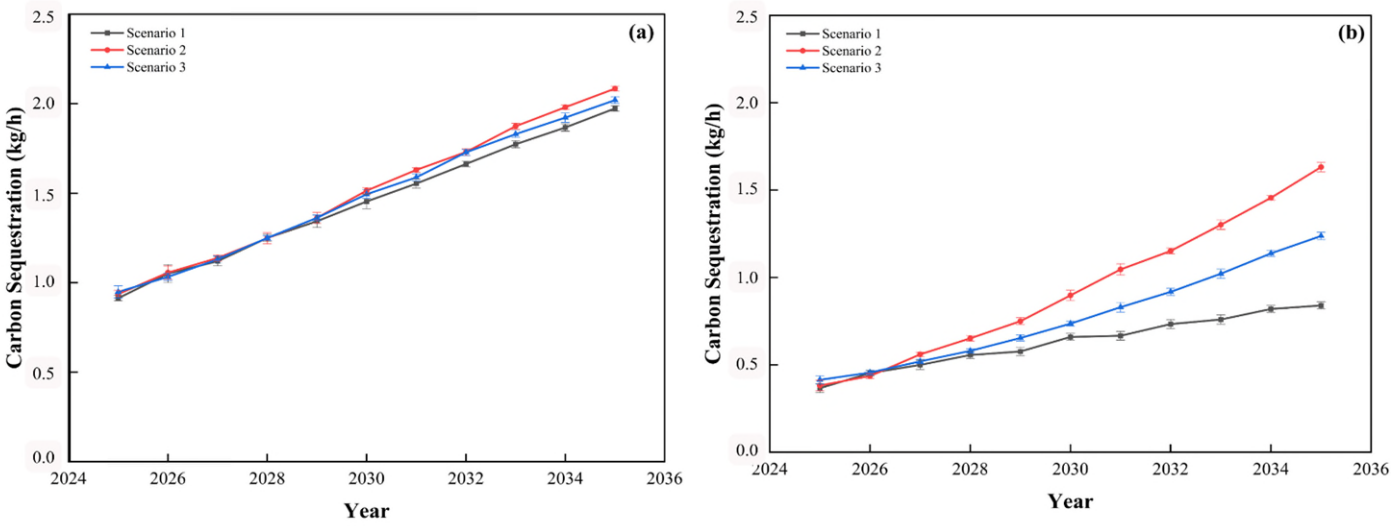


Figure 9. Carbon sequestration graph of (a) Abhirama Park (b) Apkasi Park

In Abhirama Park, carbon sequestration capacity increased in Scenario 1 from 0.91 ± 0.02 kg/h (2025) to 1.97 ± 0.02 kg/h (2035), in Scenario 2 from 0.93 ± 0.03 kg/h (2025) to 2.08 ± 0.02 kg/h (2035), and in Scenario 3 from 0.94 ± 0.04 kg/h (2025) to 2.02 ± 0.02 kg/h (2035). Both trends show the growth and expansion of tree canopies that enhances photosynthesis and biomass accumulation, consequentially increasing carbon sequestration potential over time [37]. The vegetation density and structural maturity at Abhirama Park indicate improved carbon storages when existing trees are sustainably maintained [38].

In Apkasi Park, carbon sequestration capacity also increased from 2025 to 2035, although values were lower than in Abhirama Park. In Scenario 1, it increased from 0.37 ± 0.03 kg/h (2025) to 0.84 ± 0.02 kg/h (2035), in Scenario 2 from 0.38 ± 0.03 kg/h (2025) to 1.63 ± 0.03 kg/h (2035), and in Scenario 3 from 0.41 ± 0.03 kg/h (2025) to 1.24 ± 0.02 kg/h (2035). The lower carbon sequestration is due to a smaller tree population and the dominance of young trees with small canopies, resulting in lower carbon uptake compared to mature trees [39]. The slow but steady increase indicates that carbon sequestration capacity is also influenced by tree growth, canopy development, tree species, and management strategies in urban parks [28].

3.5.2 Oxygen Production Using i-Tree Forecast

i-Tree Forecast analysis was used to model oxygen production under three management scenarios over a given period, as shown in Figure 10. This analysis illustrates the impact of each scenario on total oxygen production [3].

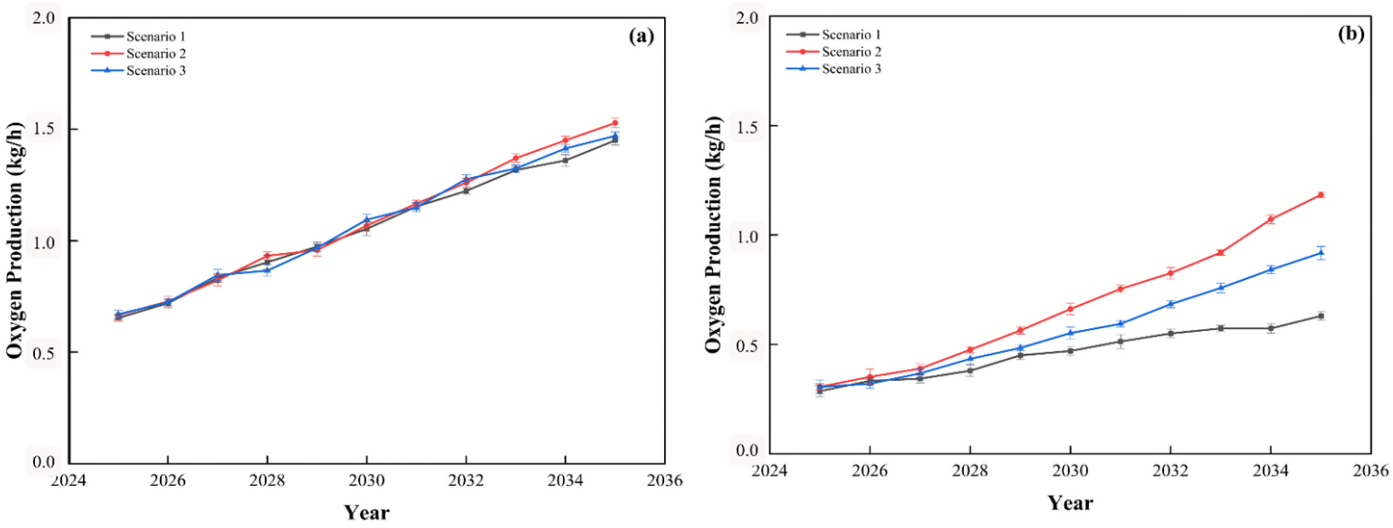


Figure 10. Oxygen Production graph of (a) Abhirama Park (b) Apkasi Park

In Abhirama Park, oxygen production increased in Scenario 1 from 0.65 ± 0.02 kg/h (2025) to 1.45 ± 0.02 kg/h (2035), in Scenario 2 from 0.66 ± 0.02 kg/h (2025) to 1.52 ± 0.03 kg/h (2035), and in Scenario 3 from 0.67 ± 0.02 kg/h (2025) to 1.47 ± 0.02 kg/h (2035). The increase in oxygen production corresponds with biomass accumulation due to tree growth and canopy expansion, as i-Tree estimates oxygen release in parallel with carbon sequestration [40]. This trend reflects the condition of the trees and their carbon sequestration capacity in urban canopies, although its economic value is limited, and indicates that well-managed green spaces can enhance ecological function [41].

In Apkasi Park, oxygen production also increased from 2025 to 2035, although values were lower than in Abhirama Park. In Scenario 1, it increased from 0.29 ± 0.03 kg/h (2025) to 0.63 ± 0.02 kg/h (2035), in Scenario 2 from 0.30 ± 0.02 kg/h (2025) to 1.18 ± 0.02 kg/h (2035), and in Scenario 3 from 0.30 ± 0.03 kg/h (2025) to 0.91 ± 0.03 kg/h (2035The increase in tree size and stand density, particularly diameter at breast height (DBH) growth and live biomass, drives higher photosynthesis and greater net carbon sequestration, resulting in increased modeled oxygen production [40]. Scenario variations in Apkasi Park indicate that greener and well-maintained vegetation enhances short-term oxygen production and supports carbon sequestration [42].

4. Conclusions

Differences in vegetation structure, microclimate conditions, and emission pressure lead to uneven ecosystem service capacity between the two parks. Abhirama Park has the bigger carbon sequestration capacity with 159 trees and mature structure (2.14 tons/year or 0.90 kg/h), yet this is far below its emission level (67.32 kg/h). In contrast, Apkasi Park has fewer and smaller trees (70 trees) with smaller sequestration abilities (0.92 tons/year or 0.39 kg/h), all while its emissions continue to rise to 141.23 kg/h by 2035 (driven by the dominance of motorcycles). The current assessment indicates that existing urban green spaces are not yet able to pivot urban emissions. To maximize carbon offsetting abilities, improving vegetation structure, increasing high-biomass trees, and controlling emission sources are essential to go alongside maintaining the existing vegetation.

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Data Availability Statement

All data generated and analyzed during this study are presented in this published article. The data used are primary data obtained directly from the research and are not derived from secondary sources.

Author Contribution

Okik Hendriyanto Cahyonugroho contributed to conceptualization, methodology, supervision, project administration, and review and editing of the manuscript. Nur Laili Alfiatin Mukharomah contributed to investigation, data curation, formal analysis, and preparation of the manuscript draft. Nur Sinta Abadiyah contributed to investigation, data curation, and formal analysis. Adityas Agung Ramandani contributed to software development and visualization. Euis Nurul Hidayah and Baranitharan Ethiraj contributed to validation and review and editing of the manuscript. Chantaraporn Phalakornkule contributed to review and editing of the manuscript. All authors have read and approved the final manuscript.

Conflicts of Interest

The authors affirm that no conflicts of interest have affected the preparation or publication of this manuscript. All ethical principles have been strictly upheld, including maintaining academic integrity, preventing plagiarism, ensuring informed consent where applicable, avoiding any form of data fabrication or falsification, and refraining from duplicate submission, publication, or redundant reporting.

Abbreviations

BAU	Business-as-usual
C	Carbon
CO_2	Carbon dioxide
DBH	Diameter at breast height
d	Horizontal distance
GOS	Green open spaces
GIS	Geographic Information System
H	Healthy
LH	Less healthy
NDVI	Normalized Difference Vegetation Index
OLI	Operational Land Imager
PAR	Photosynthetically active radiation
PUPR	Ministry of Public Works and Housing (Indonesia)
TIRS	Thermal Infrared Sensor
USGS	United States Geological Survey

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